



**HAL**  
open science

# Molecular implementation of shape-changing user interfaces

Laura Pruszeko

► **To cite this version:**

Laura Pruszeko. Molecular implementation of shape-changing user interfaces. Human-Computer Interaction [cs.HC]. Université Grenoble Alpes [2020-..], 2023. English. NNT : 2023GRALM033 . tel-04378955

**HAL Id: tel-04378955**

**<https://theses.hal.science/tel-04378955>**

Submitted on 8 Jan 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

THÈSE

Pour obtenir le grade de

**DOCTEUR DE L'UNIVERSITÉ GRENOBLE ALPES**

École doctorale : MSTII - Mathématiques, Sciences et technologies de l'information, Informatique

Spécialité : Informatique

Unité de recherche : Laboratoire d'Informatique de Grenoble

**Implémentation moléculaire d'interfaces utilisateur à changement de forme**

**Molecular implementation of shape-changing user interfaces**

Présentée par :

**Laura PRUSZKO**

Direction de thèse :

**Céline COUTRIX**

CHARGE DE RECHERCHE HDR, CNRS DELEGATION ALPES

Directrice de thèse

**Yann LAURILLAU**

MAITRE DE CONFERENCES HDR, Université Grenoble Alpes

Co-directeur de thèse

**Julien BOURGEOIS**

PROFESSEUR DES UNIVERSITES, UNIVERSITE DE BOURGOGNE

Co-directeur de thèse

Rapporteurs :

**THOMAS PIETRZAK**

MAITRE DE CONFERENCES HDR, UNIVERSITE DE LILLE

**EMMANUEL DUBOIS**

PROFESSEUR DES UNIVERSITES, UNIVERSITE TOULOUSE 3 - PAUL SABATIER

Thèse soutenue publiquement le **29 août 2023**, devant le jury composé de :

**THOMAS PIETRZAK**

MAITRE DE CONFERENCES HDR, UNIVERSITE DE LILLE

Rapporteur

**EMMANUEL DUBOIS**

PROFESSEUR DES UNIVERSITES, UNIVERSITE TOULOUSE 3 - PAUL SABATIER

Rapporteur

**MIRIAM STURDEE**

ASSISTANT PROFESSOR, UNIVERSITY OF ST ANDREWS

Examinatrice

**PATRICK REIGNIER**

PROFESSEUR DES UNIVERSITES, GRENOBLE INP

Président

Invités :

**YANN LAURILLAU**

MAITRE DE CONFERENCES HDR, UNIVERSITE GRENOBLE ALPES

**CELINE COUTRIX**

CHARGE DE RECHERCHE HDR, CNRS DELEGATION ALPES





---

**Title:** Molecular implementation of shape-changing user interfaces.....

**Keywords:** Tangible interaction, shape-changing user interfaces, human-computer interaction

**Abstract:** Shape-changing user interfaces (UIs), which refer to physical devices capable of altering their form to accommodate users, tasks, or environments, have the potential to bridge the gap between tangible user interfaces' physicality and the flexibility of graphical user interfaces. These UIs offer promising prospects, including adaptive affordances and improved eye-free interaction. However, they introduce new considerations for the HCI community to examine, as previous research has highlighted the associated challenges. Our objective is to explore the challenges and opportunities presented by modular robots as a novel approach to implementing modular shape-changing UIs. In this context, modular robots are defined as ensembles of robotic modules, which are micro-electromechanical systems embedding computational capabilities and enabling shape changes either independently or collectively. This thesis

specifically investigates the challenges related to *modular* shape-changing interfaces. The research hypothesis is that modular robots can address the limitations of current implementations of shape-changing UIs, such as pneumatic actuation, rod-based displays, and mechanical structures. Unlike these solutions, modular robots enable the addition of modules to an existing shape and facilitate the attainment of any desired shape, akin to programmable "play-doh". A crucial initial step involves isolating the design factors and comprehending their relative impact on user interaction. This thesis contributes to the field of HCI by: (1) reviewing and structuring the design space of modular shape-changing UIs and (2) conducting user studies to evaluate the impact of three parameters—module size, shape, and strength—on the design of physical interfaces.



---

**Titre :** Implémentation moléculaire d'interfaces utilisateur à changement de forme .....

**Mot clés :** Interaction tangible, interfaces à changement de forme, interaction humain-machine

**Résumé :** Les interfaces utilisateur à changement de forme, c'est-à-dire des dispositifs physiques capables de modifier leur forme pour s'adapter à l'utilisateur, à la tâche ou à l'environnement, ont le potentiel de combler le fossé entre la physicalité des interfaces tangibles et la flexibilité des interfaces graphiques. Ces interfaces offrent des perspectives prometteuses, notamment des possibilités d'adaptation et une meilleure interaction sans regarder. Cependant, étant donné que ces types d'interfaces ne sont pas couramment utilisés dans notre vie quotidienne, elles soulèvent de nouvelles considérations en termes d'utilisabilité à explorer pour la communauté de l'interaction homme-machine (IHM), comme l'ont souligné les travaux précédents. Notre objectif est d'étudier les défis et les opportunités des robots modulaires en tant que nouvelle façon d'implémenter des interfaces à changement de forme modulaires. Nous définissons un robot modulaire comme un ensemble de modules robotiques, c'est-à-dire des systèmes microélectromécaniques intégrant des capacités informatiques leur permettant de changer de forme, que ce soit de manière autonome ou non. Cette thèse étudie spécifique-

ment les défis liés aux interfaces à changement de forme *modulaires*. L'hypothèse de recherche est que les robots modulaires peuvent surmonter les inconvénients des implémentations actuelles d'interfaces à changement de forme, tels que l'actionnement pneumatique, les affichages à base de tiges et les structures mécaniques. Ces solutions ne permettent pas l'ajout de matière à l'interface et n'autorisent pas toujours la présence de zones vides, telles que des trous et des ponts. En revanche, les robots modulaires peuvent ajouter des modules à une forme préexistante et pourraient permettre de simuler n'importe quelle forme souhaitée, à l'instar d'une "pâte à modeler" programmable. Une des premières étapes nécessaires consiste à isoler les facteurs de conception et à comprendre leur impact relatif sur l'interaction utilisateur. Cette thèse contribue au domaine de l'IHM en (1) examinant et structurant l'espace de conception des interfaces utilisateur modulaires à changement de forme et (2) réalisant des études utilisateurs pour évaluer l'impact de trois paramètres impliqués dans la conception des modules d'une interface physique, à savoir leur taille, leur forme et leur force de connexion.



# TABLE OF CONTENTS

---

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Context . . . . .	2
1.1.1	Flexibility vs physicality . . . . .	2
1.1.2	Implementing shape-change as a compromise . . . . .	4
1.2	Problem statement . . . . .	7
1.3	Research methodology . . . . .	9
1.3.1	Constructing a structured cross-disciplinary design space . . . . .	10
1.3.2	Empirically exploring the impact of module design parameters . . . . .	10
1.4	Contributions . . . . .	12
1.4.1	Contribution 1: A design space for modular shape-changing UIs . . . . .	12
1.4.2	Contribution 2: Characterization and evaluation of the impact of the size, shape and bonding strength of the modules on user interaction . . . . .	13
1.5	Structure of the thesis . . . . .	15
<b>2</b>	<b>Research Topic and Motivation</b>	<b>19</b>
2.1	Introduction . . . . .	20
2.2	Shape-changing user interfaces . . . . .	21
2.2.1	Graphical vs tangible user interfaces . . . . .	21
2.2.2	Shape-changing interfaces . . . . .	24
2.3	Modular robotic systems . . . . .	28
2.3.1	Architectures . . . . .	29
2.3.2	Reconfigurations . . . . .	32
2.3.3	Homogeneity . . . . .	33
2.4	Modular shape-changing user interfaces . . . . .	35
2.4.1	Benefits and implications of modularity . . . . .	35
2.4.2	User experience of shape-change and modularity . . . . .	37
<b>I</b>	<b>A Design Space for Modular Shape-changing User Interfaces</b>	<b>41</b>
<b>3</b>	<b>Reviewing the Cross-disciplinary Literature in HCI and Robotics</b>	<b>47</b>
3.1	Introduction . . . . .	48
3.2	Methodology . . . . .	49



3.2.1	Identification . . . . .	50
3.2.2	Screening . . . . .	51
3.2.3	Eligibility . . . . .	52
3.2.4	Inclusion . . . . .	52
3.3	Corpus analysis . . . . .	54
3.3.1	Analysis 1: robotics literature . . . . .	54
3.3.2	Analysis 2: HCI literature . . . . .	54
3.3.3	Importance of unifying existing design spaces . . . . .	55
3.4	Synthesis . . . . .	56
<b>4</b>	<b>Design Properties for Modular Shape-changing User Interfaces</b>	<b>59</b>
4.1	Introduction . . . . .	60
4.2	Properties of the interface (macro scale) . . . . .	61
4.2.1	Coupling between modules (Digital /Physical) . . . . .	61
4.2.2	Combination between the digital and physical states of the UI (Digital / Physical) . . . . .	63
4.2.3	Shape-change ability (Physical) . . . . .	64
4.2.4	Reversibility (Physical) . . . . .	65
4.2.5	Dimensionality (Physical) . . . . .	65
4.2.6	Volume required for shape-change (Physical) . . . . .	66
4.2.7	Usage consumption (Physical/Interaction) . . . . .	66
4.2.8	Control over shape-change (Interaction) . . . . .	67
4.2.9	Interactivity (Interaction) . . . . .	68
4.2.10	Safety (Interaction) . . . . .	69
4.3	Properties of the modules (micro scale) . . . . .	71
4.3.1	Input, output and processing capabilities (Intra-module) . . . . .	71
4.3.2	Power storage (Intra-module) . . . . .	71
4.3.3	Size (Module) . . . . .	72
4.3.4	Shape (Module) . . . . .	72
4.3.5	Speed (Module) . . . . .	72
4.3.6	Packing (Inter-modules) . . . . .	73
4.3.7	Strength (Inter-modules) . . . . .	73
4.3.8	Others . . . . .	74
4.4	Synthesis . . . . .	75
<b>5</b>	<b>Impact between Design Properties</b>	<b>77</b>
5.1	Introduction . . . . .	78
5.2	Impact between macro-scale properties . . . . .	79

5.2.1	Impact on/with shape-changing ability . . . . .	79
5.2.2	Impact on/of control over shape-change . . . . .	80
5.2.3	Impact of interactivity on usage consumption. . . . .	81
5.3	Impact between micro-scale properties . . . . .	82
5.3.1	Impact on/of size . . . . .	82
5.3.2	Impact on/of strength . . . . .	83
5.3.3	Impact of/on power storage. . . . .	84
5.3.4	Impact of Shape on Packing. . . . .	84
5.4	Impact between micro- and macro-scale properties . . . . .	85
5.4.1	Shape-change ability . . . . .	85
5.4.2	Interactivity . . . . .	87
5.4.3	Smoothness and resolution . . . . .	87
5.4.4	Safety . . . . .	88
5.4.5	Control over shape-change . . . . .	88
5.4.6	Hierarchy . . . . .	89
5.4.7	Combination between states $\leftarrow$ I/O & processing capabilities . . . . .	89
5.4.8	Dimensionality $\leftarrow$ Shape . . . . .	89
5.4.9	Usage consumption $\leftarrow$ Power storage . . . . .	89
5.5	Synthesis . . . . .	90

## **II Evaluation of the Impact of Module Design Parameters on User Interaction** **101**

<b>6</b>	<b>Evaluating the Impact of Module Size on Interaction</b>	<b>105</b>
6.1	Introduction . . . . .	106
6.2	Related Work . . . . .	109
6.2.1	Haptic perception of tangible UIs. . . . .	109
6.2.2	Tactile discrimination of textures. . . . .	109
6.2.3	Minimal size of gaps between modules. . . . .	110
6.2.4	Tactile perception through a probe. . . . .	110
6.2.5	Tactile perception of roughness and TUIs . . . . .	111
6.2.6	Kinesthetic perception and TUIs. . . . .	111
6.3	Method . . . . .	113
6.3.1	Apparatus . . . . .	113
6.3.2	Participants . . . . .	114
6.3.3	Experimental design . . . . .	114
6.3.4	Procedure . . . . .	114

6.3.5	Data collection and analysis . . . . .	116
6.4	Experimental Results - Target Acquisition . . . . .	117
6.4.1	Performance . . . . .	117
6.4.2	Questionnaires. . . . .	118
6.5	Experimental Results - Target pursuit . . . . .	119
6.5.1	Performance . . . . .	119
6.5.2	Questionnaires . . . . .	120
6.6	Discussion . . . . .	121
6.6.1	Size of modules & target acquisition . . . . .	121
6.6.2	Size of modules & target pursuit . . . . .	122
6.6.3	Grasps observed . . . . .	122
6.6.4	Limitations of the studies . . . . .	124
6.6.5	Implications . . . . .	125
6.7	Synthesis . . . . .	126
<b>7</b>	<b>Evaluating the Impact of Module Shape and Bonding Strength on Interaction</b>	<b>129</b>
7.1	Introduction . . . . .	130
7.2	Related work . . . . .	133
7.2.1	Manipulating modular TUIs . . . . .	133
7.2.2	Magnetic actuation and bonding strength . . . . .	135
7.3	Method . . . . .	137
7.3.1	Apparatus and participants . . . . .	137
7.3.2	Experimental design . . . . .	138
7.3.3	Experimental tasks . . . . .	139
7.3.4	Procedure . . . . .	141
7.3.5	Data collection and analysis . . . . .	141
7.4	Results . . . . .	142
7.4.1	Overall results . . . . .	143
7.4.2	Results across manipulations and configurations . . . . .	145
7.5	Discussion . . . . .	152
7.5.1	Impact of module shape . . . . .	152
7.5.2	Impact of bonding strength . . . . .	153
7.5.3	Implications for the design of future interaction techniques with modular TUIs . . . . .	154
7.5.4	Implications for future technological development of modular TUIs . . . . .	155
7.6	Limitations of the study . . . . .	157
7.7	Synthesis . . . . .	158

<b>8</b>	<b>Conclusion</b>	<b>163</b>
8.1	Thesis contributions . . . . .	164
8.1.1	Theories and concepts: a structured design space for modular shape-changing UIs . . . . .	164
8.1.2	Empirical user studies: characterization and impact of three design parameters on user interaction . . . . .	166
8.2	Limitations and short-term perspectives . . . . .	169
8.2.1	Evaluation of design parameters with non-static UIs . . . . .	169
8.2.2	Safety of shape-changing UIs . . . . .	170
8.2.3	User perception and expected context of use . . . . .	170
8.3	Long-term perspectives for modular shape-changing interfaces . . . . .	172
8.3.1	Recentering reconfiguration strategies and algorithms on the user . . . . .	172
8.3.2	Exploring end-user programming with modular robotics . . . . .	173
8.3.3	Exploring temporality in shape change . . . . .	174



# LIST OF FIGURES

---

1.1	Two examples of real-life scenarios where users need both flexibility and physicality depending on the interaction context (a) A car dashboard needs physicality for eye-free driving, but can implement a touchscreen with GUI controls (e.g., to control the music, temperature, navigation). (b) The user can control the temperature of their smart home with their smartphone when they are on the go, or with a physical control panel when they are in their home. . . . .	3
1.2	Examples of two shape-changing UIs that are not modular: Knobslider is a mechanically actuated implementation, while PneuUI is pneumatically actuated. . . . .	5
1.3	Our research approach: we first defined a design space for modular shape-changing UIs [232], after which we set out to study the impact of three identified module design parameters on user interaction: (1) their size [234] and (2) their shape and bonding strength [233]. . . . .	9
1.4	Structure of the thesis. . . . .	16
2.1	This thesis presents work conducted on shape-changing interfaces, which is nested at the crossroad between GUIs and TUIs. . . . .	22
2.2	Examples of two kinds of TUIs commonly found in the HCI literature. (a) Tangible artefacts on an interactive surface allow musicians to control instruments. (b) Environmental engineers and landscape designers test out their topography design on an augmented clay display. . . . .	23
2.3	Example of early shape-changing interface implementations: Haptic Chameleon and Lumen (a,b) appeared in 2004, Siftables (c) appeared in 2007. . . . .	24
2.4	Dynaknob [298] can change between four different knob shapes to adapt its physical affordance depending on the functionality. . . . .	25
2.5	Shapebots and Materiabes are two examples of shape-changing interfaces that can be used to physically render and manipulate data. . . . .	25
2.6	Shapeshift [261] allows for a faster prototyping workflow, by pre-rendering a 3D model from OpenSCAD in 2.5D through a pin-based shape display. . . . .	26
2.7	SpaceHuman [275] augments the user by equipping them with a robotic prosthetic tail to enhance stability and safety in a microgravity context. . . . .	26
2.8	TexelBlocks [49] can, e.g., provide an interactive textured minimap. . . . .	27
2.9	CEBOT [81] was the first implementation of a modular robot. . . . .	28

2.10	Examples of modular shape-changing UIs and the three main types of architecture: (a) lattice, (b) chain and (c) swarm. . . . .	29
2.11	Example of two possible lattices for spatial arrangements of robots. . . . .	30
2.12	Example of the two different configurations for truss implementations: Variable Geometry Truss (VGT, Subfigure 2.12a), or Variable Topology Truss (VTT, Subfigure 2.12b). The main difference is that the VGT prototype on the left can reconfigure by changing the size of the beams, while the VTT prototype on the right can additionally reconfigure the nodes between the beams. . . . .	31
2.13	While shape-changing UIs are at the crossroad between TUIs and GUIs, <i>modular</i> shape-changing UIs are at the crossroad between shape-changing UIs and modular robotics. . . . .	35
2.14	Application examples for PickCells, a lattice implementation from HCI. Users can, e.g., detach a line of modules to use as a remote or change the disposition of a few modules around the device to enter a password. . . . .	36
2.15	Application examples for chainFORM [196], a chain implementation from HCI. . . . .	37
2.16	Application examples for Zooids [159], a swarm implementation from HCI. Zooids can, e.g., display objects and shapes by acting as physical pixels or communicate user input by acting as physical controllers. . . . .	37
2.17	Our structured space of properties: (left) user centered properties at the macro scale of the modular shape-changing UI, and (right) technical properties at the micro-scale of the modules. . . . .	45
3.1	Example of two modular shape-changing UIs with only one fitting our definition of a modular robot. M-Blocks (3.1a) fits our definition as the modules embed computational capabilities, whereas we do not take Dynablocks (3.1b) as they only embed passive magnets and rely on an external pin-array for reconfiguration. . . . .	48
3.2	Flowchart of the systematic review presented in this chapter, following the PRISMA methodology [167] . . . . .	49
3.3	Example of references that used “robot manipulator” in their abstract or title. The prototype shown on Subfigure 3.3a does not fit our scope. . . . .	51

4.1	The user-centered properties for modular shape-changing interfaces. The properties are further classified depending on whether they impact the interface at a digital level (dark gray), physical level (middle gray) or interaction level (light gray). <i>Combination between physical and digital states</i> is classified as impacting both digital and physical levels, as it describes the interaction between the physical and digital shape of the interface. <i>Usage consumption</i> is classified as impacting both the physical and interaction levels as it is the power consumed <i>under a standard context of use</i> . . . . .	62
4.2	Zooids is only used in tabletop contexts, whereas chainFORM is mostly used in handheld contexts. . . . .	66
4.3	The properties of modular shape-changing UIs at the scale of the modules, and their dependencies. The properties are further classified depending on whether they impact the components embedded in the module (intra-module, light gray), the whole module itself (module, middle gray) or at least two modules (inter-module, dark gray). The dotted arrows describe yet undefined impact requiring further technical experiments. . . . .	71
4.4	(a–b) Two possible lattices for spatial arrangements (packing) of robots, (c) approximation of a shape by cubic and quasi-spherical robots, and (d) range of <i>Closure</i> achieved by cubic and quasi-spherical robots. . . . .	73
5.1	The user-centered properties for modular shape-changing interfaces, and their dependencies. The properties are further classified depending on whether they impact the interface at a digital level (dark gray), physical level (middle gray) or interaction level (light gray). <i>Combination between physical and digital states</i> is classified as impacting both digital and physical levels, as it describes the interaction between the physical and digital shape of the interface. <i>Usage consumption</i> is classified as impacting both the physical and interaction levels as it is the power consumed <i>under a standard context of use</i> . . . . .	79
5.2	The properties of modular shape-changing UIs at the scale of the modules, and their dependencies. The properties are further classified depending on whether they impact the components embedded in the module (intra-module, light gray), the whole module itself (module, middle gray) or at least two modules (inter-module, dark gray). The dotted arrows describe yet undefined impact requiring further technical experiments. . . . .	82



6.1	Although the smallest modules found in HCI are the 9mm Dynablocks (Subfigure 6.1a), work in robotics proposed a design for $\varnothing 3.6$ mm modules (Subfigure 6.1b). The long-term goal is to enable long-term conceptual visions, such as Perfect Red (Subfigure 6.1c). . . . .	107
6.2	The four sliders used to investigate the impact of the size of future modules constituting the TUI: (from left to right) a current smooth slider and three sliders made of mock-up modules of $\varnothing 1$ mm, $\varnothing 2.5$ mm and $\varnothing 5$ mm. . . . .	108
6.3	Left: Evolution over time of the size and shape of modules used for modular 3D shape-changing UIs <20mm (data source and references [232] found at <a href="http://molecularhci.imag.fr">http://molecularhci.imag.fr</a> ). Right (a): In the future, modular TUIs could be able to reconfigure their shape. For instance here, a slider could become larger [54]. Right (b): The simulated robotic movement of small, interchangeable modules currently developed that could allow such changes in shape [222]. . . . .	113
6.4	Close-ups of the UI of the experimental software for the target acquisition (left) and pursuit tasks (right). . . . .	115
6.5	Left: Movement time (in ms) for each size of modules. Points show geometric means and error bars show the 95 % confidence interval. Right: Error rate (%) for each size of modules. Points show means and error bars show the 95 % confidence interval. All conditions had the same slider range on the device (8 cm) and on the screen (18 cm). . . . .	118
6.6	Results from the SEQ and TLX questionnaires for the target acquisition task. Outlined in black, participants found the slider made of $\varnothing 5$ mm modules significantly more difficult to use than the smooth (control) slider. . . . .	118
6.7	Pursuit error (% of the slider range). Points show medians and error bars show the 95 % confidence interval. All conditions had the same slider range on the device (8 cm) and on the screen (18 cm). . . . .	119
6.8	Results from the SEQ and TLX questionnaires for the pursuit task. Outlined in black, participants found the slider made of $\varnothing 5$ mm modules significantly more difficult to use than the smooth (control) slider. Outlined in gray, participants found they did not accomplished the task as successfully with the slider made of $\varnothing 5$ mm modules compared to the smooth (control) slider. . . . .	120
6.9	The 9 grasps we observed during the experiment in their three categories. . . . .	122
6.10	Target pursuit error and target acquisition time for each grasp, across sizes of modules. Boxplots show the median through the bold central line, the first and third quartile through the box and the extremums through the whiskers. . . . .	123

6.11	Number of participants according to their grasps, for the target acquisition task (left) and pursuit task (right). The “curve” grasp (yellow) was not possible with $\varnothing 5$ mm modules. . . . .	124
7.1	Using passive magnets allow for a very small form factor. However, the smaller the magnets, the weaker the bonding strength. . . . .	130
7.2	The expected trade-off between the detachability of the modules and the solidity of a modular TUI. . . . .	131
7.3	Modular TUIs enable a wide range of interaction modalities and prototypes, e.g. (a) reconfigurable smart VR environment [51], (b) reconfigurable touch-screens [179], or (c) dynamic 3D shape printings [279]. An example long-term vision for such interfaces is (d) Perfect Red [120], with modules as small as atoms, which could be achieved via modular solutions such as (e) the few mm Claytronics concept [223]. . . . .	133
7.4	GaussBricks uses passive magnets to enable small-scale building blocks, accomodating tangible interaction on mobile devices [165]. . . . .	134
7.5	Three examples of modular implementations outside of HCI that leverage magnets. 135	
7.6	Starting from existing modules from previous work (left and middle, [97]), we first tried to have fully rounded $\varnothing 2.4$ mm modules (right). However, they were too weak to keep their shape, let alone withstand user manipulation. . . . .	138
7.7	Independent variables of the prototypes studied in the chapter: two <i>module shapes</i> (cubes and rounded cubes) $\times$ three <i>magnet thicknesses</i> (0.5mm, 1mm and 2mm) [11]. The thicker the magnets, the stronger their bonding strength. The holding force on iron is 0.49N for the 0.5mm magnets, 0.98N for the 1mm magnets and 2.45N for the 2mm magnets. . . . .	139
7.8	Participants performed manipulations on either a flat configuration, i.e. one layer of 80 modules (top left), or a thick configuration, i.e. two layers of 40 modules each (bottom left). From the prototype in its initial state shown in the left, participants performed eight manipulations (right): (a) split 1 module, (b) split 2 modules, (c) split a line of modules, (d) split the prototype in half, (e) lift, (f) slide, (g) fold and (h) bend. . . . .	140
7.9	Mean Likert scores of the four questionnaires: overall difficulty (top left), overall satisfaction (top right), perceived impact of the strength (bottom left) and perceived impact of the shape (bottom right). The scales range from 1 (red - most negative response) to 7 (blue - most positive response) with 4 as the center (grey - neutral). . . . .	142
7.10	Easiness across conditions for the overall study from (1) very difficult to (7) very easy. Error bars show bootstrapped 95% CIs. . . . .	143

7.11	Satisfaction across conditions for the overall study, from (1) very difficult to (7) very easy. Error bars show bootstrapped 95% CIs. . . . .	144
7.12	Perceived impact of how the shape impacts interaction across conditions for the overall study, from (1) very negatively to (7) very positively. Error bars show bootstrapped 95% CIs. . . . .	144
7.13	Perceived impact of how the strength impacts interaction across conditions for the overall study, from (1) very negatively to (7) very positively. Error bars show bootstrapped 95% CIs. . . . .	145
7.14	Results show evidence that the lifting task was significantly harder with R0.5 in a flat configuration . Error bars show bootstrapped 95% CIs. . . . .	146
7.15	Results show evidence that splitting 1 module from the UI is harder with the C2 condition. Error Bars show bootstrapped 95% CIs. . . . .	147
7.16	Results show that the 2mm strength was perceived as having a more negative impact on the cubic modules (i.e., with C2). Error Bars show bootstrapped 95% CIs. . . . .	147
7.17	Results show that the 0.5mm strength had significantly impaired splitting a line of modules with rounded modules (i.e., with R0.5). Error Bars show bootstrapped 95% CIs. . . . .	148
7.18	Results show that the rounded shape was perceived as having a negative impact when splitting the prototype in half, and that the lowering the strength worsen the impact of having a rounded shape. Error Bars show bootstrapped 95% CIs. .	149
7.19	Results show that the rounded shape was perceived as having a negative impact on the task, with the worst condition being R0.5. Error Bars show bootstrapped 95% CIs. . . . .	150
7.20	Results show that the rounded shape was perceived as having a slightly negative impact on the task, with the worst condition being R0.5 and C1 as the best conditions. The impact of the shape was perceived as overall more positive with the 1mm strength. Error Bars show bootstrapped 95% CIs. . . . .	150
7.21	Results show that the rounded shape with 1-2mm strength was perceived as more satisfying to bend the UI with, with R1 and R2 rated the highest. Error Bars show bootstrapped 95% CIs. . . . .	151

8.1	Deux exemples de scénarios où les utilisateurs ont besoin à la fois de flexibilité et de physicalité selon le contexte d'interaction : (a) Le tableau de bord d'une voiture nécessite des contrôles physiques pour conduire, mais peut également utiliser un écran tactile avec des contrôles graphiques (par exemple, pour contrôler la radio, la température, la navigation). (b) L'utilisateur peut contrôler la température de sa maison domotique avec son smartphone en déplacement ou avec une télécommande physique chez lui. . . . .	179
8.2	KnobSlider est une implementation actionnée mécaniquement, tandis que PneUI est actionnée pneumatiquement. . . . .	181
8.3	Notre approche de recherche : nous avons d'abord défini un espace de conception pour les interfaces modulaires à changement de forme, puis nous avons entrepris d'étudier l'impact de trois paramètres de conception des modules identifiés sur l'interaction des utilisateurs. . . . .	185
8.4	Structure de la thèse. . . . .	191
8.5	Alors que les interfaces utilisateur à changement de forme se situent entre les interfaces utilisateur et les interfaces graphiques, les interfaces modulaires à changement de forme se situent entre les interfaces utilisateur à changement de forme et la robotique modulaire. . . . .	192
8.6	Our structured space of properties: (left) user centered properties at the macro scale of the shape-changing modular UI, and (right) technical properties at the micro-scale of the modules. . . . .	193
8.7	Les quatre curseurs utilisés pour étudier l'impact de la taille des futurs modules constituant l'interface utilisateur tangible : (de gauche à droite) un curseur lisse actuel et trois curseurs composés de modules prototypes de $\varnothing 1$ mm, $\varnothing 2.5$ mm et $\varnothing 5$ mm. . . . .	198



# LIST OF TABLES

---

4.1	Properties of the interface (macro-scale) for modular shape-changing UIs. . . . .	70
5.1	Expected impact of the properties at the scale of the modules (micro) on the ones at the scale of the interface (macro). . . . .	85
5.2	Description and comparison of two chain-based interactive modular shape-changing implementations: LineFORM [195] and ChainFORM [196]. Items in bold highlight the differences between the two systems. <i>*3D possible but limited, only through direct control: the modules reconfigure on a 2D plan, the user needs to detach the modules, rearrange them with a plastic joint between them to locate them in two different 2D planes.</i> . . . .	96
6.1	Mean movement time (ms), error rate (%) and score of the Single Ease Question for target acquisition (with 95 % confidence intervals). . . . .	117
6.2	Median pursuit error (%) and mean score of the Single Ease Question for pursuit.	119



# INTRODUCTION

---

## Contents

---

<b>1.1</b>	<b>Context</b> . . . . .	<b>2</b>
1.1.1	Flexibility vs physicality . . . . .	2
1.1.2	Implementing shape-change as a compromise . . . . .	4
<b>1.2</b>	<b>Problem statement</b> . . . . .	<b>7</b>
<b>1.3</b>	<b>Research methodology</b> . . . . .	<b>9</b>
1.3.1	Constructing a structured cross-disciplinary design space . . . . .	10
1.3.2	Empirically exploring the impact of module design parameters . . . . .	10
<b>1.4</b>	<b>Contributions</b> . . . . .	<b>12</b>
1.4.1	Contribution 1: A design space for modular shape-changing UIs . . . . .	12
1.4.2	Contribution 2: Characterization and evaluation of the impact of the size, shape and bonding strength of the modules on user interaction . . .	13
<b>1.5</b>	<b>Structure of the thesis</b> . . . . .	<b>15</b>

---



## 1.1 Context

This manuscript contributes to the field of Human-Computer Interaction (HCI). This research field focuses on the design, the usage and the technology involved in user interaction with computers. Although primarily a computer science field, research conducted in HCI leverages knowledge from a wide variety of fields, such as psychology, biomechanics, behavioral science or material science.

In particular, this thesis focuses on interacting with physical shape-changing user interfaces (UIs). Shape-changing UIs are physical UIs whose physical shape can dynamically change over time to support input, output or both [229]. This research field appeared as a way to bridge the gap between the flexibility of graphical UIs (GUIs) and the physicality of tangible UIs (TUIs). HCI researchers started taking interest in implementing shape-change in physical UIs as early as 2004 [181], and started exploring the opportunities of *modular* shape-changing UIs since 2007 [179]. The main goal of this thesis is to further understand and improve the design of current and future modular shape-changing UIs.

### 1.1.1 Flexibility vs physicality

Overall, human-computer interaction as a research field deals with varying levels of flexibility and physicality, in input and output modalities alike [140, 215]. In this section, we discuss the trade-off between flexibility and physicality in interactive devices.

On the one hand, Graphical User Interfaces (GUIs) are graphical, visual representations of an interface composed of, for example, buttons, icons, menus or images [71]. GUIs provide users with a visual way to interact with computers [176]. They originally appeared as a more user-friendly alternative to text-based UIs, where users relied on command-line as input (CLI) and text as output [71]. Instead, *input-wise*, GUIs can include a wide range of graphical input elements, such as buttons, menus or sliders, to control a large range of functions within an application. *Output-wise*, GUIs can display virtually anything: they can adapt to different display sizes and resolutions, making them a good fit for a wide range of devices, and are also able to greatly adapt to the needs of the user, the task or context of interaction (e.g., dynamically adapting the output to comply with accessibility concern, switching to a dark mode at night, applying regional keyboard layouts, etc). However, GUIs are essentially “*pictures under glass*” that do not allow users to “*use their hand*” [1, 158]. They rely heavily on sight, without physical cues to inform the user on the position of a particular object or control, and constrain the gestures to a small subset of what humans are capable of [1]. This lack of physicality makes them unsuitable for interaction contexts requiring eye-free interaction. For example, while physical keyboards tend to disappear from our mobile devices, they are still widely the norm for desktop computers: the

small form factor of mobile devices, with everything within sight, means they should – and can – support flexibility at the expense of physicality.

On the other hand, TUIs are physical, tangible interactive artefacts that users can touch and manipulate, with the goal of “*using physical objects to represent and manipulate digital data*” [258]. They appeal to our haptic senses, both tactile and kinesthetic, with physical affordances that convey rich sensory feedback and hint at the available actions that the users can perform with the physical object [65]. This physicality enables eye-free interaction by leveraging the spatial memory of users [212], and allows for fast and accurate manipulation [296, 158]. TUIs provide a more direct, tangible way to manipulate and interact with digital information, with a higher degree of physicality. However, TUIs lack the flexibility of GUIs, and are more physically constrained. *Input-wise*, TUIs rely on physical objects that users can touch, manipulate, or move to interact with the system. This limits the types of interactions that can be designed, as the user is physically constrained by the properties of the objects themselves. For example, if a TUI is designed with physical knobs or sliders, the interactions will be limited by the size, shape, and range of motion of these physical objects. Users have to switch between several TUIs depending on their needs (e.g., from a dial to a slider), and may need to navigate between a large number of devices, (e.g., a sound engineer with multiple sliders, dials and buttons on a mixing console), although they do not always need all of them. This can result in crowded and bulky workspaces.



(a) Dashboard inside a car.



(b) GUI and TUI thermostat controls.

Figure 1.1: Two examples of real-life scenarios where users need both flexibility and physicality depending on the interaction context (a) A car dashboard needs physicality for eye-free driving, but can implement a touchscreen with GUI controls (e.g., to control the music, temperature, navigation). (b) The user can control the temperature of their smart home with their smartphone when they are on the go, or with a physical control panel when they are in their home.

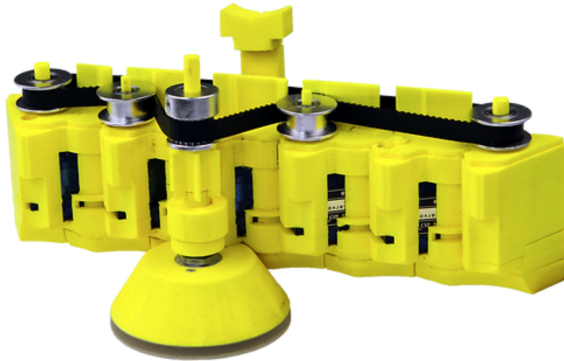
Overall, GUIs and TUIs have their own strengths and weaknesses, and the choice between them depends on the specific needs of the application and the users. Combining GUIs and TUIs

can provide users with a more intuitive, engaging, and flexible user experience, particularly in applications where physical manipulation is important. If we look at examples from our everyday lives, we see that although smartphones and tablets primarily use touchscreens as both input and output, the monitor screen(s) as output and keyboard/mouse as input are still the norm for desktop setups. In our homes, smart home devices such as thermostats, lighting systems, and security cameras, rely on a combination of GUIs and TUIs to enable users to control and interact with them. Users can control these devices using graphical interfaces on their smartphones or tablets, but some devices also include physical controls, such as buttons, knobs and sliders, that can be used to adjust settings or turn the device on or off (Figure 1.1b). Modern cars often rely on a combination of GUIs and TUIs to enable drivers to control and interact with various systems, such as the radio system, temperature control, and navigation. The dashboard may include physical controls for adjusting settings, while the graphical interface is displayed on a touchscreen or other display (Figure 1.1a). Thus, we can observe that humans rely heavily on both flexibility and physicality in their everyday lives, and that both can be relevant for a same application depending on the context.

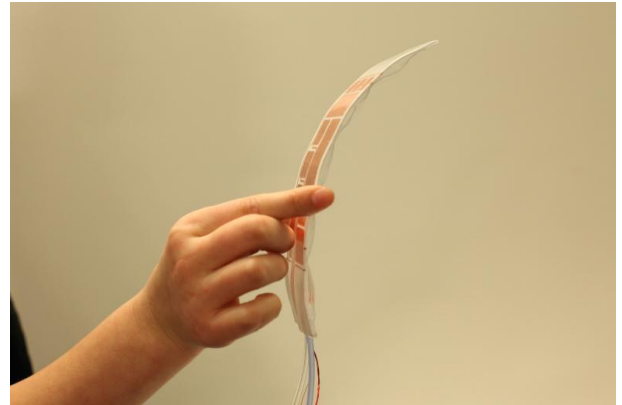
### 1.1.2 Implementing shape-change as a compromise

Underlining the need for both physicality and flexibility, we often switch between devices depending on the task or context of interaction, such as with the thermostat example, or rely on a combination of both graphical and physical interfaces, such as with the car example where physicality is required for eye-free interaction. This highlights a potential avenue for a third alternative: compromising between flexibility and physicality. HCI researchers explore two main ways of achieving this compromise: (1) allowing users to “touch” graphically rendered elements (e.g., through haptics feedback [243, 178]) or (2) allowing users to change the shape of the physical interfaces. In this thesis, we focus on the later: physical shape-changing user interfaces.

Shape-changing UIs are physical, tangible user interfaces able to change their shape and materiality over time, autonomously or not, to adapt the content or context to the user, the task or the environment [19]. Shape-changing UIs have proven especially interesting in the context of eye-free interaction in typically crowded environments. Previous work in shape-changing UIs proposed promising prototypes and interaction designs to dynamically adapt the physical interfaces in the cockpit of a plane (e.g., Gazeform [213] or Multi-plié [215]). However, adding shape-change capabilities to physical interfaces comes with challenges [19]. And these challenges are not (only) technological. For instance, how do users experience shape-change? How can we communicate what changes of shape are available, and how to trigger the change? Would users be “lost” between the different states of shape? Which user groups or context of use could most benefit from it, and how?



(a) Knobslider [140]



(b) PneuUI [310]

Figure 1.2: Examples of two shape-changing UIs that are not modular: Knobslider is a mechanically actuated implementation, while PneuUI is pneumatically actuated.

Among the proposed approaches found in the literature, *modular* shape-changing UIs emerged as a way to overcome current challenges, such as scalability [19], robustness [314], cost [314] and versatility [314]. Overall, modularity offers an interesting “*building block*” approach, and could open the way for novel physical shape-changing UIs featuring great shape resolution and a large variety of changes of shape compared to other kinds of implementations. For instance, the pneumatically actuated air pouches of PneuUI [310] (Figure 1.2b) can dynamically open/close a lid on top of a hole to support limited changes in porosity. The mechanically actuated KnobSlider [140] (Figure 1.2a) can switch between a slider state and a dial state, but cannot, for example, be split in two sliders or become a whole other device. Such changes of shape are pre-programmed at design stage and cannot be modified during interaction. In contrast, using modules as “*building block*” could provide a larger range of porosity, as removing modules could create holes of varying sizes, or transform into a greater variety of devices. The different changes of shape would not necessarily need to be planned at the design stages, as new shapes could be created through direct user deformation, or by upgrading the software to give new directions to self-reconfigurable modules, rather than upgrading the overall hardware design.

Although promising, modular shape-changing interfaces are not yet commonly found in nowadays interactive devices. Previously explored application scenarii come from the researchers themselves rather than the actual users or context of use, and in-situ evaluations are highly uncommon [19]. Thus, taking a top-down, user-centered approach in the design of novel modular shape-changing UIs, or of novel interaction techniques, is not a trivial issue. The interaction paradigms leveraged when interacting with modular shape-changing UIs may differ compared to the common GUI or static physical devices that we commonly use in our everyday life. For instance, users may have a wholly different experience using a modular smartphone (e.g., [247, 86])

compared to using a standard touchscreen. Similarly, users may have a different experience using a shape-changing set of physical controls. For instance, the user experience of using a fixed, static physical dashboard may be different than when the controls only appear when they are needed (e.g., [244, 213]). What benefits and drawbacks may emerge from interacting with such interfaces? Understanding how end-users experience shape change and how shape-changing UIs may benefit or impact them is a key step in developing and proposing usable shape-changing interfaces and take them from research communities to the industry. The next section will present the research problems related to this issue, which we focused on in this thesis.

## 1.2 Problem statement

Shape-changing UIs appeared as a compromise between the flexibility of GUIs and the physicality of TUIs. However, previous work highlighted the existence of critical challenges for the development and usage of shape-changing UIs [19]. We present here the two main problems that we focused on in this thesis.

### **Problem 1 - HCI and robotics: research in silos.**

HCI researchers often face a challenge when prototyping modular systems: while they have skills in software programming and simple electronics, they often lack expertise in advanced materials, electronics, and mechanics [19]. One solution to this problem is to collaborate with robotics researchers, who have extensive experience in modular robotics. While HCI research started exploring *modular* robotics in 2007 with Siftables [179], robotics research has conducted extensive work on the subject since 1990 [81]. They proposed several advanced configurations for modular robots and gathered hindsight on their technical benefits and drawbacks over the years [314]. The HCI community could leverage previous work from robotics to propose elaborate designs, and save time and cost in prototyping. It is important to note that robotics research focuses on the reconfiguration and locomotion capabilities of modular robots, but less on user interaction [247]. Collaborating with HCI researchers could help ensuring that modular robots are physically and ergonomically well-designed, and provide a seamless and intuitive interaction experience for users. However, these two communities often work separately and use different vocabularies, making it difficult to leverage previous work across communities. It is important to address this issue to fully benefit from each other's expertise. For example, implementations following a chain architecture, which means that modules are connected following a string or tree topology [314], are common in HCI. However, robotics researchers have found them more difficult to represent and control, despite their versatility [314]. There is little discussion on this issue in the HCI community. Collaborating with HCI researchers can help robotics researchers understand the needs, preferences, and expectations of end-users, incorporate these insights into the design of modular robots, and evaluate the effectiveness of the modular robots in real-world settings.

**Objective 1:** To bridge the gap between robotics and HCI and relate previous work from both communities to each other.

**Objective 2:** To propose a structured design space that takes into account the specificities of modular shape-changing systems in order to inform the design of future shape-changing UIs.

## **Problem 2 - Usability of modular shape-changing UIs: insufficient empirical knowledge.**

Currently, research in HCI on shape-changing user interfaces (UIs) primarily focuses on developing new prototypes and potential applications, with limited attention given to interaction design and user evaluation of existing shape-changing UIs. While some studies have been conducted with the Zooids platform [159], including eliciting user-defined controls for Zooid swarms [144], there remains a lack of thorough in-situ evaluations. This is partly due to the novelty of shape-changing UIs, as well as their lack of robustness for prolonged use [19]. Moreover, we lack knowledge on the relative effect of isolated factors to be able to evaluate a whole system at once. For instance, although we can now leverage standardized methods and protocols to directly evaluate new graphical or physical UIs, we first need to evaluate the relative effect of their factors (e.g., the effect of target size and distance in Fitts' Law to then evaluate new ways to navigate menus). To address this issue, it is necessary to isolate and understand the relative effects of various factors involved in modular shape-changing UI design before evaluating the system as a whole. One of the challenges is that interacting with shape-changing UIs leverages multiple modalities, such as visual or haptic feedback. Our work aims at facilitating more user evaluations of modular shape-changing UIs by identifying critical design factors and their impact on user interaction, drawing from prior research in HCI *and* in robotics.

One of the goals of this thesis is to open up the way for more user evaluations of modular shape-changing UIs. Not only do we need to relate previous work in HCI and robotics to understand the factors that are involved in the design of modular shape-changing UIs (Problem 1), we also need to isolate critical design factors and understand their relative effect on user interaction (Problem 2).

**Objective 3:** To isolate critical factors in the design of modular shape-changing UIs.

**Objective 4:** To understand the impact of these factors on user interaction.

## 1.3 Research methodology

Our approach to bridge the gap between the HCI and robotics fields and informing the design of modular shape-changing interfaces early on involves (1) a user-centered approach and (2) a co-advised PhD program that includes researchers from both disciplines. To account for the multidisciplinary nature of our work, we have developed a two-part methodology as illustrated in Figure 1.3, which includes:

1. **Design Space:** conducting a systematic review of the literature from both HCI and robotics to relate and structure a cross-disciplinary space of modular shape-changing UIs.
2. **User Studies:** designing and conducting user studies to isolate and evaluate the impact of three design parameters on user interaction with future modular shape-changing UIs. These parameters are module size, shape, and bonding strength.

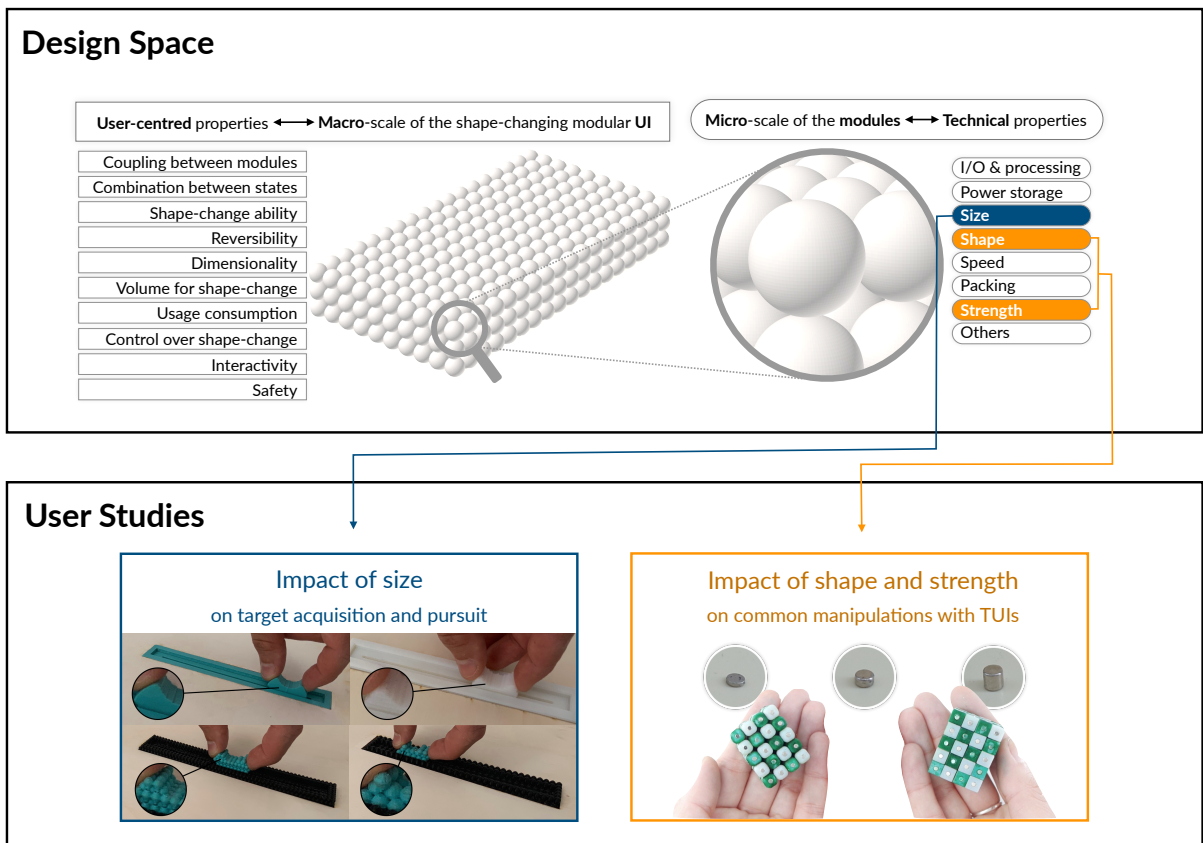


Figure 1.3: Our research approach: we first defined a design space for modular shape-changing UIs [232], after which we set out to study the impact of three identified module design parameters on user interaction: (1) their size [234] and (2) their shape and bonding strength [233].



### 1.3.1 Constructing a structured cross-disciplinary design space

HCI and robotics researchers both conducted work on modular shape-changing user interfaces over the years, but rarely interacted with each other. Moreover, the robotics community formalized and classified the technical specificities of modular robotics implementations, and specified how, for instance, the design requirements for a chain implementation differ from those of a swarm implementation [314]. However, the HCI community did not consistently leverage such classifications, and drew design requirements that each addresses a local set of design properties, rather than providing a global viewpoint on modular interfaces. As a result, although we find tools for the design of modular implementations in the literature, such as classifications and evaluation methods (e.g., [141, 239, 271, 272]), benefits and challenges (e.g., [229, 119, 19]), criteria for design (e.g., [174, 159, 247]) or they are not consistent and sometimes even contradict each others. For example, Cubimorph requires all their modules to be constantly attached [247] while Zooids require all their modules to be constantly detached [159].

We conducted a systematic review of the literature to find relevant references in both HCI and robotics, by following the PRISMA Statement (a standard four step literature survey methodology) [167, 302]. We gathered previous work focusing on design implementations, tools for design and literature surveys. We related them together to identify and merge shared design parameters, at the scale of the interface and at the scale of the individual modules. Finally, when relevant, we leveraged existing ergonomics criteria to anticipate the expected impact on user interaction [24] as well as work from the human-robot interaction community to draw early safety and security requirements [122, 123].

### 1.3.2 Empirically exploring the impact of module design parameters

When working on the structuration of the design space for modular shape-changing UIs, it appeared that design properties could be considered at two abstraction levels: what we call the *micro-scale* refers to properties at the scale of the modules, and what we call *macro-scale* refers to properties at the scale of the interface. For comparison, the GUI-equivalent of micro-scale properties would be at the scale of the pixels (e.g., their size or color), and the macro-scale properties would be at the scale of the whole UI (e.g., its resolution or interaction modalities). Subsequently, we chose to focus the remainder of this thesis on studying how the isolated *micro-scale* design properties of the modules impact user interaction. This choice was motivated by the fact that properties at the scale of the interface are heavily dependent on those at the scale of the modules [232]. Using the GUI comparison again, the size of the pixels would impact the resolution of the UI. Moreover, previous work highlighted how the current size range of the modules presents a challenge for the research community, and that there is a need for small and lightweight, albeit strong, actuation mechanisms [19]. The bonding strength and shape of

the modules were the remaining two parameters that we focused on, as they could be easily assessed with simple static 3D printed modules, which removed the fragility issue known in shape-changing UI research [19]. As for the other micro-scale properties, the impact of the packing could not be isolated without first studying the bonding strength, and the three others (i.e., speed, power storage, I/O and processing capabilities) are more challenging to implement and isolate with current hardware limitations.

First, we conducted two user studies to assess the impact of four module sizes on interaction with a linear tangible slider: a plain, smooth slider (module size  $\sim 0$ mm) and three sliders made of mock-up modules of  $\varnothing 1$ mm,  $\varnothing 2.5$ mm or  $\varnothing 5$ mm. The first user study consisted of a target pursuit task, to assess the impact of each condition on continuous linear interaction. The second user study consisted of a target acquisition task, to assess the impact of each condition on more discrete, fast-paced interaction. In order to gather qualitative subjective feedback, we conducted semi-structured interviews for both user studies. Additionally, we recorded and analyzed the grasps performed by participants to relate them with their performance and qualitative subjective results.

Second, we conducted a user study to assess the impact of two module shapes (cubes and rounded-cubes) and three levels of bonding strength between modules (low, mid and high) on common tangible manipulations. To this aim, we isolated eight types of manipulations commonly performed with (non-)modular TUIs: split (one module, two modules, a line of modules or half of the modules), lift the modules from a table, slide parts of the modules to make a controller-like shape, bend the modules akin to pressure-based interaction, fold the modules in half. We conducted a semi-structured interview to gather qualitative subjective data. We also recorded the hands of participants, but did not end up analysing the video data.

## 1.4 Contributions

Within HCI, this thesis contributes to the domain of modular shape-changing UIs, but can be extended to the broader fields of tangible and haptic interactions. Our key contributions are:

1. A structured cross-disciplinary design space for the design of modular shape-changing UIs.
2. The characterization and evaluation of the impact of three design parameters at the scale of the module on user interaction.

### 1.4.1 Contribution 1: A design space for modular shape-changing UIs

Our first contribution is a design space for modular shape-changing UIs, reviewing and organizing previous work in both HCI and robotics. This design space is articulated around two kinds of properties (macro/micro).

**The properties at the scale of the interface** (macro-scale) characterize the overall UI. Macro-scale properties are articulated around three levels: the digital level (i.e., the position and state of all modules in the computational model), the physical level (i.e., the physics of the UI, the properties of the tangible artefact made of physical modules) and the interaction level (i.e., related to and impacting the interaction design of the UI). As users interact directly with the interface, we characterize the expected impact of macro-scale properties on user interaction by relating them to previous work in HCI, ergonomics or human-robot interaction (HRI).

**The properties at the scale of the modules** (micro-scale) characterize the individual modules that compose the overall UI. Micro-scale properties are articulated around three levels: the intra-module level (i.e., elements that are embedded in the module), the module level (i.e., the envelop of the modules) and inter-modules level (i.e., if and how modules are attached to each other). The design of the modules in a shape-changing UI may be compared to the design of pixels in a GUI. Although users may focus on the overall interface rather than individual pixels, the design of the pixels (e.g., their size, shape or number/configuration) impacts the design of the interface and thus user perception.

Lastly, our design space characterizes the impact of macro- and micro-scale properties on each other. Understanding how properties impact each other is highly important, as the design of modular shape-changing UIs requires trade-offs (e.g., reducing the size of a module requires reducing the number/size of its components, which can result in reducing its battery autonomy or which I/O components it can embed). Giving designers a first overview of how altering a parameter may impact their overall design is a key aspect of our contribution.

### 1.4.2 Contribution 2: Characterization and evaluation of the impact of the size, shape and bonding strength of the modules on user interaction

Our second contribution consists of design guidelines and recommendations driven from the characterization and evaluation of the impact of three micro-scale design parameters on user interaction. We especially focused on the size, the shape and the bonding strength of the modules.

**Size of the modules.** Our contribution lies in the evaluation of module size on user interaction with physical linear sliders. Implementing modular UIs introduces the issue of surface roughness, as the gaps between modules and/or the bumps they create (especially for (quasi-)spherical modules) seldom allow for a flat, seamless surface. Previous work already studied the impact of roughness on direct touch with (1) static and (2) moving fingers [104, 263, 219, 194] and through a probe [148, 157, 319, 318] but, to our knowledge, ours is the first study on the impact of two rough objects used on each other. Indeed, implementing modular UIs may require to use two objects made of modules on each other, (e.g., a slider knob on its railing) or an object made of modules on a modular surface. In two controlled user studies, we assess the impact of three module sizes ( $\varnothing 1\text{mm}$ ,  $\varnothing 2.5\text{mm}$ ,  $\varnothing 5\text{mm}$ ) on user interaction with a linear slider to perform two tasks: a target acquisition task and target pursuit task. Although the general aim of this thesis is to contribute to the HCI area of shape-changing UIs, the fact that we used static modules in the design of our prototypes led us to take insight from the tangible interaction and haptics interaction communities. The results of our user studies may in turn contribute to these communities as well. For instance, for this contribution, we leverage previous work on the perception of roughness and programmable friction from the haptics community. Thus, we relate our results to previous studies on programmable friction, and give our conclusions on the possible implications for the design of future physical shape-changing sliders featuring programmable materiality.

**Shape and bonding strength of the modules.** Our contribution lies in the characterization of the solidity/detachability trade-off of the overall modular UI. We relate how the shape and the bonding strength of the modules impact this trade-off by conducting a user study with two shape conditions (sharp cubes and rounded cubes) and three bonding strength conditions (low, mid or high) in the context of eight common manipulations found in the literature of (non-)modular TUIs. We find several shapes of modules in the literature but the most common shapes seem to be cubes with sharp edges [84, 247, 279], cubes with rounded edges [83, 246, 86], or straight up (quasi-)spheres [206, 267, 38, 200]. When authors explain how they decided on a module shape, it seems to be most often driven by technological constraints with a few exceptions driven by usability concerns. For instance, Cubimorph chose straight edges to have a seamless surface [247] whereas the authors of Catoms argue that a quasi-sphere is the best design for miniaturisation,

as it reduces the distance between two actuators [222]. To our knowledge, no previous work studied how a straightening or rounding the edges of the modules impacts interaction with a set of tangible modules. Moreover, the impact of the bonding strength that holds modules together also appears to be driven by technology constraints. It is unclear how bonding strength would impact user interaction, especially since application scenario presented in the HCI literature require both the interface to be stable enough to hold its shape, while allowing the users to detach a module or part of the interface. For instance, Pickcells [86] requires a bonding strength strong enough to support handheld mobile interaction, but low enough that part of the modules could be detached be, for example, be shared with another user. Thus, we conduct user evaluation to gather subjective feedback on the impact of module shape and bonding strengths and give our conclusions on the possible implications for the design of modular shape-changing UIs leveraging magnets as their actuation mechanisms.

## 1.5 Structure of the thesis

This section presents the outline of the thesis structure (Figure 1.4).

First, we lay the foundations of the thesis in an introductory chapter presenting the background and related work of our research topic (Chapter 2). We present how shape-changing interfaces have emerged in the robotics and HCI research communities. Especially, we underline the key differences between the needs and usages of both communities for such interfaces, which might explain the differences in how they approached the subject over the years and the differences in the challenges they face [314, 19]. This chapter also introduces key concepts on the technical classifications of modular shape-changing interfaces, such as their architecture and reconfiguration strategies. Although implicitly user-centered, these are key concepts we need to grasp to re-center the design on the user.

We then present the work conducted in this thesis. As this thesis features two key types of contributions, we articulate the presentation of our work in two parts.

**Part I** presents our ground work, which includes our cross-disciplinary structured design space for modular shape-changing UIs. First, we present the methodology and resulting corpus analysis of a systematic literature survey focusing on previous work conducted in both HCI and robotics (Chapter 3). Then, we present our set of design properties at the scale of the overall UI (*macro-scale*) and at the scale of the individual modules (*micro-scale*) (Chapter 4). We most notably relate them to their expected impact on user interaction according to ergonomics and HRI standards. We further present how the macro- and micro-scale properties impact each other. We characterize the dependencies within macro-scale properties, within micro-scale properties, and between micro- *and* macro-scale properties (Chapter 5).

**Part II** presents our empirical evaluation of module design properties for future modular shape-changing UIs. First, we present the results of two controlled user studies on the size of modules for target acquisition and pursuit with a physical user control (Chapter 6). We study the range of usable module sizes and their implication for design. Then, we present the results of a controlled user study on the impact of module shape and bonding strength on eight common manipulations found in the literature for modular TUIs (Chapter 7).

To conclude this manuscript, Chapter 8 presents the limitations and future work of this thesis, as well the perspectives we envision for future modular shape-changing UIs.

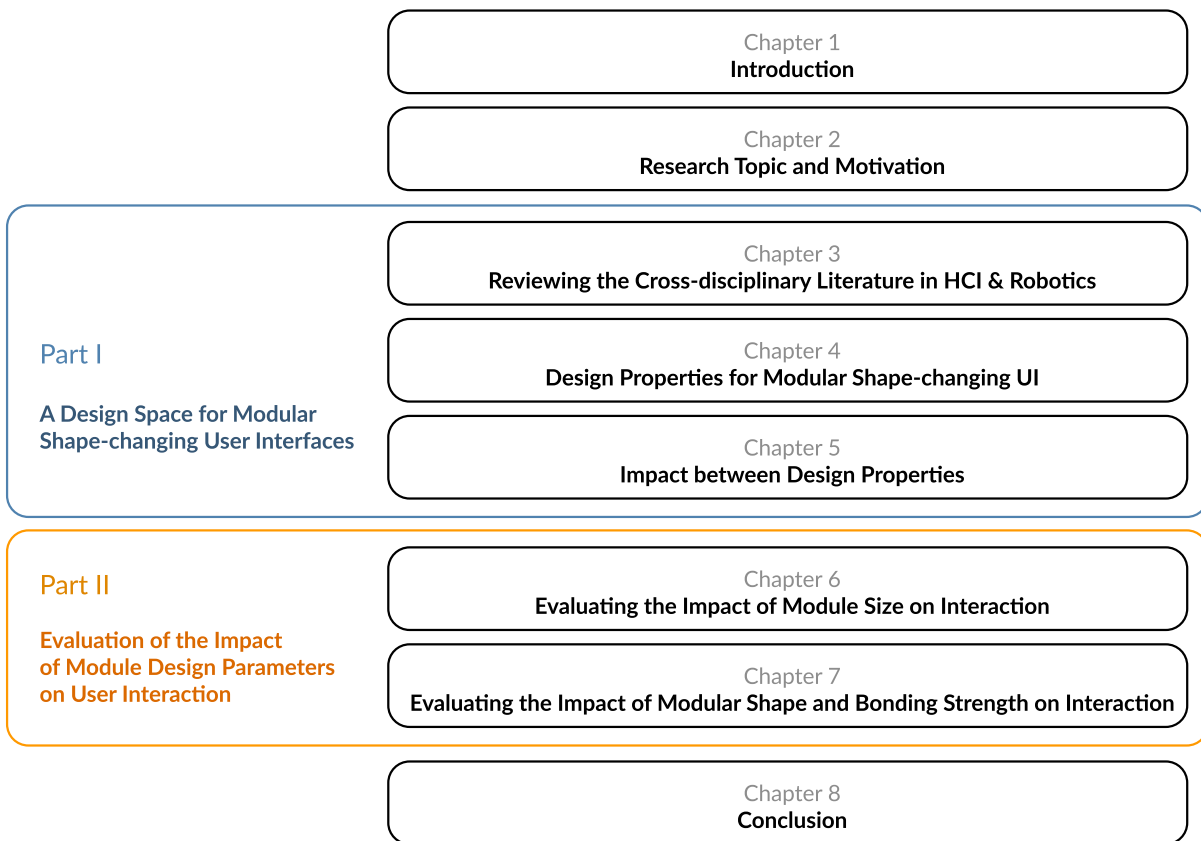


Figure 1.4: Structure of the thesis.







# RESEARCH TOPIC AND MOTIVATION

---

## Contents

---

<b>2.1</b>	<b>Introduction</b> . . . . .	<b>20</b>
<b>2.2</b>	<b>Shape-changing user interfaces</b> . . . . .	<b>21</b>
2.2.1	Graphical vs tangible user interfaces . . . . .	21
2.2.2	Shape-changing interfaces . . . . .	24
<b>2.3</b>	<b>Modular robotic systems</b> . . . . .	<b>28</b>
2.3.1	Architectures . . . . .	29
2.3.2	Reconfigurations . . . . .	32
2.3.3	Homogeneity . . . . .	33
<b>2.4</b>	<b>Modular shape-changing user interfaces</b> . . . . .	<b>35</b>
2.4.1	Benefits and implications of modularity . . . . .	35
2.4.2	User experience of shape-change and modularity . . . . .	37

---

## 2.1 Introduction

In this chapter, we explore the literature related to modular shape-changing user interfaces. The work we present in this thesis ties to previous work on shape-changing UIs from the HCI community, with concepts taking their roots from graphical and tangible UIs. Thus, we will first present these concepts to lay the foundation and motivation of our own work (Section 2.2).

In our work we also explored modular robotics and the opportunities of robotics modules to implement modular shape-changing UIs. As we will leverage vocabulary and concepts, we present related work from the robotics field (Section 2.3). We will especially present classifications of robots according to their architecture and reconfiguration type, as we will use these classifications further in Part I.

Finally, we present existing prototypes and previous work on modular shape-changing UIs implemented through modular robots, their benefits and implications, as well as the importance of evaluating how users experience shape-change and modularity (Section 2.4).

## 2.2 Shape-changing user interfaces

The HCI community has taken an ever growing interest in shape-changing user interfaces since 2004 [181]. The concept of computational devices able to dynamically change their physical shape was described in the literature as early as 1965, with Ivan Sutherland famously describing how the “*Ultimate Display*” would be a room in which the computer controls the very existence of matter [277]. In 2004, the HCI community started exploring the opportunities of changing the physical shape of an interactive object through the shape-changing control devices of Haptic Chameleon [181] (Figure 2.3a), and through the pin-based shape display Lumen [228] (figure 2.3b). They opened the way for the research field of shape-changing interfaces which would gather increasing interest in the community over the years.

This section explores why this research field appeared, how it evolved to these days and the challenges it faces.

### 2.2.1 Graphical vs tangible user interfaces

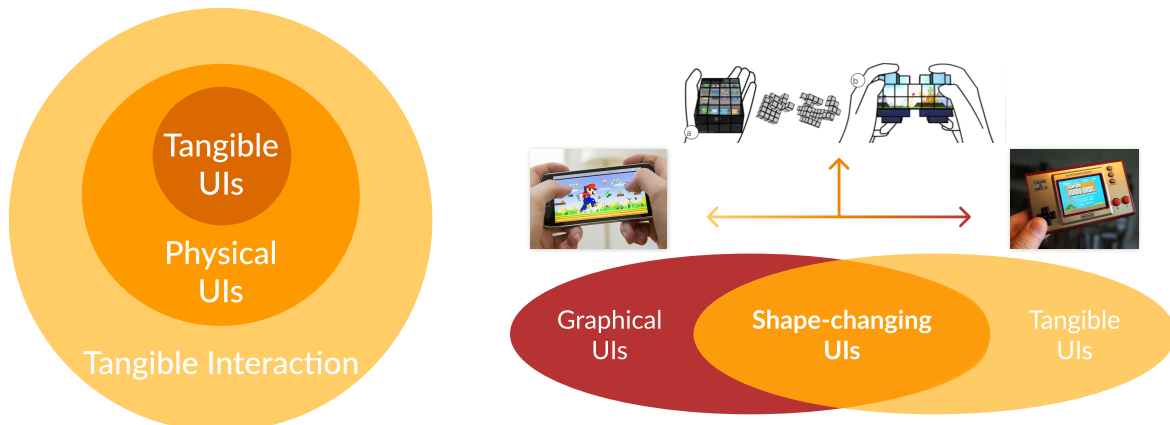
Graphical user interfaces (GUIs) appeared as a way to make personal computers more attractive by increasing their usability [176]. They initially proposed an alternative to previous interaction based on command-line input (CLI) and text output, through graphical windows, icons, menus and pointers [71]. Nowadays, they allow for a great flexibility in the interaction as they can essentially display anything over time, thanks to high resolution and high framerate devices, and can adapt to a wide range of displays and devices. Overall, this makes them able to greatly adapt to the needs of the user, the task or context of interaction.

Output-wise, the interface can accommodate the task that the user is performing by displaying the relevant information or widget at the relevant time, depending on the needs of the user or interaction context (e.g., a contextual menu to display available options, a graphical keyboard to enter a text message, a slider to move through a video).

Input-wise, direct manipulation and touchscreens in particular are becoming very common in our everyday environment, : for instance, we widely interact with them through our smartphones, ATM machines, automatic cash register in supermarkets or video game consoles. Direct manipulation allows users to directly interact with displayed GUI elements as input, without the need of an additional physical interface (e.g., a mouse or buttons) for input. However, using direct manipulation with GUIs as input lacks physical constraints as they are essentially “*pictures under glass*” that limitedly allow users to “*use their hand*” [1, 158]. This makes them unsuitable for interaction contexts requiring eye-free interaction: the displayed user controls (e.g. buttons, sliders, icons) do not have any physical or spatial cues that makes them easily findable by the user if they are not within sight.

Keyboards are a common example of such trade-off. On one hand, current mobile devices rarely feature a physical keyboard, relying instead on a graphical one displayed only when needed. However, this only works because the input and output areas are within sight. On the other hand, when typing text on a laptop or desktop computer, users need the spatial cues provided by physical keyboards. The popularity of mechanical keyboards amongst computer enthusiasts even hints that users enjoy and seek out an increased haptic feedback on physical keyboards [218]. In between, tablet devices usually feature (optional) detachable physical keyboards. Thus, users can choose between using a graphical or physical keyboard depending on the context of interaction.

In order to leverage our haptic perception and eye-hand coordination, the HCI community explored means of binding computational data to the physical environment of the user [121]. This led to the research field of Tangible UIs (TUIs). TUIs are artefacts that users can touch and manipulate, with the goal of *“using physical objects to represent and manipulate digital data”* [258]. On a side note, this definition is data-centric rather than user-centric [258], and there is no clear consensus on whether broader kinds of physical user interfaces, such as keyboards, sliders or wearables, fit this definition. The design community sometimes uses broader terms such as Tangible Interaction, but which encompasses interactive surfaces and gestural input [111], or Physical User Interfaces [280] (figure 2.1a). As TUI is the term that is still most employed in the HCI literature, we will use it in this thesis to refer to all kinds of tangible, physical UIs (physical control interfaces included).

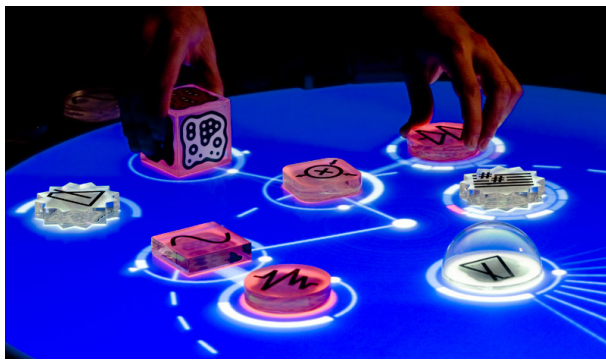


(a) We consider TUIs to be a subset of PUIs, which are themselves a kind of Tangible Interactions.

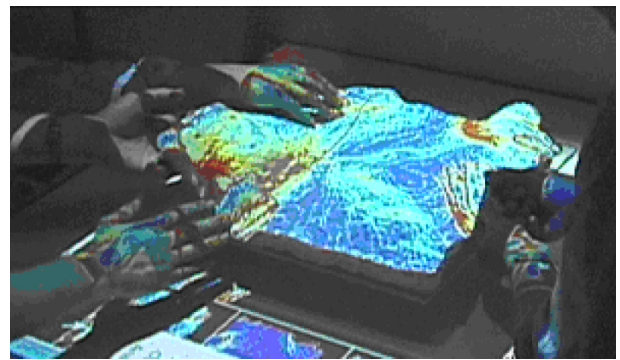
(b) Shape-changing interfaces bridge the gap between TUIs and GUIs by allowing the physical object to dynamically change its shape.

Figure 2.1: This thesis presents work conducted on shape-changing interfaces, which is nested at the crossroad between GUIs and TUIs.

TUIs started out as physical “bricks”, i.e. graspable tokens that the user can grasp and manipulate and that are a physical representation of a computational object [76]. They appeal to our haptic senses, both cutaneous and kinesthetic, with physical affordances that convey the potential actions users can perform with the physical object [65]. This physicality enables eye-free interaction by leveraging the spatial memory of users [212], and showed advantages in terms of both user manipulation (i.e., when users need to manipulate an object to a designated position) and acquisition (i.e., when users need to continuously adjust the position of an object to follow a moving target ) [296]. Moreover, users can perform a wider variety of gestures to interact with a TUI compared to a GUI, e.g. grasping, pinching, flipping, spinning, rolling or slaping it [297]. For instance, reacTable (Figure 2.2a) enable musicians to control instruments through 2D tabletop token on an interactive surface [132], Topobo proposed a constructive assembly system for school children to animate 3D forms thanks to kinetic memory [237].



(a) reacTable [132]



(b) Illuminating Clay [220].

Figure 2.2: Examples of two kinds of TUIs commonly found in the HCI literature. (a) Tangible artefacts on an interactive surface allow musicians to control instruments. (b) Environmental engineers and landscape designers test out their topography design on an augmented clay display.

Another interesting kind of tangible systems are sandscapes (e.g., [220, 118, 27]). Sandscapes are shape displays, typically made of (kinetic) sand or clay, that users can manipulate to create 2.5D shapes. The system captures the resulting changes of shape, which act as user input, and provides output through colored light projected on the UI to, for instance, highlight the topography [220] or create hedonic visual effects [27]. Thus, users can change the shape through direct manipulation, and the system can link the change of shape to computational data. They are a part of a research field relying on shape-change to represent and/or manipulate computational data : shape-changing UIs (figure 2.1b), which we will discuss further in the next subsection.

## 2.2.2 Shape-changing interfaces

Shape-changing interfaces are tangible, interactive artefacts, whose physical shape can change over time to act as output by reflecting changes in the computational data, to act as input to manipulate the computational data, or both [229]. The change of shape should convey information, meaning or affect [19], and can either be initiated by the system itself (e.g., inFORM [77], PneuUI [310]), via user manipulation (e.g., WristOrigami [324], Gaussbricks [165]), or both (e.g., Emergeables [244], Zooids [159]). However, the interface still needs to leverage some kind of computational capabilities, even if the change of shape is user-driven [19]. For example, if we look at Siftables [179] (figure 2.3c) the modules cannot reconfigure by themselves. Instead, the user can interact with them through direct manipulation to manipulate computational data: for instance, shaking one module horizontally to say "No" and vertically for "Yes", or physically grouping the modules together to group the corresponding data or apply a common tag. On the other hand, standard LEGO brick toys [94] would not qualify as shape-changing interfaces: their physical shape can change via user manipulation, but bricks are passive and do not act as input or output modalities for computational data (with the exception of LEGO Mindstorm [13]).

Users benefit from shape-change for five reasons: they can provide *adaptive affordances*, they can *physically augment the user*, *simulate objects*, *communicate informations*, and/or simply be used for *hedonic and symbolic purposes* [19].

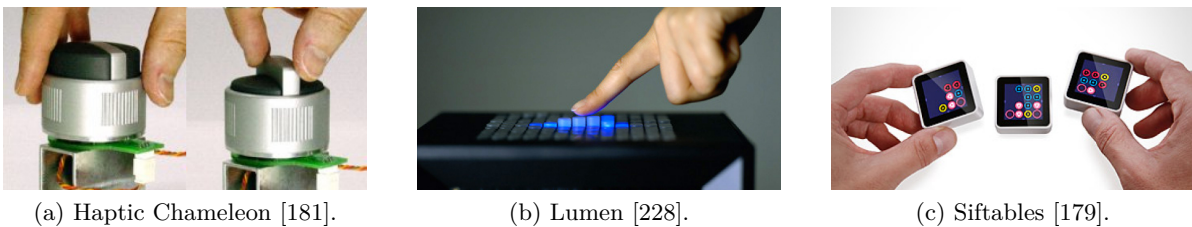


Figure 2.3: Example of early shape-changing interface implementations: Haptic Chameleon and Lumen (a,b) appeared in 2004, Siftables (c) appeared in 2007.

**Adaptive affordances.** Shape-changing interfaces can provide adaptive affordances via changing their shape to best accommodate the task, the user and/or the environment. Thus, depending on the context of the interaction, the change in shape allows for a better usability. Adaptive affordances especially led to the design of shape-changing user controls, such as KnobSlider [141], GazeForm [213], or DynaKnob [298] (figure 2.4).

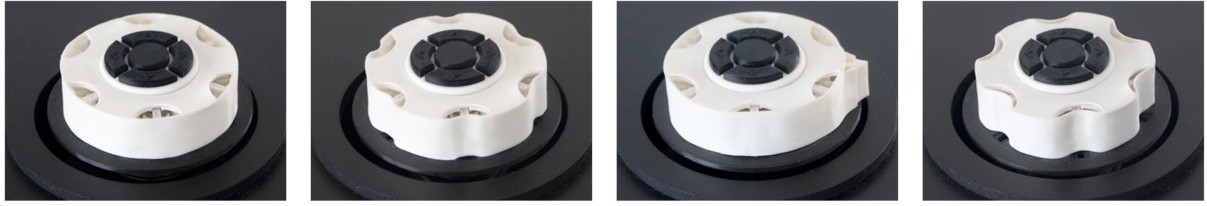
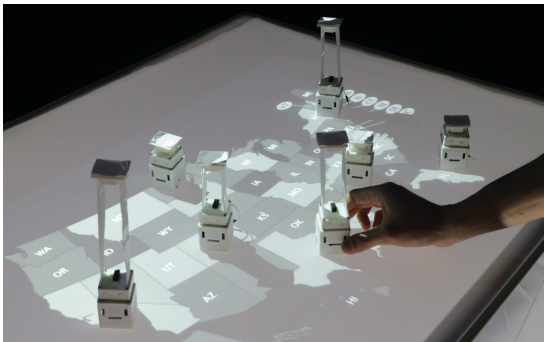
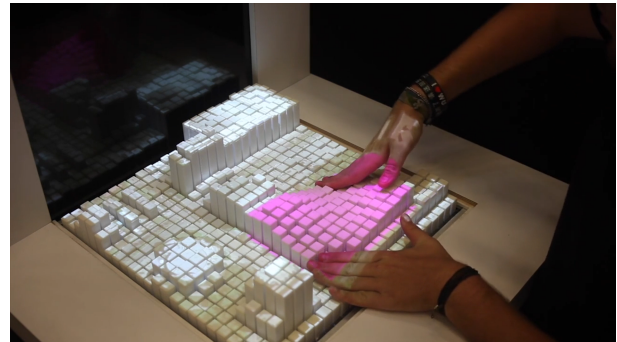


Figure 2.4: Dynaknob [298] can change between four different knob shapes to adapt its physical affordance depending on the functionality.

**Communicate informations.** Changing the shape or the materiality of an interface can communicate information to the user. Especially, similarly to how data visualization is an active research field in GUIs, data *physicalization* is a research field in TUIs and SCIs research [130, 68]. Not only can they serve as output by rendering a physical representation of the data, but they can also provide input by allowing users to interact with the physical representation of the data. Examples are mainly swarm SCIs such as Zooids [159] or ShapeBots [159] (figure 2.5a) or shape displays such as CairnFORM [57] or Materiable [197] (figure 2.5b).



(a) Shapebots [280] are swarm robots that can, e.g., show populations of states on a map.



(b) Materiable [197] is a shape display that can, e.g., allow manipulation of 3D data for city design.

Figure 2.5: Shapebots and Materiables are two examples of shape-changing interfaces that can be used to physically render and manipulate data.

**Simulate objects.** Shape-changing interfaces can be used to recreate existing or fictional objects. HCI researchers envision useful concept scenarios in 3D modeling and animation. Instead of making a time-consuming physical mockup, a shape-changing interface could dynamically render the mock-up that the user can directly manipulate and adjust to their liking (e.g., ShapeShift [261], Figure 2.6). Objects simulation can also allow for a physical representation of objects to provide haptic feedback, which would be especially useful in the context of virtual and augmented realities (e.g., shape-changing augmented display [168] or TilePoP [285]).



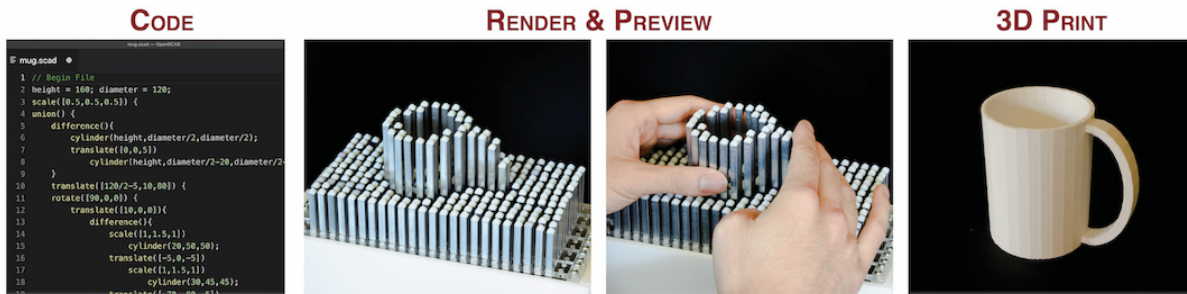


Figure 2.6: Shapeshift [261] allows for a faster prototyping workflow, by pre-rendering a 3D model from OpenSCAD in 2.5D through a pin-based shape display.

**User augmentation.** Shape-changing interfaces can provide physical augmentation *on* the user. Although internal augmentation of the body of the user is rare and can face ethical issues, external augmentation remains an open research subject. Examples in the literature aim at enhancing human dexterity through external augmentation, e.g. tail prosthesis [275] (Figure 2.7) or sixth finger [116]. We find interesting examples of wearable shape-changing UIs, such as WristOrigami [324] which proposed a foldable, multi-display smartwatch as well as a taxonomy to characterize the interactions via folding, flipping and elastic pulling.

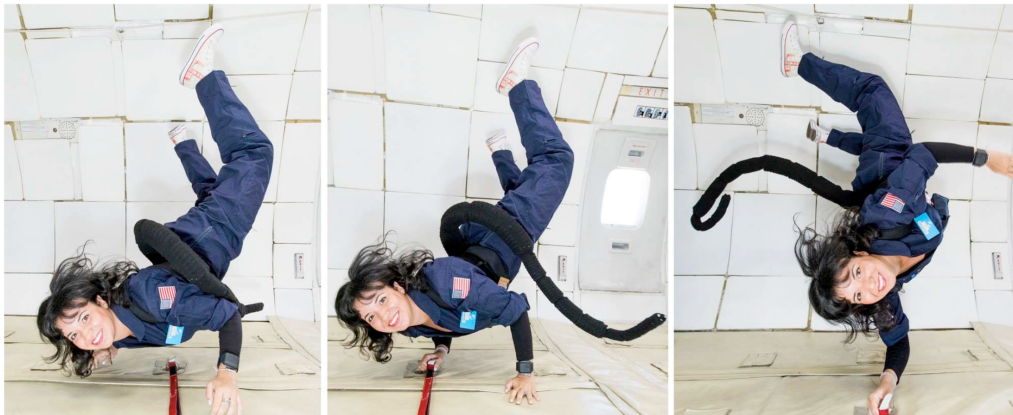


Figure 2.7: SpaceHuman [275] augments the user by equipping them with a robotic prosthetics tail to enhance stability and safety in a microgravity context.

**Hedonic and symbolic purposes** Finally, shape-changing can simply be implemented for fully hedonic and symbolic purpose. For instance, TexelBlocks [49] (Figure 2.8) provide arrays of square blocks that can rotate to display a different texture on their top face, thus providing a “materiality-changing” surface. They can, for example, provide an interactive textured minimap to expand a storybook into a stage or create a boardgame. The goal of shape-changing interfaces can be to provide an aesthetically or sensorially interesting experience to the user, without

necessarily aiming to improve user performance.

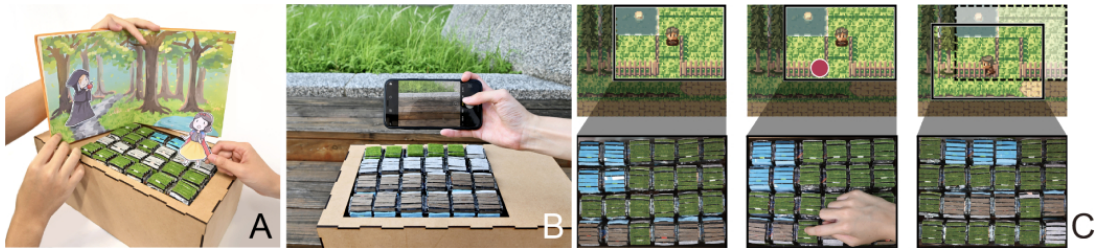


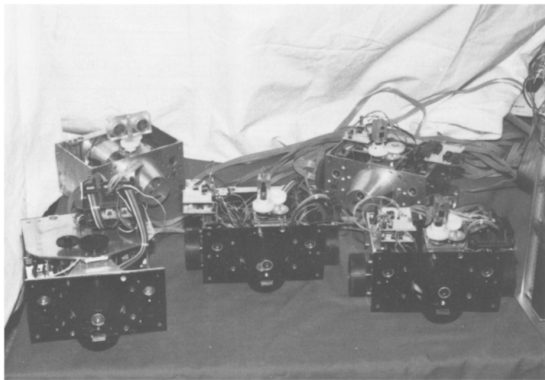
Figure 2.8: TextelBlocks [49] can, e.g., provide an interactive textured minimap.

#### Key message

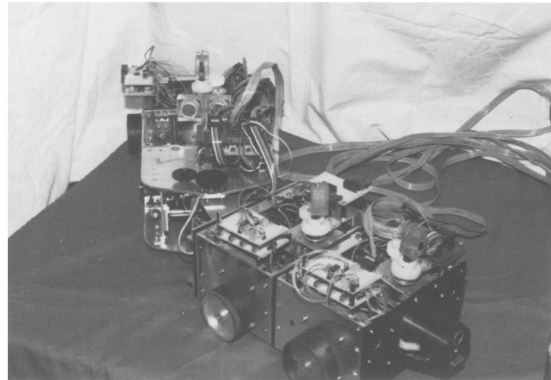
Shape-changing user interfaces are physical UIs able to dynamically change their shape. HCI researchers conducted extensive work on the topic since 2004 to serve five main purposes: (1) provide adaptative affordances, (2) communicate informations, (3) simulate objects, (4) augment users and (5) hedonic and symbolic purposes.

## 2.3 Modular robotic systems

In this thesis, we define a *modular robot* as a large number of robotic modules that can (be) spatially rearranged. We define a *robotic module* as a microelectromechanical system embedding computational capabilities. We also find that the term “*programmable matter*” commonly refers to modular robots in the robotics literature. However, we must remain cautious as different approaches from other research fields are reclaiming themselves as programmable matter. For instance, previous work in material science [161] described molecules able to change their shape as a response to an external stimulus as programmable matter. We consider solely approaches based on *modular robots*.



(a) CEBOT modules before docking.



(b) CEBOT modules after docking.

Figure 2.9: CEBOT [81] was the first implementation of a modular robot.

The robotics community explored modular robots since 1990: the first ever implementation that claimed both modularity and reconfigurability was the Cellular Robotic System (CEBOT) [81] (Figure 2.9). CEBOT was described as “*a new kind of robotic system which is able to reconfigure itself to optimal structure depending on purpose and environment*”. As a consequence of having conducted research in the field of modular robots for over 30 years, the robotics community has proposed many types of modular systems, as well as guidelines and classifications for their design. This section presents how modular robots can be classified according to their *architecture* and type of *reconfiguration*. Although these classifications were not designed with the user in mind, we will further use the following terms in the thesis and relate them to user-centered design requirements.

### 2.3.1 Architectures

Architecture describes the relative physical geometric arrangement of the modules [281]. Modular robots can either follow a single type of architecture (e.g, lattice, chain, swarm) or they may be hybrids that feature more than one type of architecture (e.g., chain×lattice hybrids). A less common architecture, that sometimes falls into the lattice category, are truss structures.



(a) Example of two lattice implementations. Top: ATRON [206]. Bottom: M-Blocks [246].

(b) Example of two chain implementations. Top: M-TRAN [156]. Bottom: UBot [325].

(c) Example of two swarm implementations. Top: Crazyswarm [230]. Bottom: Kilobot [251].

Figure 2.10: Examples of modular shape-changing UIs and the three main types of architecture: (a) lattice, (b) chain and (c) swarm.

**Lattice architecture.** Modules following a lattice architecture are arranged on a regular 2D- or 3D-grid structure called a lattice, as shown on Figure 2.11. For example, 3D M-Blocks [245] (as shown on Figure 2.10a, bottom) are cubic robotic modules that can reconfigure by rolling on each other and jumping thanks to a flywheel and permanent magnets. Another example is ATRON (as shown on Figure 2.10a, top). ATRON’s modules are spherical and can rearrange themselves by latching to their neighbours with mechanical clamps. Their goal is shape reconfiguration, locomotion (e.g., snake-like robot, wheeled-robot or legged robot) and manipulation (e.g., robot arm). There are several different lattice geometries. For instance, we find simple cubic lattices [147] (as shown on Figure 4.4a), face-centered cubic lattices [222] (as shown on Figure 4.4b), or hexagonal lattice [314]. The displacement of modules during reconfiguration is dependent on the geometry of the lattice. Both the control and motion of each module can be executed in parallel, allowing for fast and easy reconfiguration. Lattice systems could be used in the future to enable, e.g., physical computer-aided design, as they allow as many shapes as

play-doh. However, it is currently difficult to conduct HCI research with lattice systems: most contributions are simulations (e.g., [288]) or concepts (e.g., [224]), and working prototypes are few and/or too early (e.g., [206, 83, 245]). Few working prototypes support user input, but their modules cannot move by themselves [147, 173].

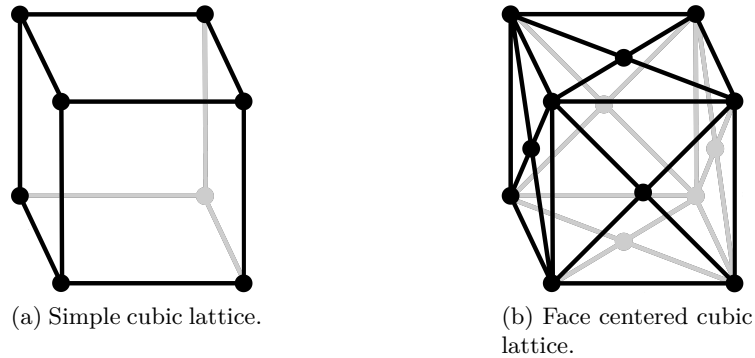


Figure 2.11: Example of two possible lattices for spatial arrangements of robots.

**Chain architecture.** Modules following a chain architecture are connected together following a string or a tree topology [314]. For instance, M-TRAN modules [156] are composed of two half-cylindrical flat parts able to rotate on a 180 degrees axis, as shown on Figure 2.10b (top). Another example are the semi-cubic UBots [325] as shown on Figure 2.10b (bottom). The robotic community not only leverages chain implementations for reconfiguration purposes, but also for locomotion: most can shift between wheel, snake or walker configurations (e.g., [156, 325, 17]).

The articulation of chained modules allow them to be stable in any position between minimum and maximum rotation of the motor joining the two modules. This makes chain implementations versatile, but also means that the displacement of their modules is serial: whereas the displacement of modules in a lattice configuration can be parallelized, the modules in a chain architecture are heavily dependent from each others when they need to move. This means that, compared to architectures allowing parallel displacement of modules, the reconfiguration of chain implementations is more difficult to control, represent and analyse [314, 290]. Chain-based systems are commonly explored in HCI research (e.g., [195, 196]).

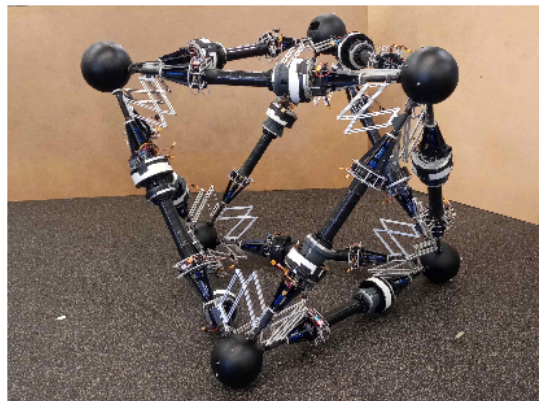
**Swarm architecture.** Modules following a swarm architecture can move independently. Examples include Kilobots [251] and CrazySwarm [230], shown in Figure 2.10c. Another type of modules, called “**mobile**” in the robotics literature, can in addition latch and delegate their mobility to their neighbor (e.g., [81]). Examples of such additional capability include the second version of Zooids [321] where modules can stack and be moved by their supporting neighbor. When modules can latch but keep being individually propelled, and only use the latching to

move collectively, they qualify as swarm (e.g., [185]). Swarm UIs may appear to be a promising approach for short-term HCI research, as we already find several example of working prototypes – some even embedding interactivity – in both the HCI and the robotics literature (e.g., [159, 40, 251, 230]).

**Truss architecture.** Modules following a truss architecture are less common compared to lattice, chain and swarms architectures. We find them primarily in the robotics field as, to our knowledge, no implementation or previous work on truss modular robots have been conducted in HCI. Although the modules in truss implementations could be described as being arranged on a 3D lattice, they differ from strictly lattice implementation by featuring linear actuators (acting as beams) connected through joints (acting as nodes) [170]. Truss systems can be further classified as either following a Variable Geometry Truss (VGT) or a Variable Topology Truss (VTT) configuration. In the case of VGTs, the modular robot achieves reconfiguration and locomotion by changing the length of the beams [99, 175]. In the case of VTTs, the modular robot changes the length of the beams *and* can self-reconfigure its nodes (i.e., the arrangement of the node between the beams can be modified) [170]. Although the HCI community hasn't yet explored truss modular robots, previous work explored deformable truss structures for low-fi fabrication and prototyping [276]. Truss modular robots could offer interesting opportunities in terms of scalable and fast shape-changing low-fidelity prototypes: changing the size of the beams would be faster than displacing or adding the modules in a strictly lattice-based implementation.



(a) Example of VGT architecture [175].



(b) Example of VTT architecture [170].

Figure 2.12: Example of the two different configurations for truss implementations: Variable Geometry Truss (VGT, Subfigure 2.12a), or Variable Topology Truss (VTT, Subfigure 2.12b). The main difference is that the VGT prototype on the left can reconfigure by changing the size of the beams, while the VTT prototype on the right can additionally reconfigure the nodes between the beams.

**Hybrid architecture.** Hybrid systems mix and match the previously mentioned architectures to leverage their benefits. For example, we find in the literature several instances of chain×lattice implementations [133, 313, 255]. They leverage the structural stability of chain implementations, while allowing the chain to reconfigure as a lattice by being able to attach/detach its modules to bypass the serial displacement dilemma of purely chain implementations. Less common, chain×mobile [108] and chain×lattice×mobile implementations [58] allow for self-assembly of chains/lattice implementations.

### 2.3.2 Reconfigurations

Reconfigurations show different abilities (e.g., self-reconfiguration or self-(dis)assembly) and different approaches (stochastic or deterministic). While self-(dis)assembly is the *(dis)connection* of modules (i.e. actuated *Modularity* [141]), self-reconfiguration is the movement of *already assembled* modules.

**Self-reconfiguration** allows for autonomous shape-change [252, 247]. Parts or all of the modules composing the interface move to change from an initial shape to a target shape. This is the most common type of reconfiguration in the literature and across architectures, ranging from lattice (e.g., [245, 38]), chain (e.g., [266, 17]), swarm (e.g., [251, 230]), mobiles (e.g., [81]), and hybrid implementations (e.g., [313, 133]).

**Self-assembly** modules are initially detached from each another (e.g., no *initial shape* but a set of unlatched robots in an unknown configuration). They individually move and latch to assemble into a larger target shape, which has greater capabilities than the individual modules [108]. Self-assembly systems are either hybrid (e.g., swarm×chain [108], mobile×chain [58], pin×lattice [279]) or use stochastic reconfiguration (as presented below) (e.g., [21, 83, 98]).

**Self-disassembly** starts from initially assembled modules, and unlatch –i.e. let go of– parts of the structure to achieve a more interesting and functional one [84, 83]. Self-disassembly is implemented through lattice architectures (e.g., [84, 83]).

**Future types of reconfiguration** are studied mostly as a vision since they present several technical challenges. For example, self-repairing systems could recover from damages (e.g., Self-Healing UI [199] shows a non-modular, non-actuated HCI prototype) by replacing faulty units [18]. Self-replicating systems could take one step further, being able to build copies of themselves [314, 327].

Additionally to these types of reconfigurations, a modular system also follows a deterministic approach and/or a stochastic approach for its reconfiguration.

**Deterministic reconfiguration** relies on the ability of the system to know or compute the location of all modules, in order to achieve a target shape. Deterministic reconfiguration is predominant across the literature: when we conducted a systematic literature review in 2021 (presented in Part I of this thesis), 153 implementations among the 159 we studied used deterministic reconfiguration.

**Stochastic reconfiguration** relies on the environment to move the robots in order to achieve a target shape. For example, the robots may be placed on a moving support surface such as a moving table [21, 83], a water tank [98] or a bag being shaken [83]. The reconfiguration relies on statistical processes [314]: in the case of self-assembly, when two modules come in contact, they share their internal state to evaluate whether they are intended to be neighbours to achieve a given overall target structure. If they do not, they repel each other [98]. The structure grows gradually, “in an organic manner” [83] until completion of the target structure.

Deterministic and stochastic reconfigurations are not mutually exclusive. For example, a system can use stochastic self-assembly to build an initial block of modules and then use deterministic self-disassembly to detach unwanted modules and reach a more complex final shape [83].

### 2.3.3 Homogeneity

Finally, modular robots may either be homogeneous or heterogeneous.

**Homogeneous** modular robots are composed of modules which all feature the same design (hardware *and* software). Most systems are homogeneous, to ease mass production, self-repair and self-reconfiguration [192, 191]. For example, all six systems shown on Figure 2.10 are homogeneous.

**Heterogeneous** modular robots are composed of modules which feature different designs (hardware *and/or* software). Typically, heterogeneous systems are composed of sub-groups of homogeneous modules [69]. Heterogeneous systems offer interesting perspectives as individual modules in a same system can embed different sensing and computational capabilities [236]. For example, the Swarmanoids platform features three kinds of modules with different hardware and behaviours [67]. The foot-bots are equipped with wheels for mobility, the hand-bots are equipped with grasping hands for climbing and manipulation and, lastly, the eye-bots are quadcopters equipped with cameras and laser pointers, able to attach and act as an overhead camera: they retrieve informations about the environment to inform the behaviour of foot-bots and hand-bots.



### Key message

Modular robots are a large number of robotic modules that can (be) spatially rearranged.

Robotics researchers explored different robot configurations since 1990.

They are commonly classified around three criteria:

- (1) architecture type (e.g., lattice vs chain),
- (2) reconfiguration type (e.g., self-reconfiguration vs self-disassembly),
- (3) whether they are homogeneous or heterogeneous.

## 2.4 Modular shape-changing user interfaces

We define *modular shape-changing UIs* as shape-changing UIs made of a large number of robotic modules, such as described in section 2.3. Modular shape-changing UIs are able to share data between modules to support interaction, for instance, to provide a visual or haptic display through the reconfiguration of their shape [145, 40] or to sense user input through touch or deformation [159, 196]. While the robotics community explored modular systems since 1990 [81], the HCI community explored how to leverage modularity in shape-changing interfaces since 2007 (Siftables [179] was modular without actuation).

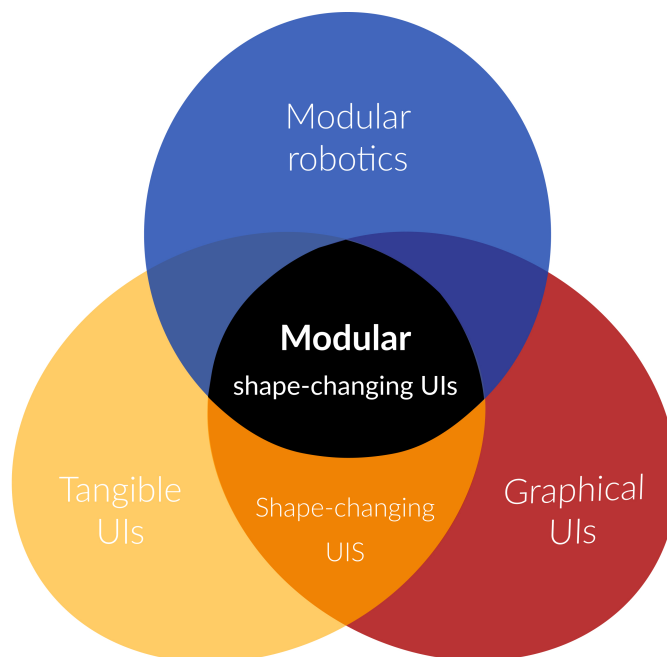


Figure 2.13: While shape-changing UIs are at the crossroad between TUIs and GUIs, *modular* shape-changing UIs are at the crossroad between shape-changing UIs and modular robotics.

### 2.4.1 Benefits and implications of modularity

According to the Morphees+ taxonomy [141], modularity not only means that the interface is able to (be) split in a number of parts, but is also able to be (re)combined while maintaining its original functionality. For this reason, approaches for the implementation of shape-changing UIs such as electromechanical actuation [140], pneumatic systems [310], or smart materials [235] are hardly modular. In order to be modular, they would need to be able to (be) split and still retain their functions, which is much easier with modular robots where each module independently integrate computational capabilities.

In contrast, modular robotics offer great perspectives to support modularity. Moreover, they seem promising to address current challenges such as scalability [19], sustainability [19], robustness [314], cost [314] and versatility [314]. In addition to being able to support modularity, modular robotics may enable *porosity*-changing UIs. Porosity is the ratio of the area of perforated parts to the total area of the shape. Modularity and porosity are key features in shape-changing UIs taxonomies (*Modularity* [141] or *Adding/Subtracting* [239], and *Porosity* [141] or *Permeability* [239]). However, porosity is also difficult to implement with other, non-modular approaches. For instance, the pneumatically actuated air pouches of PneuUI [310] can dynamically open/close a lid on top of a hole to support limited changes in porosity. Such change of shape is pre-programmed at design stage and cannot be modified during interaction. In contrast, modular shape-changing UIs may provide a larger range of porosity, even if they were not planned at design stage. Examples from the HCI literature include PickCells [86], (Figure 2.14), which are cell-like modules that the user can assemble following a lattice architecture to make a reconfigurable touchscreen device.

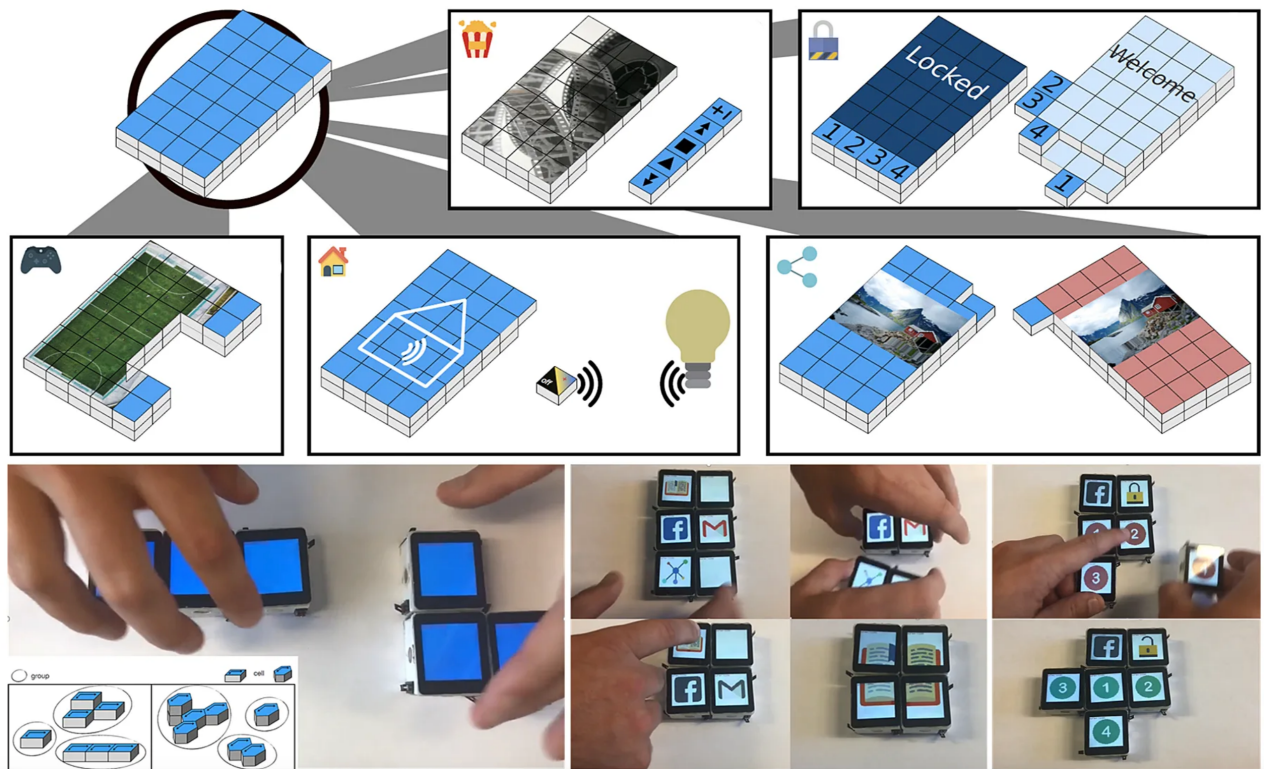
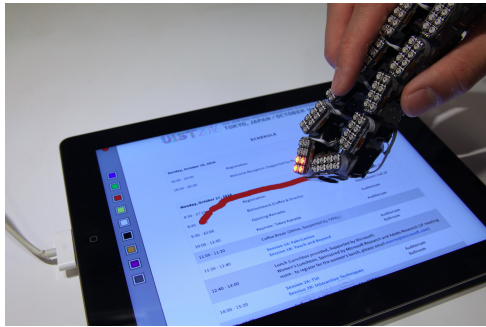
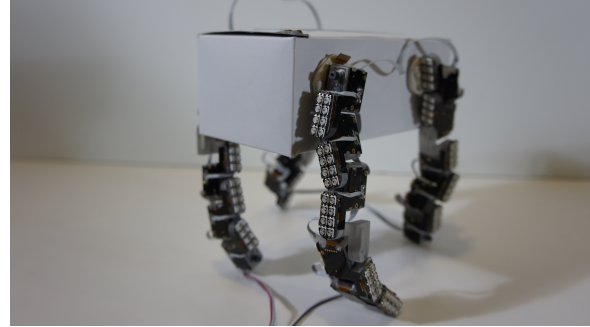


Figure 2.14: Application examples for PickCells, a lattice implementation from HCI. Users can, e.g., detach a line of modules to use as a remote or change the disposition of a few modules around the device to enter a password.

Another example is chainFORM [196] (Figure 4.2) which consists of chained rectangular modules supporting 3D reconfiguration. For instance, ChainFORM can transform its shape to provide different kinds of input widgets during tangible interaction on a touchscreen (a pen, a brush, a magnifying glass) or to provide output through animating a character or providing force feedback to become a haptic glove.



(a) chainFORM can be used as a tangible widget to interact with a touchscreen, e.g. a brush on a tablet.



(b) chainFORM can be use to animate an object, e.g. adding legs to a plain box for locomotion.

Figure 2.15: Application examples for chainFORM [196], a chain implementation from HCI.

Finally, a last example is Zooids [159] (Figure 2.16) which consist of cylindrical swarm modules enabling 2D reconfiguration on flat surfaces. Zooids applications include reconfigurable physical scatterplots. Even though progresses on modular shape-changing interfaces seem encouraging, they are still met with a lot of challenges [19].



Figure 2.16: Application examples for Zooids [159], a swarm implementation from HCI. Zooids can, e.g., display objects and shapes by acting as physical pixels or communicate user input by acting as physical controllers.

#### 2.4.2 User experience of shape-change and modularity

While modular robotics offer great perspectives for HCI, the current theoretical and technical advances of modular robotics are little centered on the user. Although robotics researchers have conducted extensive work on modular robots since 1990 [81] and proposed several advanced robot configurations as seen in Section 2.3, their implementations are mostly designed for construction

or locomotion rather than user interaction [247]. Robotics tools for the design of modular robots are not user-centered, nor take into account the impact of the technical aspects of the modules on the interaction with the user.

Benefits and drawbacks of shape-changing interfaces are important to evaluate thoroughly. In order to provide users with better usability through the implementation of shape-change in physical devices, it is important that HCI researchers seek to understand how users may benefit from the novel interaction platforms and modalities, as well as how they perceive said interaction and the resulting user experience. For instance, even though Alexander et al. [19] states that learnability and naturalness of interaction are claimed as benefits of shape-changing UIs, they are little studied so far. Comparative studies between existing devices and their shape-changing counterparts are needed to assess those benefits and drawbacks, and further justify the use of shape-changing interfaces. Specifying user-centered design rationale early on to inform the research and the design of an interactive system is a key element of user-centered design [124]. As a consequence, specifying user-centered design rationale is highly important to further enable HCI research on modular robots to support modular shape-changing UIs.

Moreover, when evaluation is conducted on a prototype through user experiments, it is generally the whole system that is evaluated. Since interacting with shape-changing interfaces combines different modalities (e.g., speed of reconfiguration, intermediate shape taken during reconfiguration, shape change state, haptic feedback, visual feedback), the individual impact of each factor on usability is hard to isolate. Integrating user experience during the design process of the final prototype, by evaluating each modality, could help for a better understanding of exactly which factor plays which role in the interaction with the final system. Although, even when adopting a user centered design approach, researchers face the lack of robustness of their prototype. In-depth evaluation is impaired by the fact that those prototypes are often too fragile and might break when used for an extended period of time, complicated to move across locations and costly both in terms of time and money to reproduce. Finally, Alexander et al. [19] state that replication of work on shape-changing interfaces is regrettably rarely conducted, since novel, unique one-off prototypes are preferred.

The main technological challenge that our present work aims at informing is the miniaturized device form factor and high resolution challenge. Since we tend to compare shape-changing user interfaces with graphical user interfaces, it is natural for end users to expect the high-resolution outputs they are used to in their everyday interactions. The output resolution should be in the mm-scale rather than in the cm-scale nowadays shape-changing interfaces implement [159]. It is challenging to achieve a high-resolution physical prototype with the same resolution as a pixel-composed graphical user interface. Nowadays modular shape-changing devices do not meet these requirements: the components used in the making of self-reconfigurable robots in modular robotics shape-changing interfaces rarely allow for mm-scaled robots. We find in the

literature many sizes for these robots and, even though there are getting smaller as technology advances (as often with electronics) they still hardly reach the mm-scale. For instance, the smallest actuated lattice modules are the the 12mm Robot Pebbles, which reconfigure through self-dissassembly [83]. Self-reconfigurable swarm implementations reached sizes as small as 26x21mm, with the Zooids platform [159], and chains can reached 25×30×12mm with ChainFORM [196].

Reducing the size of robotic modules requires reducing the size of each of their components as well, which would in turn impact other factors such as battery capacity, speed of reconfiguration or robustness of the final shape of the interface. Hence, adopting a user-centered approach in the design of modular shape-changing UIs would give guidelines and rationales to, in turn, help designers to inform their choices for future technological development. In the long term, this process would spare development time and cost as well as increase the usability of the final system.

#### Key message

HCI researchers experimented with lattice, chain and swarm architecture of modular robots, each to support novel interaction modalities. They are a great alternative to pneumatically and mechanically actuated shape-changing prototypes to propose systems whose additional changes of shape can be implemented *after* the initial designing stage.



PART I

# **A Design Space for Modular Shape-changing User Interfaces**

---





# PART I - INTRODUCTION

---

## Publication

The work presented in this Part has been published in the PACMHCI journal and presented at EICS'21 (*Engineering Interactive Computing System*) [232].

There is little empirical studies on how modular shape-changing UIs impact users. This makes it harder to build upon previous work, as we have little understanding on which design is best suited for which application. So, *how* can we learn and draw insight on how to build modular shape-changing UIs through modular robots? As we discussed in Chapter 2, the HCI community started work on shape-changing UIs in 2004 [181, 228], and proposed a first modular implementation in 2007 [179]. During that time, the robotics community has been working on modular robots since 1990 [81] and proposed several advanced robot configurations. However, their implementations are mostly designed for construction or locomotion rather than user interaction [247]. Thus, robotics tools for the design of modular robots are not user-centered, nor take into account the impact of the technical aspects of the modules on the interaction with the user. One of the reason why HCI researchers do no conduct more work by using previous work and prototypes from modular robotics researchers may be the lack of sufficient knowledge on how to build upon existing knowledge in robotics. Moreover, prototyping shape-changing UIs in general requires, among others, complex skills to leverage current knowledge in materials, electronics and mechanics, whereas the HCI community is mostly skilled in simple electronics [19].

We focus on hardware properties in this chapter since hardware prototyping of *modular* shape-changing UIs is the current greatest challenge: the hardware is still a research topic, and needs to become smaller, lighter, stronger and faster in order to be comparable with the capabilities of other approaches [19]. They are therefore seldom studied in HCI, with few configurations of robots and scenarii explored (e.g., [159, 247, 90, 195]). The existing systems are built in an ad-hoc manner, and the rationale behind design choices are not always documented. When researchers need to build a new system, they might have to start from scratch, and deal with the same design issues again. In these conditions, it is hard to explore design properties in a systematic way, and one can easily find a better solution after the implementation is finished. On the one hand, existing HCI tools for the design of shape-changing UIs (e.g., surveys, taxonomies, or challenges) globally consider all shape-changing UIs (e.g., [248, 271, 141, 19]). On the other hand, existing HCI design rationales for modular shape-changing UIs each address a

---

local set of design properties, rather than providing a global viewpoint on modular interfaces (e.g., handheld chain interfaces [247] or tabletop swarm interfaces [159]). While there are benefits in technology-agnostic designs, it is however hard to know which particular kind of robotic modules allow the implementation of a particular design.

All in all, our observation is that both community could benefit from each other’s expertise, but the gap between them is difficult to bridge. The research in both communities spans over decades, uses different vocabularies (e.g., “shape-changing UI” is never used in robotics, while “Modular Self-Reconfigurable Robots (MSR)” is never used in HCI), and was conducted with different goals in mind. Although both communities provided tools for the design of modular systems, there is no coherent set of properties taking into account their specificities and their impact on the interaction. Specifying user-centered properties early on to inform the research and the design of an interactive system is a key element of user-centered design [124]. As a consequence, specifying user-centered properties is highly important to further enable HCI research on modular robots to support modular shape-changing UIs.

The following chapters focus on providing a tool for the systematic exploration of the design properties of modular shape-changing UIs. Although challenging, as the knowledge bridges both HCI and robotics communities and covers decades of research, this is an important first step so that we can further understand the properties at play in the design of modular robots. Our aim is to bridge the gap between the previous experience of robotics researchers in building modular robots, and the need of HCI research to understand the various kinds of design parameters to take into account in the design of their implementation, as well as how they impact each other. We build upon the literature in both domains to propose:

1. A set of **properties at the scale of the interface** (*macro scale*) (Figure 2.17, left),
2. A set of **properties at the scale of the modules** (*micro scale*) (Figure 2.17, right),
3. An analysis of their dependencies.

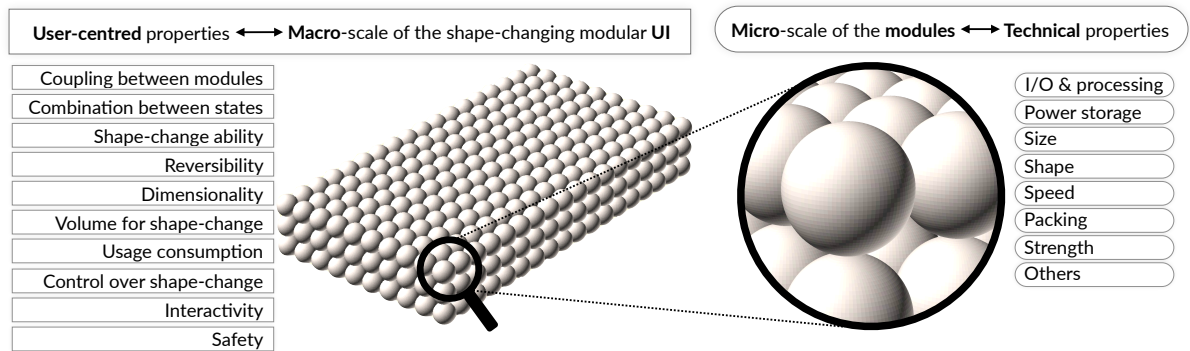


Figure 2.17: Our structured space of properties: (left) user centered properties at the macro scale of the modular shape-changing UI, and (right) technical properties at the micro-scale of the modules.



# REVIEWING THE CROSS-DISCIPLINARY LITERATURE IN HCI AND ROBOTICS

---

## Contents

---

<b>3.1</b>	<b>Introduction</b>	<b>48</b>
<b>3.2</b>	<b>Methodology</b>	<b>49</b>
3.2.1	Identification	50
3.2.2	Screening	51
3.2.3	Eligibility	52
3.2.4	Inclusion	52
<b>3.3</b>	<b>Corpus analysis</b>	<b>54</b>
3.3.1	Analysis 1: robotics literature	54
3.3.2	Analysis 2: HCI literature	54
3.3.3	Importance of unifying existing design spaces	55
<b>3.4</b>	<b>Synthesis</b>	<b>56</b>

---

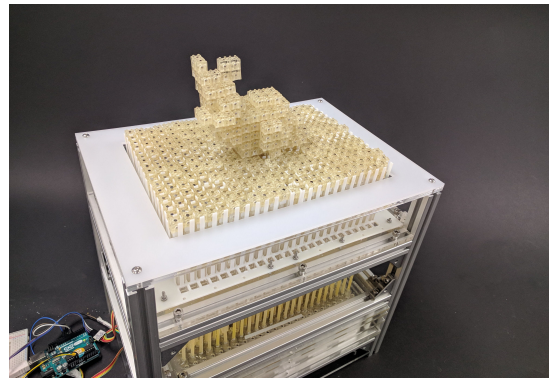
### 3.1 Introduction

Our first goal is to better understand (1) how to build modular systems and (2) how their design choices may impact user interaction. To achieve this goal, we first need to review the literature in modular shape-changing UIs, which spans across both the HCI and robotics communities.

This is challenging as work from HCI and robotics span over several decades (starting from 2007 in HCI [179], 1990 in robotics [81]), while not using the same vocabularies (e.g., “*shape-changing UI*” in HCI and “*programmable matter*” in robotics). There is also no comprehensive definition for modular robots. In this chapter, we define modular robots as an ensemble of robotic modules, i.e. microelectromechanical system embedding computational capabilities, allowing them to change shape (by themselves or not). We focus on modules embedding *computational capabilities*, and we do not solely consider *self-actuated* systems. The rationale behind that choice is that some existing implementations that rely on external actuation to change shape still embed computational capabilities.



(a) M-Blocks [245].



(b) Dynablocks [279].

Figure 3.1: Example of two modular shape-changing UIs with only one fitting our definition of a modular robot. M-Blocks (3.1a) fits our definition as the modules embed computational capabilities, whereas we do not take Dynablocks (3.1b) as they only embed passive magnets and rely on an external pin-array for reconfiguration.

We conduct a systematic exploration of the literature in both HCI and robotics. We follow the PRISMA 4-steps methodology [167] as in previous work [302]: identification, screening, eligibility and inclusion. This allows us to systematically study the literature and to gather a corpus of 605 papers. This chapter especially presents the methodology we followed and the corpus we obtained. We will further present the design properties drawn from this analysis in the two following chapters (Chapters 4 and 5).

## 3.2 Methodology

This section presents the systematic review approach that we adopted. The PRISMA Statement was initially developed as a tool to help researchers with systematic reviews to assess the benefits and harms of interventions in health care [167]. This is a four-steps methodology to report systematic reviews and meta-analyses and, although initially designed for health care intervention, it has since been commonly used in various area of research including HCI and robotics (e.g., [302, 82]). We report the flowchart describing the number of references added or removed at each step of the process in Figure 3.2.

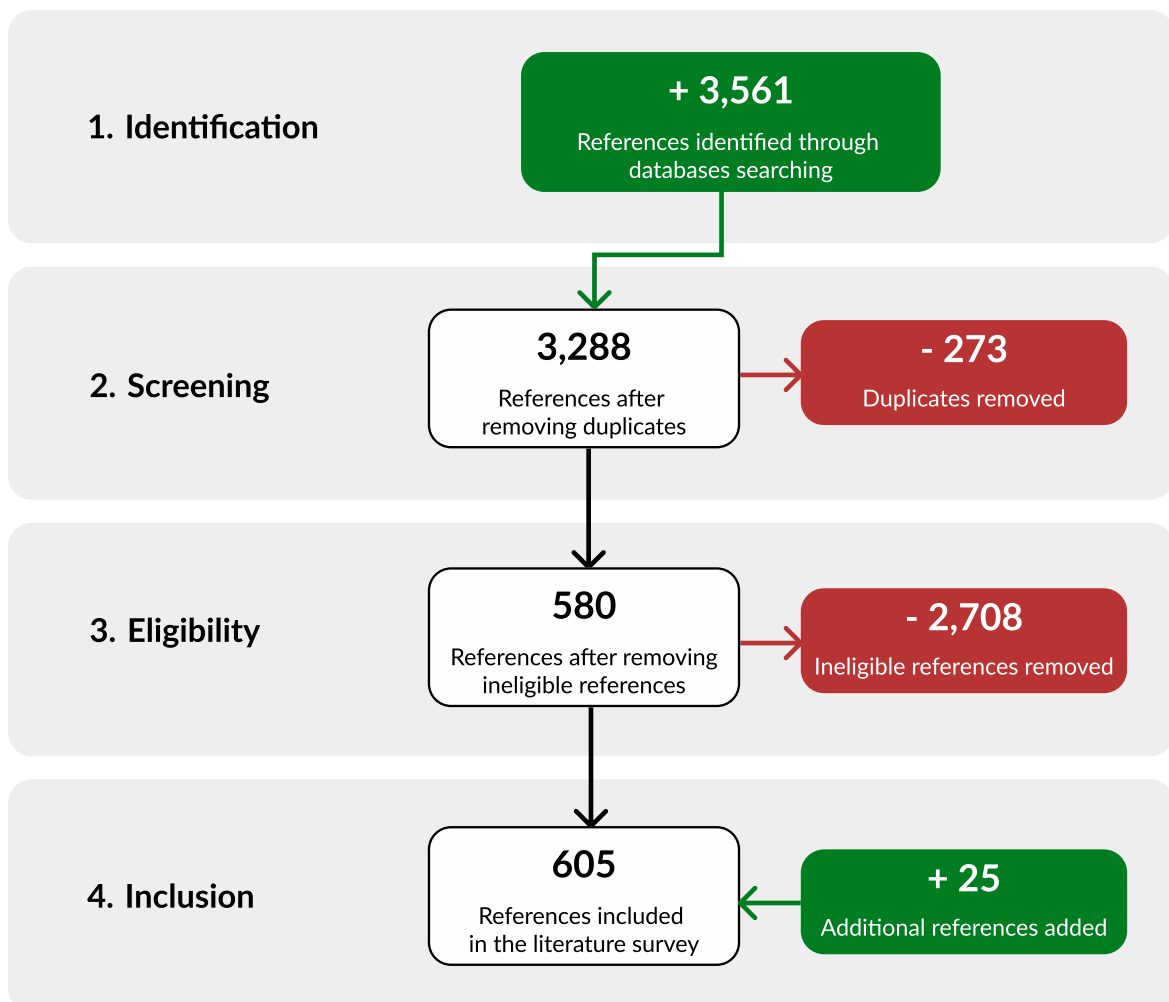


Figure 3.2: Flowchart of the systematic review presented in this chapter, following the PRISMA methodology [167]



### 3.2.1 Identification

This step follows the rules described in [302]:

1. **Advanced search:** we ran our queries using the “*advanced search*” option when applicable (e.g., not a feature on Google Scholar). Moreover, results are sorted by relevance.
2. **Minimum number of references:** we included all references if the queries returned less than 400 results.
3. **No missing references:** we included the first 400 references and manually checked the next 200 references if the queries returned more than 400 results.

We used the advanced search feature, in four major computer science digital libraries: ACM Digital Library, IEEE Xplore, Springer Link, and Science Direct. To ensure we did not miss references from other publishers, we additionally search for references on Google Scholar. We performed the search on all available data (e.g., title, keywords, abstract, full text).

Multi-disciplinarity renders choosing relevant and comprehensive keywords difficult. As we discussed in the problem statement of this thesis (Section 1.2), both HCI and robotics rarely interact with each other. We find previous work on modular systems in both communities, but they conduct research separately and disseminate their work in different venues using different vocabularies. For instance, HCI researcher often use the term of “*shape-changing UI*”, which is never used in robotics. Similarly, robotics researcher use terms such as “*programmable matter*”, which we sometimes find in HCI, or “*modular self-reconfigurable (MSR) systems*”, which we never find in HCI. Moreover, there is a wide range of keywords used by both communities, from the general modular aspect (e.g., “*modular interface*”) to specific technical aspects (e.g., “*self-assembly*”) of the interface.

To match this great diversity in keywords and make sure we do not miss any relevant paper, we chose to run two queries: (1) one using *general keywords* describing the modular aspect of the system and (2) one using *technical keywords* describing the architecture and type of reconfiguration.

**General query** Our first query was the *general keywords* query. We combined the following general keywords about modular interfaces in both HCI and robotics:

*modular AND (“programmable matter” OR “modular robot” OR “modular interface” OR “shape-changing interface”).*

This ensures that each general keyword includes the modular aspect. We obtained 277 results on ACM Digital Library, 848 results on IEEE Xplore, 1,672 results on Springer Link, 1,036 results Science Direct, and 11,600 results on Google Scholar.

**Technical query** Our second query is as follow:

*robot AND (“self-reconfigurable” OR “self-assembly” OR “self-disassembly” OR swarm OR chain OR lattice).*

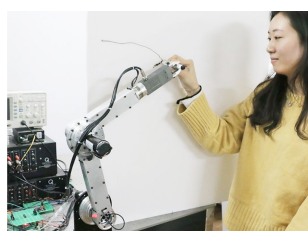
We discarded the keyword *“hybrid”* as papers describing hybrid systems further specify the architecture types (e.g., lattice×chain, chain×swarm). We obtained 4,640 results on ACM Digital Library, 7,232 results on IEEE Xplore, 44,361 results on Springer Link, 50,93 results Science Direct, and 730,000 results on Google Scholar.

For each query and on each library, we displayed the results by decreasing order of relevance. We included all references if the query returned less than 400. If the query returned more than 400 references, we included the first 400 and performed a manual check of the next 200 to ensure we did not miss relevant papers. Doing so, we obtained 1,725 references from the general query and 1,836 references from the technical query, i.e. a total of 3,561 references.

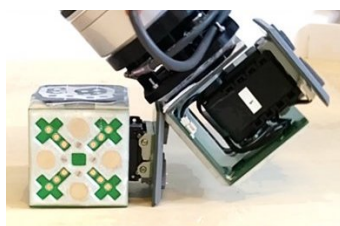
### 3.2.2 Screening

As in [82], we screened the title and abstract of each paper to remove duplicates and determine their relevance to the research question. However, we could not find any irrelevant papers at this phase. Indeed, assessing relevance solely through title and abstract proved challenging. For example, the term “modular robot” is largely used for industrial robot manipulators which are outside the scope of our work. We could not leave out these papers at the screening phase: the titles and abstracts were not enough to determined wether the paper did indeed focus on non-modular robot manipulator or, for instance, chain-based modular implementations with manipulation capabilities (Figure 3.3).

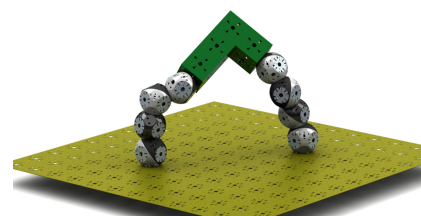
After removing 273 duplicates, we obtained a total of 3,288 references.



(a) Modular robot manipulator (MRM) prototype [66].



(b) Emerge module (left) and robot manipulator gripper (right) [187].



(c) Roombots manipulating an L-shape [34].

Figure 3.3: Example of references that used “robot manipulator” in their abstract or title. The prototype shown on Subfigure 3.3a does not fit our scope.

### 3.2.3 Eligibility

Following [302], we evaluated each paper on their *form* and *content*. Concerning *form*, we only retained papers written in English and published in a peer reviewed venue. We did not consider PhD and Master theses, as we expect such research to be identified in our identification step through their resulting peer-reviewed publications

Concerning *content*, we only retained papers matching the two following selection criteria: scope of the contribution and type of contribution.

**Scope of contribution** We considered papers that study modular shape-changing UIs, that we defined in the introduction as UIs made of a large number of robotic modules, i.e. micro-electromechanical system embedding computational capabilities, allowing them to change shape (by themselves or not).

**Type of contribution** We considered papers presenting an implementation, a tool for its design, or a survey of implementations. Among papers presenting an implementation, we considered papers either presenting a working or conceptual implementation. Among papers presenting an implementation, we only considered papers presenting hardware or interaction design contributions. Work on reconfiguration software and algorithms were left apart for this first version of our space of properties, and kept for future work.

We discarded 2,708 ineligible papers, leaving 580 references to be included.

### 3.2.4 Inclusion

Some references that we know to be relevant did not show up with our queries: two implementations [81, 247], a paper on human-swarm interaction using the Zoids platform [145] and a taxonomy [281]. First, to ensure that we do not miss any other relevant implementations, we cross-checked the implementations we found with the ones presented in the surveys and related work from our corpus. We found seven additional implementations, which we further included [81, 190, 112, 151, 299, 247, 254]. Second, we ran the query "*Human-Swarm Interaction*" through the same databases we used for the rest of our corpus. After removing duplicates and ineligible papers, we found 17 additional references which we further included. Finally, we added the taxonomy paper [281]. We hypothesize that this paper did not appear in the results of our queries because it is recent (2020).

With the inclusion of these 25 papers, we obtained a corpus of 605 papers. However, a single implementation, for instance different versions, can be described in several papers. For this reason, we found 159 unique hardware or conceptual implementations presented in a total 485

papers. We also found 92 papers describing tools for design (e.g., taxonomies) and 39 surveys of existing implementations. A single paper can present several of these types of contribution.

### 3.3 Corpus analysis

We now present the scope of contributions that we found in both literature, resulting from this analysis.

#### 3.3.1 Analysis 1: robotics literature

On the one hand, the robotics field contributed to the design space by conducting extensive surveys of previous implementations. From these surveys, they draw (1) classification and evaluation methods [70, 95, 315, 18, 281], (2) benefits and challenges of modular self-reconfigurable systems [314, 269, 36], (3) criteria for design [41, 38]. However, these contributions are not centered on the user. In particular, many of the publications presenting tools for design are centered on the technology. As we aimed for our properties to be independent from the technology in order to prevent obsolescence of the properties, we did not consider the properties that were centered on the technology. For instance, the docking mechanism (e.g., [134, 164, 183, 303]) is a low-level hardware implementation concern that is centered on the technology.

#### 3.3.2 Analysis 2: HCI literature

On the other hand, the HCI literature provides surveys and design tools centered on the user. Their contribution are: (1) classification and evaluation methods [141, 239, 271, 272], (2) benefits and challenges [229, 119, 19], (3) criteria for design [174, 159, 247], (4) how users perceive and interact with modular shape-changing UIs [171, 145, 198]. However, these tools mostly deal with the broader field of shape-changing UIs rather than focus on *modular* ones. Thus, they do not take into account the specificities of modular robotics nor the variety of robot configurations. For example, a swarm and a chain implementations do not allow the same ranges of shape-change.

Some design rationales are proposed in papers presenting implementations. For instance, the authors of Zooids stress the importance of the size of modules, as they advocates for modules as small as possible in order to make tangible UIs made of “stuff” rather than “things” [159]. However, each design rationale consider a very local and specific set of designs, rather than provide a global viewpoint. For example, LineFORM [195] proposes a design space specifically for *actuated curve interfaces*. Cubimorph [247] specifically targets *handheld chain interfaces*. Zooids [159] defines requirements for *tabletop swarm interfaces*. In addition, our literature reviews reveals inconsistencies between the design rationales. For instance, Zooids require their modules to be constantly detached, while Cubimorph require theirs to be constantly attached.

### 3.3.3 Importance of unifying existing design spaces

In HCI, it is important for design tools and rationales to encompass evaluative, comparative, and generative powers [26]. *Evaluative power* describes the ability to facilitate the assessment and evaluation of multiple design alternatives, enabling designers to objectively analyze and measure the effectiveness and usability of interfaces. *Comparative power* refers to the capability to enable systematic comparisons among different design options, helping designers in identifying optimal solutions based on predefined criteria. *Generative power* relates to the capacity to help designers generate new designs and explore innovative solutions during the design process.

As we discussed in our analysis of the literature in robotics and HCI, previous work started conducting work to address these design considerations. For instance, they proposed classifications and evaluations methods that hold evaluative and comparative powers (e.g., [239, 141, 18, 281]) and design rationales that additionally hold generative powers (e.g., [41, 38, 174, 159]). However, there remains a need to consolidate and integrate these previous work into a coherent framework that take into account the specificities of *modular* shape-changing UIs, and the variety of modular robots configurations used to implement these UIs. The primary objective of the present work is to bridge this gap by structuring and unifying previous research efforts while leveraging the evaluative, comparative, and generative powers of design tools. By doing so, we aim to contribute to the field of HCI by providing a comprehensive approach that allows the systematic exploration of the cross-disciplinary design space of modular shape-changing UIs. Our goal is to enable designers to create more effective and user-centered modular shape-changing UIs, by anticipating and reflecting on how individual design factors could impact their overall prototype design.

We will present our evaluation of the resulting structured design space by describing its evaluative, comparative and generative powers in the conclusion of Part I.

## 3.4 Synthesis

In this chapter, we presented how we conducted our systematic literature review in both HCI and robotics communities. After following a four-step methodology and filtering through an original corpus of 3,561 references, we obtained a final corpus of 605 references.

Through this literature review and the analysis of our resulting corpus, we confirmed that there is no unified design space for modular shape-changing UIs. Although both communities contribute to the scope of classifications and evaluation methods, as well as criteria for the design of modular systems, the goal that drive their work is very different: on the one hand, works from the robotic community do not take into account the user, and on the other hand, works from HCI do not take into account the specificities of the vastly different kinds of modular systems (e.g., a chain implementation vs a lattice implementation). Moreover, the robotics community conducted previous work on the benefits and challenges of modular self-reconfigurable systems whereas the HCI community conducted previous work on how users perceive and interact with modular shape-changing UIs.

In the next chapter, we present how we followed a 6-step approach to analyze our corpus and identify the properties that guide the design of modular shape-changing UIs.







# DESIGN PROPERTIES FOR MODULAR SHAPE-CHANGING USER INTERFACES

---

## Contents

---

<b>4.1</b>	<b>Introduction</b>	<b>60</b>
<b>4.2</b>	<b>Properties of the interface (macro scale)</b>	<b>61</b>
4.2.1	Coupling between modules (Digital /Physical)	61
4.2.2	Combination between the digital and physical states of the UI (Digital / Physical)	63
4.2.3	Shape-change ability (Physical)	64
4.2.4	Reversibility (Physical)	65
4.2.5	Dimensionality (Physical)	65
4.2.6	Volume required for shape-change (Physical)	66
4.2.7	Usage consumption (Physical/Interaction)	66
4.2.8	Control over shape-change (Interaction)	67
4.2.9	Interactivity (Interaction)	68
4.2.10	Safety (Interaction)	69
<b>4.3</b>	<b>Properties of the modules (micro scale)</b>	<b>71</b>
4.3.1	Input, output and processing capabilities (Intra-module)	71
4.3.2	Power storage (Intra-module)	71
4.3.3	Size (Module)	72
4.3.4	Shape (Module)	72
4.3.5	Speed (Module)	72
4.3.6	Packing (Inter-modules)	73
4.3.7	Strength (Inter-modules)	73
4.3.8	Others	74
<b>4.4</b>	<b>Synthesis</b>	<b>75</b>

---

## 4.1 Introduction

We followed the PRISMA methodology [167] and obtained a corpus of 605 papers on modular systems from both HCI and robotics. We now leverage this corpus to identify the properties involved in the design of modular systems. Our aim is to unify and structure the existing design properties and re-center them around the user. We thus take a 6-steps approach to analyze our corpus.

1. We identify the relevant properties guiding the design of existing implementations or proposed in the tools for design,
2. We merge identical properties,
3. We group the properties that complementarily define a higher-level one (e.g., coupling between modules presented in Subsection 4.2.1),
4. We precisely define the properties that we found unclear,
5. We structure them with the designer in mind (e.g., into macro and micro properties), and
6. We then study their dependencies.

We could compare the design of modular shape-changing UIs to the design of GUIs: when designing a GUI, we do not solely focus on the design of each individual pixel. The properties of the pixels are important (e.g., which size they are, which color they can take, how bright they can be), but what is also important is the design of the overall UI they compose. We follow the same rationale for the design of modular robots and modular shape-changing UIs.

First, we present the properties that impact the system at the scale of the overall interface (*macro-scale*). We draw ten properties that impact user interaction at the digital, physical and interaction levels. Then, we present the properties that impact the system at the scale of each individual module (*micro-scale*). We draw seven properties that play a role at the intra-module, overall module or inter-module levels.

## 4.2 Properties of the interface (macro scale)

This section presents the design properties at the scale of the overall interface. We identified and structured the following set of 10 design properties that apply to modular shape-changing UIs (Figure 4.1 and summarised in Table 4.1). We classify them according to which level they impact most between the system and the user: *digital*, *physical* or *interaction*:

1. *Digital level*: The properties at the digital level are related to the position and state of the modules in the computational model. Even though we left for future work the reconfiguration algorithms, we report here other high-level digital properties that impact user interaction.
2. *Physical level*: The properties at the physical level are the ones of the tangible artefact made of physical robotic modules, i.e. the physics of the UI. They impact user interaction as users will interact with the physical UI, but are not considered as being at the *interaction level* since they can be characterized even if there is no interaction.
3. *Interaction level*: The properties at the interaction level primarily impact the interaction design of the UI.

Physical and digital levels were introduced in prior work (e.g., [55]), while the interaction level stems from the current knowledge on how users interact with a modular shape-changing UI. We use ergonomics criteria [24] to characterize the expected impact of these properties on the user: they all (in)directly impact user experience as we adopt a user-centered approach, even though physical- and digital-level properties can be characterized out of an interaction context.

### 4.2.1 Coupling between modules (Digital /Physical)

Coupling between modules can be described both at the digital level (*hierarchy*), and at the physical level (*smoothness* and *resolution*).

Hierarchy defines whether the modules are standalones (i.e., driving the action by themselves) or satellites (i.e., the action is dependent on a standalone module or group of standalone modules) [87]. Satellites can be either original satellites (i.e., always synchronized to the same standalone module(s)) or borrowed satellites (i.e., able to synchronize to any standalone module(s)). Current approaches in robotics range from *standalone* (e.g., [87]) to *standalone + their satellites* (e.g., [147, 286]). In some cases, all modules are satellites and the device assuming the role of "standalone" is externalized (e.g., a micro-controller [159] or overhead controller [251]). However, it is not suitable for every context of use: for instance, a static overhead control system does not suit a mobile handheld context. Homogeneous systems do not inherently have to follow

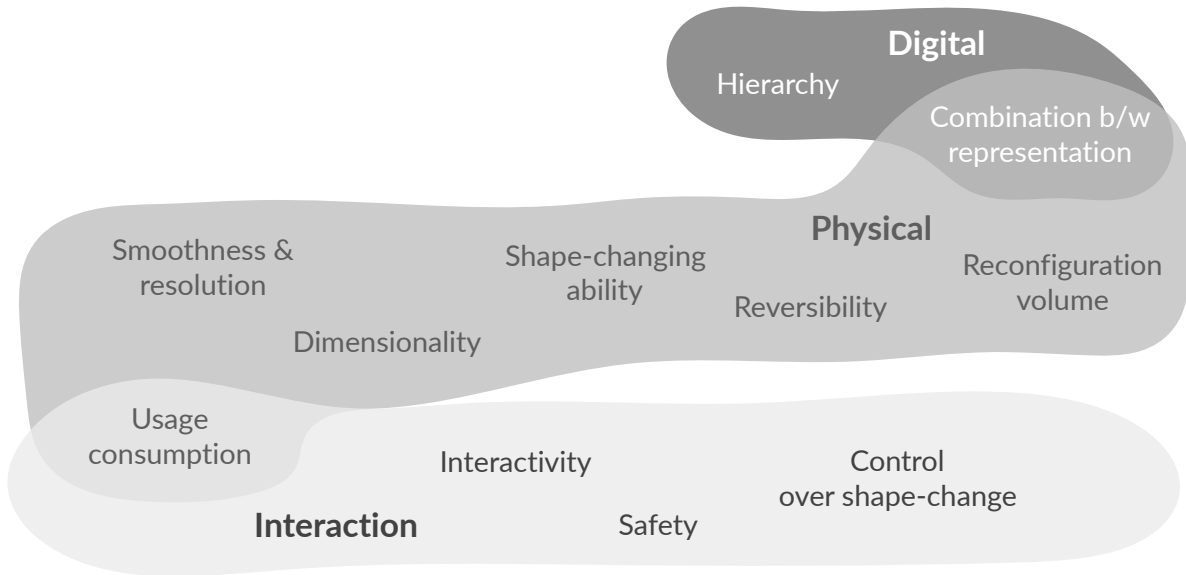


Figure 4.1: The user-centered properties for modular shape-changing interfaces. The properties are further classified depending on whether they impact the interface at a digital level (dark gray), physical level (middle gray) or interaction level (light gray). *Combination between physical and digital states* is classified as impacting both digital and physical levels, as it describes the interaction between the physical and digital shape of the interface. *Usage consumption* is classified as impacting both the physical and interaction levels as it is the power consumed *under a standard context of use*.

the standalone approach: modules may have the same hardware and software design but switch between satellite and standalone roles depending on the needs of the system or user.

Smoothness of the envelop is defined by deviations from the envelop, of the direction of the vector normal to the surface modules. We simplify this as the *gaps between modules*. A very smooth surface has been a requirement for decades, from the “operating surface texture” [76] in 1995 to the “seamless interactive surface” [247] in 2016.

Resolution of the envelop is defined as the input and output resolution at the surface of the UI, in dots per square centimeter ( $\text{d cm}^{-2}$ ) [244]. Researchers aim towards interfaces which provide high input resolution, and a high output resolution for expressive shape-change capacity [19].

The approaches to achieve a smooth envelop with high resolution depends on whether we consider each module as (1) an *individual pixel/voxel/sensel* [244], or (2) as a *set of pixels/voxels/sensels*, i.e. a small display. The first approach, where modules are individual pixels, can achieve both high *smoothness* and *resolution* through micro-scaled modules (e.g., [19, 38]). Although this approach offers more flexible and expressive shape-change, as each voxel/sensel is able to reconfigure in the space, current implementations are at the cm-scale rather than the

desirable mm-scale [19]. Nonetheless, with current modules as small as  $\varnothing 11$  mm [37], the micro-scaled approach is promising for long-term research as the size of components will decrease.

The second approach, where modules offer a small display, can achieve high *smoothness* through minimal joints between modules [247], and high *resolution* through, for instance, high resolution touchscreen displays on the faces of the modules. Even though current lattice systems are at the cm-scale, cubic implementations (e.g., [245, 84, 83]) provide seamless surfaces through minimal joint between modules. A few existing implementations embed displays on their modules ranging from arrays of LEDs (e.g., [196]) to OLED/FOLED screens (e.g., [90, 247, 87]). Swarms hardly allow for smooth physical coupling: few provide latching capabilities (e.g., [185, 67]) but most are constantly unlatched (e.g., [251, 159, 280]). This prevents the envelop of the interface to be smooth. Stochastic systems may present opportunities as they allow modules with minimal hardware (i.e. unpowered and with no locomotion ability) [307].

#### 4.2.2 Combination between the digital and physical states of the UI (Digital / Physical)

A modular shape-changing UI is characterized through two states: (1) its physical state and (2) its digital state, also referred to as “computational representation” [38]. The physical state can be described as the tangible object made of physical modules. The digital state can be described as the position and state of the modules in the computational model, due to the modules having to compute collectively in order to achieve a common goal. For perspective, non shape-changing TUIs only have a single physical state, i.e. a single physical shape [258].

Modular shape-changing UIs combine both physical and digital states. to enable both physical interaction and computer-enhanced users’ abilities anytime, Shape-changing UIs, like most new interaction techniques [125], try to build on users’ knowledge of the physical world. However, mimicking the physical world is not enough. It is desirable that the computer enhance our abilities, for instance, to perform a task faster or with less fatigue [125]. In particular, the combination between the physical and computational representations enables a shared, negotiated control over shape-change between the user and the system. If the digital state changes, the physical state should change in accordance and vice versa. For instance, if the physical state changes through direct user shape deformation, the digital state should change to match the new physical state [38]. Similarly, if the shape of the physical representation changes (e.g., by user actuation through direct shape deformation), so should the shape of the computational model [38]. If this requirement is not met, it will hinder the bandwidth between the user and the interface. With no combination between physical and digital states, the usability of the system may suffer from inconsistencies between the physical and digital states. For example, if the user interacts directly with the interface (e.g., through shape deformation) and the computational

representation does not change accordingly, the system will not know the new position of the modules, and will not be able to later control the shape of the physical representation.

Deterministic reconfiguration better allows the combination of physical and digital states, as the system knows the position of each module at all time. Stochastic implementations, however, hardly allow for combination between states: the system only knows the position of a module when it comes in contact with another, and the paths taken by the moving modules are unknown [314]. Thus, even though the computational and physical representations do match *before* and *after* the shape-change, the stochastic nature of the reconfiguration does not allow the computational representation to match the physical representation *during* the change of shape.

### 4.2.3 Shape-change ability (Physical)

Shape-change ability quantifies how much the UI can change its shape. We characterize the shape-change ability of a system through the 11 Morphees+ features [141], which provide 11 quantifiable features drawn from two established taxonomies. For instance, drone-based swarm UIs (e.g., [40]) allow limited *Curvatures* [141] as drones cannot stack. The physical shape of the interface should be able to vary over time [38, 119], in order to provide input and/or output modalities [239, 19, 119], and to support the “form follows flow” design principle [107].

We will discuss in particular the *Porosity* and *Modularity* features [141], as modular systems uniquely enable them. First, *Porosity* is the ratio of the area of perforated parts to the total area of the shape [141]. Modular systems uniquely enable a large range of sizes for holes. Second, *Modularity* is the ability of an interface to be split in at least two parts and (re)combined while maintaining its original functionality. It is computed as the number of functionally possible combinations. [141]. Prior work [247] proposes to provide users with permanently attached modules so that they cannot fall off or be lost. However, this hinders the *Modularity* of the interface. To allow for great shape-changing ability, the HCI community should aim for modules able to both attach and detach: on the one hand, if modules are constantly attached, they do not allow for changes in the *Modularity* of the interface. On the other hand, if modules are constantly detached, they do not allow users to grab a part of the interface like a solid object, as the UI is made of detached modules. Chain implementations do not allow for changes in *Modularity* as they either do not support detach-ability (e.g., [250, 195, 184]), or in a limited way [247, 266, 196]. For instance, ChainForm [196] users can unlatch modules from a neighbor, but the unlatched modules become unfunctionnal. Lattice implementations can be fully detach-able and allow for *Modularity*: a module can unlatch from all its current neighbour at once (e.g., [327, 245, 38]). Lattice systems can also be partially detach-able and do not allow for *Modularity*: a module needs to first latch to a new neighbour before unlatching from its current neighbour (e.g., [206]). Swarm implementations are either detachable or permanently

detached. Both cases allow for *Modularity*. Although permanently detached modules cannot be “physically” split through latching/unlatching, they can be “functionally” split (e.g., [144]) with two subsets of modules being their own interface, and merging back into one. We consider this behavior to match the definition of *Modularity*.

#### 4.2.4 Reversibility (Physical)

Reversibility defines if the system is able to return to its initial state and repeat the shape-change. Shape-changing UIs should allow for reversibility [239]. Deterministic systems using self-reconfiguration usually allow for reversibility. A design flaw that may impair reversibility is if the system allows modules to be only added or only removed but not the other way around. Thus, implementations solely based on self-assembly (e.g., [108]) or self-disassembly (e.g., [84, 83]), and stochastic systems, only *partially* allow reversibility: if the user wants to return to a previous shape, they need to repeat the whole self-(dis)assembly process. This leads to usability problems: as stated by the *Minimal action* ergonomic criterion [24], the number of actions the user has to perform should be minimized. Requiring users to repeat the whole process adds extra steps and increase their workload. Similarly, if the user makes a mistake, they should be able to correct only their previous action(s) and not have to repeat the whole process (*Error correction* criterion [24]).

#### 4.2.5 Dimensionality (Physical)

Existing shape-changing interfaces are able to reconfigure either in 2D (e.g., [21, 196, 159]), 2.5D (e.g., [280]) or 3D (e.g., [133, 245, 247]). Although we found several instances of 2D and 3D working prototypes, 2.5D implementations are seldom explored. Pin-based shape-changing interfaces (e.g., [77]) may provide insight to design future 2.5D modular shape-changing UIs.

Although 2D or 2.5D reconfigurations already support interesting applications [77, 159], the HCI community should aim at 3D reconfiguration as this offers exciting opportunities [247]. Examples (Architectures, Reconfigurations) The majority of swarm implementations only allow for 2D shapes on a flat surface (e.g., [251, 159]). Some provide 2.5D reconfiguration (e.g., [280]). 3D reconfiguration is supported by drone-based swarm UIs (e.g., [40]). Although chain implementations mostly allow for 3D reconfiguration, some only reconfigure in 2D (e.g., [137, 253, 320]). Notably, ChainForm’s modules [196] are only capable of 2D planar transformation. They require the user to manually add a plastic joint between two modules so that each reconfigure in different 2D planes. Thus, the system can further achieve 3D transformations, albeit limited.

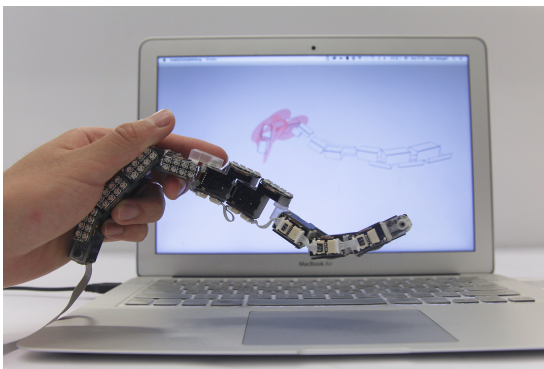
Similarly to chain implementations, most lattice implementations allow for 3D reconfiguration with few exceptions (e.g., [208, 43, 293]). Current working stochastic systems only allow for *2D reconfiguration*. Solutions to achieve stochastic reconfiguration in 3D have been explored,



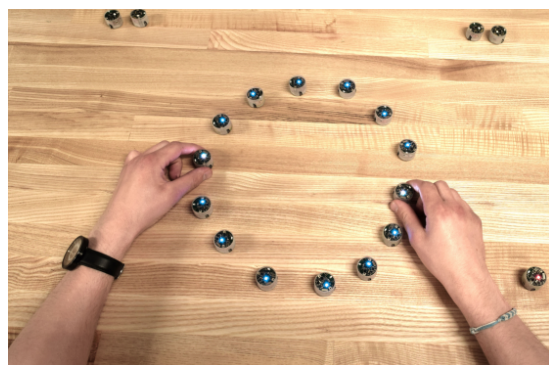
with the example of a shaken bag containing the modules [83] but only consist of concept scenarios or simulations.

#### 4.2.6 Volume required for shape-change (Physical)

The volume required for shape-change is the total volume occupied by the system throughout its change from the initial to the target shape. The total space used for reconfiguration should not exceed the union of the initial and target shapes [286]. Doing so, a user can anticipate the room required for a change of shape, even if actuated by the system [247, 119]. For instance, the device may be held in a single hand or placed on a table. In these cases, the interface should not fall or bother the persons around the users. This property is an issue for stochastic implementations where the modules can, and must, move in a large space in order to maximize their chance to encounter a relevant neighbor.



(a) chainFORM [196].



(b) Zooids [159].

Figure 4.2: Zooids is only used in tabletop contexts, whereas chainFORM is mostly used in handheld contexts.

#### 4.2.7 Usage consumption (Physical/Interaction)

The usage consumption is the power consumed under a standard context of use and the resulting expected duration of the interaction. When buying state-of-the-art devices (e.g., tablets, smartphones, laptops), the technical specifications describe not only the battery model, but also the expected autonomy under standard usage (e.g., "*Up to 10 hours of surfing the web on Wi-Fi, watching video, or listening to music*" [20]). Zooids [159] can move for one hour and can work longer under normal usage (i.e., where constant movement is not required). The usage consumption of shape-changing interfaces is little studied in the literature, with only few papers mentioning it, although it was flagged as a grand challenge of shape-changing interfaces [53, 19].

A challenge lies in the lack of knowledge of the standard usage of modular shape-changing

UIs. Evaluating standard usage is all the more difficult since (1) modular shape-changing UIs are still constrained to research prototypes, and (2) current prototypes are often not robust enough for longitudinal evaluation [19, 40]. As a result, previous work proposed concept scenarios (e.g., [40, 247, 159]) and most user experiments were conducted with 2D UIs (e.g., [146, 278]). A reasonable minimum threshold to enable user studies would be one hour. For mobile and wearable shape-changing interfaces, previous work set the goal to a full day [19].

#### 4.2.8 Control over shape-change (Interaction)

Control over shape-change describes who controls the change of shape and how this control is shared between the user and the system. Existing shape-changing interfaces provide different levels of control over shape-change [240]: direct, negotiated, indirect or system control.

**Direct control** (i.e., full user actuation) allows for the shape-change to be solely driven by the user, through direct shape deformation (e.g., [147, 87, 179]).

**Negotiated control** between the user and the system allows for both the user and the system to initiate and further share the control over the change of shape (e.g., [196, 159]).

**Indirect control** allows the system to initiate and further control the shape-change, based on inferences or interpretations of the actions of the user (e.g., [61]).

As user control is “implicit”, users need to understand the modality that the system uses to infer/interpret user action if they want to knowingly control the shape-change. E.g., Actuating Mood [61], although non-modular, changes shape according to user emotion: the user could “force” the system into their desired shape by mimicking the required emotion.

**System control** (i.e., full system actuation) allows the system to solely initiate and further control the change of shape, without any user input, neither direct nor indirect (e.g., [251, 247, 37]).

While the HCI community has been stressing the importance of actuation [119, 258], some modular systems only allow for users’ direct control of the shape (e.g., [147, 87, 179]). This is in line with the *Explicit user action* criterion [24]: the system should only react to *explicit* user action. The system should anticipate every possible user action and provide appropriate options to keep the user in control of the interaction (e.g., interrupt, pause or continue the shape-change, come back to the previous step) (*User control* criterion [24]). Moreover, the higher the level of control the user has on the shape-change, the higher their level of trust *but* the higher their workload [198]. In the future, very small modules will also cause direct control to become unpractical. Thus, users should only be required to do the least number of actions necessary

to accomplish a task, for a minimal workload (*Minimal action* criterion [24]). Actuated shape-change can help minimizing the number of steps to go from an initial shape to a target shape.

Negotiated control allows for the user to explicitly act towards shape-change, and for this shape-change to be computationally controlled. Swarm systems from HCI provide negotiated actuation between the system and the user (e.g., [159, 40]). Actuation of current chain systems are either system controlled or negotiated. Deterministic reconfiguration allows all types of control on shape-change, from directly controlled by the user to fully controlled by the system, whereas all of current stochastic implementations currently only allow for system control.

#### 4.2.9 Interactivity (Interaction)

Interactivity describes the modalities the system offers for the user to interact with it. The system can support user interaction, at least through shape-change and possibly through further input/output modalities [19, 159, 247]. Based on the related work, we propose to distinguish the following dimensions for interactivity:

1. *Changes of shape* can provide *input and/or output*, for instance input through direct shape deformation and output through visual or haptic feedback [195, 146].
2. *Other modalities* can provide *input and/or output*, for instance on each modules, direct touch interaction for input and a colored “pixel” LEDs for output [40, 159] .

The most interactive systems come from the HCI field, implementing various modalities for both input (e.g., touch [247, 159], mid-air gesture [40, 268], direct shape deformation [195, 279], wearable glove-like controller [295]) and output (e.g., LEDs [196, 40, 159], GUI displays [90], vibrotactile feedback [295], haptic patterns [146]). However, even though systems coming from the robotics field rather focus on locomotion, and that reconfiguration is not designed to *interact with users*, prior robotics work embed sensors to *interact with their environment* (e.g., temperature sensor [92], ambient light sensor [251]).

An important research challenge for modular shape-changing UIs is to lead the user to perform relevant actions (affordance), and inform the user on the alternatives when several actions are available (*Prompting* ergonomic criterion [24]). It is knowingly difficult to inform users of the transformational capabilities of a shape-changing UI [119, 107, 292]. This is even more difficult for modular shape-changing UIs as modular robots provide large transformational capabilities, unlike other shape-changing UIs (e.g., [143]). Previous work encourage designers to (1) explore affordances through shape-change [305], interaction design and material design [174] and (2) to study how users perceive and interact with modular shape-changing UIs [144].

The currently limited *shape-change ability* and *interactivity* of working implementations challenge the design of meaningful and usable interaction techniques. If the system only implements

shape-change as output, the challenges lie in the design of *dynamic affordances* [119, 292, 172] with the currently limited *shape-change ability*. If the system implements other output modalities, for example graphical displays [40], sound [147] or kinesthetic feedback [196], designers can leverage them for *prompting*. An alternative is to delegate the prompting to an additional device. For example, designers explored prompting through a separate television monitor [144], through wearables providing vibrotactile feedback [295], or through AR or VR, for example for data physicalization with swarms [103, 280].

#### 4.2.10 Safety (Interaction)

Safety quantifies how much the system may endanger the user [247], bystanders or cause damage to physical property [19]. The reconfiguration and final shape of the interface should not cause danger. A risk should be assessed through its severity, the possibility of avoidance and the redundancy [122, 123].

**Severity** is the pressure applied on a body part. The smallest maximum force that can be applied on a user's body part is against the face, with 65 N (pressure of  $110 \text{ N cm}^{-2}$ ) [122, 123]. This sounds therefore like a limit for the UI maximum force in case the interface hits a face. However, as the global pressure applied on the body depends on the contact area, the force can be high if the part of the UI touching the user is sharp or small. Solutions include designing non-sharp shape-changing UIs or using soft materials.

**Possibility of avoidance** is inversely proportional to the speed of the system. To enable avoidance, solutions include low speed for shape-change, embedding proximity sensors for stopping the reconfiguration when approaching the user –although this may hinder *interactivity*– or including an emergency stop button. A design challenge lies in finding an acceptable balance between low speed for safety and high speed for immediate feedback [142] (ergonomics criteria [24]).

**Redundancy** is the amount of time the risk is possible over a fixed amount of time.

Despite its importance, safety is seldom studied in the HCI literature (a rare example is found in [247]). Robotics, due to decade of research on actuated physical movement, has thoroughly studied safety.

Table 4.1 summarizes the properties of the interface at the macro-scale, from the *coupling between modules* to the *safety*, together with their possible values and examples from the literature. This can serve as a basis for comparing and designing modular shape-changing UIs.

Properties		Values		Examples
Coupling between modules	Hierarchy	Standalone   Original satellites   Borrowed satellites		Standalones [295] Original Satellites [190] Borrowed satellites [281]
	Surface smoothness	Size of gaps (mm)		~0 mm [245]
	Resolution of the envelop	Number of dots per unit area (d.cm <sup>-2</sup> )		0.69 d.cm <sup>-2</sup> [81]
Combination b/w physical and digital states		Yes   No		Yes [152, 245] No [40]
Shape-change ability		Morphees+ features [46]		Modularity [152]
Reversibility		Yes   No		Yes [245] No [81, 82, 103]
Dimensionality		2D   2.5D   3D		2D [152, 190] 2.5D [279] 3D [37, 245]
Volume required for shape-change		Volume (cm <sup>3</sup> )		381(L) × 381(W) × 100(H) mm <sup>3</sup> [76]
Usage consumption		Time under normal usage (min)		60 min while moving [152]
Control over shape-change		Direct   Negotiated   Indirect   System		Direct [145] Negotiated [152, 190] Indirect (none) System [37, 245, 249]
Interactivity		Input	Shape-change   Other	Shape-change [145, 191] Other [152, 249]
		Output	Shape-change   Other	Shape-change [244, 278] Other [40, 190]
Safety	Severity	Pressure on skin (N.cm <sup>-2</sup> )		Not mentioned
	Possibility of avoidance	Inversely proportional to speed (m.s <sup>-1</sup> )		0.5 m.s <sup>-1</sup> [152] 13 cm.s <sup>-1</sup> [258]
	Redundancy	Probability over fixed amount of time		Not mentioned

Table 4.1: Properties of the interface (macro-scale) for modular shape-changing UIs.

### 4.3 Properties of the modules (micro scale)

In this section, we present the properties at the micro-scale of the modules (Figure 5.2). The following micro-scale properties are technical: we will further discuss in Section 5 their impact on the user experience through their impact on the macro-scale properties. We classify them according to their abstraction level: properties at the *intra-module* level characterize elements that are embedded in the module. Properties at the *module* level characterize the envelop of the modules. Properties at the *inter-module* level characterize if and how modules are attached to each other.

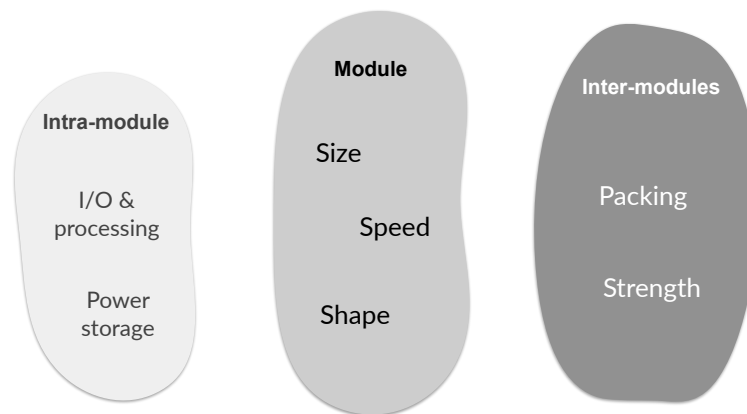


Figure 4.3: The properties of modular shape-changing UIs at the scale of the modules, and their dependencies. The properties are further classified depending on whether they impact the components embedded in the module (intra-module, light gray), the whole module itself (module, middle gray) or at least two modules (inter-module, dark gray). The dotted arrows describe yet undefined impact requiring further technical experiments.

#### 4.3.1 Input, output and processing capabilities (Intra-module)

Input, output and processing capabilities define how users interact with a *single* module. Input and output capabilities are dependent on micro-devices embedded in the module. For example, input can be supported by touch sensors [159], microphones [147], or ambient light sensor [251]. Output can be supported by a LED [196], a graphical display [90], or a speaker [147]. Processing capabilities depends on the microprocessor.

#### 4.3.2 Power storage (Intra-module)

Power storage defines how the modules are powered. Systems are either battery-powered (e.g., [251, 245]) or mains-operated (e.g., [195]). Battery-powered systems embed batteries in each module. Charging the modules is a challenge [159]. The most common approach is to charge

each module individually (e.g., [246, 159]), which can be tedious as the number of modules increases. Other approaches propose the use of a charging dock [251], or a photo-voltaic cell embedded in each module [316].

Mains-operated systems are either (1) heterogeneous, i.e. one [196] or few [147] modules are plugged-in and provide power to the others, (2) homogeneous, i.e. all modules are plugged-in [43], or (3) externalized, i.e. the modules themselves are not plugged-in, but the environment in which the reconfiguration takes place is (e.g., for stochastic [98] implementations). The heterogeneous approach is hardly suitable for large scale systems, as the modules furthest from the power supply should not see a significant drop in voltage [316]. Moreover, both heterogeneous and homogeneous modules have the issue of the power chord which needs to be taken into account during reconfiguration and/or user interaction, as it can get in the way.

### 4.3.3 Size (Module)

The size is the volume of each module, defined by the length of the edge for cubic robots [245] or the diameter for spherical robots [222]. We find many sizes in the literature: the M-Blocks' edge measures 50 mm [245], while Catoms measure  $\varnothing 11$  mm [38]. As often with electronics, their size is getting smaller as technology advances. The size of modules was presented as a central property in order for UIs to be made of “stuff” rather than “things” [159]. The hardware required for the self-actuation of deterministic systems limits our ability to manufacture the modules at a very small scale and in a large amount [307].

### 4.3.4 Shape (Module)

The shape defines the geometry of a module. While the most widespread shapes are cubes (e.g., [245, 255, 83]) and quasi-spheres (e.g., [38, 206, 266]), many other geometries are possible, such as rectangles [196], x-shaped [152, 21], or cylinders [159, 251].

### 4.3.5 Speed (Module)

The speed defines how fast a single module can move. For electrostatic or electromagnetic actuation (e.g., [245, 222]), the speed is driven by the distance between two motion actuator electrodes. Designers should take into account the trade-off between the latency to trigger the latching and the distance the module covers. For instance, if the distance between two motion actuators is small, the latching will be fast but the module will cover little distance. For mechanically-actuated implementations, the speed depends on the force of the motors. The triggering latency of these implementations is higher than for electrostatic/electromagnetic actuation, as they require more steps (e.g., align the latching mechanisms, latch, check the latching, move).

### 4.3.6 Packing (Inter-modules)

The packing defines how several modules can be spatially arranged together to form the interface. Packing can be divided into two parameters: *structure* and *density*.

*Structure* defines the way of arranging modules so that they cover a volume without overlapping. When looking for a complete coverage of the volume, i.e. with no holes between the modules, the mathematical problem is known as “tessellation” or “honeycomb” [96]. When a complete coverage is not necessary, lattice and swarm systems can follow a crystal structure [109] which describes the possible arrangements of fixed-shaped elements. For instance, one can use a Simple Cubic lattice (Figure 4.4a) or a Face-centered cubic lattice (Figure 4.4b). However, chain structures usually aim for locomotion rather than coverage. For example, common chain structures are caterpillars, wheels/crawler and multi-legged walkers [155].

*Density* defines if the structure is fully filled (high density) or not (lower density). The density is described by its number of units per volume, and applies to all types of systems.

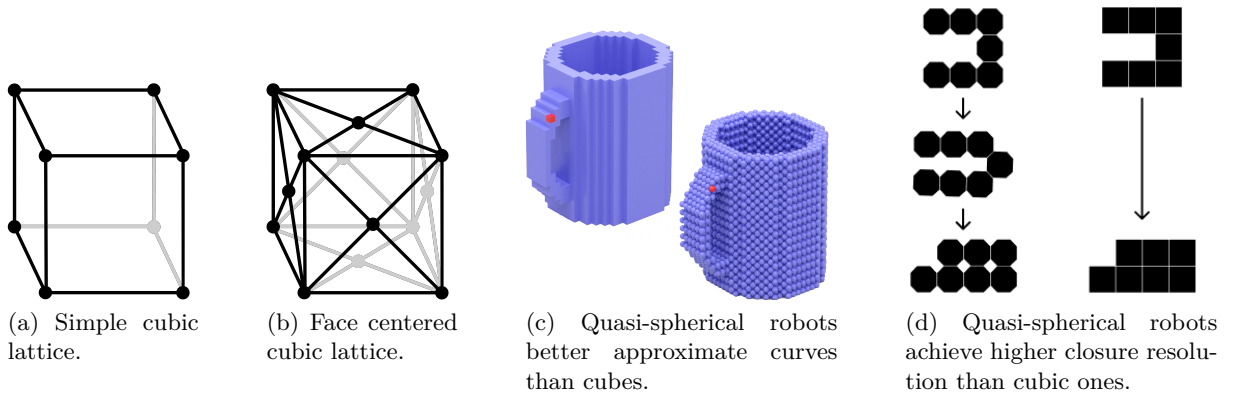


Figure 4.4: (a–b) Two possible lattices for spatial arrangements (packing) of robots, (c) approximation of a shape by cubic and quasi-spherical robots, and (d) range of *Closure* achieved by cubic and quasi-spherical robots.

### 4.3.7 Strength (Inter-modules)

The strength defines the force of the connection between a module and its neighbor(s). Strength depends on the strength of the actuation mechanism. For instance, the force of the motors for mechanical actuators (e.g., pins [280], hinges [247], clamps [206]) and the force between two conducting electrodes for electrostatic or electromagnetic actuators (e.g., [245, 222]). Strength is zero for swarm modules, as they cannot attach to each other.



### 4.3.8 Others

Other parameters exist at the module level, and include the weight and coating of modules, as well as the noise or heat they generate. We found that the weight is often correlated with size, except for “*helium catoms*” [136] which are 8 m<sup>3</sup> modules filled with helium, and thus big but light by design.

## 4.4 Synthesis

In this chapter, we uncovered and detailed our unified set of design properties drawn from our systematic literature review. We identified two types of properties: *macro-scale*, which describes properties at the scale of the overall modular UI, and *micro-scale*, which describes properties at the scale of the individual modules.

On the one hand, we observed that macro-scale properties are user-centered, and can be further classified as being digital properties, physical properties, interaction properties or a combination of two (digital/physical or physical/interaction). On the other hand, we observed that micro-scale properties are technical properties that impact the material aspect of the modules. They can be further described as intra-module properties, overall module properties or inter-module properties.

We consider that micro-scale properties do not *directly* impact the users: similarly as how users interact with the overall GUI rather than individual pixels, we considered that all user-centered properties are macro-scale. However, micro-scale properties are important to take into account for HCI researchers as they *indirectly* impact users by impacting macro-scale properties. Thus, now that we have identified these properties, we need to understand their dependencies, how they are related to each other and their impact on each other.

In the next chapter, we will characterize and analyze the dependencies and impacts between our design properties.



# IMPACT BETWEEN DESIGN PROPERTIES

---

## Contents

---

<b>5.1</b>	<b>Introduction</b> . . . . .	<b>78</b>
<b>5.2</b>	<b>Impact between macro-scale properties</b> . . . . .	<b>79</b>
5.2.1	Impact on/with shape-changing ability . . . . .	79
5.2.2	Impact on/of control over shape-change . . . . .	80
5.2.3	Impact of interactivity on usage consumption. . . . .	81
<b>5.3</b>	<b>Impact between micro-scale properties</b> . . . . .	<b>82</b>
5.3.1	Impact on/of size . . . . .	82
5.3.2	Impact on/of strength . . . . .	83
5.3.3	Impact of/on power storage. . . . .	84
5.3.4	Impact of Shape on Packing. . . . .	84
<b>5.4</b>	<b>Impact between micro- and macro-scale properties</b> . . . . .	<b>85</b>
5.4.1	Shape-change ability . . . . .	85
5.4.2	Interactivity . . . . .	87
5.4.3	Smoothness and resolution . . . . .	87
5.4.4	Safety . . . . .	88
5.4.5	Control over shape-change . . . . .	88
5.4.6	Hierarchy . . . . .	89
5.4.7	Combination between states $\leftarrow$ I/O & processing capabilities . . . . .	89
5.4.8	Dimensionality $\leftarrow$ Shape . . . . .	89
5.4.9	Usage consumption $\leftarrow$ Power storage . . . . .	89
<b>5.5</b>	<b>Synthesis</b> . . . . .	<b>90</b>

---

## 5.1 Introduction

We identified and defined the properties of modular shape-changing UIs at the macro-scale of the interface (section 4.2) and at the micro-scale of the modules (section 4.3). However, knowing which property exists and the impact of the architecture and reconfiguration type of the system may not be enough. We need to characterize how these properties impact each other. Thus, we need to further take into account the *dependencies* between them. There are dependencies within macro-scale properties, within micro-scale properties, but both macro- and micro-scale properties also impact each other. Thus, technical properties of the modules may indirectly impact user interaction with the interface through their impact on macro-scale properties.

In this chapter, we study the impact between properties. First, we present the impact within macro-scale properties. Then, we present the impact within micro-scale properties. Finally, we present the impact between macro- and micro-scale properties.

## 5.2 Impact between macro-scale properties

Figure 5.1 shows the dependencies between macro-scale properties. We present them in decreasing number of dependencies: *shape-changing ability* impacts or is impacted by 5 other properties, while *control over shape-change* impacts or is impacted by 4 other properties. Finally, *interactivity* impacts only Usage consumption.

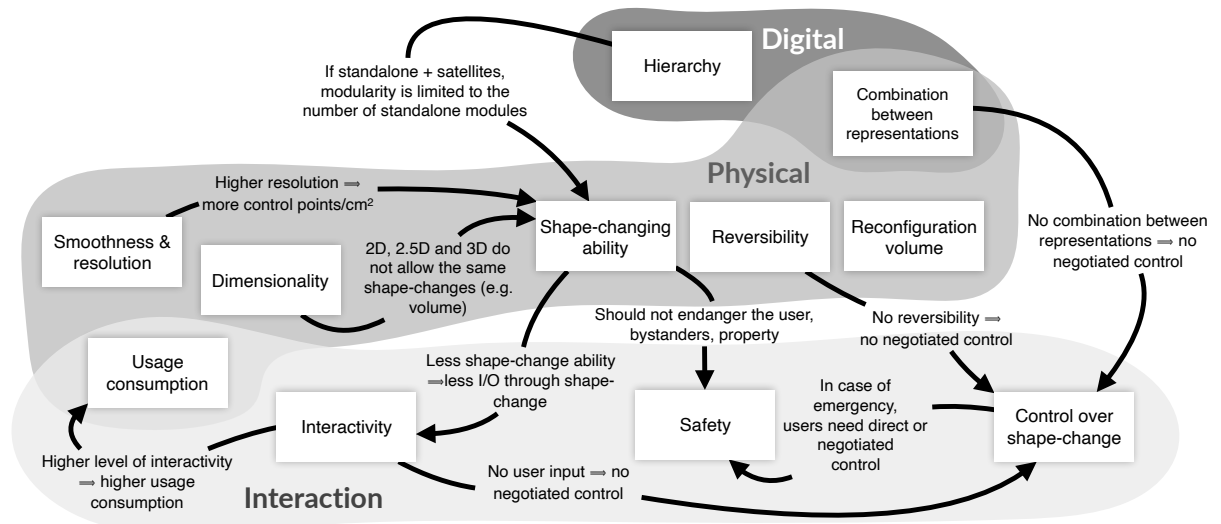


Figure 5.1: The user-centered properties for modular shape-changing interfaces, and their dependencies. The properties are further classified depending on whether they impact the interface at a digital level (dark gray), physical level (middle gray) or interaction level (light gray). *Combination between physical and digital states* is classified as impacting both digital and physical levels, as it describes the interaction between the physical and digital shape of the interface. *Usage consumption* is classified as impacting both the physical and interaction levels as it is the power consumed *under a standard context of use*.

### 5.2.1 Impact on/with shape-changing ability

**Shape-changing ability** ← **Dimensionality** Systems able to reconfigure in 2D, 2.5D and 3D do not allow for the same changes in shape: for instance, 2D implementations do not allow for changes in volume, while 2.5D implementations do not allow for changes in closure and their change in porosity is limited as they do not allow for bridges. Only 3D implementations were found to allow for all shape-change features.

**Shape-changing ability** ← **Hierarchy** The ability to change modularity is dependent on the number of standalone modules and the nature of its satellites, if any. The *Modularity* feature from [141] is described as the ability of the interface to split *and maintain its original func-*

*tion*. This causes no issue with the standalones approach, as each module can dissociate and keep functioning normally. However, when taking the standalones+satellites approach: (1) If the satellites are original satellites, removing a standalone means removing all of its synchronized satellites. If some remain in the original interface, they will stop functioning. (2) If the satellites are borrowed satellites, removing a standalone means removing none, part or all of its synchronized satellites. If some remain in the original interface, another standalone has to be available for them to synchronize and continue functioning. (3) If the standalone is externalized (e.g., a micro-controller [159] or overhead controller [251]), it cannot be removed from the interface. The satellites allow for *Modularity*.

**Shape-changing ability → Interactivity** The higher the shape-change ability, the higher the input/output possibilities through shape-change. The way shape-change conveys users input and/or system output depends on its shape-change ability. For example, ChainFORM [196] proposes a shape-changing stylus interface able to switch between a pen mode, a brush mode and a magnifying glass mode. This is enabled by the capability of ChainFORM to change *Closure*. An implementation which does not allow for *Closure* (e.g., ShapeBots [280]) would not enable this scenario. The input/output of a system and its required shape-change features will depend on the context of use. For example, permanently detached swarms do not allow users to grab a part of the interface like a solid object, as the UI is made of detached modules. Thus, although permanently detached swarm systems allow for great modularity, they may not be suitable depending on the context of use (e.g., handheld). However, a system with high shape-changing ability will overall support more input/output possibilities through shape-change.

**Shape-changing ability → Safety** The shape taken by the interface before, after and during reconfiguration should not endanger users, bystanders or properties. Shape-changing features that may be a source of concern are the *Speed* (e.g., participants expressed fear of getting hurt because of the quick reconfiguration of KnobSlider [142]), *Curvature* (e.g., if the interface is able to achieve really sharp edges) and *Strength* (e.g., with wearable UIs [19, 195, 196], very strong shapes could harm the bones or joints).

### 5.2.2 Impact on/of control over shape-change

**Control over shape-change → Safety.** The user should always be in control of the interaction, and particularly able to interrupt, cancel, pause and continue the reconfiguration (*User Control* ergonomic criterion [24]). This applies particularly to safety: when the user detects a safety concern, they should be able to stop the reconfiguration, for instance, if an on-body implementation (e.g., [195]) is hurting them or a drone (e.g., [40]) is flying toward a bystander. Explicit user control ensuring safety requires direct or negotiated control.

**Control over shape-change ← Interactivity** The system should support user input to allow explicit user control. Systems that do not support user input, either through shape-change or any other way (e.g.,[246, 133]) do not allow for direct and negotiated control.

**Control over shape-change ← Combination between physical and digital states** Negotiated control requires combined physical and digital states. If there is limited combination between both states (e.g., the physical states changes according to the digital state, but not the other way around), and the user changes the shape through direct deformation, the system will not be able to match its known computational representation and the new positions of the modules in the physical space. Thus, the system will not be able to move the modules, and only direct control will further be possible.

### 5.2.3 Impact of interactivity on usage consumption.

We expect that the higher the interactivity, the higher the usage consumption. For example, if a UI allows user input through shape-change, its usage consumption will increase as modules need to invest energy in listening to a potential modification of their location and communicating the new location to their neighbors. If a UI allows input and/or output through other modalities, its usage consumption will increase as the hardware to enable these additional modalities need to be powered.



### 5.3 Impact between micro-scale properties

The properties of the modules are not independent but impact each other. Designers should carefully consider the dependencies between properties when deciding on a design. Changing one property may not only impact another one directly (e.g., the size impacts the strength), but also indirectly (e.g., the size of the modules impacts their packing which in turn impacts the speed). We now present the property having the most impact, which is the *size* of the modules.

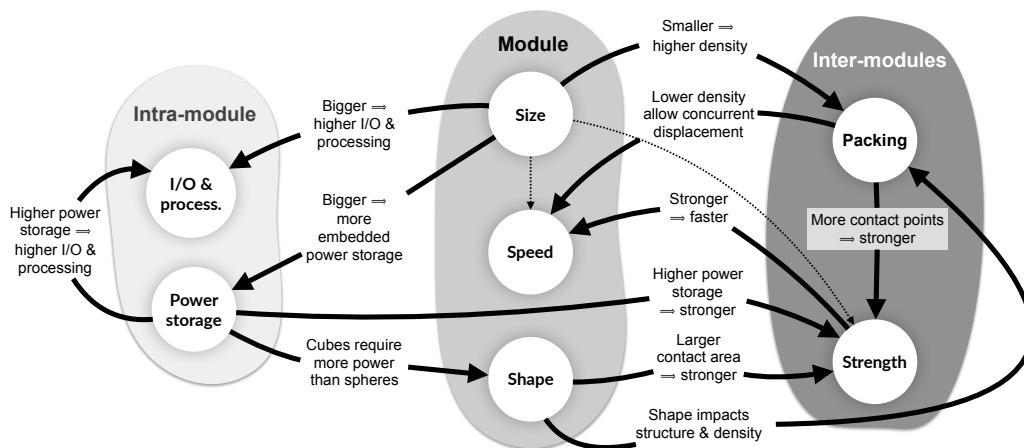


Figure 5.2: The properties of modular shape-changing UIs at the scale of the modules, and their dependencies. The properties are further classified depending on whether they impact the components embedded in the module (intra-module, light gray), the whole module itself (module, middle gray) or at least two modules (inter-module, dark gray). The dotted arrows describe yet undefined impact requiring further technical experiments.

#### 5.3.1 Impact on/of size

**Size ↔ Input/output and processing capabilities.** The bigger the modules, the higher the I/O and processing capabilities. Reducing the size of the modules implies reducing the space available to embed components. As a consequence, the smaller the modules, the smaller or the fewer the components. For example, on the one hand, the smallest existing implementations (11mm [38] and 12mm [83]) do not embed any component supporting input, and output is supported solely through shape-change. On the other hand, the  $\varnothing 26$ mm Zooids [159] are the smallest implementation embedding components for both input (touch sensor) and output (colored LED) in addition to shape-change. The more the memory of the microprocessor, the larger the surface it requires.

**Size → Power storage.** Smaller modules imply smaller *embedded* power storage. For battery-powered modules, smaller batteries means less power storage. For example, the Michigan Micro Mote (M3) [209], a mm-scale computing system, use 0.5–5mAh batteries. For comparison, the cm-scale M-blocks [246] embed 4×125mAh batteries. The size of the components is less of an issue for mains-operated implementations, as the components to power the modules are smaller than batteries (e.g., wires, connectors between modules). The smaller the modules the lighter, hence they need less power to move.

**Size → Packing.** The smaller the modules, the higher the density. For a same structure, decreasing the size of the modules results in more units per volume. However, designer should also take into account that the smaller the modules, the more the required fabrication accuracy to enable accurate packing: accurate packing of 5.00 mm ± 0.05 mm modules is easier than the packing of 1.00 mm ± 0.05 mm modules.

**Size → Speed.** Further technical experiments are needed to establish the link between size and speed, taking into account the actuation mechanism, the weight and distance between two modules. First, the smaller the modules, the slower the reconfiguration of the shape, as there are more modules to move. Second, the smaller the modules the lighter, hence the faster their displacement for the same power. Third, the smaller the modules, the smaller the distance to cover to move a module. The smaller the distance, the faster triggering of an electrostatic-/electromagnetic-actuation. For instance, magnets attract each other quickly if they are close. However, for electrostatic-/electromagnetic-actuation, a small distance between two motion actuators also implies a small the distance covered by a module. As a consequence, there is a trade-off between the triggering latency (i.e., how fast the latching occurs) and the effective distance covered.

**Size → Strength.** On the one hand, decreasing the size of the modules does not significantly impact their *individual strength*. The reason for this is that the modules are light when small, and consequently require less power for actuation [222]. On the other hand, the strength of the UI that the user will manipulate is the *strength per unit volume*. Smaller modules lead to a higher density of modules per unit volume, which may feel stronger in the users' hands.

### 5.3.2 Impact on/of strength

**Strength ← Shape.** With electrostatic and electromagnetic actuation, the larger the contact area, the stronger the bond between modules [222]. For instance, for a same size, a cubic module has bigger faces than a quasi-spherical module. For mechanical actuators, we could not find an impact of the shape on the strength.

**Strength**  $\leftarrow$  **Packing**. The higher the density, the higher the strength per unit volume. A way of increasing the strength is to increase the number of neighbors for each module (i.e. density).

**Strength**  $\rightarrow$  **Speed**. The higher the strength, the higher the speed. For electrostatic and electromagnetic actuation, the speed depends on the force of the bond between two actuator electrodes: the stronger the connection between two modules, the faster they can move – as they can provide more force to latch and attract a neighbor [222].

**Strength**  $\leftarrow$  **Power storage**. The higher the power storage, the stronger the connection. When the connection between modules needs power, the more power storage, the stronger the connection between two modules. Electrostatic actuation needs high voltage for strength [222], while electromagnetic and mechanical actuation needs high amperage. Both can be provided by a high power storage.

### 5.3.3 Impact of/on power storage.

**Power storage**  $\rightarrow$  **I/O and processing capabilities**. The higher the power storage, the higher the I/O and processing capabilities, i.e. the more components the module will be capable to power. Similarly, processing requires power.

**Power storage**  $\leftarrow$  **Shape**. Cubic shapes require a lot of power in order to move the robots [222]. Latching and moving cubes around each other, while staying connected, is hard to implement in miniature, cubic, versions. Quasi-spherical shapes enables latching and moving with lower power.

### 5.3.4 Impact of Shape on Packing.

The shape of the modules impacts their packing [221]. All shapes do not allow for the same number of actuators, nor for the same disposition of neighbors around a module. For instance, a module made of two half-cylinders joined on their round side can accommodate two neighbors [133], whereas cubes can have six [246]. Quasi-spherical designs can also have up to six neighbor [222]. However, where the position of the six neighbors on a cube is constrained to its six faces, quasi-spheres allow more possible placements (e.g., Figure 4.4d). Hence, cubes and quasi-spheres allow the highest density, but quasi-spheres allow the most diverse structures.

## 5.4 Impact between micro- and macro-scale properties

In this section, we discuss how the technical, micro-scale properties of the modules impact the user-centered, macro-scale properties of the interface. Our goal is to inform researchers on how the technical choices of their design can impact directly and indirectly the usability of the overall interface. We present these relationships starting from the macro-scale property with the highest number of impacted properties to the least.

Micro properties	Macro properties	Impact micro-macro (summary)
I/O & Processing	Hierarchy	Standalones require more processing capabilities
	Combination between states	Higher I/O & processing $\implies$ better combination
	Control over shape-change	More I/O & processing $\implies$ higher control
	Interactivity	More I/O & processing $\implies$ more interaction modalities
Power storage	Hierarchy	Standalone need higher autonomy
	Shape-change ability	Mains-operated systems impair shape-change
	Usage consumption	Higher power storage $\implies$ higher autonomy
Size	Shape-change ability	Size impacts granularity, porosity, curvature
	Smoothness and resolution	Smaller $\implies$ Higher resolution (individual pixel/voxel/sensel)
Shape	Shape-change ability	Gaps and bumps impact smoothness
	Dimensionality	Dimensionality depends on the shape (e.g., cylinders = 2D)
	Smoothness and resolution	Shape of modules impacts shape-change
	Safety	Sharp edges may hurt users
Speed	Shape-change ability	Fast speed $\implies$ fast shape-change
	Control over shape-change	Speed-control trade-off
	Safety	Fast speed $\implies$ little possibility of avoidance
	Interactivity	Speed must support immediate feedback
Packing	Shape-change ability	Packing impacts speed, stretch-ability, porosity
	Smoothness and resolution	High density $\implies$ high smoothness & resolution
Strength	Shape-change ability	Too strong impairs modularity Too weak impairs curvature, closure and zero-crossing
	Safety	Strong connection $\implies$ high severity
	Interactivity	Too weak/strong impairs direct deformation

Table 5.1: Expected impact of the properties at the scale of the modules (micro) on the ones at the scale of the interface (macro).

### 5.4.1 Shape-change ability

Shape-change ability is impacted by six micro-scale properties: shape, size, packing, strength, speed and power storage.

**Shape** The shape of the modules impacts the ability to change the *curvature*, *closure*, *zero-crossing* and *amplitude* (Figure 4.4d). Current flat, rectangular interfaces are better formed by

cubic robots. However, non-rectangular, non-flat interfaces are promising: for instance, users can be more efficient when pointing on non-flat touchscreen [249].

**Size** The smaller the modules, the more the actuation points per  $\text{cm}^2$ . Thus, the size impacts the *granularity*, *curvature* and *porosity*.

**Packing** Being able to change the structure and the density impacts many shape-change features. First, if the object is not very dense, the movements of several modules can be concurrent [286] for a faster *speed* of shape-change. Second, lowering the density of the inner structure by moving inner modules to enlarge the envelop will allow for changing the *size*. Lowering the density and choosing a specific structure could also allow for a change in the *stretch-ability* of the interface [131]. Third, denser packing allow for more control points per unit area, hence a higher *granularity*. Fourth, a change in *porosity* correlates with a change in density. The higher porosity, the fewer the units per volume, hence the lower density.

**Strength** A strong connection impairs *modularity*. A weak connection impairs *curvature*, *closure* and *zero-crossing*. If the modules stick too strongly together, it will be difficult for users to split the UI (*modularity*). However, if the modules do not stick strongly enough, it will impact their overhang capabilities and prevent large ranges of *curvature*, *closure* and *zero-crossing*.

**Speed** The faster the modules, the faster the reconfiguration of the overall interface. The *speed* at the micro-scale directly impacts the *speed* feature of the *shape-changing ability* property at the macro-scale.

**Power storage** Heterogeneous mains-operated systems<sup>1</sup> impair the *modularity* of the interface: when splitting the interface in two, if the system only has one plugged-in module acting as a power supply for the others, the removed modules cannot keep functioning (*Modularity* = 0). If the interface has several plugged-in modules, these should be distributed between both halves of the split interface to power unplugged-modules and maintain functionality. Moreover, as the modules furthest from the power supply should not see a significant drop in voltage, the possible positions of the plugged-in module(s) in the global configuration are constrained. Another point of concern is the power chord, that should not get in the way during reconfiguration and interaction.

---

1. In heterogeneous mains-operated systems, one [196] or few [147] modules are plugged-in and provide power to the others.

### 5.4.2 Interactivity

Interactivity is impacted by speed, I/O & processing capabilities and strength.

**Speed** Speed must enable immediate feedback, i.e. usable output through shape-change [159, 24].

**I/O & processing capabilities** The more the I/O & processing capabilities, the more the interaction modalities available.

**Strength** Too high or too weak strength impairs direct deformation. On the one hand, if the modules do not stick strongly enough together, users would break the interface in thousands of pieces when they manipulate it. It would render input through shape-deformation challenging, and augment user's mental workload if they need to be careful when they manipulate the system. On the other hand, if the modules stick too strongly together, users may not be able to control the system through the change of shape. The research community should either find a compromise for the strength, or, even better, enable programmable strength.

### 5.4.3 Smoothness and resolution

Smoothness and resolution are impacted by size, shape and packing.

**Size** The smaller the modules, the higher the resolution when modules are individual pixel/voxel/sensel. The size does not *directly* impact the resolution when each module embeds several pixel/voxel/sensel, i.e., a display. In this case, the resolution depends on the graphical display on the face of the modules (e.g., LED array [196], OLED display [247], FOLED display [90]). The size however *indirectly* impacts the resolution, for example through the link between size and I/O & processing capabilities (embedding an OLED display requires more space than LEDs), or size and power storage (an OLED display needs more power than LEDs).

**Shape** On the one hand, cubic modules enable flat and seamless displays (e.g., Cubimorph [247]). On the other hand, spherical modules are better to approximate curves (Figure 4.4c), but result in irregular surfaces, with gaps and bumps (e.g., Figure 4.4c). However, this impact of shape decreases when the size of the module decreases: The smaller the robots, the less the shape of each robot impacts the tactile and visual perception of the objects [46].

**Packing** The denser the packing, the higher the smoothness and resolution. On the one hand, high coverage (e.g., with using tessellation or honeycomb structures) and dense packing result in a high number of dots per centimeter. On the other hand, if the user only interacts with the

*envelop* of the interface, the inner structure may not need to provide complete coverage, and may follow a less dense packing.

#### 5.4.4 Safety

Safety is impacted by speed, shape and strength.

**Speed.** The speed of the modules may pose safety concerns. This risk should especially be taken into account if the modules have strong actuators (*Strength* property) and/or sharp edges (*Shape* property). For example, if the user touches two modules with sharp edges that quickly and strongly latch, the skin can be pinched.

**Shape.** Sharp edges can be dangerous. For example, gripping an object made of cubes may hurt more because of the cube edges, rather than a smooth object made of spheres (e.g., Figure 4.4c).

**Strength.** The strength of connection between modules can be a safety concern, as they could apply too much pressure on the skin/limbs of the user. For instance, even though the users were afraid that the fast reconfiguration of the chained prisms of the KnobSlider [142] could hurt them, the servo motors of the device are not strong enough to actually cause any harm if their fingers get pinched. Strength should especially be taken into account with on-body implementations (e.g., [196]) where the interface applies forces against the users' body joints.

Control over shape-change and Hierarchy are each impacted by two micro-scale properties.

#### 5.4.5 Control over shape-change

Control over shape-change is impacted by speed and I/O & processing capabilities.

**Speed** There is a trade-off between speed and control over shape-change. If the modules are too fast, the user may not be able to react fast enough. For example, the maximum speed of Zooids is 74 cm/s but their application use a slower speed (44 cm/s) for the user to better control the interface [159]. However, if the modules are too slow, this will impair immediate feedback [24].

**I/O & processing capabilities** The more the input/output & processing capabilities, the higher the control over shape-change. In the literature, the smallest implementations do not include input modalities and are currently system controlled.

### 5.4.6 Hierarchy

Hierarchy is impacted by I/O & processing capabilities and power storage.

**I/O & processing capabilities** High processing capabilities allow modules to be standalones. To enable modular shape-changing UIs with modules embedding lower processing capabilities, researchers use an externalized system with higher processing capabilities as a "standalone" (e.g., microcontroller [195], overhead controller [251]).

**Power storage** For battery-operated systems, the standalone(s) should not run out of battery. This would make them cease functioning and let their satellites alone, in which case the UI cannot function as expected. This can be an issue as the higher processing capabilities of standalones require more power.

Lastly, Combination between states, Dimensionality and Usage consumption are each impacted by one micro-scale property:

### 5.4.7 Combination between states $\leftarrow$ I/O & processing capabilities

The higher the I/O & processing capabilities, the better the combination between the physical and digital states. When their physical representation changes, modules need more processing capabilities (e.g., to communicate with their neighbors to estimate their new position) or sensors (e.g., accelerometers [147]) in order for their computational representation to match. If modules do not have enough input or processing capabilities, this can be externalized (e.g., projector-based tracking [159]) although this prevents mobility.

### 5.4.8 Dimensionality $\leftarrow$ Shape

The dimensionality depends on the shape of the modules. For example, cylinders will allow for 2D UIs [251, 159] and quasi-spheres or cube allow for 3D UIs [221, 246].

### 5.4.9 Usage consumption $\leftarrow$ Power storage

The higher the power storage, the higher the autonomy. However, a way of expanding usage time is to limit the energy consumption *between* reconfigurations, with modules able to retain their shape and interactive capabilities with little to no power (multistability) [247]. This allow modules to save and provide enough power for the reconfiguration. Although all surveyed 2D swarm-based implementations are battery-powered and can keep their shape without consuming energy, 3D drone-based swarm UIs [40] cannot as they need power to keep levitating. As drones are currently the only way of achieving 3D in swarm systems, only 2D swarm implementations



are currently multistable. Mains-operated systems do not have to deal with autonomy issues, but are not transportable as they need to be constantly plugged-in. This could especially be an issue with systems targeting handheld mobile scenarii (e.g., [196, 195]).

## 5.5 Synthesis

This chapter uncovered the impact between the design properties we drew from the literature in both HCI and robotics. Understanding how these properties impact each other is a critical step to make informed decisions for the design of future modular shape-changing UIs. For instance, decreasing the size of the modules without being mindful of how it will impact the overall design may result in a degradation of the input, output and processing capabilities, which would in turn result in a degradation of the interactivity, control over shape-change and/or combination between state.

Consequently, we find that, for macro-scale properties, the *shape-changing ability* property had the most dependencies (five dependencies, see 5.2.1), whereas *control over shape-change* properties came second (four dependencies, see 5.2.2). For micro-scale properties, it was the *size* and *strength* for that had the most dependencies: five for size (see 5.3.1) and four for strength (see 5.3.2). Moreover, when looking at the impact between macro- and micro-scale properties, we find that both size and strength further impact shape-changing ability.

---



# PART I - CONCLUSION

---

We presented a structured design space of modular shape-changing user interfaces. To this end, we conducted a cross-disciplinary, systematic literature review to propose (1) a set of design properties at the scale of the interface (macro-scale) and at the scale of the modules (micro-scale) and, (2) the impact of these properties on each other. This work can be *readily used* to describe and compare existing modular shape-changing UIs, allowing practitioners to choose the design which best fit their needs, and generate new design ideas by building upon knowledge from robotics and HCI.

These properties bridge the gap between the HCI and robotics fields. Our work provides a design tool allowing the *description*, the *evaluation* and the *generation* (i.e. the help for novel design) [26] of modular shape-changing UIs. The HCI community can readily use our work to inform design choices and consider alternatives. The community can build upon this work to research usable modular shape-changing UIs. To provide a first assessment of our design space and how it could be readily used as is, we systematically assess our design space through the descriptive, evaluative and generative powers from [26], and report on its limitations.

## Descriptive, evaluative and generative powers

Our contribution allows to describe, compare and generate new designs. These benefits are important to the HCI community [26]. To illustrate these three powers, we take the example of two similar interactive chain-based implementations: ChainFORM [196] and LineFORM [195]<sup>2</sup>.

First, we demonstrate the descriptive and evaluative powers of our structured space in Table 5.2. If we had to do the description and comparison of the macro-scale properties without our structured space, we would have to use at least 9 different papers: [141] (shape-changing ability), [240] (control over shape change), [239] (interactivity+reversibility), [119, 38] (combination between states), [19] (usage consumption + safety + resolution), [122, 123](detailed safety), [247] (reconfiguration volume + smoothness), [87] (hierarchy), and [271] (dimensionality). The table shows that the structured cross-disciplinary space allows to describe both systems in details. The items in bold in the table also show the difference between both systems. The structured space allows a fine comparison between these systems, despite the difficulty as they are very similar. For instance, one obvious difference between these two systems is that ChainFORM modules

---

2. More examples on the MolecularHCI website: <http://molecularhci.imag.fr/>

are detachable, while LineFORM modules are not. But our space goes further and, for example, shows the impact that implementing detachability had on the *strength* between modules: 0.8kg.cm for ChainFORM modules, much lower than the 8.3kg.cm for LineFORM modules.

Second, we demonstrate the *generative power* of our contribution by modifying a property of ChainFORM and observing the resulting direct and indirect impact on macro- and micro-scale properties. At first glance, it would seem fairly easy to implement *Modularity* (i.e., the ability to detach part of the chain while maintaining each subchain functional) with ChainFORM, as the modules can readily be detached through direct shape-deformation. However, our structured space shows that:

1. A change in the *modularity* of the UI would impact the *hierarchy* of the UI (Figure 5.1). Both subchains need at least a standalone module to operate, which is not the case in the current implementation.
2. A change in hierarchy of the UI would impact *power storage* of the modules (Figure 5.1).
3. A change in power storage of the modules would impact the *strength* of the modules (Figure 5.2).
4. (a) A change in the strength of the modules would impact *shape-changing abilities* of the UI (Figure 5.1).  
(b) A change in the strength of the modules would impact the *speed* of the modules (Figure 5.2), as each subchain will have less modules for the same power, hence can be faster.
5. A change in the speed of the modules would impact the speed of the UI, i.e., its *shape-change ability* (Figure 5.1).

As a result, our contribution helps HCI researchers to generate new designs by exploring more easily modifications of existing ones. To this aim, we provide an overview of the direct and indirect impacts of potential design choices at the micro- and macro-scale. Our contribution also helps HCI researchers to generate new designs from scratch by considering all properties one after the other, or further improve existing ones, through an understanding of the design properties for modular shape-changing UIs and how they may impact usability.

## Limitations

*Reconfiguration algorithms.* We do not discuss in this chapter the challenges of user-centered reconfiguration algorithms [314, 247]. Although this is an interesting topic, we leave it for future

---

work, and propose a structure that can easily accommodate such an extension in the future. Indeed, the current list of macro-scale properties of the entire interface can easily be extended, further detailing digital properties (Figure 5.1). Future work should address them when the hardware barriers are broken [19].

*Interactivity.* The *Interactivity* property (section 4.2.9) is currently sufficient to compare existing systems, as currently few of them are interactive. Future work can easily further detail the interaction modalities, for instance leveraging a definition of interaction modality [201].

*Safety.* The *Safety* (section 4.2.10) is currently seldom addressed in the literature. In this chapter, we used standards from the robotics and HRI communities to describe this property, but those are not specific to modular implementations. We expect that new safety concerns will arise as modular shape-changing interfaces evolve, becoming more robust and allowing researchers to conduct user experiments.

*Context of use.* A human-centered design approach should start by describing and understanding the context of use before drawing requirements and producing design solutions (bottom-up approach) [124]. However, there is no existing usage of modular shape-changing interfaces [19]: existing implementations are restricted to research prototypes often not robust enough to support user interaction [19]. Therefore, the context of use is unknown (user(s), characteristics of the user(s) or groups of users, goals and tasks of the user(s) and environment(s) of the system [124]). As a consequence, in this chapter, we took a *top-down* approach to provide a structured space and inform the early design of modular shape-changing interfaces. Future work should take into consideration the impact of macro- and micro-scale properties on the contexts of use as they arise, i.e. either existing contexts which could benefit from the implementation of modular UIs (e.g., the same way non-modular shape-changing control devices are studied to replace bulky control interfaces [213, 215]) or new usages uniquely enabled by modular shape-changing UIs.

As these limitations impact the rest of this thesis, as they are not limited to our work but span on the entire field of research, we will discuss them more extensively in the conclusion of this thesis, and relate them to the other works we conducted and will present in Part II of this manuscript.

Now that we characterized the design properties at the macro- and micro-scale, the next step is to understand how they will impact the overall design of the system and its consequent interaction techniques, and to evaluate their isolated impact on actual user interaction. In the second part of this thesis, we will present our work on the evaluation of three micro-scale design parameters: the size, shape and bonding strength of the modules.

Properties		lineFORM [73]	chainFORM [72]	
Micro-properties	I/O	none	touch sensors + LEDs	
	Processing	limited (externalized Arduino Mega)	limited (externalized Teensy 3.2)	
	Power Storage	mains-operated	mains-operated	
	Size	32x70x40mm	25x30x12mm	
	Shape	rect. parallelepiped w/ bracket	2 joined rect. parallelepiped	
	Speed	0.103 sec/60 deg	0.10 sec/60 deg	
	Density	lower (bigger modules)	higher (smaller modules)	
	Structure	chained	chained	
	Strength	8.3kg.cm	0.8kg.cm	
Macro-properties	Coupling	Hierarchy	satellites + externalized microcontroller	satellites + externalized microcontroller
		Smoothness	seamless, fabric cover	not seamless, gaps between modules
		Resolution	lower (bigger modules)	higher (smaller modules + 8 LEDs)
	Combination between states		Yes	Yes
	Shape-change ability	Amplitude	lower (17 modules)	higher (max. 32 modules)
		Zero-crossing	0-8 (17 modules)	0-16 (max. 32 modules)
		Curvature	higher (0-232°between two modules)	lower (0-119.5°between two modules)
		Speed	0.103 sec/60°	0.10 sec/60°
		Modularity	No	No
		Porosity	No	No
		Stretchability	No	No
		Granularity	max. 0.04 cp/cm <sup>2</sup>	max. 0.13 cp/cm <sup>2</sup>
		Strength	not mentioned	not mentioned
		Size	Length	Yes (max. 186cm)
	Area		Yes (max not mentioned)	Yes (max not mentioned)
	Volume		Yes (max not mentioned)	Yes (max not mentioned)
	Reversibility		Yes	Yes
	Dimensionality		3D	2D*
	Volume for shape-change		not mentioned	not mentioned
	Usage consumption		not mentioned	83mA.h per module
	Control over shape-change		negotiated	negotiated
Interactivity		shape-change	shape-change + touch + LEDs	
Safety	Severity	not mentioned	not mentioned	
	Avoidance	not mentioned	not mentioned	
	Redundancy	not mentioned	not mentioned	

Table 5.2: Description and comparison of two chain-based interactive modular shape-changing implementations: LineFORM [195] and ChainFORM [196]. Items in bold highlight the differences between the two systems.

\*3D possible but limited, only through direct control: the modules reconfigure on a 2D plan, the user needs to detach the modules, re-arrange them with a plastic joint between them to locate them in two different 2D planes.

---





---



PART II

# **Evaluation of the Impact of Module Design Parameters on User Interaction**

---

---

# PART II - INTRODUCTION

---

## Publications

The work presented in this Part has been published at  
(1) ICMF'21 (*International Conference on Multimodal Interaction*) [234] and  
(2) TEI'23 (*Tangible and Embodied Interaction*) [233].

We presented our first contribution in Part I. We provided a structured design space of ten properties at the scale of the overall interface (*macro-scale*) and seven at the scale of the individual modules (*micro-scale*). We then characterized their impact on each other, and observed that the two micro-scale properties that appear to have the most dependencies with other properties – both micro *and* macro – are the *size* and the *strength* of the modules. As these two properties seem to be critical in the overall design of a modular system, we seek to better understand their impact on user interaction. Our goal is to provide designers with an understanding of how changing these parameters may impact user interaction with their system. For instance, we could argue that having the smallest size of modules possible is desirable for the user, as it would lead to a higher resolution of the shape display, even though it would lead to lower power storage and interactivity. But would users really prefer smaller modules? Is the trade-off worth it? Thus, our work in this part will not only focus on how changing a micro-scale parameter impacts user interaction, we will also operate on a “*usability-feasibility*” trade-off.

The first chapter focuses on the evaluation of the impact of the *size* of modules on interaction. We present the designs and results of two user studies to investigate the impact of module size on target acquisition and pursuit with four tangible sliders made of modules.

The second chapter focuses on the evaluation of the impact of the *bonding strength* and, additionally, the *shape* of the modules on interaction. As we found in Chapter 5 that the shape heavily impacts the bonding strength, we want to study the combined effect of strength and shape.



# EVALUATING THE IMPACT OF MODULE SIZE ON INTERACTION

---

## Contents

---

<b>6.1</b>	<b>Introduction</b>	<b>106</b>
<b>6.2</b>	<b>Related Work</b>	<b>109</b>
6.2.1	Haptic perception of tangible UIs.	109
6.2.2	Tactile discrimination of textures.	109
6.2.3	Minimal size of gaps between modules.	110
6.2.4	Tactile perception through a probe.	110
6.2.5	Tactile perception of roughness and TUIs	111
6.2.6	Kinesthetic perception and TUIs.	111
<b>6.3</b>	<b>Method</b>	<b>113</b>
6.3.1	Apparatus	113
6.3.2	Participants	114
6.3.3	Experimental design	114
6.3.4	Procedure	114
6.3.5	Data collection and analysis	116
<b>6.4</b>	<b>Experimental Results - Target Acquisition</b>	<b>117</b>
6.4.1	Performance	117
6.4.2	Questionnaires.	118
<b>6.5</b>	<b>Experimental Results - Target pursuit</b>	<b>119</b>
6.5.1	Performance	119
6.5.2	Questionnaires	120
<b>6.6</b>	<b>Discussion</b>	<b>121</b>
6.6.1	Size of modules & target acquisition	121
6.6.2	Size of modules & target pursuit	122
6.6.3	Grasps observed	122
6.6.4	Limitations of the studies	124
6.6.5	Implications	125
<b>6.7</b>	<b>Synthesis</b>	<b>126</b>

---



## 6.1 Introduction

In Part I of this thesis, and especially in Chapters 4 and 5, we saw that the size of the modules is a central parameter in the design of modular shape-changing UIs, as it impacts a high number of other properties. On the one hand, the smaller the modules, the lesser the power storage, input/output and processing capabilities of the modules, and thus the lesser the control over shape-change and the interactivity. On the other hand, the smaller the modules, the higher the resolution of the shape. Thus, the greater the shape-change ability, the smoothness and the spatial resolution of the interface. As the technological feasibility of modular shape-changing UIs appears to be heavily dependent on the size of the modules, studying the impact of module size is important: this can help designers and researchers understand the trade-off between usability and technological feasibility. The optimal size of the modules would depend on the specific end-users and tasks: for instance, if we relate modular shape-changing UIs to existing building blocks toys on the market, we see that there is a sub-genre of LEGO bricks for toddlers, the DUPLO bricks, which are bigger to accommodate age-appropriate prehension capabilities<sup>1</sup>. By systematically evaluating varying module sizes and measuring user performance and subjective feedback, researchers can identify the optimal module size for a given interface, user group and task. But in order to open the research agenda on the evaluation of the size of modules, which scale should we first study?

In this chapter, we chose to study module sizes between 1mm and 5mm. These sizes are arguably hard for user to manipulate, which is why we focus on self-actuated mm-scale modules. The rationale behind this choice is that decreasing the size of a module is especially critical under the cm-scale, which is why we still find little implementations. Major technological advances are done in the autonomous robotics community, with the smallest module designs to date being the  $\varnothing 3.6\text{mm}$  Catoms [287] (Figure 6.3). Their goal is to go beyond that, and eventually reach the mm-scale. This is not an anecdotic or isolated goal, as previous work in HCI highlighted that future modules should tend towards an output resolution in the mm-scale rather than today’s cm-scale [19] in order to allow users to interact with “*stuff rather than things*” [159]. Extreme miniaturization of actuated modules is also key to implement well-established conceptual visions for shape-changing UIs, such as *Radical Atoms* from Ishii et al. [119] or *Ultimate Display* from Sutherland [277].

A difficulty –and motivation– of this problem lies in the fact that current technology is not yet ready for very small self-actuated modules. For instance, the smallest modules studied in HCI are the 9mm Dynablocks [279] (Figure 6.3). However, Dynablocks are not self-actuated, preventing the system to actuate their 3D display unless they lie on the dedicated table. As the smallest modules currently being designed are  $\varnothing 3.6\text{mm}$  and not readily available [287], it is not

---

1. <https://www.lego.com/en-us/themes/duplo/about>

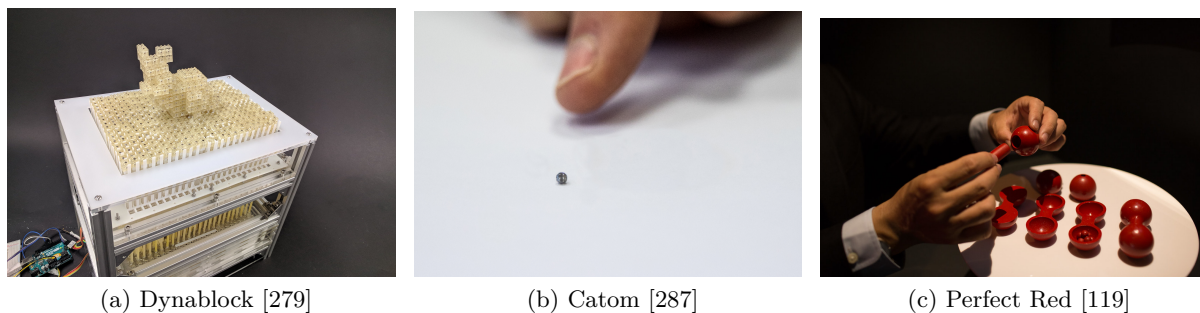


Figure 6.1: Although the smallest modules found in HCI are the 9mm Dynablocks (Subfigure 6.1a), work in robotics proposed a design for  $\varnothing 3.6\text{mm}$  modules (Subfigure 6.1b). The long-term goal is to enable long-term conceptual visions, such as Perfect Red (Subfigure 6.1c).

yet possible to prototype high-resolution modular shape-changing UIs to conduct user studies. It is therefore difficult for the research community to know how far technological research should go to decrease the size of modules in order to provide usable interaction, as we do not know how much the size of the modules impacts the interaction.

In order to study the impact of the size of modules on interaction, our approach is to hypothesize that this technology is close to enable shape-changing tangible UIs. Based on this hypothesis, we study modular *non*-shape-changing UIs with non-actuated mock-ups of modules based on the current design of this technology. This allows us to start evaluating the impact of the size of modules *between shape-changing phases*. As HCI researchers, we believe user-centered design should drive technological development as early as possible [124]. Another difficulty –and grand challenge [19]– lies in the fact that the shape of the modules can also impact user experience with modular UIs [19, 232]. We chose to study quasi-spherical modules, as this shape (1) is the most promising for miniaturization of actuated robotic modules [226] and (2) is expected to have the most impact on interaction due to the friction caused at the surface of the UI by the gaps between modules. First, as shown in Figure 6.3, while the research community mostly explores cubic modules, the robotics community found that quasi-spherical shape is a promising approach to decrease the size of modules [226]. Indeed, the technologies used to actuate cubic implementations are difficult to miniaturize (e.g., electro-magnets [327], mechanical hinges [196] or flywheels [246]), whereas the rounded edges provided by quasi-spherical modules lower the energy as necessary for miniature actuation [226]. Quasi-spherical shape is therefore a promising research direction for modular shape-changing UIs. For this reason, the impact of this shape should be assessed. Second, we expect a high difference in user experience between small and large rounded modules, as the size *and* number of gaps between rounded modules are correlated with the size of the modules. In contrast, we expect a lower difference in user experience between small and large cubic modules, as only the number of gaps is correlated with the size of the modules.

While we expect quasi-spherical modules to hinder performance of common tasks such as target acquisition and pursuit, we do not know *to which extent* their size will hinder performance. This chapter addresses this important problem to re-center technological development on users.

We present the results of two studies assessing four sizes of modules constituting a tangible UI (namely a slider): a plain, smooth slider (modules of size  $\sim 0$  mm) and three sliders made of  $\varnothing 1$  mm,  $\varnothing 2.5$  mm and  $\varnothing 5$  mm mock-up modules (Figure 6.2). We find that (1) the largest modules ( $\varnothing 5$  mm) significantly impairs performance for a pursuit task and subjective perception for pursuit and target acquisition tasks, (2) performance increases when the size of modules decreases but (3) users reportedly enjoyed the haptic feedback of  $\varnothing 1$  mm and  $\varnothing 2.5$  mm modules (e.g., to brake, change speed and change direction). These results provide deeper understanding on how users interact with a device made of small, rounded modules, to inform future technological goals for shape-changing TUI.

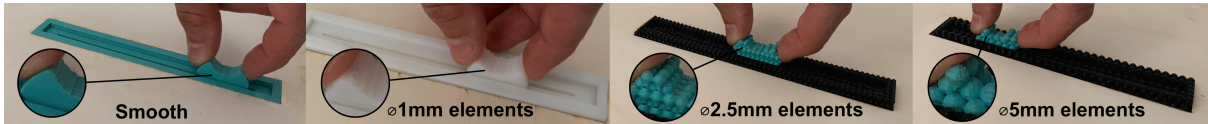


Figure 6.2: The four sliders used to investigate the impact of the size of future modules constituting the TUI: (from left to right) a current smooth slider and three sliders made of mock-up modules of  $\varnothing 1$  mm,  $\varnothing 2.5$  mm and  $\varnothing 5$  mm.

## 6.2 Related Work

The study of the size of rounded modules constituting a tangible UI builds on previous work in TUIs, haptics and psychophysics.

### 6.2.1 Haptic perception of tangible UIs.

The haptic feedback of an interface involves two kinds of perception: First, the kinesthetic perception is the perception of forces and positions by the muscles and joints [52]. Second, the tactile perception is the perception of the physical properties of an object when in contact with the skin of the user [204]. When interacting with a TUI, both kinesthetic and tactile perceptions come into play. For example, users will perceive the shape and roughness of a slider (tactile perception) and the force required to move its cursor (kinesthetic perception).

Previous works distinguish two dimensions of texture: micro (or fine) and macro [204]. Despite differences in perceptual mechanisms, micro- and macro-roughness are hard for users to separate [204]. Prior work studied roughness with groove widths of 1mm up to 8mm [148], which is in the order of magnitude of the size of the gaps between the modules constituting future reconfigurable TUIs (e.g., [77, 317, 279, 196]). On the kinesthetic level, surfaces with groove width of 5mm or 8mm give a kinesthetic feeling of detents –i.e. the feeling that the cursor is locked at a position, often spring-loaded to make the cursor move toward this position [30]– but are also on the roughness spectrum [148]. Surfaces with smaller groove width, and even micro-levels of roughness, may not give the same feeling of detents but still involve kinesthetic perception through proprioception [318]. Although we expect the size of modules to fall into the macro-roughness category (i.e., textures with spatial periods  $>200\ \mu\text{m}$ ) [157], the surface of the modules may present micro-roughness characteristics (i.e., textures with spatial periods  $<200\ \mu\text{m}$ ). We conducted a pilot comparing a smooth manufactured slider and the smooth 3D printed one of Figure 6.2 showing micro-roughness to evaluate how it might impact the results of our experiment. We found no difference. For this reason, this chapter focuses on the macro-roughness caused by modules.

### 6.2.2 Tactile discrimination of textures.

The haptics literature recognizes three fundamental dimensions of tactile perception: warmth (e.g., wood vs. metal), hardness (e.g., metal vs. foam) and roughness (e.g., sand paper is rough vs. plain paper is smooth) [204]. We particularly review prior work on roughness, as small modules impact the roughness of the interface. When users manipulate TUIs such as a slider, their fingers can (1) stick to the surface of the object, such as when fingers grasp the cursor of the slider. Their fingers can also (2) move tangentially to the surface of the object, such as when fingers swipe a surface. Their fingers can also (3) move a proxy (also called a probe) tangentially

to the surface of the object, such as when manipulating an object on a surface or the cursor on its support surface. We thus report results on tactile perception through direct touch with (1) static and (2) moving fingers (e.g., [104, 263, 219, 194]), and through moving probes (3) (e.g., [148, 157, 319, 318]).

The perception of roughness is primarily driven by changes in groove width [148, 160]. Human tactile perception of textures with moving fingers heavily depends on the size of the gaps between bumps [46], rather than the size of the bumps. The deeper the skin of the finger can penetrate into the groove between tactile modules, the rougher the user perceives the surface. Specifically, the perception of roughness (1) increases with the distance between the raised tactile modules, (2) increases with the height of the raised modules and, (3) modestly decreases when the size of the raised modules increases [263].

### 6.2.3 Minimal size of gaps between modules.

Users better perceive roughness when they perform tangential movements [188, 263], such as when they perform target acquisition or pursuit with a TUI. The tactile discrimination of two points is more accurate when the fingers move across the surface of the object: the finger's *static* two-points discrimination normal ability is  $<6$  mm and its *moving* two-points discrimination normal ability is  $<2$  mm [114, pp.146-148][63, pp.118-121]. We will not study gaps  $>6$  mm because humans are able to discriminate two points  $>6$  mm away from each other, even when their finger is static; Also, robots are already research at sizes  $<6$  mm. Additionally, increasing the surface roughness impacts the kinesthetic perception of friction [263, 204]. When the gaps and bumps of a rough surface are repeated in a 2D texture, such as with abrasive paper [105], the thresholds are even lower. Through static contact of the finger, users perceive textures if the size of their modules is  $>0.1$  mm [105]. With moving contact, human tactile perception is possible for modules of sizes  $<0.1$  mm [105], extending to amplitudes as small as 10 nm for wrinkled surfaces [262]. Based on this we will study modules as small as allowed by standard 3D printers available to the general public. Overall, prior work primarily focus on the perception of roughness, rather than on its impact on another, primary task, such as target acquisition and pursuit, as we do in this chapter.

### 6.2.4 Tactile perception through a probe.

The literature on haptics and psychophysics studied the perception of roughness through a probe, i.e. the tip of a stylus (e.g., [148, 157, 319, 318]). E.g., with a tip of size 3 mm, humans are able to perceive gaps of size as small as 0.125 mm. However, this work does not study *task performance* on a textured surface through a probe, nor through a *textured probe* or through a probe with a *different and larger shape*. Manipulating two rough objects on each others, e.g. a

rough slider cursor on a rough railing, results in multiple contact points covering a larger contact surface. We do not know yet how these previous results would apply to larger objects and how they relate to common tasks such as target acquisition and pursuit. This is however important to assess to help the design of future modular shape-changing TUIs. Prior work also proposed tools to capture and generate textures through an active haptic probe and tested the correct perception of the captured then regenerated textures [56]. In contrast, our work aims at assessing the impact on task performance of the texture resulting from small modules constituting the TUI.

### 6.2.5 Tactile perception of roughness and TUIs

Previous work explored the change of tactile perception of the roughness of the UI. For instance, prior work explores vibrotactile feedback for tangible dials [33]. Such feedback can easily be perceived even with a static contact of the finger. It is therefore different from the feedback provided by rough surfaces of reconfigurable TUIs made of small modules. To our knowledge, the literature in tangible UIs did not explore roughness beyond its subjective perception and abstract qualities [115]. Tactile perception to perform grasp and lift manipulation has been studied [91]: the shape of the object in the region of contact with the skin has a strong effect on grip and lift tasks. However, we do not know yet how the roughness of the surface of the reconfigurable TUI –caused by its small modules– affects the performance of common interactive tasks such as target acquisition and pursuit.

### 6.2.6 Kinesthetic perception and TUIs.

Modular implementation of TUIs will cause friction, as the size of modules is correlated with friction [263]. Previous work explored the change of the kinesthetic perception through programmable friction and movement resistance. Programmable friction improves overall movement time and the time to stop the cursor after entering the target with a tactile graphical slider [163]. Variable movement resistance on a tangible slider such as with the FireFader [29] improves performance of eye-free interaction [169] or the kinesthetic visualization and manipulation of sound [284]. In prior work, programmable friction and movement resistance were applied in the area of the target. On the contrary, in this chapter we are interested in studying the impact of the roughness, and its resulting friction, on the *whole surface* of the TUI. Previous work also explored the impact of the resolution of pin-based display on a target pursuit task [244]. However, this work did not explore target acquisition tasks. Another limitation is the single, rather large ( $\varnothing 15$  mm) size of pins compared to current, smooth and plain TUIs. In addition, the proposed implementation of a slider does not build on top of current widespread sliders. This makes difficult the generalization of this result to widespread sliders made of smaller round modules arranged in 3D such as the ones of Figure 6.2 and 6.3ab.

On one hand, while prior work inform on the human tactile perception according to the size of the gaps between the modules constituting the reconfigurable TUI, it primarily focuses on direct touch. When interaction through probes was studied, these probes are far from widespread TUIs such as dials and sliders, and the tasks performed by participants are far from the tasks performed with TUIs. On the other hand, prior work studied the impact of friction and movement resistance on target acquisition tasks that are widespread in TUIs. However, the friction and movement resistance are applied in the area of the targets only, on the contrary to future reconfigurable TUIs made of small modules. We could not find previous work assessing how the size of modules might impact the performance or the user experience for such tasks.

## 6.3 Method

We conduct two user experiments assessing the impact of the size of rounded modules constituting a TUI when using a tangible slider. One experiment uses a target acquisition task and the other one a pursuit task. For each task, we assess the performance, and the perceived task difficulty and workload.

### 6.3.1 Apparatus

We chose to study a plain, smooth slider like current sliders as a control condition, and sliders made of modules of three different sizes. Figure 6.3 shows the modular shape-changing systems that can reconfigure in 3D and that reached a size smaller than 20cm [232]. The smallest ones being designed are the quasi-spherical 3D Catoms [287]. We chose to design our experimental apparatus with modules under  $\varnothing 5\text{mm}$ , as we expect them to be especially impacted by the usability/technological-feasibility trade-off. First,  $\varnothing 1\text{mm}$  is the smallest size we achieved with current mainstream 3D printers. Second, we chose to study  $\varnothing 5\text{mm}$  spheres, as higher sizes importantly impair the global shape of the TUI. Finally, we chose an intermediate size of  $\varnothing 2.5\text{mm}$  to uniformly study performance in the  $\varnothing 0\text{-}5\text{mm}$  range.

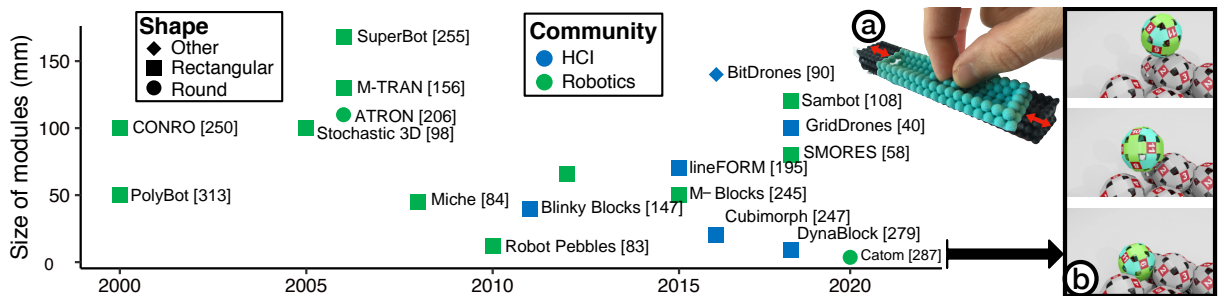


Figure 6.3: Left: Evolution over time of the size and shape of modules used for modular 3D shape-changing UIs  $< 20\text{mm}$  (data source and references [232] found at <http://molecularhci.imag.fr>). Right (a): In the future, modular TUIs could be able to reconfigure their shape. For instance here, a slider could become larger [54]. Right (b): The simulated robotic movement of small, interchangeable modules currently developed that could allow such changes in shape [222].

We 3D printed the sliders. The STL models, printers and materials used for the prototypes are provided in the supplementary material for replicability. Our cursor is based on a manufactured, widespread one (Figure 6.2) [73]. In order to provide a passive haptic feedback comparable to current sliders, the arrangement of the spheres provides a hole for the rail, in which the cursor moves (Figure 6.2). To allow for a comfortable manipulation of the slider, we provided a support surface around the mock-up (Figure 6.2). To log the location of the cursor, we mounted the prototypes of modular cursor and casing of modular sliders on a slide potentiometer, as



shown in the supplementary video. For accuracy, we chose a 100 mm-long Bourns PTB0143-2010BPB103 [3] over other sizes and manufacturers, as, for instance, PaletteGear 60 mm-long sliders could not be as accurate as 100 mm-long ones [54]. We connected the potentiometers to a computer through a Teensy 3.6 board running the Firmata firmware. The experimental software runs at 60 fps. We choose the Teensy 3.6 board for its high performance and its ability to handle 12 bits of resolution when reading the potentiometer. The supplementary video shows how the prototypes work and how participants used the prototypes during the experiment.

We used VisibleSim<sup>2</sup> [289], an open simulator of small robots, to obtain an accurate lattice model of robots for the casing and cursor, for each of the three chosen resolution of modules.

To accurately print the sliders with modules of size  $\varnothing 2.5$  mm and  $\varnothing 5$  mm, we used Ultimaker 3 [4] and PLA [2]. We later dissolved the PVA support material [5] to accommodate the small gaps between spheres. For the slider with  $\varnothing 1$  mm modules, we used a Stratasys Polyjet printer [7] with vero resin [6] to reach sufficient resolution. For the smooth slider, i.e. plain 3D printed prototype, we used an Ultimaker 3 [4] and PLA [2].

### 6.3.2 Participants

We recruited 24 participants from the local campus. Participants only took part in one of the experiments. Twelve participants performed the target acquisition task (4 female, 8 males,  $M = 31.33$  y.o.,  $SD = 5.69$ ) and the other twelve participants performed the pursuit task (4 female, 8 males,  $M = 30.8$  y.o.,  $SD = 7.6$ ). All were occasional users of tangible sliders.

### 6.3.3 Experimental design

Target acquisition and pursuit tasks are common in the literature for tangible interaction [75, 296, 128, 244]. The within-subject independent variable was the size of the modules: Smooth, i.e. no modules (plain 3D printed), spheres of  $\varnothing 1$  mm, spheres of  $\varnothing 2.5$  mm, and spheres of  $\varnothing 5$  mm. The different levels of sizes were presented in permuted order (latin square).

### 6.3.4 Procedure

The experimenter verifies the tactile sensitivity of the dominant hand's thumb, index and middle fingers through two-points discrimination test [114, 63] and the Semmes-Weinstein monofilament aesthesiometer [28]. There was no sensitivity impairment susceptible to skew the results. The participant then sits in front of a laptop running the experimental software and is presented with the first prototype, on the side of their dominant hand. The participant adjusts the location

---

2. VisibleSim aims at being the most generic possible so that any kind of distributed program could easily be plugged in. VisibleSim supports platforms like Catoms3D [222], Catoms2D [135], SmartBlocks [225], Blinky-Blocks [147] and many more. As a consequence, this approach can foster replication and extension.

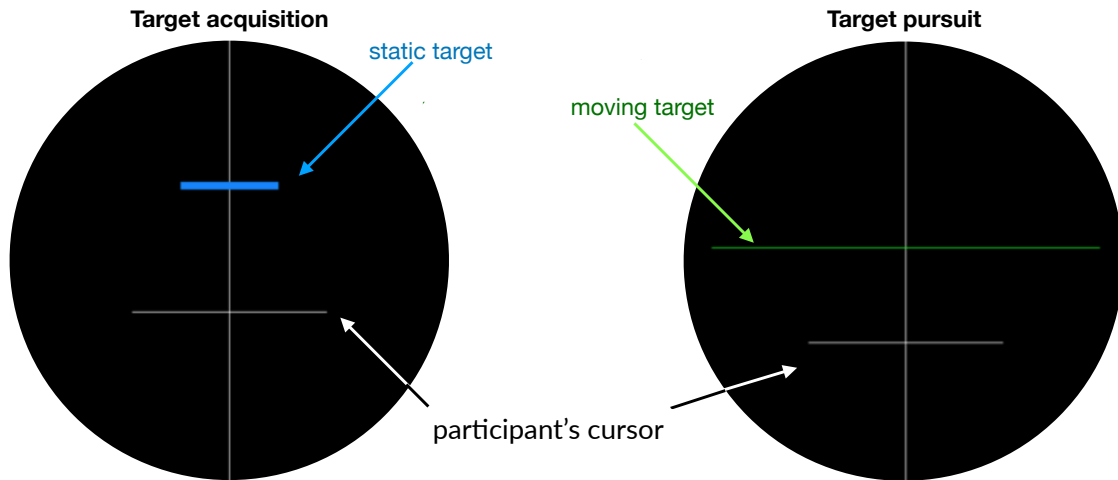


Figure 6.4: Close-ups of the UI of the experimental software for the target acquisition (left) and pursuit tasks (right).

of the box to comfortably reach the highest and lowest values of the slider. The experimenter secures the location of the box with blu tack. The participant then performs the task. For both tasks, the user controls a 1 mm-thick (4.4px) on-screen cursor with their dominant hand, along an 180 mm-long (800px) vertical axis displayed on-screen (Figure 6.4). As the potentiometer measures 100 mm, the on-screen cursor moves faster than the physical one with a CD gain of 1.8. The transfer function is a linear mapping.

The participants do not wear earplugs to cancel the noise caused by the friction: We focus in this very first study on the measure of the impact of the size of the modules. As suggested in [207], we leave for future work the identification of the factors causing this impact, such as, e.g., the friction, or the noise caused by this friction.

### Target acquisition task

A blue rectangle acting as a target is shown on the vertical axis (Figure 6.4). The widths ( $W$ ) and distances ( $D$ ) of the targets are randomized ( $W=8\text{px}$  or  $W=35\text{px}$ ,  $D=90\text{px}$  or  $D=400\text{px}$ ) and result in three rounded Fitts' Index of Difficulty (ID): 1.8, 3.6 and 5.7. The target becomes green when the cursor is within the target. The participant validates by pressing the space key of a laptop with their non-dominant hand. If they validate outside the target, we log an error. The task ends when the target is successfully acquired. After completing a training with 5 targets, the participant is required to successfully validate 5 blocks of 26 targets. As the distance ( $D$ ) is the distance between two consecutive targets, the first and last targets are dummies to re-position the cursor at the center of the screen. Thus, the first and last targets are discarded during analysis. Participants can take breaks between blocks. Instructions require the participant to

be as quick and accurate as possible. To account for speed-accuracy trade-off, the experimental software compute the error rate and instruct the participant to speed up (error rate  $< 4\%$ ) or slow down ( $> 4\%$ ) between blocks.

### **Target pursuit task**

A 1 mm-thick (4.4px) green target is moving up and down the vertical axis (Figure 6.4). The target moves at constant speed in a linear motion and darts off at pseudo-random intervals (as in [128, 244]). Instructions require the white cursor, controlled by the user, to be as close as possible to the green target. Participants complete two trials of 90s, as in [75, 128, 244]. They can take a break between trials.

After completion of the task, the participant fills a questionnaire. The procedure is repeated with each of the four sizes of modules. At the end of the experiment, the participant fills a final questionnaire. We conducted interviews after the task using the explicitation interview method [301]. The experiment lasts around 30 minutes.

### **6.3.5 Data collection and analysis**

For the target acquisition task, we collect movement time, error rate and distance from target center to the cursor. For the target pursuit task, we collect the pursuit error for every frame during the experiment. For both, we gather subjective feedback: First, we gather overall perceived difficulty with a Single Ease Question [306] (*Overall, how difficult or easy did you find this task?*). The participant answers on a seven points Likert scale. Second, we gather perceived workload with a NASA Task Load Index (TLX) questionnaire which assesses six items: mental, physical and temporal demand, performance, effort, and frustration [101]. We use the unweighted version which is as reliable but faster to complete [100, 189]. We also record synchronized videos of the participants' arms, hands and eyes. The experimenter took note of used limbs and user behaviour.

We chose to compare the impact of the size of the modules on our chosen measures as in previous work [62, 149]. Other widespread experimental procedures (e.g., two-alternative forced choice [32], free-magnitude estimation [105], or just-noticeable difference [126]) require to many sizes of spheres or only assess the impact on a subjective measure.

## 6.4 Experimental Results - Target Acquisition

In this section, we report our results on the impact of the size of modules constituting the slider on the performance of users performing a target acquisition task. We particularly report in table 6.1 our results on movement time, error rate and SEQ score.

### 6.4.1 Performance

While our participants were asked to aim at a 4% error rate, we wanted to account for any residual bias in speed-accuracy trade-off. A common approach is to use the effective width [265]. However, in order to measure actual movement times, we chose in our experimental procedure to measure the movement time *until successful target acquisition* as in [78]. In this case, we can directly analyze movement times and error rates separately [50].

	Movement Time (ms)	Error rate (%)	SEQ
Smooth	1441.29, CI[1302.49, 1580.08]	2.28, CI[1.22, 3.34]	6.08, CI[5.29, 6.61]
∅1 mm	1471.04, CI[1332.84, 1609.23]	3.57, CI[1.78, 5.36]	5.25, CI[4.31, 5.84]
∅2.5 mm	1506.15, CI[1386.21, 1626.08]	3.11, CI[1.7, 4.53]	5.33, CI[4.56, 5.87]
∅5 mm	1508.95, CI[1366.27, 1651.63]	1.94, CI[1.02, 2.87]	4.92, CI[3.8, 5.5]

Table 6.1: Mean movement time (ms), error rate (%) and score of the Single Ease Question for target acquisition (with 95 % confidence intervals).

**Movement Time.** Figure 6.5 shows the geometric mean of the movement time [256] for each size of modules, with its 95 % confidence interval. Since we obtain a p-value of 0.021 with Shapiro-Wilk’s test on our data, we cannot assume the normality of our data. We therefore perform an Aligned Rank Transform (ART) [308]. We conducted a one-way analysis of variance (ANOVA) on the aligned data and showed no significant difference between the movement times of the different sizes of modules ( $F(3,33)=1.81$ ,  $p>.05$ ).

**Error Rate.** Since we obtain a p-value of 0.0003 with Shapiro-Wilk’s test on our data, we cannot assume the normality of our data. We therefore align our data with the ART method. We conducted a one-way analysis of variance (ANOVA) on the aligned data and showed no significant difference between the error rate of the different sizes of modules ( $F(3,33)=1.67$ ,  $p>.05$ ).

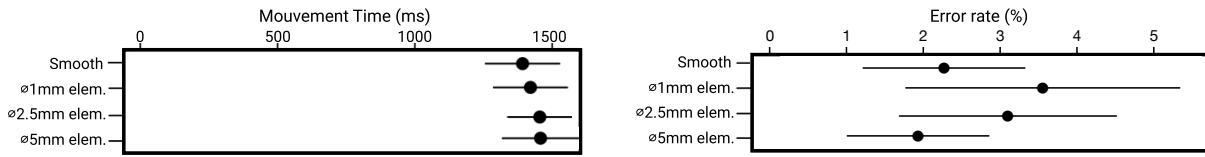


Figure 6.5: Left: Movement time (in ms) for each size of modules. Points show geometric means and error bars show the 95 % confidence interval. Right: Error rate (%) for each size of modules. Points show means and error bars show the 95 % confidence interval. All conditions had the same slider range on the device (8 cm) and on the screen (18 cm).

### 6.4.2 Questionnaires.

Figure 6.6 shows the results from the Single Ease Question and Nasa TLX questionnaires for the target acquisition task.

As questionnaires provide Likert scale data, we used the ART method to align their data, e.g., the mean SEQ scores. We conducted a one-way ANOVA to compare the impact of the size of modules on the aligned SEQ score. As there was significance ( $F(3,33)=4.0637, p<.05$ ), we carried out post-hoc pairwise comparisons based on Kenward-Roger approximation. Participants perceived the task as significantly more difficult with the slider made of ø5 mm modules compared to the smooth slider ( $p<.05$ ).

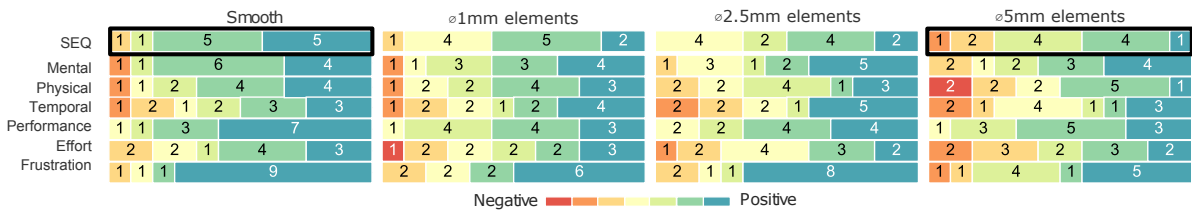


Figure 6.6: Results from the SEQ and TLX questionnaires for the target acquisition task. Outlined in black, participants found the slider made of ø5 mm modules significantly more difficult to use than the smooth (control) slider.

We conducted a one-way ANOVA to compare the impact of the size of modules on each aligned TLX item score and found no significant differences between the TLX items of the different sizes of modules. The raw scores for the SEQ and TLX questionnaires can be found in the supplementary material.

## 6.5 Experimental Results - Target pursuit

In this section, we report our results on the impact of the size of modules on the performance of users performing a target pursuit task. We particularly report in table 6.2 our results on pursuit error and SEQ score.

	Pursuit error (%)	SEQ
Smooth	1.27, CI[1.25, 1.28]	5.42, CI[4.80, 6.03]
∅1 mm	1.32, CI[1.31, 1.33]	4.33, CI[3.56, 5.11]
∅2.5 mm	1.42, CI[1.40, 1.43]	4.5, CI[3.8, 5.2]
∅5 mm	1.68, CI[1.66, 1.69]	3.83, CI[2.81, 4.85]

Table 6.2: Median pursuit error (%) and mean score of the Single Ease Question for pursuit.

### 6.5.1 Performance

Figure 6.7 shows the median pursuit error for each size of modules. The median of the pursuit error is a better indicator of the data central tendency [54]. Since we obtain a p-value  $< 0.001$  with Barlett's test on our data, we cannot assume the normality of our data. We aligned our data using ART [309]. We then conducted a one-way analysis of variance (ANOVA) on the aligned data that showed a significance difference ( $F(3,33)=17.879$ ,  $p<.01$ ). We carried out post-hoc pairwise comparisons based on Kenward-Roger approximation [139] and showed two significant increase in pursuit error: First, the slider made of ∅5 mm modules lead to significantly more error compared to all other sizes (smooth ( $p<.0001$ ), ∅1 mm modules ( $p<.0001$ ) and ∅2.5 mm modules ( $p<.01$ )). Second, the slider made of ∅2.5 mm modules lead to significantly more error compared to the smooth slider ( $p<.05$ ).

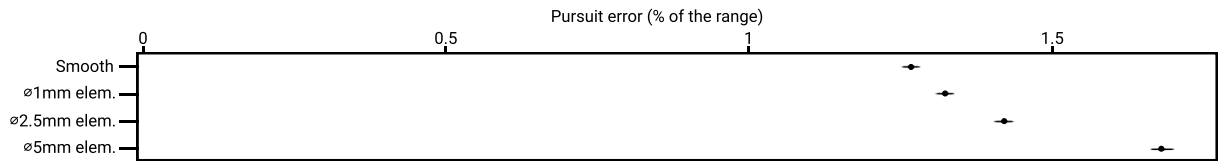


Figure 6.7: Pursuit error (% of the slider range). Points show medians and error bars show the 95 % confidence interval. All conditions had the same slider range on the device (8 cm) and on the screen (18 cm).

### 6.5.2 Questionnaires

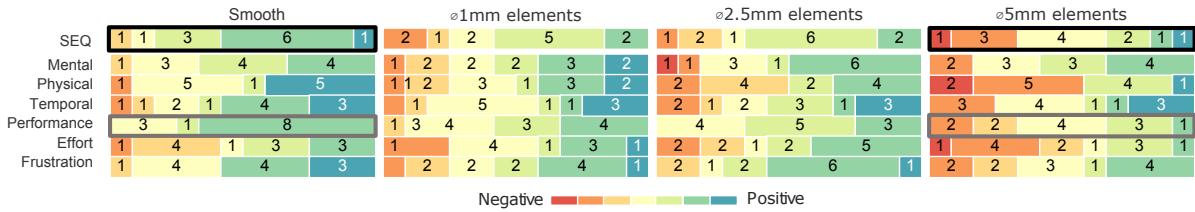


Figure 6.8: Results from the SEQ and TLX questionnaires for the pursuit task. Outlined in black, participants found the slider made of ø5 mm modules significantly more difficult to use than the smooth (control) slider. Outlined in gray, participants found they did not accomplished the task as successfully with the slider made of ø5 mm modules compared to the smooth (control) slider.

Figure 6.8 shows the results from the Single Ease Question and Nasa TLX questionnaires for the pursuit task.

We followed the same statistical approach as for the questionnaire data of the target acquisition task. We compare the impact of the size of modules on the aligned SEQ score. As there was significance ( $F(3,33)=2.978, p<.05$ ), we carried out post-hoc pairwise comparisons. The task was perceived as significantly more difficult with the slider made of ø5 mm modules compared to the smooth slider ( $p<.05$ ). We compare the impact of the size of modules on each aligned TLX item score. There was a significant impact of the size of modules on the perceived performance ( $F(3, 33)=3.9714, p<.05$ ). Post-hoc pairwise comparisons show that the slider made of ø5 mm modules significantly decreased the perceived performance compared to the smooth slider ( $p<.01$ ). Results from the final questionnaire comparing the size showed that all users ranked the slider made of ø5 mm modules last for the SEQ as well as for the physical demand (“*The task was physically demanding.*”) and frustration items (“*I felt discouraged/irritated while performing the task.*”) of the TLX. The raw scores for the SEQ and TLX questionnaires are available in the supplementary material.

## 6.6 Discussion

### 6.6.1 Size of modules & target acquisition

Experimental results showed that, even though increasing the size of the modules did not significantly impact performance, the task was perceived as significantly harder with the  $\varnothing 5$  mm modules. This is consistent with participant feedback from interviews. Only two participants expressed liking the slider made of  $\varnothing 5$  mm modules (P14 *"the large notches helped me to be accurate"*, P17 *"I like the [slider made of  $\varnothing 5$  mm modules] because I think I didn't make any error with it"*). The other participants expressed disliking the slider made of  $\varnothing 5$  mm modules, as they reportedly perceived it as frustrating: it is too loud (e.g., P21 *"the noise is annoying"*) and is physically uncomfortable to operate (e.g., P20 *"it was annoying to move it"* and P24 *"it's just to the touch, without moving it. I don't like big spheres."*).

Overall, participants agreed that all sliders were similar but had distinctive qualities. On the one hand, the smooth slider allows for faster movements and accurate adjustments. However, participants complained that it led them to overshoot more. On the other hand, the sliders made of  $\varnothing 1$  mm to  $\varnothing 2.5$  mm modules provide haptic feedback which helped to prevent overshoots and accurately stop on the target. Even though participants reportedly enjoyed the sliders made of  $\varnothing 1$  mm to  $\varnothing 2.5$  mm modules, most still rated the smooth slider as easiest to complete the task with. Our hypothesis is that even though the smooth slider causes overshoots, its increased speed of movement to initially reach the target compensates for the adjustment time required by the overshoot. Participants expressed that, despite their preferences, they did not think any size of modules significantly impacted their performance. For example, P20 said that with the slider made of  $\varnothing 5$  mm modules, *"completing the task was no problem, I just didn't like it"*.

Previous work found that programmable friction improves the time to stop the cursor after entering the target and improves overall movement time for non-tangible graphical sliders controlled through direct touch [163]. This is consistent with our results with tangible sliders: in prior work [163], as friction was only applied *on the target*, users benefit from (1) the faster movements enabled by low friction to initially reach the target and (2) the higher friction on the target to reduce overshoots. Our results are important as the HCI community takes a growing interest in new shapes, materials and textures [227, 115, 19], in particular for reconfigurable TUIs made of small modules (e.g., [166, 77, 317, 279, 196, 159, 90]). Future TUIs can leverage materials that can change roughness or size of modules, such as wrinkling materials (e.g., [214, 79]) with changing zero-crossing physical feature [141]. It is important that future materials are able to change roughness *only in dedicated, programmable locations corresponding to potential targets*, e.g. to prevent overshoots while ensuring a comfortable interaction, as shown in our target acquisition experiment.



### 6.6.2 Size of modules & target pursuit

The size of modules impacts target pursuit more than acquisition. Participants were less accurate at pursuit as the size increased. As the size of modules is correlated with friction [263], we explained this result with the varying friction between the cursor and the rail of the slider. During interviews, participants commented on the relationship between friction, size of modules and performance. On the one hand participants mentioned preferring the plain slider for continuously pursuing the target, whereas it caused overshoots when the target darted off. On the other hand, participants mentioned that larger modules provided haptic feedback. They preferred the sliders made of  $\varnothing 1$  mm to  $\varnothing 2.5$  mm modules when the target darted off, and said these rendered braking, changing speed and changing direction easier, thus preventing overshoots. This is consistent with the results and user feedback of the target acquisition task.

Even though participants liked the haptic feedback provided by modules, the performance suffered from the large “bumps” made by  $\varnothing 5$  mm modules. When the cursor is in a gap between bumps, it is difficult to move because of static friction [241] and because of the deep and steep slope for the cursor to climb the next module. Our results thus support previous work advocating for lower friction [39, 22, 23, 241], probably because the friction resulting from modules is high compared to prior work that found no effect [47].

### 6.6.3 Grasps observed

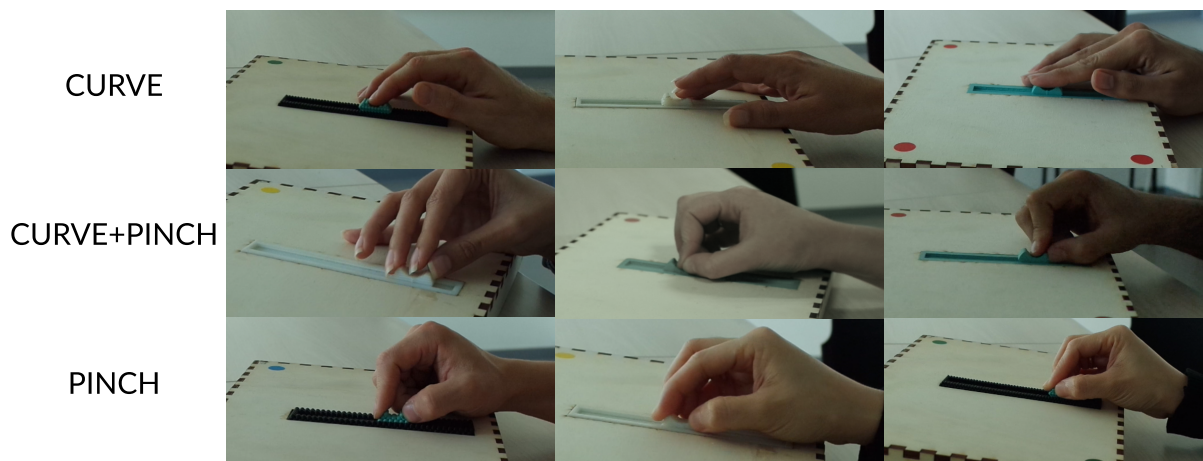


Figure 6.9: The 9 grasps we observed during the experiment in their three categories.

Tangible sliders allow for several grasps. In particular, when the finger is on the central concave curve of the cursor (“curve” grasp, Figure 6.10), users can simultaneously control several sliders [25, p.140]. Thus, supporting this “curve” grasp is important. To explore the suitability of a modular implementation for this grasp, we report how participants grasp the cursor in the

video recordings of both target acquisition and pursuit tasks. We observed between and within subject variation in grasps. Figure 6.9 shows nine different grasps that we observed during the experiments. Participants first tried multiple grasps for a same slider. We only report here the grasp they settle on after the first target acquisition block or pursuit trial. We categorize the grasps we found in the three following categories of common grasps for tangible sliders [73] (Figure 6.10, left):

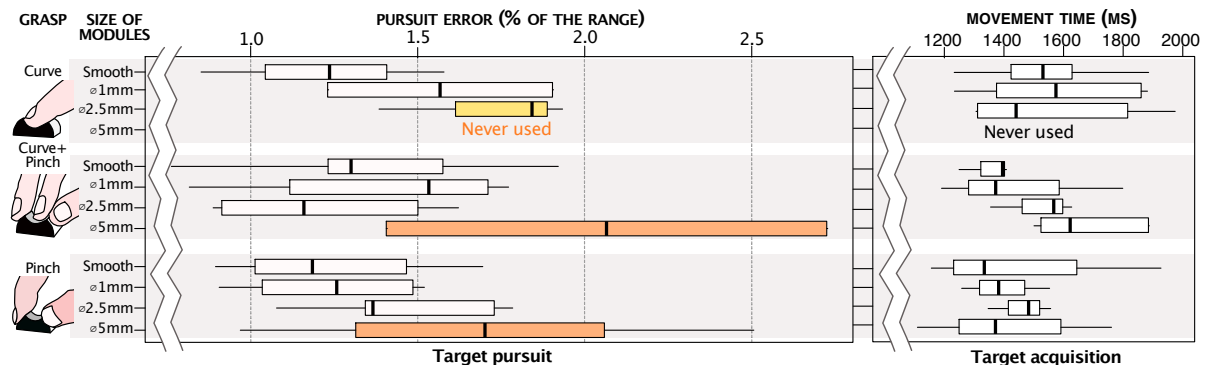


Figure 6.10: Target pursuit error and target acquisition time for each grasp, across sizes of modules. Boxplots show the median through the bold central line, the first and third quartile through the box and the extremums through the whiskers.

**Curve** is the grasp of the cursor with a single finger placed in the cursor’s central concave curve; **Pinch** is the grasp of the cursor between two fingers, often the index and the thumb; **Curve+Pinch** is the grasp combining a pinch between one or two finger(s), often the middle and the thumb, and another finger, often the index, in the cursor’s concave curve.

The smooth slider and the slider with  $\varnothing 1$  mm modules present close performance for all three grasps (Figure 6.10). The slider with  $\varnothing 2.5$  mm modules caused a higher error with the *Curve* grasp for the pursuit task (yellow in Figure 6.10). The slider with  $\varnothing 5$  mm modules (orange in Figure 6.10) do not allow for the *Curve* grasp at all, while the *Curve+Pinch* grasp caused high error. The *Pinch* grasp showed the best performance, although its accuracy with  $\varnothing 5$  mm modules is still far from the other sizes for the pursuit task.

We hypothesize that this is due to the interaction between the size of the modules and the contact forces applied with the *Curve* grasp. E.g., P5 said about the smooth slider and the slider with  $\varnothing 1$  mm modules, that *they are a lot smoother so I have to be aware, I have to change the force that I’m applying*. P9 said *I think that it’s the force too, that I’m not pressing on it the same way so it grips less*. With the smooth slider, increasing the contact force between the cursor and the railing does not impair the performance since they are both smooth. With  $\varnothing 1$  mm modules, it seems that the bumps and gaps are small enough to accommodate the contact forces of a *Curve* grasp without impairing the performance. With  $\varnothing 2.5$  mm modules, the *Curve* grasp

impairs the performance for the pursuit task. Applying rather tangential forces (either with the *Curve+Pinch* or *Pinch* grasps) results in better performance. With  $\varnothing 5$  mm modules, applying contact forces renders the movement of the cursor challenging. E.g., P5 performs the *Curve* grasp: "[on the smooth slider] *this is easy with one finger*. [switches to  $\varnothing 1$  mm modules] *easy* [switches to  $\varnothing 2.5$  mm modules] *still easy* [switches to  $\varnothing 5$  mm modules, the cursor gets stuck] *no, not easy*". The *Curve+Pinch* grasp shows little improvement for  $\varnothing 5$  mm modules. For this reason, most participants used the *Pinch* grasp: 6/12 for target acquisition and 10/12 for pursuit, as shown in figure 6.11, Large size of modules ( $\varnothing 5$  mm) prevents rich grasps opportunities, and causes lower performance and lower satisfaction.

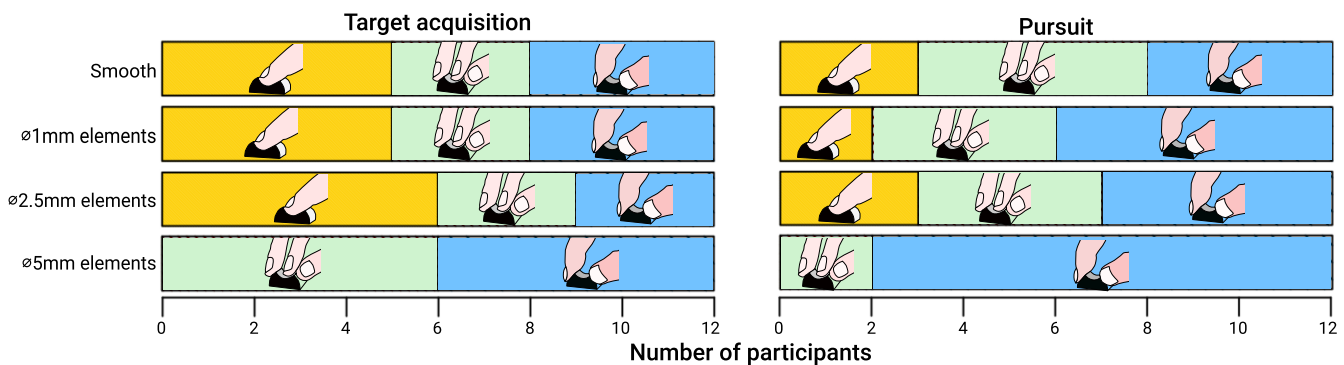


Figure 6.11: Number of participants according to their grasps, for the target acquisition task (left) and pursuit task (right). The “curve” grasp (yellow) was not possible with  $\varnothing 5$  mm modules.

#### 6.6.4 Limitations of the studies

These studies are limited to the impact of the macro-texture of quasi-spherical modules. Depending on the future actual implementation, their micro-texture, the strength of their bond, the friction at their surface, their shape, their arrangements, etc. might also have an impact on the results. In particular, we left the micro-texture apart for these studies, as a pilot experiment comparing a standard slider and a 3D printed one did not show any difference in performance. However, it is possible that the micro-texture further impairs the interaction when applied at the surface of small modules. We plan to assess this in a future separate experiment when the first implementations are available. The studies presented here are a first and necessary step towards informing the design of small robotic modules for user interaction with modular TUIs. To our knowledge, these are the first studies assessing the design parameters of small modules constituting TUIs.

### 6.6.5 Implications

Modular interfaces will enable the change of the physical shape to support multiple *interaction* modalities [35] for users' input and/or system's output [19]. We evaluated the impact of the size of rounded modules on target acquisition and pursuit with a slider. Our results already inform the design of *rounded* modules constituting modular interfaces when they take the shape of a *slider*.

First, an alternative for future modular reconfigurable TUIs in the future are cubic modules, although such small *and actuated* cubic modules were never proposed so far. The smallest cubic modules we know to allow for 3D shapes are Dynablocks [279] (9 mm). However these are not self-actuated. We hypothesize that cubic modules would lead to higher target acquisition and pursuit performance compared to rounded ones. Indeed, only the number of gaps is correlated with the size of cubic modules. In contrast, the size *and* number of gaps between rounded modules are correlated with the size of the rounded modules. Our results can then be used as a worst case scenario for the performance with cubic modules. Future work should assess the precise impact of the size of cubic modules on user experience.

Second, a modular reconfigurable TUI can change to other TUIs besides sliders. Other widespread TUIs are push buttons and dials [140, 25]. We expect the impact of the size of rounded modules to be comparable for dials, as the rotation of the dial on the support surface will also cause friction. We hypothesize that the contact area between a dial and its support surface (between 78 and 707 mm<sup>2</sup> [25, p.136]) is comparable to the contact area between the cursor of the slider and its support surface, as recommended [73] and studied in the chapter (231 mm<sup>2</sup>). Our results also offer a first measure for future modular tangible UIs offering object translation on a table [258]: These objects could change shape in the future thanks to a modular implementation, allowing to change their affordance [186] or the shape of their support surface depending on the scenario of use [93]. Such tangible objects are currently made of large modules [159], but prior work called for decreasing the size of these modules [159], in order to allow for larger shape resolution [141]. Future technological development can now consider user performance to decide for a target size.

## 6.7 Synthesis

In this chapter, we explored the impact of the size of rounded modules on potential future modular tangible UIs. We will conclude this chapter by summarizing the key design guidelines we can draw from our experimental results, and how this work ties with the rest of this thesis.

For target pursuit, our experimental results showed that pursuit accuracy decreases when the size of modules increases. A smooth surface is especially beneficial for the continuous movement involved in following a moving target. However, in our protocol, the target could also *dart off*. In this case, our results and subjective feedback showed that a smooth surface could hinder the task as it caused overshoot. Instead, participants expressed that they prefer sliders with  $\varnothing 1$  mm to  $\varnothing 2.5$  mm modules to reach darting-off targets, as the increased haptic feedback and friction reportedly helped them changing speed, changing direction and breaking. Although adding friction helped in this case, it seems that  $\varnothing 5$  mm modules is too big of a size as they impaired both performance and subjective feedback.

For target acquisition, experimental results show that the size of the modules did not significantly impact performance. Subjective feedback from our participants is consistent with the results of the pursuit task: as target acquisition does not require continuous movements, but rather fast movements and breaking on a specific area to reach the target, it yielded similar feedback as when the target darted off in the pursuit task. Thus, participants from the target acquisition task also reportedly enjoyed the haptic feedback from the modules. The  $\varnothing 5$  mm condition however impacted subjective feedback, as participants reportedly found it harder to operate. It is interesting to note that although participants did not report that this condition impacted their perceived performance, they still didn't like it for other reasons, such as the sound it made or how it felt under the fingers.

We found that the higher the size of the modules, the fewer the grasps user can perform on the slider's cursor. Impairing the rich grasping possibilities of TUIs can prevent, for instance, their abilities to act as external cognitive aids [259, 129]. Our studies show that the research should consider how the design of these emerging UIs impacts not only user performance and subjective perception, but also the grasping possibilities. Our studies show the importance of addressing the grand challenge [19] of developing  $<\varnothing 5$  mm modules.

We will now investigate the impact of two other major micro-scale properties on interaction: the *bonding strength* and the *shape* of the modules.





# EVALUATING THE IMPACT OF MODULE SHAPE AND BONDING STRENGTH ON INTERACTION

---

## Contents

---

<b>7.1</b>	<b>Introduction</b> . . . . .	<b>130</b>
<b>7.2</b>	<b>Related work</b> . . . . .	<b>133</b>
7.2.1	Manipulating modular TUIs . . . . .	133
7.2.2	Magnetic actuation and bonding strength . . . . .	135
<b>7.3</b>	<b>Method</b> . . . . .	<b>137</b>
7.3.1	Apparatus and participants . . . . .	137
7.3.2	Experimental design . . . . .	138
7.3.3	Experimental tasks . . . . .	139
7.3.4	Procedure . . . . .	141
7.3.5	Data collection and analysis . . . . .	141
<b>7.4</b>	<b>Results</b> . . . . .	<b>142</b>
7.4.1	Overall results . . . . .	143
7.4.2	Results across manipulations and configurations . . . . .	145
<b>7.5</b>	<b>Discussion</b> . . . . .	<b>152</b>
7.5.1	Impact of module shape . . . . .	152
7.5.2	Impact of bonding strength . . . . .	153
7.5.3	Implications for the design of future interaction techniques with modular TUIs . . . . .	154
7.5.4	Implications for future technological development of modular TUIs . . . . .	155
<b>7.6</b>	<b>Limitations of the study</b> . . . . .	<b>157</b>
<b>7.7</b>	<b>Synthesis</b> . . . . .	<b>158</b>

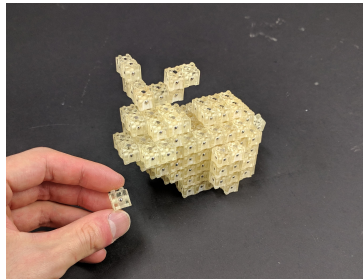
---



## 7.1 Introduction



(a) Blinky Blocks, 40mm [147].



(b) Dynablocks, 9mm [279].



(c) Magnetic Quadrupoles, 2.4mm [97].

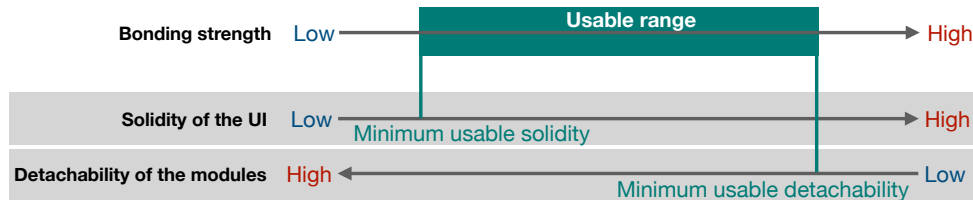
Figure 7.1: Using passive magnets allow for a very small form factor. However, the smaller the magnets, the weaker the bonding strength.

After studying on the impact of the *size* of the modules, we set out to study the impact of their *bonding strength* and *shape*. We find that using passive magnets as the bonding mechanism of the modules offers great perspectives for miniaturization, but that the smaller the modules, the smaller the magnets need to be, and the weaker the bonding strength (Figure 7.1). Moreover, as we conduct our evaluation of isolated design factors on static apparatus (i.e., not actual robots), we decided to broaden our scope for the work conducted in this chapter: although the work presented in the previous chapters was focused on informing the design of modular shape-changing UIs implemented through modular robots, we wanted to allow more people from the HCI community to leverage the work presented here. Thus, we contribute to the design of modular shape-changing UIs, but also of modular *tangible* UIs (TUIs), even if they do not embed computational capabilities.

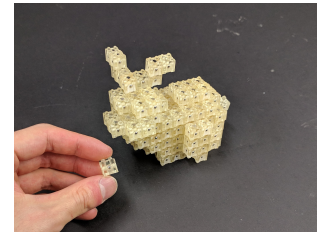
Modular tangible User Interfaces (TUIs), similarly to modular robots, enable interaction through an ensemble of small scale physical elements –called modules– that the system *or* the user can rearrange to, e.g., adapt to the user, the task or the environment [19]. The novel benefit that such interfaces provides is their highly customizable and small form factor, as they do not need to embed computational capabilities, enabling a wide range of possible shapes [141]. This opens new opportunities for tangible interaction. For example, Dynablock (Figure 7.2b) proposed dynamic 3D printing of user-reconfigurable objects composed of magnetic cubes [279]. GaussBricks allow 2D interaction on a touchscreen [165].

We currently lack knowledge on the trade-off between the detachability of the modules and the solidity of the overall modular UI (Figure 7.2a). On the one hand, if the modules stick strongly together they should form a robust modular UI, but may be more difficult to detach

and reconfigure for the user. On the other hand, if the bonding strength between modules is low, they would be easier to detach and reconfigure for the user, but the overall modular UI might lack robustness.



(a) The bonding strength should be low enough so users can detach the modules manually, while strong enough for the UI to hold its shape.



(b) Example of an object made of modules [279].

Figure 7.2: The expected trade-off between the detachability of the modules and the solidity of a modular TUI.

In this chapter, we seek to understand how this trade-off impacts user interaction with modular TUIs. We conduct the first study with passive magnets as bonding mechanism. Passive magnets –although not as strong as other alternatives, e.g., mechanical clamps [206] hinges [247], electromagnets [102, 202]– are simple to use, and allow the modules to self-align [246]. Magnets help users to reconfigure UIs made of small scale modules, both in 2D (e.g., [165, 86]) and in 3D (e.g., [246, 279]). Moreover, their low cost and small size factor enable scalable, cheap and highly reconfigurable modular UIs. For magnetic modules, we expect the detachability/solidity trade-off of the interface to depend on the holding force of the magnets themselves (that we call “*bonding strength*”), and on the shape of the modules. As with LEGO brick toys [94], we also expect the detachability/solidity trade-off to depend on the configuration of the modules: prior work mentioned that the denser the overall structure, the stronger it should be (Part I), but did not conduct a user study to measure this impact and inform future design. The problem we address in this chapter is the lack of knowledge on the *usable range of bonding strength between magnetic modules* (Figure 7.2a) –i.e. the trade-off between detachability and solidity– as well as *how the shape of the modules and their configuration* may further impact this trade-off.

Addressing this problem is important and timely (1) to inform current technological development, and (2) to avoid arbitrary and ad-hoc design choices in the future. The contributions in the field of modular TUIs are still at the design and prototype stages rather than interaction techniques and studies in the wild (e.g., [165, 279, 86]). Existing prototypes currently make use of ad-hoc shapes and strengths that are technology-driven and may not be optimized for users. The lack of user studies is a known challenge in the general field of shape-changing UIs. This is mainly explained by the fact that (1) isolating experimental factors and their effect is difficult with such UIs [19], and (2) the prototypes are often not robust enough to withstand prolonged

user manipulation [19]. However, we expect that research on modular TUIs will advance in the upcoming years as the technology improves.

In order to overcome the challenges of conducting user studies with modular TUIs, we leverage recent work from robotics [97] to build simple passive magnetic modules of  $6 \times 6 \times 6 \text{ mm}^3$ . In a controlled user study, we gathered subjective ratings (*difficulty*, *satisfaction*, *impact of shape* and *impact of strength*) across eight types of tangible manipulations and two module configurations, performed with three levels of bonding strength –low (0.5mm-thick magnets of 0.49N), mid (1mm, 0.98N) and high (2mm, 2.45N)– and two module shapes (cubes and rounded cubes).

Experimental results not only confirm the existence of a detachability/solidity trade-off, but also measure the impact of module shape and bonding strength on the trade-off. Participants found cubic modules easier and more satisfying to manipulate, as they made for a robust UI even with low bonding strength. On the other hand, detaching one or two modules is easier and more satisfying with either rounded modules, as the gaps between rounded modules make them more prehensile, or cubic modules with lower strength (i.e., 0.5mm magnets). Bending the UI is easier with rounded modules with 1-2mm magnets, as rounded modules make the whole UI more flexible.

## 7.2 Related work

To conduct the work presented in this chapter, we studied the related work on (1) TUIs and how users manipulate them, as well as (2) how magnetic actuation was previously leveraged in both HCI and robotics, and how they took into account the impact of the strength.

### 7.2.1 Manipulating modular TUIs

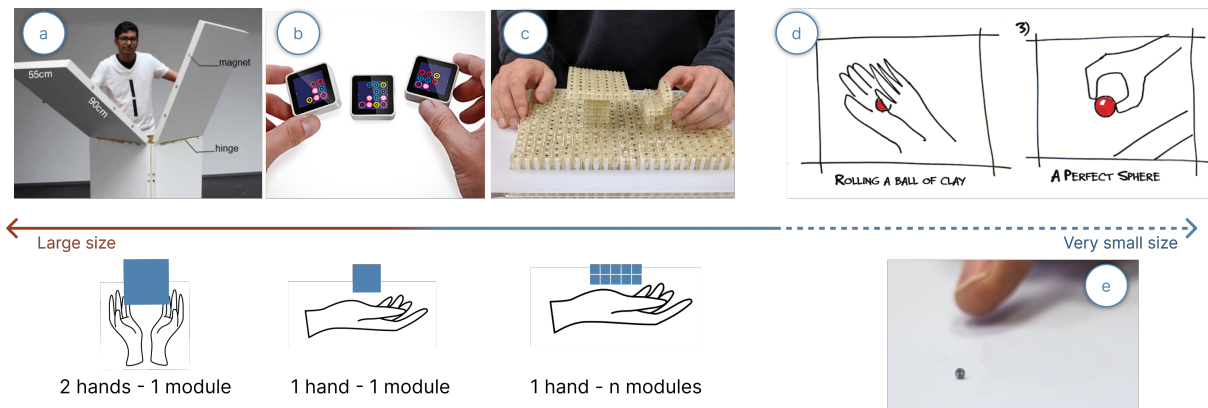


Figure 7.3: Modular TUIs enable a wide range of interaction modalities and prototypes, e.g. (a) reconfigurable smart VR environment [51], (b) reconfigurable touchscreens [179], or (c) dynamic 3D shape printings [279]. An example long-term vision for such interfaces is (d) Perfect Red [120], with modules as small as atoms, which could be achieved via modular solutions such as (e) the few mm Claytronics concept [223].

Previous work proposed a wide range of concepts and prototypes of modular UIs. In this section, we classify them according to how users manipulate them, which is dependent on the size of the modules. Similarly as how users do not hold a needle the same way as the handle of a hammer [74], users do not interact with modules at a scale of several tens of centimeters compared to modules under the centimeter scale.

*2 hands – 1 module interaction* with large (decimeter) scale modules, which require users to interact with them using both hands (e.g. TurkDeck [51] or Foxels [216]).

*1 hand – 1 module interaction* with cm-scale modules that users can grasp one at a time (e.g. Siftables [179], Blinky Blocks [147] or Pickcells [86]).

*1 hand – n modules interaction* with cm- to mm-scale modules that users can grasp together (e.g., GaussBricks [165], Dynablock [279], or chainFORM [196]).

As a side note, we do not take into account swarm interfaces (e.g., Zooids [159], ShapeBots [280]) as they typically move independently and at a distance from each other and have

little to no bonding. We also do not take into account shape displays (e.g., inFORM [77], Haptic Edge [127]) as they are constantly attached.

We particularly consider small modules enabling *1 hand - n modules* interaction. We study the smallest modules possible because research is currently trying to miniaturize modular TUIs (e.g., [19, 159, 120]). However, very few work has been conducted on modules under 1cm, especially 3D ones (see Figure 2 of [234]). HCI calls for miniature modules [120, 159, 19] to enable interaction with “stuff rather than things” [159] where the module is not the *interactive device* in itself, but the *material* used to create the UI. Radical Atom [120] states that the step between vision and technological implementation is to study users’ needs. To open the way for research on small-scale modular TUIs and the novel interaction they could offer, we need to understand the user experience of manipulating such interfaces.

We particularly consider modules connected through magnets in order to easily prototype small modules. Passive magnets (e.g., [165, 97]) are the simplest among the docking mechanisms that seem to offer the most potential for miniaturization, with electrostatic actuators (e.g., [134, 182]), electromagnets (e.g., [83, 102]), and a combination of passive magnets with an additional actuation mechanism (e.g., pins [279], flywheel [246]). On the contrary, existing prototypes relying on mechanical docking mechanisms (e.g., hinges [196], clamps [206], hooks [304]), are difficult to miniaturize [19], which impairs their suitability for *1 hand - n modules interaction*.

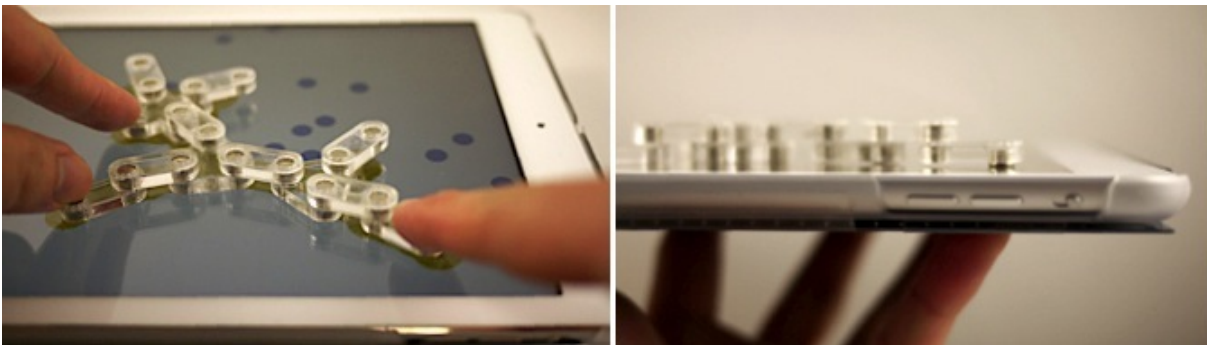


Figure 7.4: GaussBricks uses passive magnets to enable small-scale building blocks, accomodating tangible interaction on mobile devices [165].

Previous work on modular TUIs proposed different interaction techniques and application scenarii. For example, Dynablock allows the user to programmatically “print” a shape and further refine it via direct manipulation [279] (see Figure 7.2b). PickCells enables physically reconfigurable touchscreens made of square screen cells that users can split to share with other users, change the shape of the device or create additional controls (e.g., a remote or a switch) [86]. GaussBricks proposed building blocks for tangible interaction on mobile touchscreens [165] (Figure 7.4). They leverage the elastic-like forcefeedback of magnetic forces to implement novel in-

teractions, e.g. bending, pinching or stretching the modular TUI. However, to our knowledge, previous work used ad-hoc bonding strength between modules and did not report their design rationale. Consequently, it is difficult for later designers to learn how to design tangible modules, and especially to leverage previous experience to decide on which bonding strength would work best for which application.

In order to enable the prospective application scenarii and interaction techniques proposed in prior work, we need to study how the detachability/solidity trade-off impacts the different types of manipulations they proposed. We further describe these manipulations in section 7.3.3.

### 7.2.2 Magnetic actuation and bonding strength

Although we find a wide range of modular TUI prototypes and interaction modalities, to our knowledge previous work did not study the impact on user interaction of the bonding strength of the modules nor their shape. The lack of robustness of prototypes is a well-known issue in shape-changing interface research [19]. It reduces the opportunities to conduct controlled user studies and further understand the user experience of such interfaces [19].

In the HCI literature, we found magnetic implementations for other kinds of applications. For example, they can be implemented to provide haptic feedback (e.g., magnetic haptic patterns [311], force-feedback [312, 323]) or sense users' input in tangible controllers (e.g., [117, 312]). However, prior work do not provide insights on the impact of bonding strength in the context of modular TUIs.



Figure 7.5: Three examples of modular implementations outside of HCI that leverage magnets.

As we discussed earlier in this thesis, robotics researchers explored modular robots since 1990 [81]. Among the different robot configuration they explored, a few leveraged the benefits of magnets. For instance, Robot Pebbles used electromagnets for self-disassembly [83] (Figure 7.5a), M-Blocks used passive magnets as their bonding mechanisms, with an internal flywheel to drive their movement [245] (Figure 7.5b), and the magnetic quadrupoles presented in [97] (Figure 7.5c) explored passive magnets assembled in a magnetic field to form arbitrary shapes.

And some of their contributions actually studied the technical strength trade-off: a docking mechanism between modules should aim at (1) maximizing the strength to achieve sufficient structure robustness while (2) minimizing the strength required to detach [60, 59]. However, they did not take a user-centered approach to evaluate this trade-off, nor their overall implementation design: the robotics community focuses on construction and locomotion rather than user interaction [247].

When searching for industry standards, we did not find studies nor guidelines on the detachability/solidity trade-off. We did find safety information related to the strength of magnets, especially on ingestion hazard. The U.S. Consumer Product Safety Commission advises that small magnets used in manipulated objects should have a flux index of 50 kG<sup>2</sup>.mm<sup>2</sup> or less [12, 8]<sup>1</sup>. The Toy Association states that strong magnets present a serious risk to children, and that safety standards prohibit the use of the powerful rare earth magnets in toys [9]. However, we did not find studies nor guidelines on the detachability/solidity trade-off. We believe that companies must have conducted such studies in the past, e.g. to design magnetic building block toys for children, but their results were not published. To fill this gap, we open this area of research by sharing all our study material together with our results.

---

1. kG<sup>2</sup> mm<sup>2</sup> = pole surface area mm<sup>2</sup> x square of the maximum flux density in kiloGauss kG<sup>2</sup>

## 7.3 Method

We conducted a controlled user study to investigate three levels of bonding strength between modules and two module shapes when manipulating a modular tangible prototype. We study their impact on eight manipulations from the literature with two different configurations of modules. Our goal is to understand how these design factors impact the trade-off between detachability of the modules and solidity of the prototype, by studying their impact on subjective user ratings when performing each manipulation with each condition.

### 7.3.1 Apparatus and participants

To study three levels of bonding strength (Figure 7.7a), we used three types of magnets varying in thickness: 0.5, 1 and 2mm thick magnets [11]. The resulting bonding strength of the modules depends on the thickness of the magnets they embed. The thicker the magnets, the stronger their bonding strength. The holding force on iron is 0.49N for the 0.5mm magnets, 0.98N for the 1mm magnets and 2.45N for the 2mm magnets.

To study module shape, we first reviewed the module shape found in the literature. We find that current modules shapes range from cubes with sharp edges (e.g., [84, 247, 279]) via cubes with rounded edges [83, 246, 86], to quasi-spheres (e.g., [206, 267, 38, 200]). We left for future work shapes such as cylinders and triangles as they support 2D reconfiguration rather than 3D and/or allow for limited to no bonding between modules (e.g., [210, 159, 210, 162]).

To combine bonding strength and shape into a prototype, we first modeled our module as a cube in 3D. As research tends to miniaturize modules, we wanted to have the smallest module possible, while still being able to assess three different levels of bonding strength. We first tried having the smallest and roundest modules possible, but they were far too weak: only lightly shaking the table they were on would lead them to fall apart (see Figure 7.6).

The thinnest magnets available to the general public that we found could still allow our modules to hold their shape are 0.5mm. Thus, they serve as our weakest strength. The strongest magnets we used are 2mm thick. We found that 0.2mm slim envelope between the magnets is the slimmest and strongest design, resulting in an edge for the module  $> 2 + 2 + 0.2 = 4.2\text{mm}$ . Further increasing the thickness of the magnets results in the repelling forces at the center of the modules being too strong. Thus, 2mm thick magnets serve as our strongest strength. Lastly, we chose an intermediate thickness of 1mm.

We rounded the corners of the modules as much as possible without impairing the surface that would embed the magnets (Figure 7.7b): with magnets diameter being  $\varnothing 2\text{mm}$ , the rounded corners of a  $6 \times 6 \times 6\text{mm}$  cube still allow for at least a  $\varnothing 2\text{mm}$  flat surface when rounded (Figure 7.7). This allowed for the bonding strength due to magnets to be identical between cubic



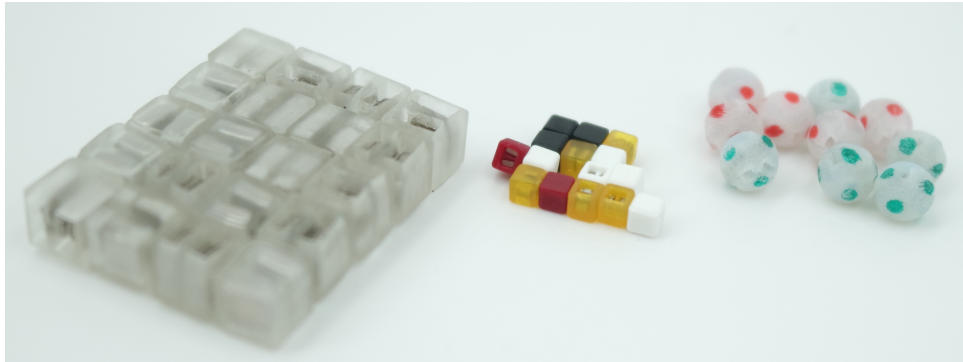


Figure 7.6: Starting from existing modules from previous work (left and middle, [97]), we first tried to have fully rounded  $\varnothing 2.4\text{mm}$  modules (right). However, they were too weak to keep their shape, let alone withstand user manipulation.

and rounded conditions.

For each condition, we 3D printed 80 modules using a Connex Stratasys Inkjet printer [10] (480 modules in total). We glued the magnets in each faces of the modules. Magnets induce the issue of geometric frustration: each features a south and a north pole, with only south-north able to bond together and south-south/north-north repelling each others. To compose with this issue, each module has either all its faces south-facing or north-facing. We spray painted the south-facing modules black and the north-facing ones white for identification. Thanks to this, we can easily arrange the modules in a black and white checkerboard pattern as shown in Figure 7.8.

We recruited 12 participants from the local campus. Half self-identified as women and the other half as men ( $M = 28.33$  y.o.,  $SD = 10.2$ ).

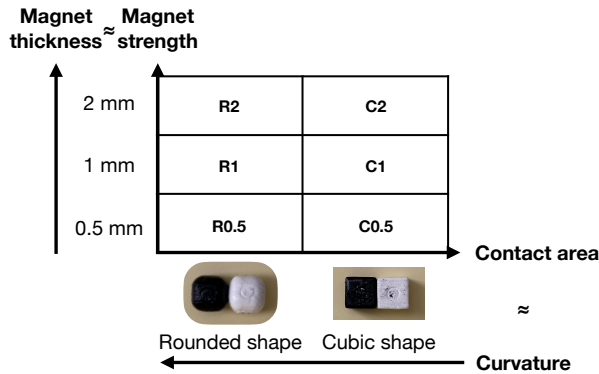
### 7.3.2 Experimental design

Our experiment follows a within-subject design with two independent variables (Figure 7.7):

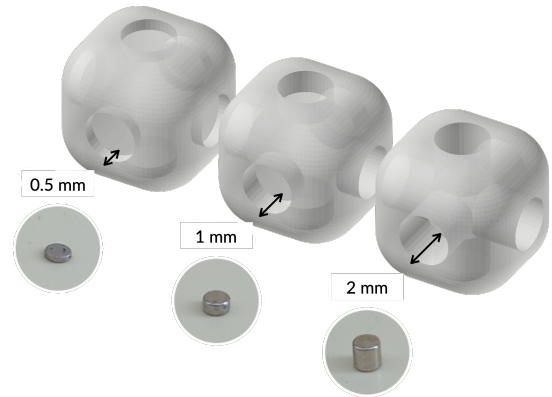
*Shape* refers to the curvature of the edges of the cubes: either *cubic* (sharp edges) or *rounded*.

*Bonding strength* depends on the thickness of the magnets: 0.5 mm (0.49N holding force on iron), 1 mm (0.98N holding force on iron), and 2mm (2.45N holding force on iron).

We refer to the combination of each condition by (1) a letter relating to its shape (R for rounded, C for cubic) and (2) a number related to its strength (0.5, 1 or 2), e.g. rounded modules with 2mm magnets are condition “R2”. The order of presentation of the conditions was counterbalanced through a latin square, with both shape and bonding strength separately taken into account.



(a) Independent variables from the experiments. We refer to them by a letter (Rounded: R, Cubic: C)  $\times$  their magnet thickness. E.g., rounded modules  $\times$  2mm magnets are condition R2.



(b) Side by side comparison of the three magnet thicknesses used in this chapter.

Figure 7.7: Independent variables of the prototypes studied in the chapter: two *module shapes* (cubes and rounded cubes)  $\times$  three *magnet thicknesses* (0.5mm, 1mm and 2mm) [11]. The thicker the magnets, the stronger their bonding strength. The holding force on iron is 0.49N for the 0.5mm magnets, 0.98N for the 1mm magnets and 2.45N for the 2mm magnets.

We collected four subjective dependant variables through a questionnaire: perceived difficulty “Overall, how difficult or easy did you find this task?”, perceived satisfaction (Overall, how dissatisfying or satisfying did you find the task?), perceived impact of the strength (Overall, how did the strength impact the easiness/difficulty and satisfaction/dissatisfaction?), perceived impact of the shape (Overall, how did the edge type impact the easiness/difficulty and satisfaction/dissatisfaction?). We gather additional qualitative subjective feedback with a semi-structured interview at the end of the experiment.

### 7.3.3 Experimental tasks

We reviewed the TUI literature to select the eight tasks our participants performed, presented as in Figure 7.8 from (a) to (h): split (a–d), lift (e), slide (f), fold (g) and bend (h). Based on our literature review, we considered the split task to be different depending on the number of manipulated modules: users may split one module (1), two modules (2), a line of modules (3) or half of the modules (4). We studied each of these four tasks separately.

First, TUIs report on widespread manipulations such as *translation* on a surface [296, 165, 159, 280], *rotation* on a surface [296, 294, 280], *lifting* from a surface [203, 280, 158]. However, during a pilot experiment, we found that varying the shape and bonding strength of the modules had little to no effect on translating and rotating tasks. For this reason, we only considered *lifting*

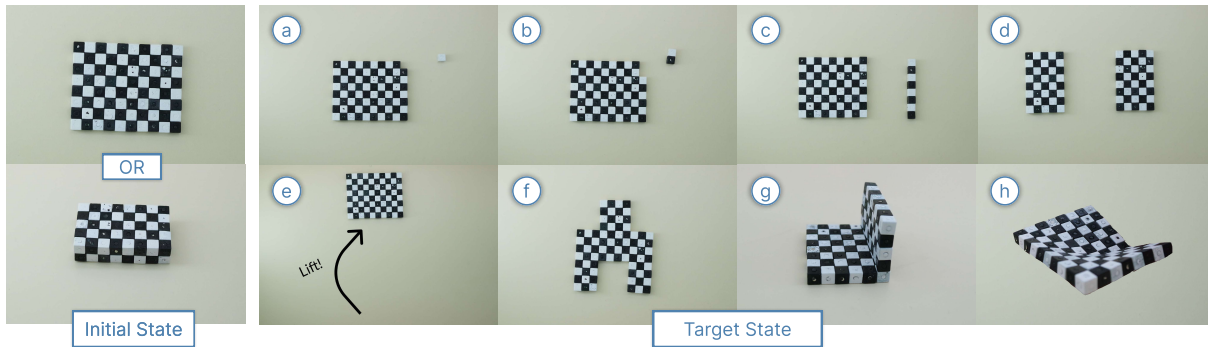


Figure 7.8: Participants performed manipulations on either a flat configuration, i.e. one layer of 80 modules (top left), or a thick configuration, i.e. two layers of 40 modules each (bottom left). From the prototype in its initial state shown in the left, participants performed eight manipulations (right): (a) split 1 module, (b) split 2 modules, (c) split a line of modules, (d) split the prototype in half, (e) lift, (f) slide, (g) fold and (h) bend.

in our experiment.

Second, non-modular shape-changing UIs enable specific manipulative tasks to support the change of shape. For example, they allow *bending* [88, 42, 310, 89], *folding* [238, 324], *stretching* [310, 205], *twisting* [42]. We found that, when applied to magnetic modular UIs *stretching* and *twisting* may lead to the same resulting shape: these lead to *splitting* the interface in the end. For this reason, we considered *bending*, *folding* and *splitting* for our experiment.

Third, modular UIs made of small elements enable specific manipulative tasks to support reconfiguration. From the references studied in our related work section, we found three main types of manipulations. Users can *split* the interface by separating one or multiple modules from the UI (e.g., [147, 48, 165, 322, 86]). Users can *bend* the interface, e.g., bend the whole surface (e.g., [196, 195, 165]), a corner [248, 165] or squeeze a ring [165]. Users can make parts of the interface *slide* against each other, e.g. to create handles to go from a rectangle shape to a game controller [247, 86], making a multi-parameter slider or dial [48]. For this reason, we considered *sliding* in our experiment in addition to *bending* and *splitting*.

Moreover, as previous work highlighted the impact of the thickness during tangible object manipulation [158], we want to test the manipulation on both flat and thick surfaces, i.e., a configuration with one or two layers of modules as shown in Figure 7.8 (left). Participants performed all eight tasks with the flat configuration and six tasks with the thick configuration: we found fold (Figure 7.8-g) and bend (Figure 7.8-h) too difficult in our pilot experiment. For instance, folding was not possible with thick prototypes –they directly split the prototype in two halves.

### 7.3.4 Procedure

After signing an informed consent form, the participant sits in front of a table with a delimited manipulation area. The experimental software presents the participants with a picture of a starting State A (e.g., a rectangular block) as shown in Figure 7.8 (left), and a target State B (e.g., the rectangular block split in two halves) as shown in Figure 7.8 (right). Reaching state B only requires the use of one elementary manipulation. There is no indication as to how the UI was grabbed to reach State B, to avoid biasing the manipulation. The experimenter places the first prototype on the manipulation area, mimicking State A. The participant manipulates the prototype to reach State B. The task is repeated three times to allow exploring different strategies. After completion of the task, the participant fills a short questionnaire. They are then presented with the next task to perform (i.e., new State A and B pictures) while the experimenter presents the next prototype. This procedure is repeated for each manipulation and each condition.

### 7.3.5 Data collection and analysis

We collected a total of 1008 data points for each question: 12 participants  $\times$  3 bonding strengths  $\times$  2 shapes  $\times$  14 tasks (6 with the thick configuration and 8 with the flat one).

To analyze them, we rely on estimation techniques with 95% confidence intervals as recommended by the APA [72] and which is becoming more and more a standard practice in HCI research (e.g., [31, 154, 260, 193, 138]). The effect size is computed between the scores of each questionnaire item for each condition, and refers to the difference between their geometric means. When interpreting the graphs, we conduct (1) an analysis of the means and confidence intervals across conditions and (2) pairwise analysis to identify the effect size between them. If the error bar (bootstrapped 95% CIs) do not overlap with 0, we consider that the difference between the two variables yields significance, the degree of which depending on the effect size. While we use estimation techniques, a p-value reading of our results is possible by comparing our CIs with common p-value spacing as shown in prior work [153].

## 7.4 Results

We now present our main results. We report the detailed mean score for each item in the questionnaire (i.e., difficulty, satisfaction, perceived impact of strength and perceived impact of shape) in Figure 7.9.

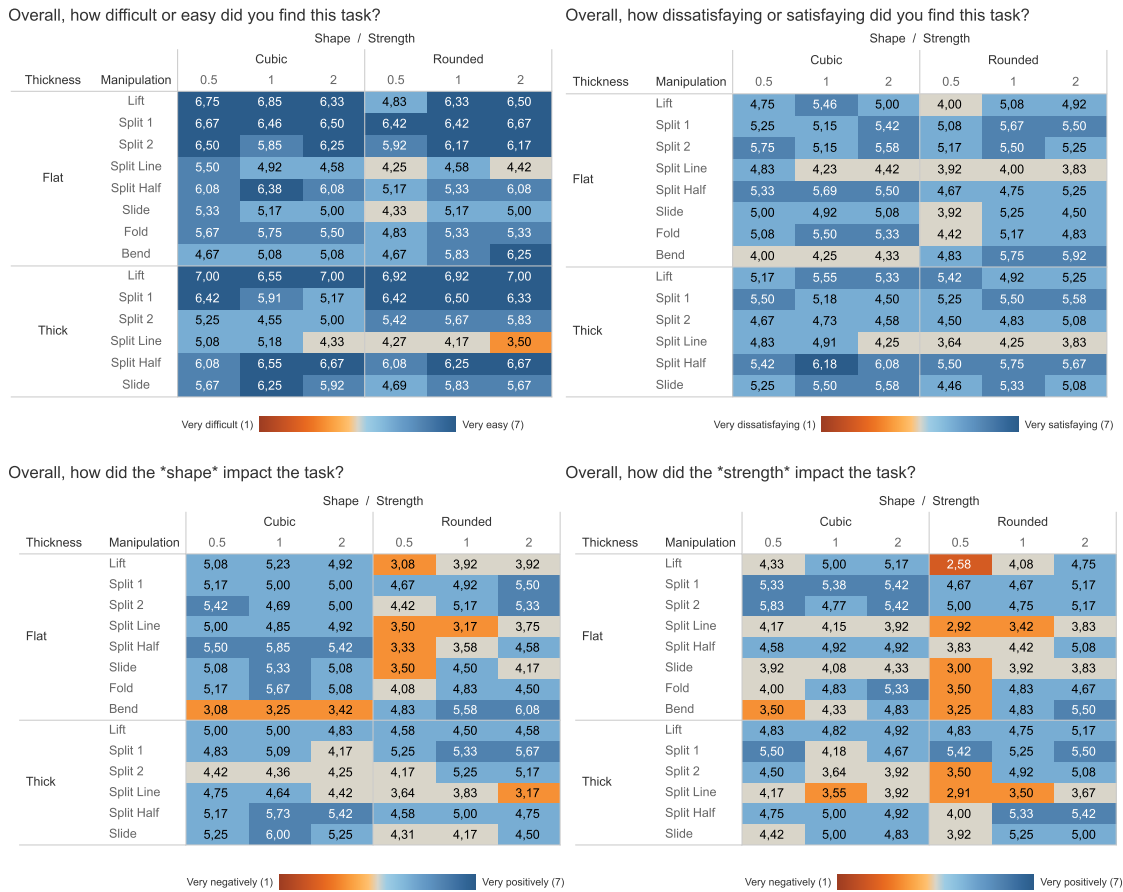


Figure 7.9: Mean Likert scores of the four questionnaires: overall difficulty (top left), overall satisfaction (top right), perceived impact of the strength (bottom left) and perceived impact of the shape (bottom right). The scales range from 1 (red - most negative response) to 7 (blue - most positive response) with 4 as the center (grey - neutral).

### 7.4.1 Overall results

We first report the overall results of our user study. We look into the scores of each item of the questionnaire across conditions.

In this section we do not discriminate between manipulation (i.e., the eight manipulations performed) nor configuration of the UI (i.e., flat with one layer of modules or thick with two layers of modules). We will look into this further in section 7.4.2.

#### Difficulty

Participants rated the tasks as slightly more difficult with the rounded modules (Easiness = 5.62/7 (1 = very difficult, 7 = very easy), CI [5.49,5.73]) compared to the cubic ones (5.8, CI [5.68,5.91]). Participants rated the tasks as slightly more difficult with the 0.5mm strength (5.6, CI [5.44,5.74]) compared to the 2mm strength (5.74, CI [5.59,5.88]). The tasks were overall more difficult with the R0.5 condition compared to all other conditions (Figures 7.10a and 7.10b).

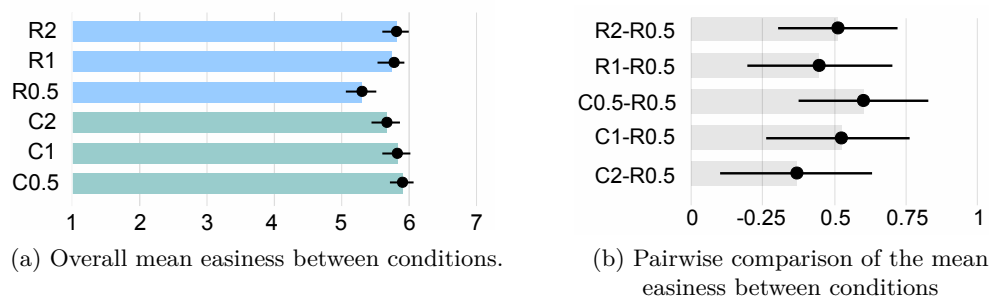


Figure 7.10: Easiness across conditions for the overall study from (1) very difficult to (7) very easy. Error bars show bootstrapped 95% CIs.

#### Satisfaction

We find evidence that participants rated the rounded modules (Satisfaction = 4.93/7 (1 = very dissatisfying, 7 = very satisfying), CI [4.79, 5.05]) to be overall slightly less satisfying compared to the cubic ones (5.1, CI [4.97, 5.21]). As shown in Figures 7.11a and 7.11b, the results show strong evidence that the participants rated the tasks to be overall less satisfying with the R0.5 condition compared to all other conditions. Overall, 0.5mm strength (4.84, CI [4.68, 5.0]) was rated as slightly less satisfying compared to 1mm (5.15, CI [4.99, 5.29]) and 2mm (5.05, CI [4.89, 5.21]).

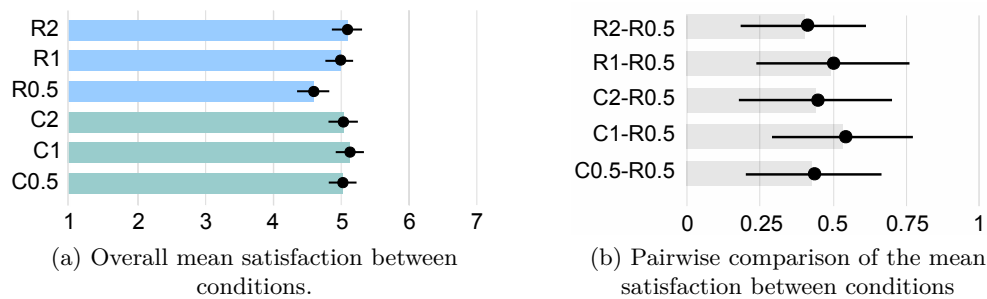


Figure 7.11: Satisfaction across conditions for the overall study, from (1) very difficult to (7) very easy. Error bars show bootstrapped 95% CIs.

### Impact of the shape

For this item, we asked participants to rate how they perceived the impact of the shape on the completion of the task, from very negatively (1) to very positively (7).

Overall, a cubic shape was perceived more positively (4.92, CI [4.79, 5.04]) compared to a rounded one (4.46, CI [4.31, 4.59]). As shown in Figures 7.12a and 7.12b, there is clear evidence that the R0.5 condition scored the lowest, and that C1 scored higher than C2, R2, R1 and R0.5.

These results are consistent with the results from each Shape  $\times$  Strength conditions as shown in Figure 7.12. Not only is there clear evidence that the R0.5 condition (4.14, CI [3.9, 4.35]) scored more negatively than any condition, but there is also smaller evidence that R1 (4.6, CI [4.3, 4.78]) scored more negatively than both C1 (5.05, CI [4.82, 5.26]) and C0.5 (4.92, CI [4.72, 5.1]), and that R2 (4.69, CI [4.41, 4.92]) scored more negatively than C1. This is supported by pairwise analysis.

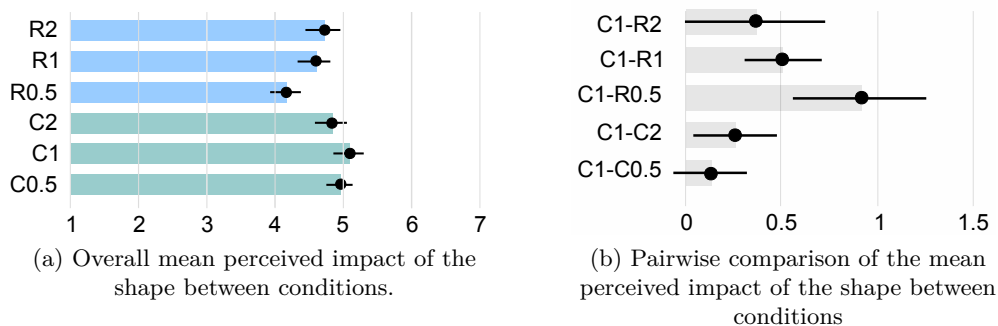


Figure 7.12: Perceived impact of how the shape impacts interaction across conditions for the overall study, from (1) very negatively to (7) very positively. Error bars show bootstrapped 95% CIs.

### Impact of the strength

For this item, we asked participants to rate how they perceived the impact of the bonding strength on the completion of the task, from very negatively (1) to very positively (7).

Overall, there is evidence that participants rated the 0.5mm strength (3.82, CI [3.59, 4.05]) as having a more negative impact compared to the 1mm (4.57, CI [4.36, 4.76]) and 2mm (4.85, CI [4.65, 5.04]) strengths. 2mm was rated as having a slightly better impact compared than 1mm. This is supported by pairwise analysis.

Moreover, when looking at each Shape  $\times$  Strength conditions on Figure 7.13, we see a stronger impact of the strength on the rounded modules. There is evidence that R0.5 (3.8, CI [3.59, 4.04]) was rated as having a more negative impact compared to R1 (4.57, CI [4.36, 4.76]) and R2 (4.84, CI [4.64, 5.04]). There is also smaller evidence that R2 scored higher than R1. We observe less variation for cubic modules, with only the C2 (4.75, CI [4.54, 4.95]) condition rated marginally better than the C1 (4.56, CI [4.35, 4.77]) and C0.5 (4.56, CI [4.32, 4.77]) conditions.

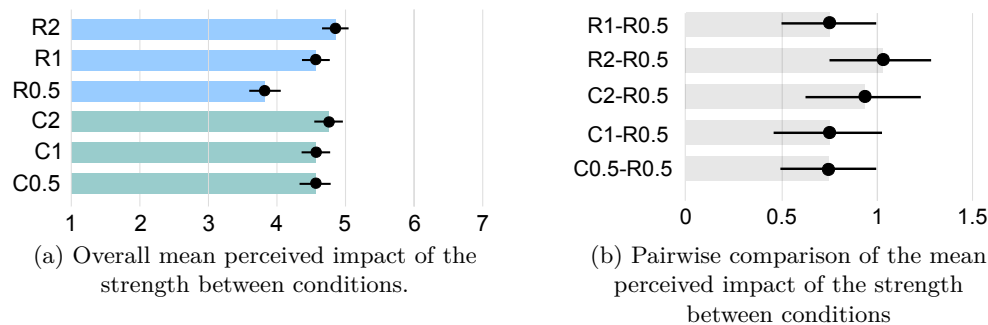


Figure 7.13: Perceived impact of how the strength impacts interaction across conditions for the overall study, from (1) very negatively to (7) very positively. Error bars show bootstrapped 95% CIs.

#### 7.4.2 Results across manipulations and configurations

In the previous section, we discussed the overall results of the four items of the questionnaire. However, these results were aggregated across the 8 manipulations (Figure 7.8 (right)) and configuration of the prototype (Figure 7.8 (left)). This does not reflect the fact that participants rated the conditions differently depending on which manipulation they had to perform with them, and with which UI configuration (Figure 7.9). In this section, we refine our analysis by reporting users ratings for each manipulation and module configuration of the prototype.

In particular, we present the most important effect for each manipulation. To generate the other results and to reproduce these results, we include our data and analysis script in the



supplementary material.

## Lift

Overall, lifting was rated as the easiest task to perform with the thick configuration (6.9, CI [6.61,6.97]), but only second best with the flat configuration (6.27, CI [5.93, 6.51]). The reason is that, with a flat configuration, participants found the task to be harder with R0.5 (Figure 7.14). Indeed, we find strong evidence that (1) the cubic modules (5.01, CI [4.71, 5.31]) were perceived as having a more positive impact on the task compared to the rounded ones (4.1, CI [3.78, 4.40]) and that (2) for rounded modules, the stronger the better: the higher strength of R2 (4.96, CI [4.5, 5.42]) was perceived as having a more positive impact on the task compared to both R0.5 (3.71, CI [3.0, 4.38]) and R1 (4.42, CI [3.96, 4.92]). This is consistent with feedback from the interviews, e.g. P7 said about 0.5mm conditions that *“they are so weak that they deform and break just by lifting them.”*

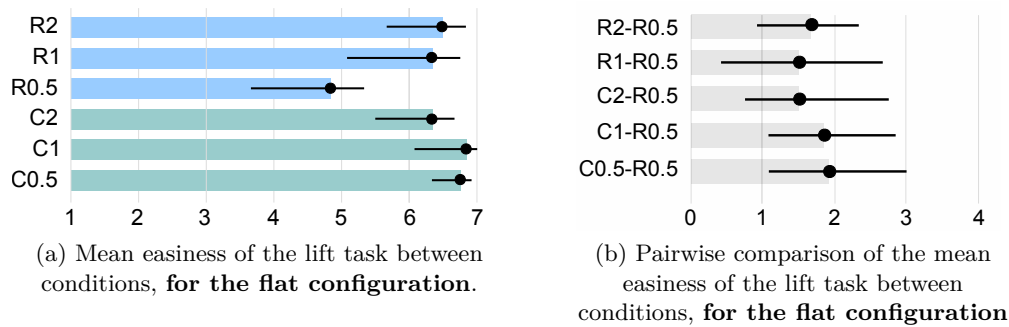


Figure 7.14: Results show evidence that the lifting task was significantly harder with R0.5 in a flat configuration . Error bars show bootstrapped 95% CIs.

## Split

Participants were asked to perform four kinds of splitting tasks, i.e. to either split 1 module, 2 modules, a line of modules or half of the prototype from the rest of the prototype.

**Split 1 module** Overall, splitting one module from the prototype was rated as the easiest task with the flat configuration (6.52, CI [6.33, 6.66]). However, for the thick configuration (6.13, CI [5.83, 6.32]) (Figure 7.15a and 7.15b), we find that (1) the task was easier with rounded modules and (2) for cubic modules, the task was rated as slightly easier as the strength decreases, with C0.5 rated the easiest. On the other hand, we find evidence that C2 scored lower than any condition except C1. This is consistent with user feedback, e.g. P8 said that with C2 *“it’s hard, I don’t have fingernails, I can’t grab it!”*

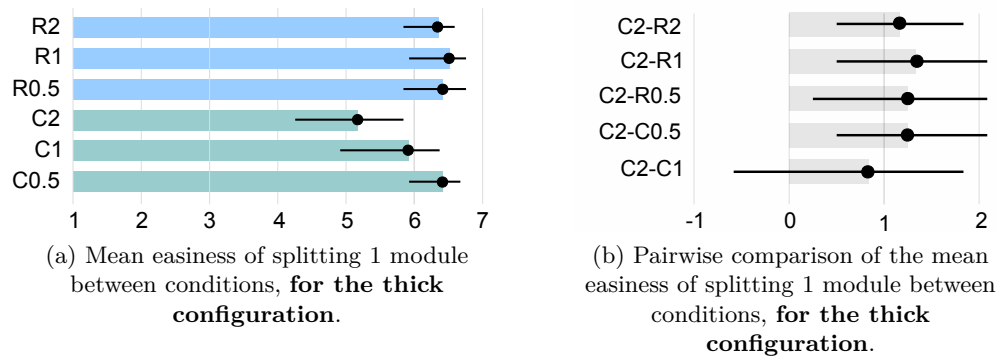


Figure 7.15: Results show evidence that splitting 1 module from the UI is harder with the C2 condition. Error Bars show bootstrapped 95% CIs.

**Split 2 modules** Overall, splitting two modules from the prototype was perceived as easier with the flat configuration (6.13, CI [5.92, 6.3]) compared to the thick configuration (5.3, CI [4.96, 5.56]). Especially, for the thick configuration, we find differences in how the strength was perceived across rounded and cubic modules (Figure 7.16a and 7.16b). We find evidence that 0.5 strength had a negative impact for rounded modules, with R0.5 (3.5, CI [2.83, 4.17]) scoring lower than R1 (4.92, CI [4.25, 5.5]) and R2 (5.08, CI [4.25, 5.58]), whereas 0.5 strength had a positive impact on cubic modules, with C0.5 (4.5, CI [3.58, 5.17]) scoring (marginally) higher than C1 (3.64, CI [2.64, 4.27]) and C2 (3.92, CI [3.42, 4.42]). As a result, although the task was perceived easier with rounded modules (5.64, CI [5.28, 5.92]) compared to cubic ones (4.94, CI [4.37, 5.37]), C0.5 was perceived easier compared to R0.5.

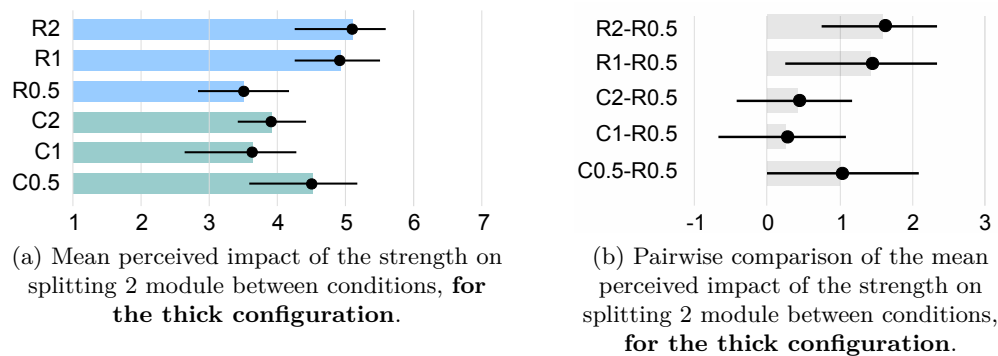


Figure 7.16: Results show that the 2mm strength was perceived as having a more negative impact on the cubic modules (i.e., with C2). Error Bars show bootstrapped 95% CIs.

**Split line of modules** Overall, splitting a line of modules from the prototype was rated as the most difficult task, both with the flat (4.71, CI [4.36, 5.01]) and thick configurations (4.41, CI

[4.03, 4.76]). Still, there is evidence that the task was easier with cubic modules (4.93, CI [4.57, 5.24]) compared to the rounded ones (4.2, CI [3.85, 4.52]). Indeed, results show strong evidence that participants perceived a cubic shape as positively impacting the task (4.76, CI [4.42, 5.06]) compared to a rounded shape (3.51, CI [3.1, 3.9]). Moreover, results from Figures 7.17a and 7.17b show that, the lower the strength of rounded modules, the more negative the impact on the task, with R0.5 perceived more negatively than all other conditions. P5 commented “*ok that’s less easy*” when performing the task with R1, and added “*wow this seems complicated*” when using R2. P5 felt that “*it’s frustrating*” when using R2.

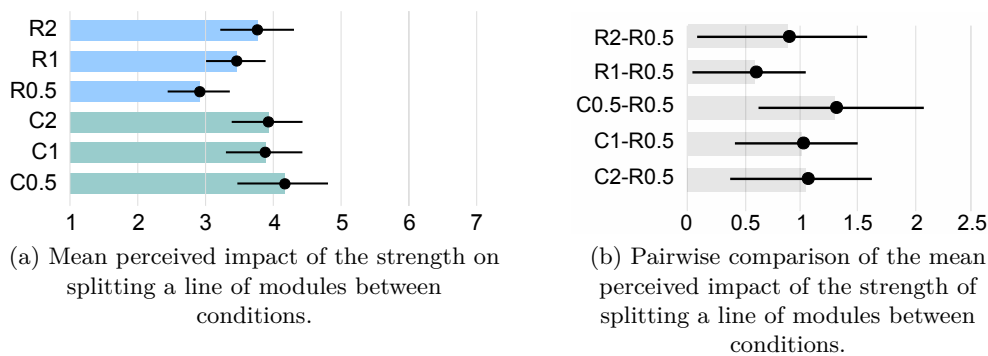


Figure 7.17: Results show that the 0.5mm strength had significantly impaired splitting a line of modules with rounded modules (i.e., with R0.5). Error Bars show bootstrapped 95% CIs.

**Split half of the modules** Results show that splitting the interface in two halves was perceived as easier with the thick configuration (6.38, CI [6.11, 6.55]) compared to the flat configuration (5.86, CI [5.52, 6.11]). In both cases, we observe that rounded modules and lower strength impair the interaction. Especially, for the flat configuration, we find strong evidence that (1) participants rated the shape of the cubic conditions (5.59, CI [5.22, 5.89]) as having a better impact on the task compared to rounded ones (3.83, CI [3.39, 4.25]) and that (2) the task was perceived as easier with cubic modules (6.19, CI [5.68, 6.46]) compared to rounded modules (5.52, CI [5.02, 5.89]). Moreover, we find evidence that decreasing the strength of rounded modules further worsen the perceived impact of the shape on the task for a flat configuration, as shown on Figures 7.18a and 7.18b. In addition, the higher the strength, the easier the task: R2 (6.08, CI [5.5, 6.5]) was easier than both R0.5 (5.17, CI [4.33, 5.75]) and R1 (5.33, CI [4.25, 6.0]). This is consistent with user feedback, e.g. P11 commented that “*the cubic ones are more suitable for detaching large blocks, it’s easier to grab a big chunk*”, and further added that “*as for strength, when it’s too weak it becomes a real pain when it comes to grabbing big chunks because you’re breaking things you didn’t want to break.*”

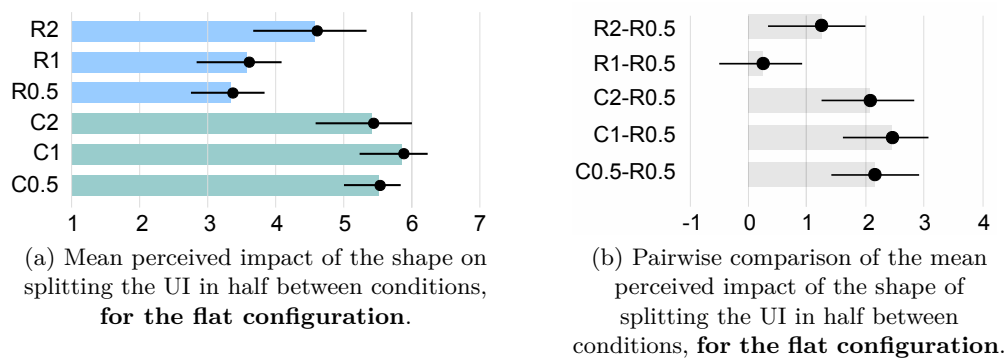


Figure 7.18: Results show that the rounded shape was perceived as having a negative impact when splitting the prototype in half, and that the lowering the strength worsen the impact of having a rounded shape. Error Bars show bootstrapped 95% CIs.

### Slide

Overall, the sliding task was easier with the thick configuration (5.66, CI [5.37, 5.88]) compared to the flat configuration (5.0, CI [4.68, 5.25]). P5 commented that *“ah yes it’s easier with a layer underneath actually!”* As shown on Figure 7.19, we find strong evidence that the shape of cubic modules was perceived as having a more positive impact on sliding compared to rounded ones, with R0.5 scoring lowest and C1 scoring highest. Especially for the thick configuration, the task was rated as easier with (1) cubic modules (5.94, CI [5.53, 6.22]) compared to rounded ones (5.38, CI [4.97, 5.68]), and (2) with 1mm (6.04, CI [5.63, 6.33]) and 2mm strengths (5.79, CI [5.33, 6.12]) compared to 0.5mm (5.16, CI [4.6, 5.52]). Rounded modules with low strength were perceived as the most difficult (R0.5: 4.69, CI [3.85, 5.15]), while cubic modules with mid strength were the easiest (C1: 6.25, 5.5, 6.58). C1 was rated significantly higher than R0.5, C0.5 (5.67, CI [4.75, 6.08]) and R1 (5.83, CI [5.42, 6.17]). With both flat and thick configurations, we also find that R0.5 (4.2, CI [3.52, 4.72]) was rated as less satisfying than any condition except R2 (4.79, CI [4.13, 5.29]).

### Fold

Participants only performed this task on a flat configuration, as folding was not possible with thick prototypes –they directly split the UI in two halves. Figures 7.20a and 7.20b show evidence that the shape of cubic modules had a more positive impact on the task compared to rounded ones. Overall, results show that participants mostly liked cubic modules with 1mm strength (C1), but disliked rounded modules with 0.5mm strength (R0.5):

(1) The task was more difficult with R0.5 (4.83, CI [3.58, 5.58]) compared to C1 (5.75, CI [4.83, 6.17]).

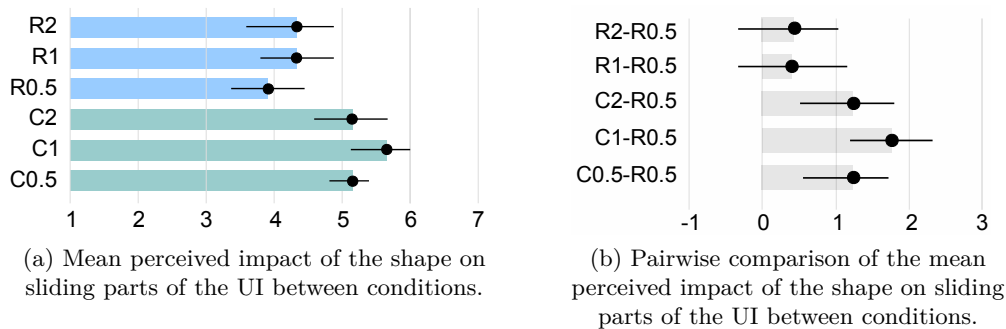


Figure 7.19: Results show that the rounded shape was perceived as having a negative impact on the task, with the worst condition being R0.5. Error Bars show bootstrapped 95% CIs.

- (2) The task was less satisfying with R0.5 (4.41, CI [3.33, 5.0]) compared to both C1 (5.5, CI [4.9, 5.83]) and R1 (5.17, CI [4.5, 5.59]).
- (3) The impact of 0.5mm (3.75, CI [3.25, 4.21]) was perceived more negatively than both 1mm (4.83, CI [5.17, 4.33]) and 2mm (5.0, CI [4.37, 5.46]), with R0.5 (3.5, CI [2.83, 4.17]) scoring lower than both C1 (4.83, CI [4.25, 5.17]) and R1 (4.83, CI [4.0, 5.25]). P5 commented that “in the end C1 is not bad for the things I couldn’t do before”.

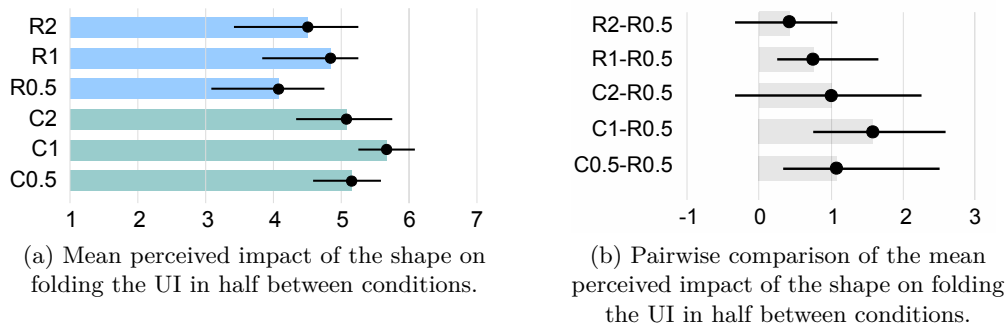


Figure 7.20: Results show that the rounded shape was perceived as having a slightly negative impact on the task, with the worst condition being R0.5 and C1 as the best conditions. The impact of the shape was perceived as overall more positive with the 1mm strength. Error Bars show bootstrapped 95% CIs.

## Bend

Participants only performed this task on a flat configuration. Overall, participants preferred to bend the UI using rounded modules with 1-2mm strength, while they disliked cubic modules, especially with 0.5mm strength. Figures 7.21a and 7.21b show strong evidence that bending was more satisfying with the rounded modules compared to cubic ones, especially with 1-2mm

strength: R1 and R2 were both more satisfying than all other conditions. Results also show that R2 (6.25, CI [5.5, 6.58]) was perceived as easier than all conditions except for R1 (5.83, 4.67, 6.42), which was rated as easier than both R0.5 (4.67, CI [3.42, 5.5]) and C0.5 (4.67, 3.75, 5.33). P12 commented that “*I see an advantage to rounded modules, especially for the bending task because it’s impossible with cubes*”, and P7 added that “*I didn’t know how to deform the squares without breaking them*”.

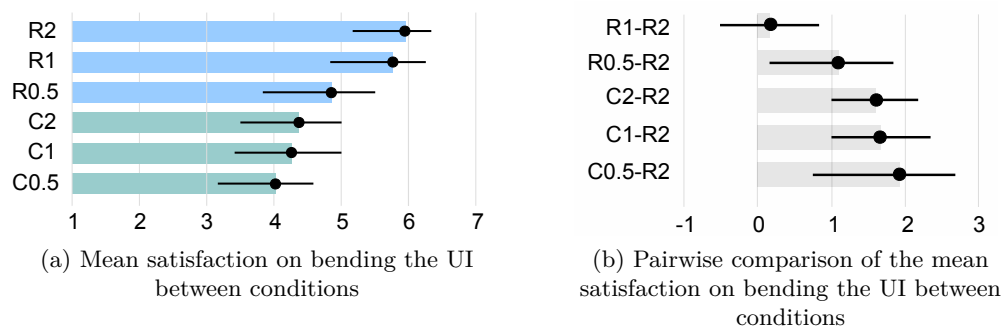


Figure 7.21: Results show that the rounded shape with 1-2mm strength was perceived as more satisfying to bend the UI with, with R1 and R2 rated the highest. Error Bars show bootstrapped 95% CIs.

## 7.5 Discussion

In this section, we discuss how the results of our user study can be readily used by HCI researchers working on modular TUIs, and how they can improve or extend them in the future.

We first explore the impact of the *shape* of the modules, then the impact of their *bonding strength* and then we discuss their implications for the design of interaction techniques and future technological development of modular TUIs.

### 7.5.1 Impact of module shape

Cubic modules reportedly have a more positive impact on the manipulation, and make the prototype easier and more satisfying to manipulate, except for bending and detaching one or two modules.

*Detaching modules.* The gaps in between rounded modules are found to be helping their prehensibility when the user needs to dislodge just one or two modules from the UI. For example, for detaching one/two rounded modules, P1 expressed that “*I just have to wedge my fingernails in between and they easily come apart*”, and for the cubic ones “*the corners dig into the fingertips, it’s not comfortable*” but also that “*the cubes are easier detaching lines or splitting in two*”. P11 expressed that “*the cubic ones are more for detaching large blocks, it’s easier to grab a big chunk, but when it comes to bending or recovering small pieces, then I’d rather have the rounded edges*”. On the one hand, rounded modules were especially disliked when the task required users to move a block of modules (i.e., split a line, split in half and slide). These manipulations required the participants to apply force on the top and bottom of the interface in a pinch grasp. A line or block of cubes, which do not have gaps between them, stay stiff and hold their shape, whereas rounded modules are more prone to falling off. On the other hand, the lack of gaps between cubic modules not only limits their prehensibility, but also increases the strength of the overall UI by granting it higher structural density. This benefits users when they need to detach blocks of modules.

*Bending the UI.* The gaps between rounded modules and their rounded edges give the interface a higher flexibility during bending tasks, whereas the straight edges of cubic modules make them split apart. Future design of modular TUIs should take the shape of the modules into account, as the elastic-like force feedback aspect of magnetic UIs was a major point in the design of GaussBricks [165] (Figure 7.4). Moreover, the HCI community takes a growing interest in tangible UIs allowing pressure-based interaction (e.g., [14, 80]). As current soft TUIs supporting pressure input do not allow yet for modularity, it would be interesting to test the limits of the flexibility of magnetic modular TUIs to propose an interface supporting both pressure, bending and modularity.

### 7.5.2 Impact of bonding strength

Overall, a mid to high bonding strength is perceived as wielding a more positive impact on user manipulation, and makes the prototype easier and more satisfying to manipulate. This is consistent with interviews. For example, P1 expressed that *“When it’s not strong enough, that’s a disadvantage. Everything falls apart.”*, while P8 expressed that *“I liked it better when the strength was stronger, [...] otherwise [the modules] go all over the place.”* P12 added that, for the splitting or sliding tasks, *“when they are too weak [...] you have a 50% chance of having more modules coming off than what you intended”*. We find great variation in the ratings according to the manipulation users had to perform, but also depending on the shape of the modules and their configuration. Designers should carefully take these parameters into account in order to make sound design decisions for future modular TUIs.

Overall results show that R0.5 scored the lowest on all 4 items (difficulty, satisfaction, shape impact and strength impact). This is consistent with participants feedback, e.g. P6 *“the weakest strength with the rounded ones was when I complained most, it was coming off by itself”*. Moreover, when looking at the results for each manipulation, we find that R0.5 had a negative impact on all tasks except split 1 module, where it was more neutral. Even the lift manipulation, which was reportedly very easy, was more difficult with the R0.5 condition. P7 expressed that *“they are so weak that they deform and break just by lifting them”*. The combined effect of the strength makes worst the previously discussed effect of the rounded shape. Lowering the strength weakens their solidity further and, according to experimental results, 0.5mm is already too low for rounded modules. In order to overcome this, designers can either (1) increase the bonding strength of the modules or (2) use a denser configuration of modules to increase the overall solidity of the UI. For instance, the edges can be sharper than the rounded ones we experimented. However, for tasks such as detaching one or two modules, too much strength might also wield negative results. P9 expressed that their preference went towards *“not too strong I would say. I found the R2 too strong and I couldn’t manipulate them well.”* P7 added that they preferred detaching the rounded modules because *“[they] are more grippy, especially since they have trouble coming off when the magnet is strong”*. Participants did not appear to have this same feedback on needing a strong, yet not-too-strong condition for the bending task.

On the other hand, lowering the strength did not seem to negatively impact cubic modules that much. As expressed by P3, *“all cubic conditions, no matter how strong or weak the force is, I felt like it is quite stable.”* P12 added that *“even with the weak magnets I can manipulate them better”*. Experimental results show that C0.5 still impaired tasks were participants had to apply force on blocks (i.e., split half and slide) compared to stronger cubic conditions. However, their lower strength proved to be an advantage when participants had to detach small parts. Splitting one or two modules was slightly easier with C0.5 compared to C1 and C2, and splitting a line



was overall easier with C0.5 out of every condition. As expressed by P10, “*for the strength it was more satisfying when you felt [the modules] were holding on, but it became more difficult to detach small parts. I don’t know to what extent but there is a trade-off. More satisfying to handle though.*” The lack of gaps between cubic modules seems to not only limit their prehensibility, but also increases the strength of the overall UI by granting it higher structural density. This benefits users when they need to detach blocks of modules. But it further impairs them when they need to detach only one or two modules at a time, where C0.5 scored better than C1 and C2. This is even clearer when the structure density is further increased with the thick configuration.

### 7.5.3 Implications for the design of future interaction techniques with modular TUIs

The modularity of TUIs uniquely enables interaction techniques such as splitting, for instance one module [179, 86], and/or few modules at a time [102, 279]. Splitting allows reconfiguring the shape of the UI [257, 279] or sharing with another user [179, 86]. In our study, we find that cubic modules could be an issue for such interaction techniques. Rounding the corners of the modules, or providing users with some other kind of prehensile modality (e.g., textures or dents), would ease splitting. However, designers should carefully mind the impact on solidity. There could be benefits in trading higher detachability for lower solidity depending on the interaction context, for instance if the modules are manipulated on a surface rather than held in the hand.

Most prior work on modular TUIs explored interaction techniques to be used on a table (e.g., [326, 179, 304, 147]). A few handheld interaction techniques were also proposed with Pickcells [86]. The solidity is critical if modules fall off in a handheld context compared to a tabletop one. Prior work tackled this issue by requiring modules to be constantly attached [247]. This extreme solution hinders the reconfigurability of the interface. To propose future interaction techniques with handheld modular TUIs, designers require both detachability and solidity. From our study, we find that a strength lower than that of our 0.5mm magnets (i.e., 0.49N holding force), especially with rounded modules, would not fit a handheld context. Results show that designers should either use higher bonding strength, or use alternatives to increase the solidity of the UI, such as sharper edges or denser/thicker configuration by stacking modules.

Prior work proposed interaction techniques leveraging the flexibility of the UI. Examples include bending the UI (e.g., [16, 270]), pressure-based input (e.g., [14, 80]) and providing elastic-like force feedback [165]. Our study shows that rounded modules are promising to implement such interaction techniques with modular TUIs. Future work on such techniques with modular TUIs should focus on solving the solidity drawback of rounded modules.

#### 7.5.4 Implications for future technological development of modular TUIs

Our results will impact future technological development in both HCI and robotics. Current HCI implementations focus on cubic modules and need the user to be able to detach one, two or an ensemble of modules in their application scenarii [180, 179, 257, 279, 86]. Our study shows that the detachability/solidity trade-off is not a consistent one. Splitting one or two cubic modules was difficult as they are hardly prehensile. Detaching a line or a block of modules requires both high solidity for the modules to hold their shape, but also high detachability where the UI needs to split. To tackle this inconsistency, a perspective would be to use programmable bonding strength, possibly with electromagnetic or electrostatic actuators (e.g., [182, 245]). However, they are not readily available, more complex and less robust than passive magnets [245].

Another perspective is to explore shape-changing modules that can switch between sharp and rounded edges, as the gaps between rounded edges make the modules more prehensile and lowers the overall strength of the UI. Examples at a higher scale include the shape-changing hard disk that could change from a cube to a quasi-sphere [110]. However, making such shape-changing modules at the mm-scale is challenging. Future work could find opportunities in smart materials and soft robotics to dynamically change the shape of the modules. For instance, current advances in robotics explore deformable robotic modules using shape memory alloys that can switch between quasi-spheres and cubes by flattening their sides [224].

Another perspective for actuated, programmable modules could be their ability to self-reconfigure, e.g., programmatically change their configuration in certain locations to increase or decrease the density of the UI structure, and thus its solidity. The system could help user re-configure the interface (e.g., driven by the modules [247, 246] or by external forces [83, 279]). The interface could also provide users with feed-forward indicating where and when the interface can be split. Current implementations in robotics focus on quasi-spherical modules to enable miniaturization, as a quasi-spherical design reduces the travel distance between contact points between modules [223]. There might be another trade-off between the strength needed for the modules to reconfigure, and the strength needed to hold their shape. Future work should investigate the benefits and drawbacks of this trade-off as soon as the technology allows it.

From our results, we see that a cubic design better supports users manipulation with mm-scale modules: the smaller the module, the smaller the magnets they can embed, and thus the weaker their bonding strength. The cubic modules did not suffer much from the lower strength, whereas our lowest strength already significantly impaired the rounded ones. Moreover, cubic modules have a wider contact area between them, and can thus embed larger – stronger – magnets. E.g., with our  $6 \times 6 \times 6 \text{mm}^3$  prototypes we only used  $\varnothing 2 \text{mm}$  magnets since the contact area between modules is only  $2 \times 2 \text{mm}^2$  for rounded modules. The available area for cubic modules, on the other hand, is  $6 \times 6 \text{mm}^2$ . We expect that further rounding the edges would exacerbate our

results: the rounder the module, the smaller the contact areas and the bigger the gaps. Thus, the higher the detachability and the lower the solidity of the interface. An avenue for future work could be to find an optimal module shape for this trade-off, e.g., cubes with a sharp edge but a dent, a notch or a surface texture that would improve detachability. Further alternatives are rounded polygons with more faces than a cube, thus allowing for more contact points between modules and stronger overall TUI, while allowing grasping their edges. Future work can leverage our results to improve splitting tasks with cubic modules to enable current application scenarii.

## 7.6 Limitations of the study

While our study can already inform the design of modular TUIs and technological development, future work will extend and refines its results.

As pointed out in prior work, isolating factors that may have an impact on bonding strength, such as the size, the weight or the arrangement of modules (Chapter 5), is challenging [19]. While our study isolate the bonding strength, the shape and the thickness of the interface, future work should study other related design parameters such as the size, the weight or the arrangement of modules.

Our experimental prototypes were not actuated. While the field of non-actuated modular TUI (e.g., [86, 180, 179, 279, 257]) can already benefits from our results, we cannot be sure how our results will apply to future actuated modules. Research in actuated modules currently explore electromagnetic [102, 202] and electrostatic actuators [223, 182]. As the technology advances and the size of actuators decreases, future work should replicate this study to verify that our results apply to actuated modules.

We collected subjective ratings on easiness, satisfaction, and impact of strength and shape on the completion of the task. Subjective ratings are a major measure informing our knowledge on user experience with a prototype, especially with novel interaction paradigms [242, 231, 15]. Future work could extend our work further by gathering objective data, such as the users' time and effort to reconfigure the modular TUI.

First, we did not measure the time to complete the tasks in our study as we left the participants free to explore different manipulations. This made the comparison difficult. Future work should leverage the qualitative data on how the participants manipulated the prototypes to select the best manipulation strategies and compare completion time.

Second, the effort could be measured through the force applied by participants on the prototypes. Candidates technologies are, e.g., electromyography (EMG). The use of surface EMG to study gesture-based interactions is common in HCI [282, 45, 283]. EMG measures muscle activity but is not reliable to measure the actual force users apply on a surface [44]. E.g., the muscle of the thumb can show high activity when the user contracts it without actually applying force on the prototype. The effort could alternatively be measured by a glove worn by the participant [300]. Unfortunately, using gloves impairs grip force [274]. Future work should consider using other alternatives such as using sensors embedded in or on the prototype [80]. Subsequent work is needed to embed sensors in our prototype: embedding sensors between the modules is not straightforward as it would lower their bonding strength.

## 7.7 Synthesis

Modular TUIs enable new interaction techniques through their highly customizable form-factor. Magnetic modular TUIs offer great opportunities in terms of cost, scalability and miniaturization. In this chapter, we presented the first user study on how the shape and bonding strength of such modules impact common manipulations from HCI literature.

We provide the first study of the trade-off between the detachability of the modules and the solidity of the UI. As expected, the higher the bonding strength, the higher the solidity but the lower the detachability. But, although we initially aimed at finding a single usable range (Figure 7.2), we found that the range of suitable bonding strengths and shapes depends on the manipulation.

We show that cubic  $6 \times 6 \times 6 \text{ mm}^3$  plastic modules with magnets of 0.98N-2.45N holding strength on iron provide optimal easiness and satisfaction when manipulating large blocks of modules and for folding and lifting the prototype, while 0.49N holding force impaired these tasks. Rounded  $6 \times 6 \times 6 \text{ mm}^3$  plastic modules with 2.45N holding strength on iron provide optimal easiness and satisfaction for precise detachment of 1 or 2 modules at a time and for bending tasks, while 0.49N holding strength significantly impairs these tasks. We expect the additional weight of cm-scale modules to have limited impact on our results: for instance, with a 0.49N holding force on iron and a weight of 0.31g, two of our cubic modules embedding 0.5mm magnets (i.e., condition C0.5) need a pull force of 0.49N to detach. Using modules three times heavier (0.93g) would only increase the necessary pull force to 0.50N.

Changing the configuration of the modules, e.g., the thickness of the TUI, is a way of increasing/decreasing the solidity. For example, although rounded modules with 0.49N holding strength impaired the lifting task on a flat configuration, there was no similar decrease in satisfaction nor easiness when using a thicker configuration with two layers of modules instead of one. The HCI community can readily leverage this work to inform the design of interaction techniques and technological implementation. We expect future work on programmable bonding strength and self-reconfigurable actuated modules to overcome the challenge for detaching several modules, requiring both high solidity and high detachability.

When we investigated the impact of the size in Chapter 6, we used spherical modules. This resulted in gaps and bumps on the surface that made it feel rough, and we showed that the resulting increased friction could help participants in braking and changing directions. There could be benefits in shape-changing *modules*. On the one hand, the modules could either be fully cubic to provide a smooth surface (Chapter 6) and overall solid UI (Chapter 7). On the other hand, the modules could change shape to provide more haptic feedback on designated areas (Chapter 6) or make some modules easier to detach by making them more prehensile (Chapter 7).





## PART II - CONCLUSION

---

We presented our contributions on the evaluation of the impact of three micro-scale design properties on interaction. First, we evaluated the impact of module *size* on target pursuit and target acquisition (Chapter 6). Second, we evaluated the impact of module *shape* and *bonding strength* on performing eight common manipulations from the HCI literature (Chapter 7).

For the impact of the *size*, we observed a greater effect on target pursuit rather than target acquisition. Designers should carefully consider and evaluate the level of friction they implement in tangible UIs depending on whether their target tasks involve continuous or more discrete movements. Perspectives and future work on reconfigurable tangible UIs made of modules  $< \varnothing 5$  mm also include the study of their arrangements in order to change tactile and kinesthetic feedback only in dedicated, programmable locations corresponding to potential targets. Such a material would entice users to touch the interface on particular locations, and prevent overshoots while ensuring a comfortable interaction.

For our study on module *shape* and *bonding strength*, a limitation to keep in mind is that we used smaller modules than what is currently available, as we want to inform the design of future high resolution modular UIs. Prior work proposed modules larger than ours, at the cm-scale (e.g., [179, 304, 147, 83, 245], or the 9mm Dynablocks [279]). We believe that our results can apply to these cm-scale modules: on the one hand, increasing the size of the modules would enable a larger contact area and bigger –thus stronger– embedded magnets. We expect the additional weight of cm-scale modules to have limited impact on our results. With larger modules but with the same magnetic bonding strength, the number of contact points per unit volume (i.e., granularity [141]) is lower. This might decrease the solidity of the UI. Designers should then carefully choose a module configuration that compensates the lower number of contact points per volume, such as a thicker configuration (Part I), or increases the strength of the magnets. Although prior work in HCI proposed modules at the cm-scale, future work goes towards reducing the size of modules [159, 120] to enable a higher granularity, i.e. more modules per unit volume [141]. The work we presented aims at informing this future work.

We will now conclude this thesis, and discuss our overall contributions, limitations and perspectives.





# CONCLUSION

---

## Contents

---

<b>8.1 Thesis contributions . . . . .</b>	<b>164</b>
8.1.1 Theories and concepts: a structured design space for modular shape-changing UIs . . . . .	164
8.1.2 Empirical user studies: characterization and impact of three design parameters on user interaction . . . . .	166
<b>8.2 Limitations and short-term perspectives . . . . .</b>	<b>169</b>
8.2.1 Evaluation of design parameters with non-static UIs . . . . .	169
8.2.2 Safety of shape-changing UIs . . . . .	170
8.2.3 User perception and expected context of use . . . . .	170
<b>8.3 Long-term perspectives for modular shape-changing interfaces . . .</b>	<b>172</b>
8.3.1 Recentering reconfiguration strategies and algorithms on the user . . . .	172
8.3.2 Exploring end-user programming with modular robotics . . . . .	173
8.3.3 Exploring temporality in shape change . . . . .	174

---

## 8.1 Thesis contributions

Our work mainly contributes to the HCI area of shape-changing user interfaces. Moreover, our work can be further described as contributing to:

1. **Theories and concepts**, by proposing a structured design space for modular shape-changing interfaces, through leveraging work from both the HCI and robotics literature (Part I).
2. **Empirical knowledge**, by conducting three controlled user studies to characterize and understand the impact of three design parameters on user interaction: the size, shape and bonding strength of the modules (Part II). The results of these user studies can be further extended to the areas of tangible and haptic interaction. First, we linked our results with previous work on programmable friction from the haptics community (Chapter 6). Second, we studied 3D printed static apparatuses that did not change shape, and took insight from previous work from the TUI community (Chapter 7).

In this section, we summarize our contributions in these two areas of HCI.

### 8.1.1 Theories and concepts: a structured design space for modular shape-changing UIs

The first problem we encountered in the context of this thesis was the research in silos between HCI and robotics, and the subsequent lack of a structured design space. When studying previous work, we found that both the HCI and robotics communities both conducted extensive work on modular shape-changing UIs, but that their vocabulary and design requirements were neither structured nor coherent. The two key challenges of this contribution were that:

- On the one hand, previous work in HCI essentially focused on a narrow set of guidelines that matched their specific design.
- On the other hand, previous work in robotics proposed literature surveys and design guidelines, but focused on locomotion and reconfiguration rather than user interaction.

For example, the design rationales from Cubimorph required their modules to be constantly attached as to not fall or be lost [247]. This is a coherent design rationale for chain implementations, but cannot be applied to swarm implementations which require their modules to be detached and move independently from each other [159]. Most lattice implementations that follow a “building blocks” approach also need their modules to allow for detachability (e.g., [147, 279, 86]). At the same time, robotics researchers did relate their design guidelines to the

different types of architectures and reconfiguration type of their implementations [85, 177, 273]. However, previous work in HCI and robotics both studied modular shape-changing UIs for different motivations and usage. As they rarely collaborate, this results in both communities publishing in different venues with different vocabularies. For example, while HCI researchers often use the term “*shape-changing user interface*” (or SCIs), it is never used in the robotics field as they rather employ “*modular self-reconfigurable robot*” (or MSR). This makes it hard to leverage work across communities.

**The first objective of this thesis** was to understand previous work on modular shape-changing UIs in both robotics and HCI, and how they relate to each other. We conducted a thorough literature review of previous work from both HCI and robotics. We categorized each articles according to their contribution (i.e., either design implementations, tools for design or literature surveys). In order to understand, unify and structure the design space for modular shape-changing UIs, we took a six step approach to analyse our corpus:

1. **Identifying.** We identified the properties for the design of modular shape-changing UIs in the literature from HCI and robotics.
2. **Merging.** We merged the properties that were identical (e.g., “*hierarchy*” is found across several publications with different names, for instance master/slave or standalone/satellite).
3. **Grouping.** We grouped the properties that complementarily define a higher-level one (e.g., “*detachability*” is part of the “*shape-change ability*” of the interface, under the “*modularity*” type of shape-change).
4. **Defining.** We precisely defined the properties that we found unclear.
5. **Structuring.** We structured the properties with the designer in mind (i.e., into macro- and micro-scale properties).
6. **Studying.** Lastly, we studied the dependencies between properties, and related them to each other.

This corpus analysis allowed us to complete our first objective and layed the ground work for our second objective.

**The second objective of this thesis** was to provide a structured overview of the prior work to ground future development into a rational exploration. To this aim, we leveraged our corpus analysis and existing classifications of modular robots to relate the properties with the specificities of each kind of architecture and reconfiguration types. Our contribution is a set

of coherent design properties (1) at the scale of the interface itself (macro-scale) and (2) at the scale of the modules (micro-scale). Moreover, in order to facilitate design choices and their prioritisation depending on user requirements, we proposed (3) a characterization of the impact of the properties on each other.

Overall, our contribution is a structured design space that allows designers to describe and compare existing systems, as well as generate new designs. We gave an example of the descriptive, evaluative and generative power of our work in the conclusion of Part I. The characterization of the impact of the design properties on each other is a key contribution to allow the generation of new designs. Designers can anticipate early in the design stages how changing a specific design parameter might impact the other ones – either at the scale of the interface or at the scale of the modules.

### 8.1.2 Empirical user studies: characterization and impact of three design parameters on user interaction

The second problem we encountered in the context of this thesis was the lack of user studies and the resulting lack of empirical knowledge on the impact of modularity and shape-change on user interaction. One of the main reasons for this lack of user studies is that shape-changing prototypes are often not robust enough to withstand prolonged user interaction [19]. Moreover, current evaluations are conducted on the whole system [19]. This can lead to biases, as the relative impact of isolated factors are not well known. For example, if we were to directly conduct user evaluation of chainFORM [196], the impact of the size of the modules, the resolution of the interface, the speed of reconfiguration, the strength of the applied haptic feedback or the available changes of shapes would be hard to dissociate from each others.

As our goal was to open up the way for more user evaluation of modular shape-changing UIs, we started our research agenda on the topic by isolating individual factors involved in the design of modular shape-changing UIs and evaluated their relative impact on user interaction.

**The third objective of this thesis** was to isolate critical factors in the design of modular shape-changing UIs. We leveraged our design space, as well as previous work which highlighted current and expected challenges in shape-changing research [19], to identify and isolate three critical design parameters: the *size*, *shape* and *bonding strength* of the modules (see Part II).

**The fourth objective of this thesis** was to understand the impact of the isolated factors on user interaction. We thus conducted user experiments to understand how these parameters impact interaction, and to provide design guidelines to the HCI community. Our goal was to

inform the user-centered design of future modular shape-changing interfaces by involving users early on in the design stages.

Overall, our **contribution** to the area of empirical studies in HCI can be described along two main axes:

1. **Impact of module size** on target pursuit and target acquisition, with a characterization of the impact of the grasp on efficiency and subjective feedback. Some take-away results from our study were that, overall (1) the smaller the modules, the higher the performance, (2) participants enjoyed the friction of  $\varnothing$ 1mm and  $\varnothing$ 2.5mm modules as they helped them brake and change directions, (3) the bigger the modules, the fewer the grasps that can be performed.
2. **Impact of module shape and bonding strength** on performing eight common manipulations from the literature, with the characterization of a solidity-detachability trade-off. Some take-away results from our study were that (1) cubic modules are overall easier and more satisfying to manipulate, except for precision and bending tasks, (2) low strength impairs UI solidity, but high strength impairs precision tasks with cubic modules.

We provide the STL files and potentiometer specifications to replicate the apparatus of the study presented in Chapter 6. They can be found in the paper and as supplementary materials <sup>1</sup>. We provide the data, analysis script, STL files and video data for the work presented in Chapter 7. They can be found as supplementary material <sup>2</sup> and on Zenodo (for the video data, available upon request) <sup>3</sup>.

---

1. <https://dl.acm.org/doi/10.1145/3462244.3479936>

2. <https://dl.acm.org/doi/10.1145/3569009.3572731>

3. <https://doi.org/10.5281/zenodo.7372398>

## 8.2 Limitations and short-term perspectives

We now present the limitations and the short-term perspectives of our work. Although the research presented in this thesis came with some limitations, it also yielded interesting results and opened the way for exciting perspectives.

### 8.2.1 Evaluation of design parameters with non-static UIs

One of the main limitations – and subsequent perspective – of our work is the fact that we conducted user studies on static, non-actuated modules. The reason for this is that shape-changing UIs are notably known for their limited ability to withstand long-term user interaction due to their lack of robustness [19]. Thus, first evaluating the impact of micro-scale design parameters with static modules allowed us to easily isolate the factors and understand their impact on user interaction. This also limited the bias other design parameters might otherwise cause. For example, the size of the modules impacts their structure and packing, as well as their bonding strength (Chapter 5, p.72-73). In retrospect, if we used legitimate actuated modules of different sizes for the experiment presented in chapter 6, it would have been more challenging to interpret our results and tell whether the impact on user interaction and the variation in the results were solely due to the changes of size or should be attributed to another factor (e.g., the bonding strength depending on the actuators we would have used).

Thus, we would encourage further user studies on:

1. **Isolated design parameters that require non-static modules.** For instance, the *speed* of modules is tricky to evaluate with static modules. A way to bypass this may be to emulate modules and their movement by using extended reality (XR) combined with active haptic technology. However, this may come with further limitations. There is a need for studies on how the results from studies conducted in XR/haptics are replicable and transferable to real life actuated modules.
2. **The combined impact of different design parameters.** This would not only provide further understanding on how users experience the whole UI, but would also enable researchers to highlight and study the potential trade-offs that might exist between properties. For example, what would users prefer between having smaller modules and high resolution, or stronger bonding strength and overhang capabilities? How much would they be willing to compromise, and in which context? We expect that such studies can be conducted with both static and actuated prototypes.



## 8.2.2 Safety of shape-changing UIs

In chapter 4, we defined the *Safety* design parameter. However, we found very little previous work on the safety of modular shape-changing UIs – and of shape-changing UIs in general. One rare example is the Zooids platform [159] for which they lowered the speed because of safety concerns. We leveraged previous work from the HRI community, but it is unclear how this would actually apply to the specificities of shape-changing UIs and their different actuation types. For instance, the safety concerns of a pneumatically actuated soft robot are different compared to the safety concerns of modules using electromagnets as their actuation mechanisms. Examples of such concerns are that the pneumatically actuated UI might explode due to too much air pressure, whereas the skin of the user might get pinched between two robotic modules using too strong electromagnets. Similarly, the safety depends on the type of modular robots (e.g., swarms, chains or lattice) and their context of use. For instance, a chain of modules used to make a haptic glove [196] could apply too much pressure on the joints of the user, whereas a swarm of drones for mid-air 3D animation [40] might fall down mid-air and hurt a passerby.

We would encourage the community to conduct studies on the safety of shape-changing UIs. A promising way to nudge researchers into assessing the safety of their system would be to provide them with comprehensible metrics and experimental protocols to easily report potential safety concerns. These metrics could then be crossreferenced and compared to understand the differences and commonalities in safety concerns between different kinds of actuations and architectures, and later form a taxonomy.

## 8.2.3 User perception and expected context of use

Understanding the impact of a system on user interaction, conducting studies on user acceptance or choosing new interaction designs is heavily dependent on the usage and overall application scenarii of the system. For example, designing a novel prototype and its interaction modalities would lead to different design choices depending on whether it is geared towards a tabletop context or a mobile handheld context. However, there is no existing context of use for modular shape-changing UIs drawn from real-life usage, as they are not common place in our everyday life. Some previous work did present concept scenarii. However, these scenarii are imagined by researchers and are never tested with actual users, let alone in-situ [19]. For instance, Cubimorph [247] presented a scenario where a user can switch the shape of their handheld modular mobile phone between a flat surface to display a map, a rectangular smartphone-like shape to fit in her pocket, and a controller-like shape to play a video game. ChainFORM [196] proposed several application scenarii, such as a multi-user interface made of a chain of modules that display a Pong video game, or a stylus that can detect grasp to switch between a pen mode, a brush mode or a magnifying glass mode. As the technology advances and prototypes become

robust enough, the need will arise for studies that will help us understand the actual way users use and adopt (modular) shape-changing UIs. Understanding how our designs may impact user interaction in real life context will allow us to further improve them.

Understanding *how and why* users expect to use modular devices, and taking into account the specificities of the different kinds of systems (e.g., a chain, swarm or lattice architecture may not be suited for the same applications), would give another perspective to the research on modular shape-changing UIs. Similarly, as modular robots are currently not found in our everyday life, users might express some concerns and be reticent in using them, let alone adopting them instead of their current alternatives. Should our work as researcher be based on the premises that the target users we introduce in our concept scenario will perceive the new concept, prototype or interaction modality as exciting and helpful? Could our users instead be reluctant to use our system due to concerns about, for instance, its perceived safety, robustness, usefulness? Thus, there is a need to understand how users *perceive* modular shape-changing UIs. Previous work – us included – notably made claims about the opportunities of shape-changing UIs. One instance of such claims is that they offer great naturalness, linking shape-changing implementations to Natural User Interfaces (NUIs) [106], and enhanced learnability [217, 64]. However, we still lack user studies to assess these claims [19]. Future work should try to understand whether users would be willing to use our systems, what their current alternatives are and what their concerns may be in the adoption of a new interactive system.

## 8.3 Long-term perspectives for modular shape-changing interfaces

We now conclude the thesis by discussing long-term perspectives for the future of modular shape-changing UIs. We believe that, once the hardware barriers are taken down, novel challenges will arise. We especially find three long-term perspectives that we believe will be critical in the future development of modular shape-changing UIs.

1. How will we design user-centered reconfiguration algorithms?
2. Who will be responsible for providing content for future shape-changing devices?
3. As the different states of shape-change would constitute the different devices available to the user, how will the temporal aspect of switching between states to change devices impact interaction modalities?

### 8.3.1 Recentering reconfiguration strategies and algorithms on the user

In Part I, we discussed that we left work on reconfiguration algorithms, including user-centered motion control and planning, for future work. Previous work in HCI focused on user-centered hardware and interaction techniques with the already reconfigured shape. However, few approached the issue of how to take the user into account in the choice of reconfiguration strategies. We mentioned several times in this thesis that robotics researchers focus more on userless reconfiguration and locomotion [247]. This results in them conducting extensive work on reconfiguration algorithms, especially motion planning (e.g., [328, 113, 170, 291]), but (1) which are tested in “*ideal*”, controlled conditions [314] and (2) which are not readily suited for user interaction. For instance, some implementations can overcome obstacles in uncertain environments (e.g., modules assembling in a chain to cross a gap, go over a rock or climb stairs [155]) as their design was geared towards terrain exploration. However, contrary to a human limb, they make the assumption that the obstacles they need to overcome are static, and reconfiguring the modules around an obstacle do not imply the same safety issues as reconfiguring around, for instance, a human hand. Thus, even with extensive existing work, the robotics field is still facing challenges in both control and planning [314], and there is a need for HCI researchers contributing to the work on motion control and planning to provide a user-centered perspective. We mentioned in our work presented in Part I that our design space can be readily refined to accommodate new properties at the digital level in the future, such as reconfiguration algorithms.

All in all, there is a need for user-centered reconfiguration algorithms and strategies that drives the change of shape. These algorithms should take into account the position of the user and the context in which the interaction takes place. Indeed, not only should the reconfiguration

of the modules adapt to *how* the user is interacting with them, they should also adapt to where the interaction takes place. For instance, if the application scenario requires mobile handheld interaction (e.g., while walking or taking the bus), then the change of shape should be careful to maintain the centre of gravity of the device, so that it does not fall out of the hands of the user. Would the user be responsible for anticipating the change of shape – and thus center of gravity – of the device? If the system follows a lattice architecture where the modules are detachable (e.g., using magnets as actuation mechanisms), the system may need to prioritise a shape-change strategy that minimises the risk of modules falling.

### 8.3.2 Exploring end-user programming with modular robotics

Throughout the thesis, we spoke of long-term concepts such as Sutherland’s *Ultimate Display* [277], or Ishii’s *Perfect Red* [121]. These concepts foreshadow a kind of “programmable matter” made of self-reconfigurable modules under the mm-scale. A legitimate question that could arise if we ever achieved such high resolution modular shape-changing UIs would be: *what* content and applications are supported by the shape-changing device? In the introduction of this thesis we compared self-reconfigurable robotic modules with pixels, and the overall modular shape-changing UI with GUIs. However, even though users can technically display whatever they want with GUIs, they are not typically the ones that design and develop the GUI applications they interact with. So, similarly to designers and programmers that provide content for our smartphones, computers or AR/VR devices, *who* will provide content for modular shape-changing UIs? Previous work explored current and upcoming challenges in the design of content for shape-changing UIs [19]. For instance, they highlighted the importance of identifying key application domains (such as data physicalization) or the importance of designing content for the visual and physical configuration of the display and user input. However, their exploration is still constrained by the idea that the user will interact with content designed by an expert. We find that there could be benefits in exploring end-user programming in the context of modular robots for future modular shape-changing UIs. This could empower users by implementing a true “building block” approach where users can design and customize their own application.

End-user programming (or end-user development) refers to the process of providing non-expert users with concepts, methods and tools to program or customize the behavior of a software or hardware system [150, 211]. In the context of modular shape-changing UIs, end-user programming can be a powerful tool for enabling users to create custom behaviors and applications for their robotic modules without requiring expertise in robotics or programming. By providing end-users with tools to program and customize the behavior of these modules, we can further enhance their flexibility and versatility. End-user programming for modular robots can also benefit from collaboration and knowledge-sharing among users. There could be platforms allowing end-users to share their custom applications with others, similarly to how 3D makers

provide their design files on, for instance, Thingiverse <sup>4</sup>.

By providing a platform for users to share their custom behaviors and applications, we can create a community-driven ecosystem of modular shape-changing UI programming that can benefit users with different levels of expertise.

### 8.3.3 Exploring temporality in shape change

The concept of graspable UIs was originally coined to provide users with physical “handles” they could grasp and manipulate to directly interact with computational data [76, 75]. The first TUIs were introduced with *space-multiplexed* input in mind, where one device controls one function. Space multiplexing is not unique to TUIs. For instance, the controls in a car are space-multiplexed [75] and previous work explored multitouch surfaces to directly interact with GUI elements (e.g., for collaboration [264]). However, other kind of devices we interact with daily leverage *time-multiplexed* input modalities, such as computer mice or standard smartphone touchscreens. They control several functions and behaviour on the device, such as menu selection, scrolling or drag-and-dropping items [75].

Implementing shape-change introduces the issue of space *vs.* time multiplexing in input modalities. To give a working example from a real-life context, we can look at the differences between mixing consoles in recording studios compared to outdoor concert settings. In a recording studio, the controls are typically space-multiplexed, with each set of device (i.e., buttons, sliders, dials) controlling one individual parameter for one individual musician. But what happens if there are too many musicians? And what happens in an outdoor concert setting, where the space constraint leads to much smaller mixing table setups? This is the reason for mixing tables with parametrable controls. This implements a layer of time-multiplexing on the otherwise space-multiplexed controls. For instance, the sound engineer can parameter the settings for the singer, thus changing the computational data through the physical device. Then, they can select another musician parameters profile (e.g., the guitarist), so that the controls (e.g., the sliders) move to reflect the computational data of the new musician profile.

We expect this kind of space and time multiplex trade-off to play a role in future modular shape-changing UIs. As the shape-changing UI can switch between different type of controls, how would this reflect in the space and time multiplex of input interactions? Moreover, how would this impact the cognitive load of the users, as the different devices available (e.g., the changes of shapes) would be scattered across *time* rather than *space*? Future work could draw insight from research in other fields, such as Natural Language Interaction (NLI). For instance, when interacting with a vocal assistant, the different options available are not displayed. They

---

4. <https://www.thingiverse.com/>

are either spoken, or the user needs to cognitively situate themselves in the interaction. We can expect this kind of interaction strategies to translate in shape-changing user interaction.



# SYNTHÈSE EN FRANÇAIS

---

## Avant-propos

Nous fournissons dans ce chapitre une traduction française de l'intégralité des chapitres d'introduction (Chapitre 1) et de conclusion (Chapitre 8), ainsi qu'un résumé des autres chapitres du manuscrit.

## Introduction

### Contexte

Ce manuscrit contribue au domaine de l'interaction humain-machine (IHM). Ce domaine de recherche concerne la conception, l'usage et les technologies impliqués dans l'interaction entre l'utilisateur et les machines. Bien qu'étant principalement un domaine informatique, les travaux menés en IHM s'appuient sur une grande variété de domaines, tels que la psychologie, la biomécanique, les sciences du comportement et la science des matériaux.

Dans le cadre de cette thèse, nous nous intéressons plus particulièrement aux interfaces utilisateur physiques à changement de forme. Les interfaces à changement de forme sont des interfaces physiques dont la forme peut changer de manière dynamique dans le temps pour proposer et supporter des modalités en entrée, en sortie ou les deux [229]. Ce domaine de recherche est apparu comme un moyen de combler l'écart entre la flexibilité des interfaces graphiques et la physicalité des interfaces tangibles. Les chercheurs en IHM ont commencé à s'intéresser à l'implémentation du changement de forme dans les interfaces physiques dès 2004 [181], et ont exploré les opportunités des interfaces à changement de forme *modulaires* depuis 2007 [179]. L'objectif principal de cette thèse est de mieux comprendre et améliorer la conception des interfaces à changement de forme *modulaires*.

### Flexibilité contre physicalité

Dans cette section, nous abordons le compromis entre flexibilité et physicalité dans les dispositifs interactifs. En général, l'interaction humain-machine en tant que domaine de recherche traite de niveaux variables de flexibilité et de physicalité, tant dans les modalités d'entrée que de sortie [140, 215].

D'une part, les interfaces graphiques sont des représentations graphiques et visuelles d'une interface composée, par exemple, de boutons, d'icônes, de menus ou d'images [71]. Les inter-



faces graphiques offrent aux utilisateurs un moyen visuel d'interagir avec les ordinateurs [176]. Elles sont initialement apparues comme une alternative plus conviviale aux interfaces basées sur du texte, où les utilisateurs se fiaient à des entrées sous forme de lignes de commande (CLI) et à des retours textuels en sortie [71]. En ce qui concerne les modalités d'entrées, les interfaces graphiques peuvent inclure une large gamme d'éléments d'entrée graphiques, tels que des boutons, des menus ou des curseurs, pour contrôler un grand nombre de fonctions au sein d'une application. En ce qui concerne les modalités de sorties, les interfaces graphiques peuvent s'adapter à différentes tailles d'écran et résolutions, ce qui les rend adaptées à une large gamme de dispositifs. Elles peuvent également s'adapter aux besoins de l'utilisateur, de la tâche ou du contexte d'interaction (par exemple, adapter dynamiquement l'affichage pour répondre aux problématiques d'accessibilité, basculer en mode sombre la nuit, proposer des régionaux en fonction du langage, etc.). Cependant, les interfaces graphiques sont essentiellement des « *images sous un écran de verre* » qui n'autorisent pas les utilisateurs à « *utiliser leur main* » [1, 158]. Elles reposent fortement sur la vue, sans indications physiques pour informer l'utilisateur sur la position d'un objet ou d'un contrôle particulier, et limitent les gestes à un sous-ensemble restreint de ce dont les humains sont capables [1]. Ce manque de physicalité peut les rendre inadaptées à certains contextes d'interaction, notamment ceux nécessitant une interaction sans regarder. Par exemple, bien que les claviers physiques aient tendance à disparaître de nos appareils mobiles, ils font toujours largement figure de norme sur les ordinateurs de bureaux : la petite taille des appareils mobiles, avec tout à portée de vue, signifie qu'ils doivent – et peuvent – favoriser la flexibilité au détriment de la physicalité.

D'autre part, les interfaces tangibles sont des dispositifs interactifs physiques et tangibles que les utilisateurs peuvent toucher et manipuler, dans le but de « *représenter et manipuler des données numériques à l'aide d'objets physiques* » [258]. Elles font appel à notre perception haptique, tant tactile que kinesthésique, avec des affordances physiques qui transmettent un retour sensoriel riche et suggèrent aux utilisateurs quels actions sont disponibles et comment les effectuer avec l'objet physique [65]. Cette physicalité permet une interaction sans regard en exploitant la mémoire spatiale des utilisateurs [212] et permet une manipulation rapide et précise [296, 158]. Les interfaces tangibles offrent un moyen plus direct et tangible de manipuler et d'interagir avec des informations numériques, avec un degré de physicalité plus élevé. Cependant, les interfaces tangibles n'ont pas la flexibilité des interfaces graphiques et sont plus physiquement contraignantes. En ce qui concerne les modalités en entrée, les interfaces tangibles reposent sur des objets physiques que les utilisateurs peuvent toucher, manipuler ou déplacer pour interagir avec le système. Cela limite les types d'interactions possibles, car l'utilisateur est physiquement contraint par les propriétés des objets eux-mêmes. Par exemple, si une interface tangible est conçu avec des boutons ou des curseurs physiques, les interactions seront limitées par la taille, la forme et l'amplitude de mouvement de ces objets physiques. Les utilisateurs doivent passer

---

d'une interface tangible à une autre en fonction de leurs besoins (par exemple, d'un bouton à un curseur) et peuvent avoir besoin de naviguer entre un grand nombre de dispositifs (par exemple, un ingénieur du son avec plusieurs curseurs, boutons et boutons sur une console de mixage), bien qu'ils n'aient pas toujours besoin de tous ces éléments. Cela peut entraîner des espaces de travail encombrés et encombrants.



(a) Tableau de bord à l'intérieur d'une voiture.



(b) Contrôles de thermostat graphique et physiques..

Figure 8.1: Deux exemples de scénarios où les utilisateurs ont besoin à la fois de flexibilité et de physicalité selon le contexte d'interaction : (a) Le tableau de bord d'une voiture nécessite des contrôles physiques pour conduire, mais peut également utiliser un écran tactile avec des contrôles graphiques (par exemple, pour contrôler la radio, la température, la navigation). (b) L'utilisateur peut contrôler la température de sa maison domotique avec son smartphone en déplacement ou avec une télécommande physique chez lui.

Dans l'ensemble, les interfaces graphiques et tangibles ont chacune leurs forces et leurs faiblesses, et le choix entre les deux dépend des besoins spécifiques de l'application et des utilisateurs. La combinaison de interface graphique et tangible peut offrir aux utilisateurs une interaction plus intuitive, immersive et flexible, notamment dans les applications où la manipulation physique est importante. Si nous examinons des exemples de notre vie quotidienne, nous constatons que, bien que les smartphones et les tablettes utilisent principalement des écrans tactiles à la fois en tant que modalité d'entrée et de sortie, les écrans (type moniteur) en tant que modalité de sortie et le clavier/souris en tant que modalité d'entrée sont encore la norme pour les ordinateurs de bureau. Dans nos maisons, les appareils domotiques tels que les thermostats, les systèmes d'éclairage et les caméras de sécurité utilisent une combinaison d'interfaces graphiques et tangibles pour permettre aux utilisateurs de les contrôler et d'interagir avec eux. Les utilisateurs peuvent contrôler ces appareils à l'aide d'interfaces graphiques sur leurs smartphones ou tablettes, mais certains appareils incluent également des commandes physiques, telles que des boutons, des boutons rotatifs et des curseurs, qui peuvent être utilisés pour ajuster les paramètres ou allumer/éteindre

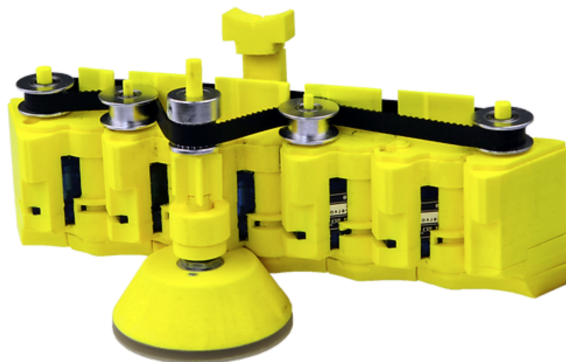
l'appareil (Figure 8.1b). Les voitures modernes utilisent souvent une combinaison d'interfaces graphiques et tangibles pour permettre aux conducteurs de contrôler et d'interagir avec divers systèmes, tels que la radio, le contrôle de la température et la navigation. Le tableau de bord peut inclure des commandes physiques pour ajuster les paramètres, tandis que l'interface graphique est affichée sur un écran tactile ou un autre affichage (Figure 8.1a). Cela montre qu'il existe un besoin à la fois de flexibilité et de physicalité, et que les deux peuvent être pertinents pour une même application en fonction du contexte.

### **Implémenter le changement de forme comme compromis**

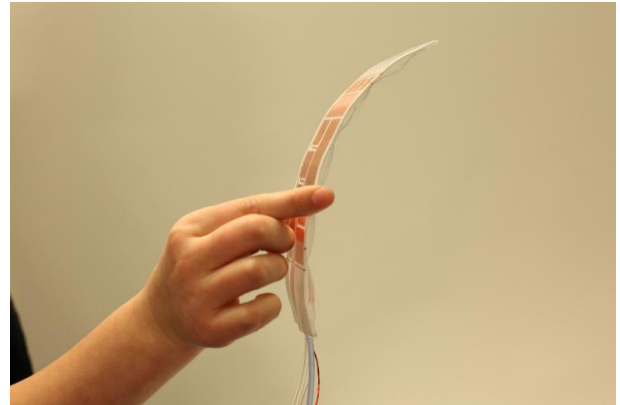
Il est nécessaire d'avoir à la fois de la physicalité et de la flexibilité en fonction du contexte de nos interactions quotidiennes. Cela peut se traduire par le fait que les utilisateurs doivent passer d'un appareil à un autre en fonction de la tâche ou du contexte d'interaction, comme dans l'exemple du thermostat, ou devoir utiliser une combinaison d'interfaces graphiques et physiques, comme dans l'exemple de la voiture où la physicalité est nécessaire pour une interaction sans regarder. Nous étudions une troisième alternative : un compromis entre physicalité et flexibilité. Les chercheurs en IHM explorent deux principales façons de parvenir à ce compromis : (1) permettre aux utilisateurs de "toucher" des éléments graphiques (par exemple, grâce à du retour haptique [243, 178]) ou (2) permettre aux utilisateurs de changer la forme des interfaces physiques. Dans cette thèse, nous nous concentrons sur la seconde option : des interfaces utilisateur tangibles pouvant changer leur forme physique.

Les interfaces utilisateur à changement de forme sont des interfaces tangibles capables de modifier leur forme au fil du temps, de manière autonome ou non, afin de s'adapter au contenu ou au contexte en fonction de l'utilisateur, de la tâche ou de l'environnement [19]. Les interfaces utilisateur à changement de forme se révèlent particulièrement intéressantes dans le contexte de l'interaction sans regarder dans des environnements généralement encombrés. De précédents travaux portant sur les interfaces utilisateur à changement de forme ont proposé des prototypes et des interactions prometteuses. Nous retrouvons notamment la possibilité d'adapter le tableau de bord d'un avion (par exemple, Gazeform [213] ou Multi-plié [215]). Cependant, implémenter le changement de forme pour des interfaces physiques présente un lot de défis [19]. Et ces défis ne sont pas (uniquement) technologiques. Par exemple, comment les utilisateurs perçoivent-ils le changement de forme ? Comment pouvons-nous communiquer les changements de forme disponibles, et comment les déclencher ? Les utilisateurs se sentiraient-ils "perdus" entre les différentes étapes du changement ? Quels types d'utilisateurs ou quels contextes d'utilisation pourraient spécifiquement en bénéficier, et comment ?

Parmi les approches proposées dans la littérature, les interfaces utilisateur changeantes de forme *modulaires* ont émergé comme un moyen de surmonter les défis actuels. Ces défis sont



(a) KnobSlider [140]



(b) PneuUI [310]

Figure 8.2: KnobSlider est une implementation actionnée mécaniquement, tandis que PneuUI est actionnée pneumatiquement.

principalement la scalabilité [19], la robustesse [314], le coût [314] et la polyvalence des interfaces [314]. Dans l'ensemble, la modularité offre une approche intéressante semblable aux blocs de constructions, et pourrait ouvrir la voie à de nouvelles interfaces à changement de forme offrant une grande résolution de forme et une grande variété de changements de forme comparés à d'autres types d'implémentations. Par exemple, les poches d'air pneumatiques de PneuUI [310] (Figure 8.2b) peuvent ouvrir/fermer dynamiquement un couvercle sur le dessus d'un trou pour permettre des changements limités de porosité. KnobSlider est actionné mécaniquement [140] (Figure 8.2a) et peut passer d'un curseur linéaire à un bouton rotatif. En revanche, l'appareil ne peut pas être divisé en deux curseurs ou se transformer en un tout autre dispositif. Ces changements de forme sont préprogrammés lors de la conception et ne peuvent pas être modifiés pendant l'interaction. En revanche, l'utilisation de modules en tant qu'éléments de construction pourrait offrir une plus grande fourchette de porosité, puisqu'enlever des modules pourrait créer des trous de tailles différentes, ou se transformer en une plus grande variété de dispositifs, puisque les modules peuvent se reconfigurer en un grand nombre de configurations. Les différents changements de forme n'auraient pas nécessairement besoin d'être planifiés lors de la conception, car de nouvelles formes pourraient être créées par déformation directe par l'utilisateur, ou automatiquement par le système en faisant déplacer les modules de manière autonome, plutôt qu'en devant refaire une toute nouvelle conception et un tout nouveau dispositif.

Bien que prometteuses, les interfaces modulaires à changement de forme ne sont pas encore couramment présentes autour de nous. Les scénarios d'application explorés dans la littérature proviennent principalement des chercheurs eux-mêmes, plutôt que des utilisateurs réels ou du contexte d'utilisation, et les évaluations in situ sont très rares [19]. Par conséquent, adopter une approche ascendante centrée sur l'utilisateur dans la conception de nouvelles interfaces ou

de nouvelles techniques d'interaction, n'est pas une tâche facile. Les paradigmes d'interaction utilisés lors de l'interaction avec des interfaces modulaires à changement de forme peuvent différer par rapport aux interfaces graphiques actuelles ou aux dispositifs physiques statiques que nous utilisons généralement dans notre vie quotidienne. Par exemple, les utilisateurs peuvent avoir une expérience totalement différente en utilisant un smartphone modulaire (par exemple, [247, 86]) par rapport à un écran tactile standard. De même, les utilisateurs peuvent avoir une expérience différente lorsqu'ils interagissent avec des contrôles à changement de forme comparé à leurs contrôles statiques. Par exemple, l'utilisation d'un tableau de bord physique fixe et statique peut être différente comparé à si les commandes n'apparaissent que lorsque cela est nécessaire (par exemple, en fonction du regard ou du contexte [244, 213]). Quels avantages et inconvénients peuvent émerger de l'interaction avec de telles interfaces ? Comprendre comment les utilisateurs finaux perçoivent le changement de forme et comment les interfaces à changement de forme peuvent les avantager ou les impacter est une étape clé pour développer et proposer des interfaces à changement de forme utilisables et les faire passer des communautés de recherche à l'industrie. La prochaine section présentera les problèmes de recherche liés à cette question, et sur lesquels nous nous sommes focalisés dans cette thèse.

## Énoncé du problème

Les interfaces utilisateur à changement de forme ont émergé en tant que compromis entre la flexibilité des interfaces graphiques et la physicalité des interfaces tangibles. Cependant, les travaux antérieurs ont souligné l'existence de défis critiques pour le développement et l'utilisation d'interfaces à changement de forme [19]. Nous présentons ici les deux principaux problèmes sur lesquels nous avons travaillé dans le cadre de cette thèse.

### Problème 1 - IHM and robotique: recherche en silos

Les chercheurs en IHM sont souvent confrontés à un défi lors de la conception de systèmes à changement de forme : bien qu'ils possèdent des compétences en programmation logicielle et en électronique basique, ils manquent souvent d'expertise en science des matériaux, électronique et mécanique avancés [19]. Dans notre cas, une solution à ce problème serait de collaborer avec des chercheurs en robotique, qui ont une vaste expérience en robotique modulaire. Alors que la recherche en IHM a commencé à explorer la robotique *modulaire* en 2007 avec Siftables [179], la recherche en robotique a mené des travaux approfondis sur le sujet depuis 1990 [81]. Ils ont proposé plusieurs configurations avancées de robots modulaires et ont accumulé des connaissances sur leurs avantages et inconvénients techniques au fil des années [314]. La communauté IHM pourrait tirer parti des travaux antérieurs en robotique pour proposer des prototypes élaborés et gagner en temps et en coûts lors des phases de conception et de prototypage. Il est important de noter que la recherche en robotique se concentre davantage sur les capacités de reconfiguration

---

et de locomotion des robots modulaires que sur l'interaction utilisateur [247]. La collaboration avec des chercheurs en IHM peut contribuer à ce que les robots modulaires soient bien conçus sur le plan physique et ergonomique, et offrent une expérience d'interaction fluide et intuitive pour les utilisateurs. Cependant, ces deux communautés travaillent souvent séparément et utilisent des vocabulaires différents, ce qui rend difficile la mise en commun des travaux et le dialogue entre les communautés. Il est important de résoudre ce problème pour profiter pleinement de l'expertise de chacun. Par exemple, les configurations en chaîne sont courantes en IHM, mais les chercheurs en robotique ont trouvé plus difficile de les représenter et de les contrôler, malgré leur polyvalence [314]. Il y a peu de discussions sur cette question dans la communauté IHM. La collaboration avec des chercheurs en IHM peut aider les chercheurs en robotique à comprendre les besoins, les préférences et les attentes de leurs potentiels utilisateurs finaux, à intégrer ces connaissances dans la conception de robots modulaires et à évaluer l'efficacité de ces robots dans des environnements réels.

**Objectif 1 :** Comblent le fossé entre la robotique et l'IHM et mettre en lien les travaux antérieurs des deux communautés.

**Objectif 2 :** Proposer un espace de conception structuré qui tienne compte des spécificités des systèmes modulaires à changement de forme, afin d'informer leur conception.

## **Problème 2 - Utilisabilité des interfaces modulaires à changement de forme : connaissance empirique insuffisante**

Actuellement, la recherche en IHM sur les interfaces utilisateur à changement de forme se concentre principalement sur le développement de nouveaux prototypes et de potentielles applications. Il y a encore peu de travaux dont les contributions sont dédiés à l'évaluations des prototypes avec des utilisateurs réels, ou à des techniques d'interaction. Bien que certaines études aient été menées avec la plateforme *Zooids* [159], notamment une étude d'élicitation sur comment les utilisateurs imaginent contrôler un essaim de robot [144], il y a encore un manque d'évaluations approfondies in-situ. Cela est en partie dû à la nouveauté des interfaces à changement de forme, ainsi qu'à leur manque de robustesse qui empêche une utilisation prolongée [19], nécessaire pour des études utilisateur poussées. De plus, nous manquons de connaissances sur l'effet relatif des facteurs isolés pour pouvoir évaluer un système dans son ensemble. Par exemple, bien que nous puissions maintenant utiliser des méthodes et des protocoles standardisés pour évaluer directement de nouvelles interfaces graphiques ou physiques, nous devons d'abord évaluer l'effet relatif de leurs facteurs (par exemple, l'effet de la taille et de la distance de la cible dans la loi de Fitts), pour ensuite évaluer de nouvelles façons de naviguer dans les menus. Pour remédier à

ce problème, il est nécessaire d’isoler et de comprendre les effets relatifs des différents facteurs impliqués dans la conception d’interfaces modulaires à changement de forme avant d’évaluer le système dans son ensemble. L’un des défis est que l’interaction avec les interfaces à changement de forme mobilise plusieurs modalités, telles que le retour visuel ou haptique. Notre travail vise à faciliter davantage d’évaluations utilisateurs en identifiant les facteurs de conception critiques et leur impact sur l’interaction utilisateur, en s’appuyant sur les recherches en IHM *et* en robotique.

L’un des objectifs de cette thèse est de faciliter l’évaluations utilisateurs des interfaces modulaires à changement de forme. Nous devons non seulement mettre en lien les travaux antérieurs en IHM et en robotique afin de comprendre les facteurs impliqués dans la conception de ces interfaces (Problème 1), mais nous devons également isoler les facteurs de conception critiques et comprendre leur effet relatif sur l’interaction utilisateur (Problème 2).

**Objectif 3 :** Isoler les facteurs critiques dans la conception des interfaces modulaires à changement de forme.

**Objectif 4 :** Comprendre l’impact de ces facteurs sur l’interaction utilisateur.

### Méthodologie de recherche

Notre approche pour combler le fossé entre les domaines de l’IHM et de la robotique, et pour informer la conception des interfaces modulaires à changement de forme dès le début implique (1) une approche centrée sur l’utilisateur et (2) un programme de doctorat supervisé conjointement par des chercheurs des deux disciplines.

Pour tenir compte de la nature multidisciplinaire de notre travail, nous avons développé une méthodologie en deux parties, qui comprend :

1. La réalisation d’une revue systématique de la littérature dans les domaines de l’IHM et de la robotique afin de relier et structurer l’espace interdisciplinaire des interfaces modulaires à changement de forme.
2. La conception et la réalisation d’études utilisateurs visant à isoler et évaluer l’impact de trois paramètres de conception sur l’interaction des utilisateurs avec les futures interfaces modulaires à changement de forme. Ces paramètres sont la taille des modules, leur forme et la force de liaison.

La Figure 8.3 présente notre approche de recherche : nous avons d’abord défini un espace de conception pour les interfaces modulaires à changement de forme [232], puis nous avons entrepris d’étudier l’impact de trois paramètres de conception des modules identifiés sur l’interaction des utilisateurs : (1) leur taille [234] et (2) leur forme et leur force de liaison [233].

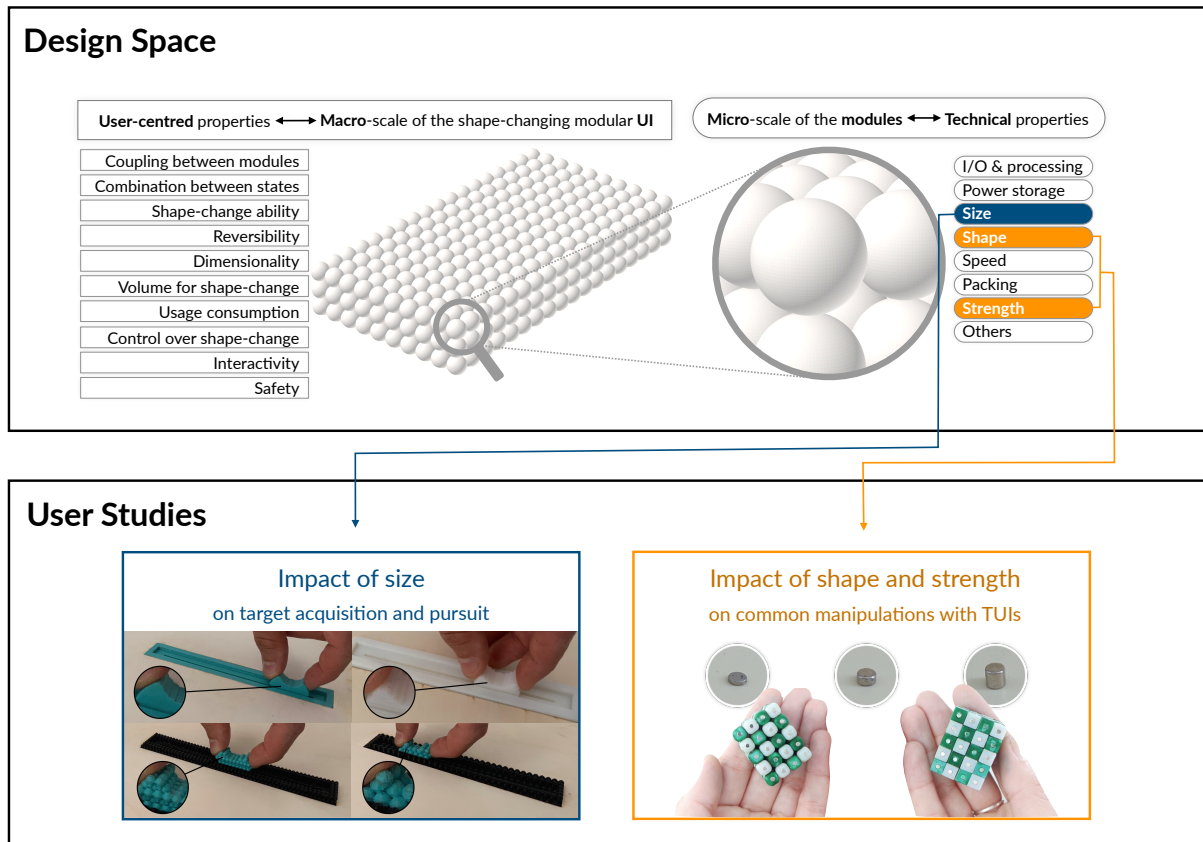


Figure 8.3: Notre approche de recherche : nous avons d’abord défini un espace de conception pour les interfaces modulaires à changement de forme, puis nous avons entrepris d’étudier l’impact de trois paramètres de conception des modules identifiés sur l’interaction des utilisateurs.

### Construction d’un espace de conception interdisciplinaire structuré

Les communautés IHM et robotique ont toutes deux réalisé des travaux sur les interfaces utilisateur modulaires à changement de forme au fil des années, mais ont rarement interagi. De plus, la communauté robotique a mené des travaux visant à formaliser et classer les spécificités techniques des implémentations de robotique modulaire. Ils ont également spécifié comment, par exemple, les exigences de conception pour un robot modulaire de type “chaîne” diffèrent de celles d’une implémentation en essaim [314]. Cependant, la communauté IHM n’a pas systématiquement exploité de telles classifications. A l’inverse, nous retrouvons des exigences de conception qui abordent chacune un ensemble local de propriétés de conception, plutôt qu’une vision globale. Par conséquent, bien que nous trouvions des outils pour la conception de systèmes modulaires dans la littérature, ils ne sont pas forcément cohérents et sont parfois même contradictoires. Par exemple, Cubimorph exige que tous les modules soient constamment attachés [247], tandis que Zooids exige que tous les modules soient constamment détachés [159].



Nous avons réalisé une revue systématique de la littérature pour étudier les travaux antérieurs à la fois en IHM et en robotique, en suivant la méthode PRISMA (une méthodologie standard en quatre étapes)[167, 302]. Nous avons recueilli des références axées sur des implémentations, des outils pour la conception et des revues de la littérature. Nous les avons mis en lien pour identifier et fusionner les paramètres de conception communs, à l'échelle de l'interface et à l'échelle des modules individuels. Enfin, lorsque cela était pertinent, nous avons utilisé des critères ergonomiques existants pour anticiper l'impact attendu sur l'interaction utilisateur[24], ainsi que des travaux de la communauté Interaction Humain-Robot pour définir des exigences préliminaires en matière de sécurité [122, 123].

### **Explorer empiriquement l'impact des paramètres de conception des modules**

Il apparait que les propriétés de conception peuvent être considérées à deux niveaux d'abstraction : ce que nous appelons l'échelle "*micro*" fait référence aux propriétés à l'échelle des modules, et ce que nous appelons l'échelle "*macro*" fait référence aux propriétés à l'échelle de l'interface. Par comparaison, l'équivalent à l'échelle micro des interfaces graphiques serait à l'échelle des pixels (par exemple, leur taille ou leur couleur), tandis que les propriétés à l'échelle macro seraient à l'échelle de l'ensemble de l'interface utilisateur (par exemple, sa résolution ou ses modalités d'interaction). Par la suite, nous avons choisi de concentrer le reste de cette thèse sur l'étude de l'impact des propriétés de conception isolées à l'échelle micro sur l'interaction utilisateur. Ce choix a été motivé par le fait que les propriétés à l'échelle de l'interface dépendent fortement de celles à l'échelle des modules [232]. En reprenant la comparaison avec les interfaces graphiques, la taille des pixels aurait un impact sur la résolution de l'interface. De plus, des travaux antérieurs ont souligné que la plage de tailles actuelle des modules pose un défi pour la communauté de recherche, et qu'il est nécessaire de disposer de mécanismes d'actionnement petits et légers, mais solides [19]. La force de liaison et la forme des modules sont les deux autres paramètres sur lesquels nous nous sommes concentrés, car ils pouvaient être facilement évalués avec des modules 3D statiques imprimés en 3D. Cela élimine le problème de fragilité connu dans la recherche sur les interfaces à changement de forme [19]. Quant aux autres propriétés à l'échelle micro, l'impact de l'arrangement des modules ne pouvait pas être isolé sans étudier au préalable la force de liaison, et les trois autres (c'est-à-dire la vitesse, le stockage d'énergie, les capacités d'Entrée/Sortie et de traitement) sont plus difficiles à mettre en œuvre et à isoler en raison des limitations matérielles actuelles.

Tout d'abord, nous avons réalisé deux études utilisateurs pour évaluer l'impact de quatre tailles de modules sur l'interaction avec un curseur tangible linéaire : un curseur lisse et simple (taille du module 0 mm) et trois curseurs composés de modules factices de  $\varnothing 1$  mm,  $\varnothing 2,5$  mm ou  $\varnothing 5$  mm. La première étude utilisateur consistait en une tâche de poursuite de cible, afin d'évaluer l'impact de chaque condition sur l'interaction linéaire continue. La deuxième étude utilisateur

---

consistait en une tâche d'acquisition de cible, afin d'évaluer l'impact de chaque condition sur une interaction plus discrète et rapide. Dans le but de recueillir des retours subjectifs qualitatifs, nous avons mené des entretiens semi-structurés pour les deux études utilisateurs. De plus, nous avons enregistré et analysé les prises effectuées par les participants afin de les mettre en relation avec leurs performances et les résultats subjectifs qualitatifs.

Ensuite, nous avons réalisé une étude utilisateur pour évaluer l'impact de deux formes de modules (cubes et cubes arrondis) et de trois niveaux de force de liaison entre les modules (faible, moyen et élevé) sur des manipulations tangibles courantes. Dans cette optique, nous avons isolé huit types de manipulations couramment réalisées avec des interfaces tangibles (modulaires ou non) : séparer les modules (un module, deux modules, une ligne de modules ou la moitié des modules), soulever les modules d'une table, faire glisser une partie des modules pour former une forme de manette, plier les modules de manière similaire à une interaction basée sur la pression, plier les modules en deux. Nous avons mené des entretiens semi-directifs pour recueillir des données subjectives qualitatives. Nous avons également filmé les mains des participants, mais nous n'avons pas analysé les données vidéo.

## Contributions

Dans le domaine de l'interaction humain-machine, cette thèse contribue au domaine des interfaces utilisateur modulaires à changement de forme, mais peut également être étendue aux domaines plus larges, tels que l'interaction tangible ou haptique. Nos principales contributions sont les suivantes :

1. Un espace de conception structuré pour la conception d'interfaces utilisateur modulaires à changement de forme.
2. La caractérisation et l'évaluation de l'impact de trois paramètres de conception à l'échelle des module sur l'interaction utilisateur.

### **Contribution 1 : Un espace de conception pour les interfaces utilisateur modulaires à changement de forme.**

Notre première contribution est un espace de conception pour les interfaces utilisateur modulaires à changement de forme, qui étudie et structure les travaux antérieurs en IHM et en robotique. Cet espace de conception est articulé autour de deux types de propriétés (macro/micro).

**Les propriétés à l'échelle de l'interface** (échelle macro) caractérisent l'interface utilisateur dans son ensemble. Les propriétés à l'échelle macro sont articulées autour de trois niveaux : Le niveau numérique (c'est-à-dire la position et l'état de tous les modules dans le modèle computationnel). Le niveau physique (c'est-à-dire la physique de l'interface utilisateur, les propriétés

de l'artefact tangible composé de modules physiques). Le niveau d'interaction (c'est-à-dire les éléments liés à la conception de l'interaction entre l'interface et l'utilisateur). Étant donné que les utilisateurs interagissent directement avec l'interface, nous caractérisons l'impact attendu des propriétés à l'échelle macro sur l'interaction utilisateur en les reliant aux travaux antérieurs en IHM, en ergonomie ou en interaction homme-robot.

**Les propriétés à l'échelle des modules** (échelle micro) caractérisent les modules individuels qui composent l'interface utilisateur dans son ensemble. Les propriétés à l'échelle micro sont articulées autour de trois niveaux : Le niveau intra-module (c'est-à-dire les éléments incorporés dans le module). Le niveau du module (c'est-à-dire l'enveloppe du module). Le niveau inter-modules (c'est-à-dire si et comment les modules sont attachés les uns aux autres). La conception des modules dans une interface utilisateur à changement de forme peut être comparée à la conception des pixels dans une interface graphique. Bien que les utilisateurs se concentrent sur l'interface dans son ensemble plutôt que sur les pixels individuels, la conception des pixels (par exemple leur taille, leur forme ou leur nombre/configuration) a un impact sur la conception de l'interface et donc sur la perception de l'utilisateur.

Enfin, notre espace de conception caractérise l'impact des propriétés à l'échelle macro et micro les unes sur les autres. Comprendre comment les propriétés s'impactent mutuellement est extrêmement important, car la conception d'interfaces utilisateur à changement de forme modulaire nécessite des compromis (par exemple, réduire la taille d'un module nécessite de réduire le nombre/taille de ses composants, ce qui peut entraîner une réduction de son autonomie de batterie ou des composants d'E/S qu'il peut intégrer). Donner aux concepteurs une première vue d'ensemble de l'impact de l'altération d'un paramètre sur leur conception globale est un aspect clé de notre contribution.

## **Contribution 2: Caractérisation et évaluation de l'impact de la taille, de la forme et de la force de liaison des modules sur l'interaction utilisateur**

Notre deuxième contribution consiste en des lignes directrices et des recommandations de conception issues de la caractérisation et de l'évaluation de l'impact de trois paramètres de conception à l'échelle micro sur l'interaction utilisateur. Nous nous sommes particulièrement concentrés sur la taille, la forme et la force de liaison des modules.

**Taille des modules.** Notre contribution réside dans l'évaluation de la taille des modules sur l'interaction utilisateur avec des curseurs linéaires physiques. L'implémentation d'interfaces modulaires pose le problème de la rugosité de surface, car les espaces entre les modules et/ou les bosses qu'ils créent (en particulier pour les modules (quasi-)sphériques) ne permettent généralement pas d'obtenir une surface plate et lisse. Des travaux antérieurs ont déjà étudié l'impact de la rugosité

---

lors du contact direct avec des doigts (1) statiques et (2) en mouvement [104, 263, 219, 194] et à l'aide d'une sonde [148, 157, 319, 318], mais, à notre connaissance, notre étude est la première à étudier l'impact de deux objets rugueux utilisés l'un sur l'autre. En effet, la mise en œuvre d'interfaces modulaires peut nécessiter l'utilisation de deux objets constitués de modules l'un sur l'autre (par exemple, un bouton de curseur sur son rail) ou d'un objet constitué de modules sur une surface. Dans le cadre de deux études utilisateur contrôlées, nous évaluons l'impact de trois tailles de modules ( $\varnothing 1\text{mm}$ ,  $\varnothing 2.5\text{mm}$ ,  $\varnothing 5\text{mm}$ ) sur l'interaction utilisateur avec un curseur linéaire pour effectuer deux tâches : une tâche d'acquisition de cible et une tâche de poursuite de cible. Bien que l'objectif général de cette thèse soit de contribuer à la recherche en IHM sur les interfaces à changement de forme, le fait que nous ayons utilisé des modules statiques dans la conception de nos prototypes nous a amenés à nous inspirer des domaines de l'interaction tangible et de l'interaction haptique. Les résultats de nos études utilisateur peuvent à leur tour contribuer à ces domaines. Par exemple, pour cette contribution, nous nous appuyons sur des travaux antérieurs sur la perception de la rugosité et du frottement programmable issus de la communauté haptique. Nous relient donc nos résultats à des études antérieures sur le frottement programmable et tirons des conclusions sur les implications possibles pour la conception de futurs curseurs physiques à changement de forme offrant une physicalité programmable.

**Forme et force de liaison des modules.** Notre contribution réside dans la caractérisation du compromis entre solidité et détachabilité de l'interface utilisateur modulaire dans son ensemble. Nous établissons un lien entre la forme et la force de liaison des modules et l'impact de ce compromis en menant une étude utilisateur avec deux conditions de forme (cubes avec des arêtes vives et cubes arrondis) et trois conditions de force de liaison (faible, moyenne ou élevée) dans le contexte de huit manipulations courantes que l'on retrouve dans la littérature sur les interfaces tangibles (non-)modulaires. Nous trouvons plusieurs formes de modules dans la littérature, mais les formes les plus courantes semblent être des cubes à bords droits [84, 247, 279], des cubes à bords arrondis [83, 246, 86], ou des quasi-sphères [206, 267, 38, 200]. Le choix des auteurs concernant la forme de leurs modules semble le plus souvent dicté par des contraintes technologiques, avec quelques exceptions motivées par des considérations d'utilisabilité. Par exemple, Cubimorph a choisi des bords droits pour obtenir une surface lisse [247], tandis que les auteurs des Catoms soutiennent qu'une quasi-sphère est la meilleure forme pour miniaturiser les modules, car elle réduit la distance entre deux actionneurs [222]. À notre connaissance, aucune étude antérieure n'a étudié comment arrondir les bords des modules pourrait impacter l'interaction avec un ensemble de modules tangibles. De plus, la force de liaison qui maintient les modules ensemble semble également être dictée par des contraintes technologiques. L'influence de la force de liaison entre les modules sur l'interaction utilisateur n'est pas claire, notamment parce que les scénarios d'application présentés dans la littérature en IHM nécessitent à la fois que l'interface soit

suffisamment stable pour maintenir sa forme tout en permettant aux utilisateurs de détacher un module ou une partie de l'interface. Par exemple, Pickcells [86] nécessite une force de liaison suffisamment forte pour permettre d'interagir de manière mobile en tenant l'interface dans la main, mais suffisamment faible pour que certains modules puissent être détachés, par exemple pour être partagés avec un autre utilisateur. Ainsi, nous conduisons une étude utilisateur pour recueillir des retours subjectifs sur l'impact de la forme et de la force de liaison des modules, et nous en tirons des conclusions sur les implications possibles pour la conception d'interfaces modulaires à changement de forme utilisant des aimants comme mécanismes d'actionnement.

## Structure de la thèse

Cette section présente le plan de la thèse (Figure 8.4).

Tout d'abord, nous posons les bases de la thèse dans un chapitre d'introduction qui présente les travaux connexes et le contexte de la recherche (Chapitre 2). Nous y exposons comment les interfaces à changements de forme ont émergé dans les communautés de recherche en robotique et en IHM. En particulier, nous soulignons les différences clés entre les besoins et les utilisations de ces deux communautés pour de telles interfaces, ce qui peut expliquer les différences dans la manière dont elles ont abordé le sujet au fil des ans et les différences dans les défis auxquels elles sont confrontées [314, 19]. Ce chapitre présente également les concepts clés relatifs aux classifications techniques des interfaces à changements de forme modulaires, tels que leur architecture et leurs stratégies de reconfiguration. Bien que implicitement centré sur l'utilisateur, il est essentiel de comprendre ces concepts pour recentrer la conception sur l'utilisateur.

Ensuite, nous présentons les travaux réalisés dans cette thèse. Comme cette thèse comprend deux types principaux de contributions, nous articulons la présentation de notre travail en deux parties.

La **Partie I** présente nos travaux préliminaires, qui comprennent notre espace de conception structuré interdisciplinaire pour les interfaces à changements de forme modulaires. Tout d'abord, nous présentons la méthodologie et l'analyse de corpus résultant d'une revue systématique de la littérature axée sur les travaux antérieurs réalisés en IHM et en robotique (Chapitre 3). Ensuite, nous présentons notre ensemble de propriétés de conception à l'échelle de l'interface globale (*macro-échelle*) et à l'échelle des modules individuels (*micro-échelle*) (Chapitre 4). Nous les relient notamment à leur impact attendu sur l'interaction utilisateur selon les normes en ergonomie et en interaction homme-robot (Chapitre 5). Nous présentons également comment les propriétés à l'échelle macro et micro s'influencent mutuellement.

La **Partie II** présente notre évaluation empirique de trois paramètres de conception impliqués dans l'implémentation d'interfaces à changements de forme modulaires. Tout d'abord, nous présentons les résultats de deux études utilisateurs contrôlées sur la taille des modules pour

---

l'acquisition et le suivi de cibles avec un curseur linéaire tangible (Chapitre 8.3.3). Nous étudions la fourchette de tailles de modules utilisables et leurs implications pour la conception. Ensuite, nous présentons les résultats d'une étude utilisateur contrôlée sur l'impact de la forme et de la force de liaison des modules sur huit manipulations couramment trouvées dans la littérature sur les interfaces tangibles (non-)modulaires (Chapitre 8.3.3).

Pour conclure ce manuscrit, le Chapitre 8.3.3 présente les limitations et les travaux futurs de cette thèse, ainsi que les perspectives que nous envisageons pour la conception futures d'interfaces modulaires à changements de forme.

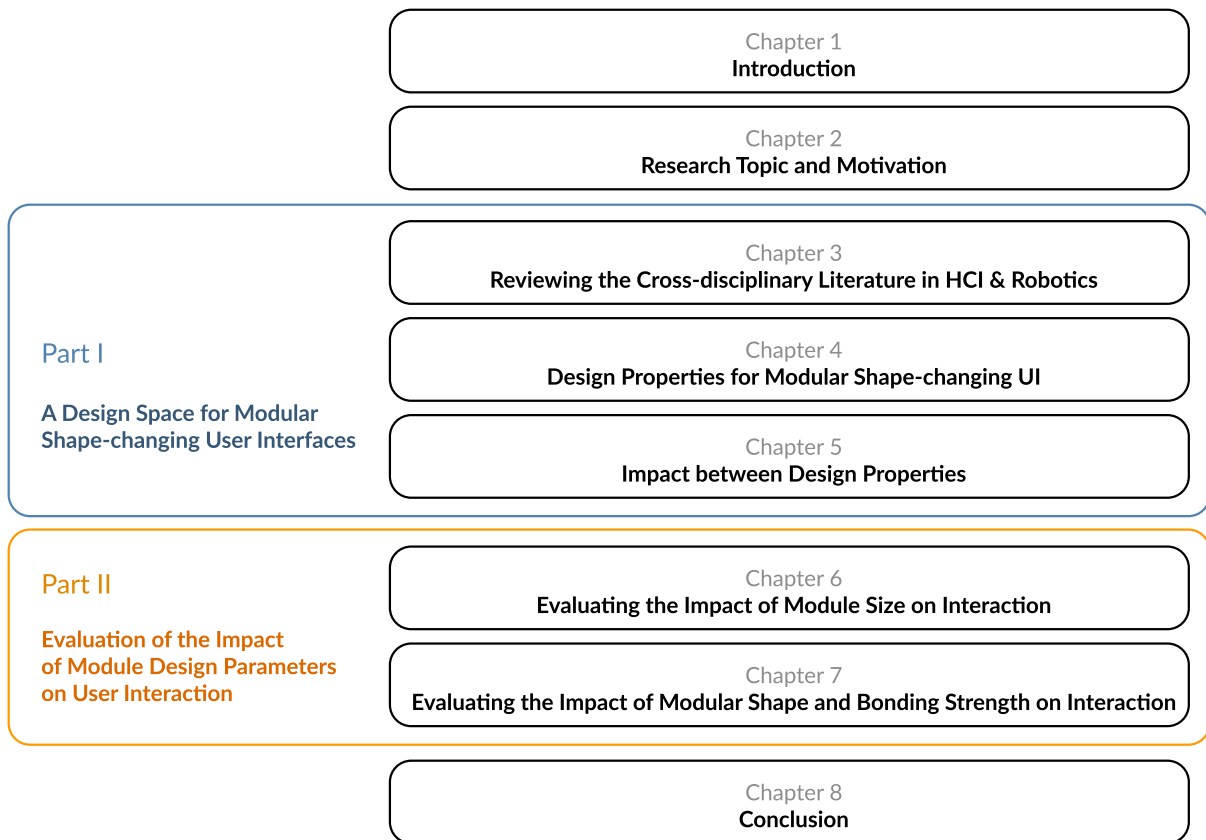


Figure 8.4: Structure de la thèse.

## Etat de l’art

Dans ce chapitre, nous explorons la littérature en IHM et en robotique concernant les interfaces utilisateur modulaires à changement de forme. Le travail que nous présentons dans cette thèse s’inscrit dans la continuité des travaux antérieurs sur les interfaces utilisateur à changement de forme de la communauté IHM, avec des concepts tirent leurs origines des interfaces graphiques et tangibles. C’est pourquoi nous présentons d’abord ces deux concepts pour poser les bases et la motivation de notre propre travail (Section 2.2).

Dans le cadre de cette thèse, nous avons également exploré la robotique modulaire et les opportunités qu’elle présente pour l’implémentation d’interfaces modulaires à changement de forme. Comme nous utiliserons leur vocabulaire et leurs concepts, nous présentons les travaux connexes dans le domaine de la robotique (Section 2.3). Nous présentons notamment les classifications de robots modulaires en fonction de leur architecture et de leur type de reconfiguration, car nous utilisons ces classifications dans la Partie I.

Enfin, nous présentons les prototypes existants et les travaux précédemment menés sur l’implémentation d’interfaces utilisateur à changement de forme avec des robots modulaires, leurs avantages et implications, ainsi que l’importance d’évaluer comment les utilisateurs perçoivent et expérimentent le changement de forme et la modularité (Section 2.4).

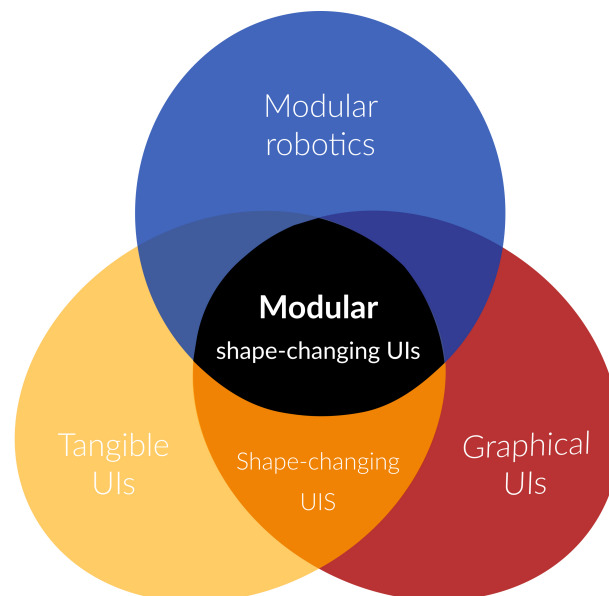


Figure 8.5: Alors que les interfaces utilisateur à changement de forme se situent entre les interfaces utilisateur et les interfaces graphiques, les interfaces modulaires à changement de forme se situent entre les interfaces utilisateur à changement de forme et la robotique modulaire.

---

## Partie 1 - Un espace de conception pour les interfaces utilisateur modulaires à changement de forme

### Publication

Le travail présenté dans cette partie a été publié à EICS'21  
(*Engineering Interactive Computing System*) [232].

Les chapitres de cette partie présentent nos travaux sur l'exploration systématique de la littérature sur les interfaces modulaires à changement de forme, qui ont conduit à l'étude et à la structuration de l'espace de conception interdisciplinaire. Étant donné que les travaux sur le sujet couvrent à la fois les communautés IHM et robotiques et englobent des décennies de recherche, il s'agit d'une première étape importante afin de mieux comprendre les propriétés à prendre en compte dans la conception d'interfaces modulaires à changement de forme. Notre objectif est de combler le fossé entre l'expertise des chercheurs en robotique dans la conception et la réalisation de robots modulaires, et le besoin des chercheurs en IHM de comprendre les différents paramètres de conception à prendre en compte dans leur implémentation, ainsi que leur impact mutuel. Nous nous appuyons sur la littérature des deux domaines pour proposer :

1. Un ensemble de **propriétés à l'échelle de l'interface** (*macro-échelle*) (Figure 8.6, gauche),
2. Un ensemble de **propriétés à l'échelle des modules** (*micro-échelle*) (Figure 8.6, droite),
3. Une analyse de leurs dépendences.

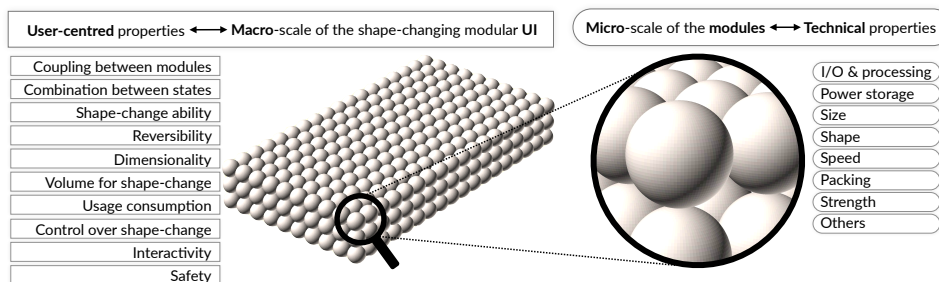


Figure 8.6: Our structured space of properties: (left) user centered properties at the macro scale of the shape-changing modular UI, and (right) technical properties at the micro-scale of the modules.



## **Partie 1 - Chapitre 3 : Etude de la littérature interdisciplinaire en IHM et en robotique**

Notre premier objectif est de mieux comprendre (1) comment concevoir et implémenter des systèmes modulaires et (2) comment les choix de conception peuvent avoir un impact sur l'interaction utilisateur. Pour atteindre cet objectif, nous devons d'abord examiner la littérature sur les interfaces utilisateur modulaires à changement de forme, qui couvre à la fois les communautés IHM et robotique.

Cela représente un défi car les travaux en IHM et en robotique s'étendent sur plusieurs décennies (à partir de 2007 en IHM [179] et de 1990 en robotique [81]), sans utiliser les mêmes vocabulaires (par exemple, "interface utilisateur à changement de forme" en IHM et "matière programmable" en robotique). Il n'existe d'ailleurs aucune définition exhaustive pour "robots modulaires". Dans ce chapitre, nous définissons les robots modulaires comme un ensemble de modules robotiques, c'est-à-dire des systèmes micro-électromécaniques intégrant des capacités de calcul, leur permettant de changer de forme (par eux-mêmes ou non). Nous nous concentrons sur les modules incorporant des "capacités de calcul" et nous ne considérons pas uniquement les systèmes "auto-actionnés". Cette décision est motivée par le fait que certaines implémentations existantes qui reposent sur une action externe pour changer de forme intègrent néanmoins des capacités informatiques.

Nous menons une exploration systématique de la littérature à la fois en IHM et en robotique. Nous suivons la méthodologie en quatre étapes PRISMA [167], comme dans des travaux antérieurs [302] : identification, sélection, éligibilité et inclusion. Cela nous permet d'étudier systématiquement la littérature et de rassembler un corpus de 605 articles. Ce chapitre présente notamment la méthodologie que nous avons suivie et le corpus que nous avons obtenu. Nous présentons ensuite les propriétés de conception tirées de cette analyse dans les deux chapitres suivants (Chapitres 4 et 5).

---

## Partie 1 - Chapitre 4 : Paramètres de conception pour les interfaces utilisateur modulaires à changement de forme

Nous avons suivi la méthodologie PRISMA [167] et obtenu un corpus de 605 articles sur les systèmes modulaires provenant à la fois de l'IHM et de la robotique. Nous exploitons maintenant ce corpus pour identifier les propriétés impliquées dans la conception de systèmes modulaires.

Notre objectif est d'unifier et de structurer les propriétés de conception existantes et de les recentrer autour de l'utilisateur. Nous adoptons donc une approche en six étapes pour analyser notre corpus.

1. Nous identifions les propriétés pertinentes guidant la conception des implémentations existantes ou proposées.
2. Nous fusionnons les propriétés identiques.
3. Nous regroupons les propriétés qui définissent de manière complémentaire une propriété de niveau supérieur (par exemple, le couplage entre les modules présenté dans la sous-section 4.2.1).
4. Nous définissons précisément les propriétés que nous avons trouvées peu claires.
5. Nous les structurons en gardant à l'esprit le concepteur (par exemple, en les classant en propriétés macro et micro).
6. Enfin, nous étudions leurs dépendances.

Nous pouvons comparer la conception des interfaces utilisateur modulaires à changement de forme à la conception des interfaces utilisateur graphiques (GUI) : lors de la conception d'une interface graphique, nous ne nous concentrons pas uniquement sur la conception de chaque pixel individuel. Les propriétés des pixels sont importantes (par exemple, leur taille, les couleurs qu'ils peuvent prendre, leur luminosité), mais ce qui est surtout important du point de vu de l'utilisateur final, c'est l'ensemble de l'interface que ces pixels composent, et avec laquelle il interagit.

Nous suivons le même raisonnement pour la conception de robots modulaires et d'interfaces utilisateur modulaires à changement de forme.

Tout d'abord, nous présentons les propriétés qui influencent le système à l'échelle de l'interface au niveau globale (macro-échelle). Nous identifions dix propriétés qui influencent l'interaction de l'utilisateur aux niveaux numérique, physique et interactif.

Ensuite, nous présentons les propriétés qui influencent le système à l'échelle de chaque module individuel (micro-échelle). Nous identifions sept propriétés qui jouent un rôle au niveau intra-module, module global ou inter-module.

## Partie 1 - Chapitre 5 : Impact entre les propriétés

Nous avons identifié et défini les propriétés des interfaces utilisateur modulaires à changement de forme à l'échelle macro de l'interface (section 4.2) et à l'échelle micro des modules (section 4.3). Cependant, savoir quelles propriétés existent et comprendre l'impact de l'architecture et du type de reconfiguration du système peut ne pas être suffisant. Nous devons caractériser comment ces propriétés s'impactent mutuellement. Ainsi, nous devons prendre en compte les *dépendances* entre elles. Il existe des dépendances au sein des propriétés à l'échelle macro, au sein des propriétés à l'échelle micro, mais les propriétés macro et micro s'impactent également mutuellement. Par conséquent, les propriétés techniques des modules peuvent avoir un impact indirect sur l'interaction de l'utilisateur avec l'interface par le biais de leur impact sur les propriétés à l'échelle macro.

Dans ce chapitre, nous étudions l'impact entre les propriétés. Tout d'abord, nous présentons l'impact au sein des propriétés à l'échelle macro. Ensuite, nous présentons l'impact au sein des propriétés à l'échelle micro. Enfin, nous présentons l'impact entre les propriétés à l'échelle macro et micro.

---

## Partie 2 : Evaluation de l'impact de paramètres de conceptions des modules sur l'interaction utilisateur

### Publications

- Les travaux présentés dans cette partie ont été publiés à
- (1) ICMI'21 (*International Conference on Multimodal Interaction*) [234] et
  - (2) TEI'23 (*Tangible and Embodied Interaction*) [233].

Nous avons présenté notre première contribution dans la Partie I. Nous avons fourni un espace de conception structuré comprenant dix propriétés à l'échelle globale de l'interface (*macro-échelle*) et sept à l'échelle des modules individuels (*micro-échelle*). Ensuite, nous avons caractérisé leur impact les unes sur les autres et avons observé que les deux propriétés à l'échelle micro qui semblent avoir le plus de dépendances avec les autres propriétés, à la fois micro et macro, sont la *taille* et la *force* des modules. Étant donné que ces deux propriétés semblent être critiques dans la conception globale d'un système modulaire, nous cherchons à mieux comprendre leur impact sur l'interaction avec l'utilisateur. Notre objectif est de fournir aux concepteurs une compréhension de l'impact de la modification de ces paramètres sur l'interaction avec leur système. Par exemple, nous pourrions soutenir que la plus petite taille possible des modules est souhaitable pour l'utilisateur, car cela conduirait à une résolution plus élevée de l'affichage de la forme, même si cela entraînerait une capacité de stockage d'énergie et une interactivité plus faibles. Mais est-ce que les utilisateurs préféreraient vraiment des modules plus petits ? Le compromis en vaut-il la peine ? Ainsi, notre travail dans cette partie ne se concentrera pas seulement sur l'impact de la modification d'un paramètre à l'échelle micro sur l'interaction avec l'utilisateur, mais nous opérerons également sur un compromis « *utilisabilité-faisabilité* ».

Le premier chapitre met l'accent sur l'évaluation de l'impact de la *taille* des modules sur l'interaction. Nous présentons notamment comment les travaux connexes en haptique et en psychophysique ont réalisé des études approfondies sur la perception de la rugosité et des interfaces composées de petites sphères, mais manquent d'études sur l'impact de l'utilisation de deux interfaces tactiles rugueuses l'une sur l'autre. Nous présentons les conceptions et les résultats de deux études utilisateurs pour étudier l'impact de la taille des modules sur l'acquisition de cibles et la poursuite avec quatre curseurs linéaires tangibles composés de modules.

Le deuxième chapitre se concentre sur l'évaluation de l'impact de la *force de liaison* et, en plus, de la *forme* des modules sur l'interaction. Étant donné que nous avons constaté dans le Chapitre 5 que la forme a un impact important sur la force de liaison, nous souhaitons étudier l'effet combiné de la force et de la forme.

## Partie 2 - Chapitre 6 : Étude de l'impact de la taille des modules sur l'interaction

Dans la Partie I de cette thèse, et plus particulièrement dans les chapitres 4 et 5, nous avons constaté que la taille des modules est un paramètre central dans la conception des interfaces utilisateur modulaires à changement de forme, car elle influence un grand nombre d'autres propriétés. D'une part, plus les modules sont petits, moins ils offrent de capacités de stockage d'énergie, d'entrée/sortie et de traitement, ce qui se traduit par un contrôle moindre sur le changement de forme et l'interactivité. D'autre part, plus les modules sont petits, plus la résolution de la forme est élevée. Ainsi, plus la capacité de changement de forme est grande, plus l'interface est fluide et la résolution spatiale est élevée. Étant donné que la faisabilité technologique des interfaces utilisateur modulaires à changement de forme semble dépendre fortement de la taille des modules, il est important d'étudier l'impact de la taille des modules. Cela peut aider les concepteurs et les chercheurs à comprendre le compromis entre l'utilisabilité et la faisabilité technologique.

Nous présentons les résultats de deux études évaluant quatre tailles de modules constituant une interface tangible (plus précisément un curseur) : un curseur lisse et simple (modules d'une taille d'environ 0 mm) et trois curseurs composés de modules factices ("*mockup*") de  $\varnothing 1$  mm,  $\varnothing 2.5$  mm et  $\varnothing 5$  mm. Nous constatons que : (1) les plus grands modules ( $\varnothing 5$  mm) affectent significativement les performances lors d'une tâche de poursuite et la perception subjective lors des tâches de poursuite et d'acquisition de cible, (2) les performances s'améliorent lorsque la taille des modules diminue, mais (3) les utilisateurs ont apprécié les retours haptiques des modules de  $\varnothing 1$  mm et  $\varnothing 2.5$  mm (par exemple, pour freiner, changer de vitesse et changer de direction). Ces résultats fournissent une compréhension approfondie de la manière dont les utilisateurs interagissent avec un dispositif composé de petits modules arrondis, ce qui permet d'orienter les objectifs technologiques futurs pour les interfaces tangibles à changement de forme.

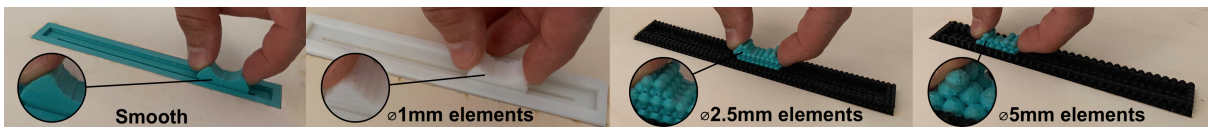


Figure 8.7: Les quatre curseurs utilisés pour étudier l'impact de la taille des futurs modules constituant l'interface utilisateur tangible : (de gauche à droite) un curseur lisse actuel et trois curseurs composés de modules prototypes de  $\varnothing 1$  mm,  $\varnothing 2.5$  mm et  $\varnothing 5$  mm.

---

## Partie 2 - Chapitre 7 : Évaluation de l'impact de la forme des modules et de la résistance de liaison sur l'interaction

Dans ce chapitre, nous cherchons à comprendre comment le compromis entre la solidité globale de l'interface et la détachabilité des modules affecte l'interaction de l'utilisateur avec des interfaces tangibles modulaires. Nous menons une première étude avec des aimants passifs comme mécanisme de liaison entre des modules physiques. Les aimants passifs, bien qu'ils ne soient pas aussi puissants que d'autres alternatives, telles que des pinces mécaniques [206], des charnières [247] ou des électroaimants [102, 202], sont simples à utiliser et permettent aux modules de s'aligner automatiquement [246]. Les aimants aident les utilisateurs à reconfigurer des interfaces utilisateur composées de modules à petite échelle, à la fois en 2D (par exemple, [165, 86]) et en 3D (par exemple, [246, 279]). De plus, leur faible coût et leur petite taille permettent l'implémentation d'interfaces utilisateur modulaires évolutives, bon marché et hautement reconfigurables. Pour les modules magnétiques, nous nous attendons à ce que le compromis détachabilité/solidité de l'interface dépende de la force des aimants eux-mêmes (que nous appelons "*force de liaison*"), ainsi que de la forme des modules. Comme avec des briques LEGO [94], nous nous attendons également à ce que le compromis détachabilité/solidité dépende de la configuration des modules : des travaux antérieurs ont mentionné que plus la structure globale est dense, plus elle doit être solide (Partie I), mais aucune étude utilisateur n'a été réalisée pour mesurer cet impact et informer la conception. Le problème que nous abordons dans ce chapitre est le manque de connaissances sur la *plage utilisable de la résistance de liaison entre les modules magnétiques* – c'est-à-dire le compromis entre détachabilité et solidité – ainsi que *comment la forme des modules et leur configuration* peuvent influencer davantage ce compromis.

Aborder ce problème est important et opportun (1) pour informer le développement technologique et (2) pour éviter des choix de conception arbitraires et ad hoc à l'avenir. Les contributions dans le domaine des interfaces tangibles modulaires en sont encore aux stades de la conception et des prototypes plutôt que des techniques d'interaction et des études sur le terrain (par exemple, [165, 279, 86]). Les prototypes existants utilisent actuellement des formes et des résistances ad hoc qui sont technologiquement motivées et peuvent ne pas être optimisées pour les utilisateurs.

Cependant, nous prévoyons que la recherche sur les interfaces tangibles modulaires progressera au cours des prochaines années à mesure que la technologie s'améliorera.

Pour surmonter les défis de la réalisation d'études utilisateurs avec des interfaces tangibles modulaires, nous nous appuyons sur des travaux récents en robotique [97] pour construire de simples modules magnétiques passifs de  $6 \times 6 \times 6 \text{ mm}^3$ . Dans une étude utilisateur contrôlée, nous recueillons des évaluations subjectives (*difficulté, satisfaction, impact de la forme et impact de*

*la résistance*) pour huit types de manipulations tangibles et deux configurations de modules, réalisées avec trois niveaux de force de liaison – faible (aimants de 0,5 mm d'épaisseur et 0,49 N), moyen (1 mm, 0,98 N) et élevé (2 mm, 2,45 N) – et deux formes de modules (cubes et cubes arrondis).

Les résultats expérimentaux confirment non seulement l'existence d'un compromis entre détachabilité et solidité, mais mesurent également l'impact de la forme des modules et de la force de liaison sur ce compromis. Les participants ont trouvé les modules cubiques plus faciles et plus satisfaisants à manipuler, car ils offrent une interface stable et robuste même avec une faible force de liaison. En revanche, détacher un ou deux modules est plus facile et plus satisfaisant avec des modules arrondis, car les espaces entre les modules arrondis les rendent plus préhensiles, ou avec des modules cubiques avec une force de liaison plus basse (c'est-à-dire des aimants de 0,5 mm). Courber l'interface est plus facile avec des modules arrondis équipés d'aimants de 1 à 2 mm, car ils rendent toute l'interface plus flexible mais sont assez résistants pour ne pas casser.

---

## Conclusion

### Contributions de la thèse

Notre travail contribue principalement au domaine de l'IHM dans le domaine des interfaces utilisateurs à changements de forme. De plus, notre travail peut également être décrit comme contribuant à :

1. **Théories et concepts**, en proposant un espace de conception structuré pour les interfaces modulaires à changement de forme, en s'appuyant sur les travaux en IHM et en robotique.
2. **Connaissances empiriques**, en réalisant trois études utilisateurs contrôlées pour caractériser et comprendre l'impact de trois paramètres de conception sur l'interaction utilisateur : la taille, la forme et la force de liaison des modules. Les résultats de ces études peuvent également être étendus aux domaines de l'interaction tangible et haptique. Premièrement, nous avons relié nos résultats à des travaux antérieurs sur la friction programmable issus de la communauté haptique (Chapitre 8.3.3). Deuxièmement, nous avons étudié des dispositifs statiques imprimés en 3D qui ne changent pas de forme, en nous appuyant sur des travaux antérieurs de la communauté des interfaces tangibles (Chapitre 8.3.3).

Dans cette section, nous résumons nos contributions.

### **Théories et concepts : un espace de conception structuré pour les interfaces utilisateur modulaires à changement de forme**

Le premier problème que nous avons rencontré dans le contexte de cette thèse était la recherche cloisonnée entre IHM et la robotique, et par conséquent, l'absence d'un espace de conception structuré. En étudiant les précédents travaux menés dans ces communautés, nous avons constaté que les chercheurs en IHM et robotique avaient réalisé un travail approfondi sur les interfaces utilisateur modulaires à changement de forme, mais que leur vocabulaire et leurs exigences en matière de conception n'étaient ni structurés ni cohérents. Les deux principaux défis de cette contribution étaient les suivants :

- D'une part, les travaux antérieurs en IHM se sont essentiellement concentrés sur un ensemble restreint de directives qui correspondaient à leur conception spécifique.
- D'autre part, les travaux antérieurs en robotique ont proposé des revues de la littérature et des directives de conception, mais se sont concentrés sur la locomotion et la reconfiguration plutôt que sur l'interaction utilisateur.



Par exemple, les choix de conception de Cubimorph exigeaient que leurs modules soient constamment attachés pour éviter de tomber ou d’être perdus [247]. Ceci est une raison cohérente pour les implémentations en chaîne, comme c’est le cas pour Cubimorph, mais ne peut pas être appliquée aux implémentations en essaim qui nécessitent que les modules soient détachés et se déplacent indépendamment les uns des autres [159]. La plupart des implémentations en treillis qui suivent une approche "blocs de construction" nécessitent également que les modules puissent être détachés (par exemple, [147, 279, 86]). Parallèlement, les chercheurs en robotique ont établi des lignes directrices de conception en relation avec les différents types d’architectures et de types de reconfiguration de leurs implémentations [85, 177, 273]. Cependant, les travaux antérieurs en IHM et en robotique ont tous deux étudié des interfaces utilisateur modulaires à changement de forme dans le cadre de motivations et d’utilisations différentes. Étant donné qu’ils collaborent rarement, cela se traduit par des publications dans des espaces différents avec un vocabulaire différent. Par exemple, alors que les chercheurs en IHM utilisent souvent le terme “*interface à changement de forme*”, ce terme n’est jamais utilisé dans le domaine de la robotique où l’on préfère le terme “*robot modulaire à reconfigurable automatique*”. Cela rend difficile la capitalisation des travaux réalisés dans les deux communautés.

**Le premier objectif de cette thèse** était de comprendre les travaux antérieurs sur les interfaces utilisateur modulaires à changement de forme à la fois en robotique et en IHM, et comment ils se rapportent les uns aux autres. Nous avons réalisé une revue systématique de la littérature en IHM et en robotique. Nous avons catégorisé chaque article en fonction de sa contribution (c’est-à-dire des implémentations, des concepts, des outils de conception ou des revues de littérature). Afin de comprendre, unifier et structurer l’espace de conception des interfaces utilisateur modulaires à changement de forme, nous avons suivi une approche en six étapes pour analyser notre corpus :

1. **Identifier.** Nous avons identifié les propriétés pour la conception des interfaces utilisateur modulaires changeantes de forme dans la littérature de l’IHM et de la robotique.
2. **Fusionner.** Nous avons fusionné les propriétés qui étaient identiques (par exemple, “*hiérarchie*” se retrouve dans plusieurs publications sous des noms différents, tels que maître/esclave ou autonome/satellite).
3. **Grouper.** Nous avons regroupé les propriétés qui définissent de manière complémentaire un niveau supérieur (par exemple, “*détachabilité*” fait partie de la *capacité de changement de forme*” de l’interface, dans le cadre de la forme de changement “*modularité*”).
4. **Définir.** Nous avons précisément défini les propriétés que nous avons jugées peu claires.

- 
5. **Structurer.** Nous avons structuré les propriétés en gardant à l'esprit le concepteur, en les regroupant en propriétés à l'échelle macro et micro.
  6. **Étudier.** Enfin, nous avons étudié les dépendances entre les propriétés et les avons reliées les unes aux autres.

Cette analyse du corpus nous a permis de remplir notre premier objectif et de poser les bases de notre deuxième objectif.

**Le deuxième objectif de cette thèse** était de fournir un aperçu structuré des travaux antérieurs afin de fonder les développements futurs sur une exploration rationnelle. Dans ce but, nous avons exploité notre analyse de corpus et les classifications existantes de robots modulaires pour mettre en lien les propriétés avec les spécificités de chaque type d'architecture et de reconfiguration. Notre contribution est un ensemble de propriétés de conception cohérentes : (1) à l'échelle de l'interface elle-même (macro-échelle) et (2) à l'échelle des modules (micro-échelle). De plus, afin de faciliter les choix de conception et leur priorisation en fonction des besoins des utilisateurs, nous avons proposé (3) une caractérisation de l'impact des propriétés les unes sur les autres.

Dans l'ensemble, notre contribution est un espace de conception structuré qui permet aux concepteurs de décrire et de comparer les systèmes existants, ainsi que de générer de nouvelles conceptions. Nous avons donné un exemple du pouvoir descriptif, évaluatif et génératif de notre travail dans la conclusion de la partie 8.3.3. La caractérisation de l'impact des propriétés de conception les unes sur les autres est une contribution clé qui permet la génération de nouvelles conceptions. Les concepteurs peuvent anticiper dès les premières étapes de conception comment le fait de modifier un paramètre de conception spécifique peut avoir un impact sur les autres - que ce soit à l'échelle de l'interface ou à l'échelle des modules.

### **Études empiriques auprès des utilisateurs : caractérisation et impact de trois paramètres de conception sur l'interaction utilisateur**

Le deuxième problème rencontré dans le cadre de cette thèse était le manque d'études utilisateurs et le manque de connaissances empiriques sur l'impact de la modularité et du changement de forme sur l'interaction utilisateur. L'une des principales raisons de ce manque d'études est que les prototypes d'interfaces à changement de forme sont souvent insuffisamment robustes pour supporter une manipulation prolongée avec des utilisateurs [19]. De plus, les évaluations actuelles sont menées sur l'ensemble du système [19]. Cela peut entraîner des biais, car l'impact relatif des facteurs isolés n'est pas bien connu. Par exemple, si nous devions directement mener une évaluation utilisateur de chainFORM [196], il serait difficile de dissocier l'impact de la taille des

modules, de la résolution de l'interface, de la vitesse de reconfiguration, de la force du retour haptique appliqué ou des possibilités de changement de forme disponibles les uns des autres.

Dans le but de favoriser davantage d'évaluations utilisateurs dans le domaine des interfaces utilisateur modulaires à changement de forme, nous avons entamé le programme de recherche en isolant les facteurs individuels impliqués dans la conception de telles interfaces et en évaluant leur impact relatif sur l'interaction utilisateur.

**Le troisième objectif de cette thèse** était d'isoler les facteurs critiques dans la conception des interfaces utilisateur modulaires à changement de forme. Nous avons utilisé notre espace de conception, ainsi que des travaux antérieurs qui ont mis en évidence les défis actuels et attendus dans la recherche sur le changement de forme [19], pour identifier et isoler trois paramètres de conception critiques : la *taille*, la *forme* et la *force de liaison* des modules (voir Partie II).

**Le quatrième objectif de cette thèse** était de comprendre l'impact des facteurs isolés sur l'interaction utilisateur. Nous avons donc mené des expériences utilisateur pour comprendre comment ces paramètres influencent l'interaction et fournir des lignes directrices de conception à la communauté IHM. Notre objectif était d'informer la conception centrée sur l'utilisateur des futures interfaces modulaires à changement de forme en impliquant les utilisateurs dès les premières étapes de conception.

Dans l'ensemble, notre **contribution** à la recherche empirique en IHM peut être décrite selon deux axes principaux :

1. **Impact de la taille des modules** sur la poursuite et l'acquisition de cibles, avec une caractérisation de l'impact de la prise sur l'efficacité et les retours subjectifs. Quelques résultats clés de notre étude ont montré que, globalement :
  - (a) Plus les modules sont petits, meilleures sont les performances,
  - (b) Les participants ont apprécié la friction des modules de  $\varnothing 1\text{mm}$  et  $\varnothing 2.5\text{mm}$  car elle les a aidés à freiner et à changer de direction,
  - (c) Plus les modules sont grands, moins de prises peuvent être effectuées.
2. **Impact de la forme des modules et de la force de liaison** sur l'exécution de huit manipulations courantes issues de la littérature, avec la caractérisation d'un compromis entre solidité et détachabilité. Quelques résultats clés de notre étude ont montré que :
  - (a) les modules cubiques sont globalement plus faciles et plus satisfaisants à manipuler, sauf pour les tâches de précision et de flexion,

- 
- (b) une faible force de liaison nuit à la solidité de l'interface utilisateur, tandis qu'une force de liaison élevée entrave les tâches de précision avec des modules cubiques.

Nous fournissons les fichiers STL et les spécifications des potentiomètres pour reproduire les prototypes de l'étude présentée dans le chapitre 8.3.3. Ils peuvent être trouvés dans l'article et en tant que matériel supplémentaire <sup>5</sup>. Nous fournissons les données, le script d'analyse, les fichiers STL et les données vidéo pour le travail présenté dans le chapitre 8.3.3. Ils peuvent être trouvés en tant que matériel supplémentaire <sup>6</sup> et sur Zenodo (pour les vidéos des manipulations effectuées par les participants, disponibles sur demande) <sup>7</sup>.

### **Limitations et perspectives à court terme**

Nous présentons maintenant les limitations et les perspectives à court terme de notre travail. Bien que les travaux de recherche présentés dans cette thèse présentent certaines limitations, ils ont ouvert la voie à des perspectives futures qu'il est intéressant de traiter.

### **Évaluation des paramètres de conception avec des interfaces utilisateur non statiques**

L'une des principales limitations - et perspectives futures - de notre travail est le fait que nous avons réalisé nos études utilisateur sur des modules statiques, non actionnés. La raison en est que les interfaces utilisateur à changement de forme sont particulièrement connues pour leur capacité limitée à supporter une manipulation prolongée par les utilisateurs, en raison notamment de leur manque de robustesse [19]. Ainsi, évaluer d'abord l'impact des paramètres de conception à l'échelle micro avec des modules statiques nous a permis d'isoler facilement les facteurs et de comprendre leur impact sur l'interaction utilisateur. Cela a également limité le biais que d'autres paramètres de conception pourraient autrement causer. Par exemple, la taille des modules affecte leur structure et leur agencement, ainsi que leur force de liaison (Chapitre 5). Avec le recul, si nous avions utilisé des modules actionnés légitimes de différentes tailles pour l'expérience présentée dans le chapitre 8.3.3, il aurait été plus difficile d'interpréter nos résultats et de déterminer si l'impact sur l'interaction utilisateur et la variation des résultats étaient uniquement dus aux changements de taille ou devaient être attribués à un autre facteur.

Ainsi, nous encouragerions davantage d'études utilisateur sur :

---

5. <https://dl.acm.org/doi/10.1145/3462244.3479936>

6. <https://dl.acm.org/doi/10.1145/3569009.3572731>

7. <https://doi.org/10.5281/zenodo.7372398>

**1. Les paramètres de conception isolés qui nécessitent des modules non statiques.**

Par exemple, la *vitesse* des modules est difficile à évaluer avec des modules statiques. Une solution consiste à émuler les modules et leur mouvement en utilisant la réalité étendue (RE) combinée à une technologie haptique active. Cependant, cela peut entraîner d'autres limitations. Il est nécessaire d'étudier dans quelle mesure les résultats des études menées en RE/haptique sont reproductibles et transférables aux modules actionnés réels.

**2. L'impact combiné de différents paramètres de conception.** Cela permettrait non seulement de mieux comprendre comment les utilisateurs perçoivent l'ensemble de l'interface utilisateur, mais aussi de mettre en évidence et d'étudier les compromis potentiels qui pourraient exister entre les propriétés. Par exemple, qu'est-ce que les utilisateurs préféreraient entre des modules plus petits et une résolution élevée, ou une plus grande force de liaison et des capacités de surplomb ? Jusqu'à quel point seraient-ils prêts à faire des compromis, et dans quel contexte ? Nous pensons que de telles études peuvent être menées à la fois avec des prototypes statiques et actionnés.**Sécurité des interfaces utilisateur à changement de forme**

Dans le chapitre 4, nous avons défini le paramètre de conception *Sécurité*. Cependant, nous avons constaté que très peu de travaux antérieurs se sont penchés sur la sécurité des interfaces utilisateur modulaires à changement de forme - et des interfaces à changement de forme en général. Un exemple rare est la plateforme Zooids [159], pour laquelle les auteurs mentionnent avoir réduit la vitesse en raison de problèmes de sécurité. Nous avons exploité les travaux antérieurs sur le sujet menés en Interaction Homme-Robot, mais il n'est pas clair comment leurs résultats s'appliqueraient effectivement aux spécificités des interfaces utilisateur à changement de forme et à leurs différents types d'actionnement. Par exemple, les problèmes de sécurité d'un robot souple activé pneumatiquement sont différents de ceux d'un module utilisant des électroaimants comme mécanisme d'actionnement. Des exemples de tels problèmes sont le risque d'explosion d'une interface utilisateur pneumatique en raison d'une pression d'air excessive, ou le risque de pincement de la peau de l'utilisateur entre deux modules robotiques utilisant des électroaimants trop puissants. De plus, la sécurité dépend du type de robots modulaires (par exemple, essaims, chaînes ou treillis) et de leur contexte d'utilisation. Par exemple, une chaîne de modules utilisée pour fabriquer un gant haptique [196] pourrait exercer une pression excessive sur les articulations de l'utilisateur, tandis qu'un essaim de drones pour une animation 3D en plein air [40] pourrait tomber en plein vol et blesser un passant.

Nous encourageons la communauté à mener des études sur la sécurité des interfaces utilisateur à changement de forme. Une manière prometteuse d'inciter les chercheurs à évaluer la sécurité de leur système serait de leur fournir des métriques compréhensibles et des protocoles

---

expérimentaux pour signaler facilement les problèmes potentiels de sécurité. Ces métriques pourraient ensuite être croisées et comparées afin de comprendre les différences et les similitudes dans les problèmes de sécurité entre les différents types d'actionnement et d'architectures, et former ultérieurement une taxonomie.

### **Perception de l'utilisateur et contexte d'utilisation attendu**

Comprendre l'impact d'un système sur l'interaction utilisateur, mener des études sur l'acceptation de l'utilisateur ou choisir de nouvelles conceptions d'interaction dépend fortement de l'utilisation et des scénarios d'application globaux du système. Par exemple, concevoir un nouveau prototype et ses modalités d'interaction conduirait à des choix de conception différents en fonction de savoir s'il est destiné à un contexte de table ou à un contexte de manipulation mobile. Cependant, il n'existe pas de contexte d'utilisation existant pour les interfaces utilisateur à changement de forme modulaires tiré de l'utilisation réelle, car elles ne sont pas courantes dans notre vie quotidienne. Certains travaux antérieurs ont présenté des scénarios conceptuels. Cependant, ces scénarios sont imaginés par les chercheurs et ne sont jamais testés avec de vrais utilisateurs, encore moins *in situ* [19]. Par exemple, Cubimorph [247] a présenté un scénario où un utilisateur peut changer la forme de son téléphone mobile modulaire en passant d'une surface plate pour afficher une carte, à une forme rectangulaire semblable à un smartphone pour s'adapter à sa poche, et à une forme de manette pour jouer à un jeu vidéo. ChainFORM [196] a proposé plusieurs scénarios d'application, tels qu'une interface multi-utilisateurs composée d'une chaîne de modules affichant un jeu vidéo de type Pong, ou un stylet capable de détecter comment l'utilisateur le prend en main pour passer d'un mode stylo, à un mode pinceau ou à un mode loupe. À mesure que la technologie progresse et que les prototypes deviennent suffisamment robustes, il deviendra nécessaire de mener des études qui nous aideront à comprendre la manière réelle dont les utilisateurs utilisent et adoptent les interfaces à changement de forme (modulaires ou non). Comprendre comment nos choix de conception peuvent influencer l'interaction utilisateur dans le contexte de la vie réelle nous permettra de les améliorer davantage.

Comprendre *comment et pourquoi* les utilisateurs s'attendent à utiliser des dispositifs modulaires et tenir compte des spécificités des différents types de systèmes (par exemple, une architecture en chaîne, en essaim ou en treillis peut ne pas convenir aux mêmes applications) apporterait une autre perspective à la recherche sur les interfaces utilisateur modulaires à changement de forme. De même, comme les robots modulaires ne font actuellement pas partie de notre vie quotidienne, les utilisateurs pourraient exprimer certaines préoccupations et être réticents à les utiliser, encore moins à les adopter au lieu de leurs alternatives actuelles. Notre travail en tant que chercheurs devrait-il être basé sur l'hypothèse que les utilisateurs cibles que nous présentons dans notre scénario conceptuel percevront le nouveau concept, prototype ou modalité d'interaction

comme excitant et utile ? Est-ce que nos utilisateurs pourraient plutôt hésiter à utiliser notre système en raison de préoccupations concernant, par exemple, sa sécurité perçue, sa robustesse, son utilité ? Il est donc nécessaire de comprendre comment les utilisateurs perçoivent les interfaces utilisateur modulaires à changement de forme. Des travaux antérieurs, y compris les nôtres, ont notamment avancé des affirmations sur les possibles opportunités offertes par les interfaces utilisateur à changement de forme. Par exemple, il a été avancé qu'elles offriraient une grande naturalité d'interaction, en associant les implémentations de systèmes à changement de forme aux interfaces utilisateur naturelles [106], et une meilleure capacité d'apprentissage [217, 64]. Cependant, nous manquons toujours d'études utilisateur pour évaluer ces affirmations [19]. Les travaux futurs devraient viser à comprendre si les utilisateurs sont disposés à utiliser nos systèmes, quelles sont leurs alternatives actuelles et quelles pourraient être leurs préoccupations lors de l'adoption d'un nouveau système interactif.

### **Perspectives à long terme pour les interfaces modulaires à changement de forme**

Nous concluons maintenant la thèse en discutant des perspectives à long terme pour l'avenir des interfaces modulaires à changement de forme. Une fois les obstacles matériels surmontés, notre avis est que de nouveaux défis feront surface. Nous identifions en particulier trois perspectives à long terme que nous estimons cruciales pour le développement futur des interfaces modulaires à changement de forme.

1. Comment convenir des algorithmes de reconfiguration centrés sur l'utilisateur ?
2. Qui sera responsable de fournir du contenu pour les futurs appareils à changement de forme ?
3. Étant donné que les différentes formes de l'interface constituent les différents appareils disponibles pour l'utilisateur, quel serait l'impact de l'aspect temporel du passage d'une forme à l'autre sur les modalités d'interaction ?

### **Recentrer les stratégies et algorithmes de reconfiguration sur l'utilisateur**

Dans la partie 8.3.3, nous avons discuté du fait que nous avons laissé de côté les travaux sur les algorithmes de reconfiguration, y compris le contrôle et la planification centrés sur l'utilisateur, pour de futures recherches. Les travaux antérieurs en IHM se sont concentrés sur l'interaction avec l'interface déjà reconfigurée. Cependant, peu ont abordé la question de la prise en compte de l'utilisateur dans le choix des stratégies de reconfiguration. Nous avons mentionné à plusieurs reprises dans cette thèse que les chercheurs en robotique se concentrent davantage sur la reconfiguration et la locomotion sans utilisateur [247]. Cela se traduit par des travaux approfondis sur

---

les algorithmes de reconfiguration, notamment la planification des mouvements (par exemple, [328, 113, 170, 291]), mais (1) qui sont testés dans des conditions contrôlées “*idéales*”[314] et (2) qui ne conviennent pas forcément à l’interaction avec l’utilisateur. Par exemple, certaines implémentations peuvent surmonter des obstacles dans des environnements incertains (par exemple, des modules s’assemblant en chaîne pour franchir un vide, passer par-dessus un rocher ou monter des escaliers [155]) car leur conception est axée sur l’exploration de terrains. Cependant, elles partent du principe que les obstacles à surmonter sont statiques contrairement à un membre humain, et la reconfiguration des modules autour d’un obstacle n’implique pas les mêmes problèmes de sécurité que la reconfiguration autour, par exemple, d’une main. Ainsi, même avec de nombreux travaux existants, le domaine de la robotique est encore confronté à des défis à la fois en matière de contrôle et de planification [314], et il est nécessaire que les chercheurs en IHM contribuent aux travaux sur le contrôle et la planification des mouvements en adoptant une perspective centrée sur l’utilisateur. Nous avons mentionné dans nos travaux présentés dans la partie I que notre espace de conception peut être facilement affiné pour accueillir de nouvelles propriétés au niveau numérique, telles que les algorithmes de reconfiguration.

En fin de compte, il est nécessaire de développer des algorithmes et des stratégies de reconfiguration centrés sur l’utilisateur qui guident le changement de forme. Ces algorithmes doivent prendre en compte la position de l’utilisateur et le contexte dans lequel a lieu l’interaction. En effet, non seulement la reconfiguration des modules doit s’adapter à la manière dont l’utilisateur interagit avec eux, mais elle doit également s’adapter à l’endroit où se déroule l’interaction. Par exemple, si le scénario d’application nécessite une interaction mobile à la main (par exemple, en marchant ou en prenant le bus), alors le changement de forme doit être réalisé avec précaution afin de maintenir le centre de gravité de l’appareil, afin qu’il ne tombe pas des mains de l’utilisateur. L’utilisateur serait-il responsable d’anticiper le changement de forme - et donc de centre de gravité - de l’appareil ? Si le système suit une architecture en treillis où les modules sont amovibles (par exemple, en utilisant des aimants comme mécanismes d’actionnement), le système peut avoir besoin de privilégier une stratégie de changement de forme qui minimise le risque de chute des modules.

### **Exploration de la programmation par les utilisateurs avec la robotique modulaire**

Tout au long de la thèse, nous avons parlé de concepts à long terme tels que l’« Ultimate Display » de Sutherland [277] ou le « Perfect Red » d’Ishii [121]. Ces concepts préfigurent une sorte de « matière programmable » composée de modules auto-reconfigurables à l’échelle du millimètre. Une question légitime qui pourrait se poser si nous parvenions à réaliser de tels interfaces modulaires auto-reconfigurables à haute résolution serait : *quels* contenus et applications sont pris en charge par l’appareil à changement de forme ? Dans l’introduction de cette thèse, nous avons comparé les modules robotiques auto-reconfigurables à des pixels, et l’interface modulaire à



changement de forme dans son ensemble aux interfaces graphiques (GUI). Cependant, bien que les utilisateurs puissent techniquement afficher ce qu'ils veulent avec les interfaces graphiques, ils ne sont généralement pas ceux qui conçoivent et développent les applications avec lesquelles ils interagissent. Ainsi, de manière similaire aux concepteurs et développeurs qui fournissent du contenu pour nos smartphones, ordinateurs ou dispositifs de réalité augmentée/virtuelle, *qui* fournira du contenu pour les interfaces modulaires à changement de forme ? Des travaux antérieurs ont exploré les défis actuels et futurs dans la conception de contenu pour les interfaces modulaires à changement de forme [19]. Par exemple, ils ont souligné l'importance d'identifier les domaines d'application clés (tels que la visualisation de données) ou l'importance de concevoir du contenu en fonction de la configuration visuelle et physique de l'affichage et de l'entrée utilisateur. Cependant, leur exploration est encore limitée par l'idée que l'utilisateur interagira avec du contenu conçu par un expert. Nous pensons qu'il pourrait être intéressant d'explorer la programmation par les utilisateurs dans le contexte de la robotique modulaire pour les futures interfaces modulaires à changement de forme. Cela pourrait permettre aux utilisateurs de concevoir et personnaliser leurs propres applications, en mettant en œuvre une véritable approche de « blocs de construction ».

La programmation par les utilisateurs finaux (ou développement par les utilisateurs finaux) fait référence au processus consistant à fournir aux utilisateurs non experts des concepts, des méthodes et des outils pour programmer ou personnaliser le comportement d'un logiciel ou d'un système matériel [150, 211]. Dans le contexte des interfaces modulaires à changement de forme, la programmation par les utilisateurs finaux peut être un outil puissant pour permettre aux utilisateurs de créer des comportements et des applications personnalisés pour leurs modules robotiques sans nécessiter de compétences en robotique ou en programmation. En fournissant aux utilisateurs finaux des outils pour programmer et personnaliser le comportement de ces modules, nous pouvons accroître leur flexibilité et leur polyvalence. La programmation par les utilisateurs finaux pour les robots modulaires peut également bénéficier de la collaboration et du partage des connaissances entre les utilisateurs. Il pourrait exister des plateformes permettant aux utilisateurs finaux de partager leurs applications personnalisées avec d'autres, de manière similaire à la mise à disposition des fichiers de conception 3D sur, par exemple, Thingiverse <sup>8</sup>.

En fournissant une plateforme permettant aux utilisateurs de partager leurs comportements et applications personnalisés, nous pouvons créer un écosystème de programmation d'interfaces modulaires à changement de forme axé sur la communauté, qui peut bénéficier aux utilisateurs de différents niveaux d'expertise.

---

8. <https://www.thingiverse.com/>

---

## Explorer la temporalité dans le changement de forme

Le concept d'interfaces utilisateurs saisissables (*"graspable UIs"*) a été initialement introduit pour fournir aux utilisateurs des "poignées" physiques qu'ils pouvaient saisir et manipuler pour interagir directement avec des données informatiques [76, 75]. Les premières interfaces tangibles ont été introduites en envisageant une entrée spatialement multiplexée, où *un* dispositif contrôle *une* fonction. La multiplexation spatiale n'est pas propre aux interfaces tangibles. Par exemple, les commandes d'une voiture sont spatialement multiplexées [75], et des travaux antérieurs ont exploré des surfaces multitouch pour interagir directement avec des éléments d'interface graphique (par exemple, pour la collaboration [264]). Cependant, d'autres types d'appareils avec lesquels nous interagissons au quotidien utilisent des modalités d'entrée temporellement multiplexées, comme les souris d'ordinateur ou les écrans tactiles des smartphones. Ils contrôlent plusieurs fonctions et comportements de l'appareil, tels que la sélection de menus, le défilement ou le glisser-déposer d'éléments [75].

L'implémentation du changement de forme pose la question de la multiplexation spatiale *vs.* temporelle dans les modalités d'entrée. Prenons un exemple concret dans un contexte de la vie réelle en observant les différences entre les consoles de mixage dans les studios d'enregistrement comparées aux consoles utilisées lors de concerts en plein air. Dans un studio d'enregistrement, les contrôles sont généralement spatialement multiplexés, et chaque ensemble de contrôle (c'est-à-dire les boutons, curseurs, molettes) contrôlent un paramètre individuel pour un musicien individuel. Mais que se passe-t-il s'il y a trop de musiciens ? Et que se passe-t-il lors d'un concert en plein air, où les contraintes d'espace conduisent à des configurations de table de mixage beaucoup plus petites ? C'est la raison pour laquelle il existe des tables de mixage avec des contrôles paramétrables. Cela introduit une couche de multiplexage temporel sur les contrôles normalement multiplexés spatialement. Par exemple, l'ingénieur du son peut paramétrer ses réglages pour le chanteur, modifiant ainsi les données informatiques via ses contrôles physique. Ensuite, il peut sélectionner un autre profil de paramètres pour un autre musicien (par exemple, le guitariste), de sorte que les contrôles (par exemple, les curseurs linéaires) se déplacent pour refléter les données informatiques du nouveau profil de musicien.

Nous nous attendons à ce que ce type de compromis entre la multiplexation spatiale et temporelle joue un rôle dans les futures interfaces utilisateur modulaires à changement de forme. Comme l'interface utilisateur à changement de forme peut passer d'un type de contrôle à un autre, comment cela se refléterait-il dans la multiplexation spatiale et temporelle des interactions ? De plus, comment cela influencerait-il la charge cognitive des utilisateurs, puisque les différents dispositifs disponibles (par exemple, les changements de forme) seraient dispersés dans le *temps* plutôt que dans l'*espace* ? Les futurs travaux pourraient tirer des enseignements de la recherche menée dans d'autres domaines, tels que l'interaction en langage naturel (Natural Lan-

guage Interaction, NLI). Par exemple, lors de l'interaction avec un assistant vocal, les différentes options disponibles ne sont pas affichées dans l'espace. Elles sont soit énoncées à voix haute, soit l'utilisateur doit se situer cognitivement dans l'interaction. Nous pouvons nous attendre à ce que ce type de stratégies d'interaction se traduise dans l'interaction utilisateur avec des interfaces à changement de forme.

---



# BIBLIOGRAPHY

---

- [1] A brief rant on the future of interaction design. <http://worrydream.com/ABriefRantOnTheFutureOfInteractionDesign/>, 2011.
- [2] Polymax pla. <https://eu.polymaker.com/product/polymax-pla/>, 2019.
- [3] Ptb series - low profile slide potentiometer. [https://www.bourns.com/docs/product-datasheets/ptb.pdf?sfvrsn=11289f1\\_7](https://www.bourns.com/docs/product-datasheets/ptb.pdf?sfvrsn=11289f1_7), 2019. Accessed: 2019-09-12.
- [4] Ultimaker 3: Complex 3d prints made easy. <https://ultimaker.com/3d-printers/ultimaker-3>, 2019. Accessed: 2019-09-12.
- [5] Ultimaker pva material: water soluble support. <https://ultimaker.com/materials/pva>, 2019. Accessed: 2019-09-12.
- [6] Verowhite resin material for 3d printing. <https://www.sculpteo.com/en/materials/polyjet-resin-material/verowhite-polyjet-resin-material/>, 2019.
- [7] What is polyjet technology for 3d printing? <https://www.stratasys.com/polyjet-technology>, 2019.
- [8] Magnet sets - astm f3458-21. <https://www.cpsc.gov/Regulations-Laws--Standards/Voluntary-Standards/Topics/Magnet-Sets>, 2020.
- [9] The toy association statement on magnets in toys. <https://www.toyassociation.org/PressRoom2/IndustryStatements/ToySafety/statement-on-magnets.aspx>, 2020.
- [10] Connex3 objet500 and objet350. <https://www.stratasys.com/3d-printers/objet-350-500-connex3>, 2022.
- [11] Hkcm engineering e.k. professional magnet supplier. <https://www.hkcm.de/>, 2022.
- [12] Safety standard for magnets. <https://www.federalregister.gov/documents/2022/01/10/2021-27826/safety-standard-for-magnets>, 2022.
- [13] LEGO® MINDSTORMS® | invent a robot | official LEGO® shop FR, 2023.
- [14] Alexander T. Adams, Elizabeth L. Murnane, Phil Adams, Michael Elfenbein, Pamara F. Chang, Shruti Sannon, Geri Gay, and Tanzeem Choudhury. Keppi: A Tangible User

- 
- Interface for Self-Reporting Pain. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, pages 1–13, Montreal QC, Canada, 2018. ACM Press.
- [15] David Ahlström, Khalad Hasan, and Pourang Irani. Are you comfortable doing that?: acceptance studies of around-device gestures in and for public settings. In *Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services - MobileHCI '14*, pages 193–202, Toronto, ON, Canada, 2014. ACM Press.
- [16] Teemu T. Ahmaniemi, Johan Kildal, and Merja Haveri. What is a device bend gesture really good for? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 3503–3512. ACM.
- [17] Reem J. Alattas, Sarosh Patel, and Tarek M. Sobh. Task-Based Design of Modular Robots: Evolutionary Approach. In *2018 IEEE International Conference on Mechatronics and Automation (ICMA)*, pages 1787–1793, August 2018. ISSN: 2152-744X.
- [18] Reem J. Alattas, Sarosh Patel, and Tarek M. Sobh. Evolutionary modular robotics: Survey and analysis. *Journal of Intelligent & Robotic Systems*, 95(3):815–828, 2019.
- [19] Jason Alexander, Anne Roudaut, Jürgen Steimle, Kasper Hornbæk, Miguel Bruns Alonso, Sean Follmer, and Timothy Merritt. Grand Challenges in Shape-Changing Interface Research. In *the CHI 2018 Conference*, pages 1–14, New York, New York, USA, 2018.
- [20] Apple. iPad 10.2-inch - technical specifications, 2020. Library Catalog: [www.apple.com](http://www.apple.com).
- [21] Nora Ayanian, Paul J. White, A’da’im Ha’la’sz, Mark Yim, and Vijay Kumar. Stochastic control for self-assembly of XBots. In *Volume 2: 32nd Mechanisms and Robotics Conference, Parts A and B*, pages 1169–1176. ASMEDC, 2008.
- [22] Myroslav Bachynskiy, Gregorio Palmas, Antti Oulasvirta, Jürgen Steimle, and Tino Weinkauff. Performance and ergonomics of touch surfaces: A comparative study using biomechanical simulation. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, CHI '15*, pages 1817–1826, New York, NY, USA, 2015. ACM.
- [23] Ravin Balakrishnan and I. Scott MacKenzie. Performance differences in the fingers, wrist, and forearm in computer input control. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems, CHI '97*, pages 303–310, New York, NY, USA, 1997. ACM.
- [24] Christian Bastien and Dominique L Scapin. Ergonomic criteria for the evaluation of human-computer interfaces. page 83, 1993.

- 
- [25] K. Baumann and B. Thomas. *User Interface Design of Electronic Appliances*. Londo: CRC Press, 2001.
- [26] Michel Beaudouin-Lafon. Designing interaction, not interfaces. In *Proceedings of the Working Conference on Advanced Visual Interfaces, AVI '04*, page 15–22, New York, NY, USA, 2004. Association for Computing Machinery.
- [27] Steffi Beckhaus, Roland Schröder-Kroll, and Martin Berghoff. Back to the sandbox: playful interaction with granules landscapes. In *Proceedings of the 2nd international conference on Tangible and embedded interaction, TEI '08*, pages 141–144. Association for Computing Machinery.
- [28] J. A. Bell. Sensibility evaluation. *Rehabilitation of the hand*, 1978.
- [29] Edgar Berdahl and Alexandros Kontogeorgakopoulos. The firefader: Simple, open-source, and reconfigurable haptic force feedback for musicians. *Comput. Music J.*, 37(1):23–34, March 2013.
- [30] Edgar Berdahl, Julius O. Smith, Stefan Weinzierl, and Gunter Niemeyer. Force-sensitive detents improve user performance for linear selection tasks. *IEEE Transactions on Haptics*, 6(2):206–216, 2013.
- [31] Lonni Besançon, Mehdi Ammi, and Tobias Isenberg. Pressure-based gain factor control for mobile 3d interaction using locally-coupled devices. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pages 1831–1842. ACM, 2017.
- [32] Sanjiv K. Bhatia, Vasudevan Lakshminarayanan, Ashok Samal, and Grant V. Welland. Human face perception in degraded images. *J. Visual Communication and Image Representation*, 6:280–295, 1995.
- [33] Andrea Bianchi, Ian Oakley, Jong Keun Lee, Dong Soo Kwon, and Vassilis Kostakos. Haptics for tangible interaction: a vibro-tactile prototype. page 2, 2011.
- [34] Stéphane Bonardi, Massimo Vespignani, Rico Moeckel, and Auke Jan Ijspeert. Collaborative manipulation and transport of passive pieces using the self-reconfigurable modular robots roombots. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2406–2412, November 2013. ISSN: 2153-0866.
- [35] Jullien Bouchet, Laurence Nigay, and Thierry Ganille. Icare software components for rapidly developing multimodal interfaces. In *Proceedings of the 6th International Conference on Multimodal Interfaces, ICMI '04*, page 251–258, New York, NY, USA, 2004. Association for Computing Machinery.



- 
- [36] J. Bourgeois and S. C. Goldstein. Distributed intelligent mems: Progresses and perspectives. *IEEE Systems Journal*, 9(3):1057–1068, Sep. 2015.
- [37] Julien Bourgeois. Programmable matter: forming objects with modular robots. In *14th International Symposium on Distributed Autonomous Robotic Systems (2018)*, Boulder, CO, United States, oct 2018.
- [38] Julien Bourgeois, Benoît Piranda, André Naz, Nicolas Boillot, Hakim Mabed, Dominique Dhoutaut, Thadeu Tucci, and Hicham Lakhlef. Programmable matter as a cyber-physical conjugation. *SMC*, 2016.
- [39] James V Bradley. Optimum Knob Diameter. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 11(4):353–360, August 1969.
- [40] Sean Braley, Calvin Rubens, Timothy R. Merritt, and Roel Vertegaal. GridDrones: A self-levitating physical voxel lattice for 3d surface deformations. In *Extended Abstracts of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, pages 1–4. ACM Press, 2018.
- [41] Manuele Brambilla, Arne Brutschy, Marco Dorigo, and Mauro Birattari. Property-driven design for robot swarms: A design method based on prescriptive modeling and model checking. 9(4):17:1–17:28, 2014.
- [42] Eric Brockmeyer, Ivan Poupyrev, and Scott Hudson. PAPILLON: designing curved display surfaces with printed optics. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 457–462, St. Andrews Scotland, United Kingdom, October 2013. ACM.
- [43] Byoung Kwon An. Em-cube: cube-shaped, self-reconfigurable robots sliding on structure surfaces. In *2008 IEEE International Conference on Robotics and Automation*, pages 3149–3155. IEEE, 2008.
- [44] T.W. Calvert and A.E. Chapman. The relationship between the surface EMG and force transients in muscle: Simulation and experimental studies. *Proceedings of the IEEE*, 65(5):682–689, 1977.
- [45] Baptiste Caramiaux, Marco Donnarumma, and Atau Tanaka. Understanding Gesture Expressivity through Muscle Sensing. *ACM Transactions on Computer-Human Interaction*, 21(6):31:1–31:26, January 2015. Number: 6.
- [46] C J Cascio and K Sathian. Temporal cues contribute to tactile perception of roughness. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 21(14):5289–5296, July 2001.

- 
- [47] Géry Casiez, Nicolas Roussel, Romuald Vanbelleghem, and Frédéric Giraud. Surfpad: Riding towards targets on a squeeze film effect. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 2491–2500, New York, NY, USA, 2011. ACM.
- [48] Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2189–2192, Austin Texas USA, May 2012. ACM.
- [49] Vivian Hsinyueh Chan, Yu-Chen Chan, Pin-Hsuan Peng, and Lung-Pan Cheng. Texel-Blocks: Dynamic surfaces for physical interactions. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–5. ACM.
- [50] Olivier Chapuis and Pierre Dragicevic. Effects of motor scale, visual scale, and quantization on small target acquisition difficulty. *ACM Transactions on Computer-Human Interaction*, 18(3):1–32, 2011.
- [51] Lung-Pan Cheng, Thijs Roumen, Hannes Rantzsch, Sven Köhler, Patrick Schmidt, Robert Kovacs, Johannes Jasper, Jonas Kemper, and Patrick Baudisch. TurkDeck: Physical virtual reality based on people. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, pages 417–426. ACM, 2015.
- [52] Andy Cockburn and Stephen Brewster. Multimodal feedback for the acquisition of small targets. *Ergonomics*, 48(9):1129–1150, 2005.
- [53] Marcelo Coelho and Jamie Zigelbaum. Shape-changing interfaces. 15(2):161–173, 2011.
- [54] Céline Coutrix and Cédric Masclat. Shape-Change for Zoomable TUIs: Opportunities and Limits of a Resizable Slider. In *Human-Computer Interaction – INTERACT 2015*, pages 349–366. Springer International Publishing, Cham, September 2015.
- [55] Céline Coutrix and Laurence Nigay. Op: A novel programming model for integrated design and prototyping of mixed objects. In Pedro Campos, Nicholas Graham, Joaquim Jorge, Nuno Nunes, Philippe Palanque, and Marco Winckler, editors, *Human-Computer Interaction – INTERACT 2011*, pages 54–72, Berlin, Heidelberg, 2011. Springer Berlin Heidelberg.
- [56] H. Culbertson, J. Unwin, and K. J. Kuchenbecker. Modeling and rendering realistic textures from unconstrained tool-surface interactions. *IEEE Transactions on Haptics*, 7(3):381–393, 2014. Conference Name: IEEE Transactions on Haptics.

- 
- [57] Maxime Daniel, Guillaume Rivière, and Nadine Couture. CairnFORM: a shape-changing ring chart notifying renewable energy availability in peripheral locations. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '19, pages 275–286. Association for Computing Machinery.
- [58] J. Davey, N. Kwok, and M. Yim. Emulating self-reconfigurable robots - design of the smores system. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4464–4469, Oct 2012.
- [59] Jay Davey, Ngai Kwok, and Mark Yim. Emulating self-reconfigurable robots - design of the SMORES system. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4464–4469, Vilamoura-Algarve, Portugal, October 2012. IEEE.
- [60] Jay Davey, Jimmy Sastra, Matt Piccoli, and Mark Yim. ModLock: A manual connector for reconfigurable modular robots. In *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3217–3222, October 2012. ISSN: 2153-0866.
- [61] Felecia Davis, Asta Roseway, Erin Carroll, and Mary Czerwinski. Actuating mood: design of the textile mirror. In *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction - TEI '13*, page 99. ACM Press, 2013.
- [62] Andrea De Cesarei and Maurizio Codispoti. Effects of picture size reduction and blurring on emotional engagement. *PLOS ONE*, 5(10):1–7, 10 2010.
- [63] A. Lee Dellon. *Somato Sensory Testing and Rehabilitation*. AOTA, 1997.
- [64] Debargha Dey, Coen de Zeeuw, Miguel Bruns, and Bastian Pfleging. Shape-changing interfaces as eHMIs: Exploring the design space of zoomorphic communication between automated vehicles and pedestrians. In *13th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, pages 137–141. ACM.
- [65] Tom Djajadiningrat, Kees Overbeeke, and Stephan Wensveen. But how, donald, tell us how? on the creation of meaning in interaction design through feedforward and inherent feedback. In *Proceedings of the 4th conference on Designing interactive systems: processes, practices, methods, and techniques*, DIS '02, pages 285–291. Association for Computing Machinery.
- [66] Bo Dong, Tianjiao An, Fan Zhou, Keping Liu, and Yuanchun Li. Decentralized robust zero-sum neuro-optimal control for modular robot manipulators in contact with uncertain environments: theory and experimental verification. *97(1):503–524*.

- 
- [67] Marco Dorigo, Dario Floreano, Luca Maria Gambardella, Francesco Mondada, Stefano Nolfi, Tarek Baaboura, Mauro Birattari, Michael Bonani, Manuele Brambilla, Arne Brutschy, Daniel Burnier, Alexandre Campo, Anders Lyhne Christensen, Antal Decugniere, Gianni Di Caro, Frederick Ducatelle, Eliseo Ferrante, Alexander Forster, Javier Martinez Gonzales, Jerome Guzzi, Valentin Longchamp, Stephane Magnenat, Nithin Mathews, Marco Montes de Oca, Rehan O'Grady, Carlo Pinciroli, Giovanni Pini, Philippe Retornaz, James Roberts, Valerio Sperati, Timothy Stirling, Alessandro Stranieri, Thomas Stutzle, Vito Trianni, Elio Tuci, Ali Emre Turgut, and Florian Vaussard. Swarmanoid: A novel concept for the study of heterogeneous robotic swarms. 20(4):60–71, 2013.
- [68] Pierre Dragicevic, Yvonne Jansen, and Andrew Vande Moere. Data physicalization. In Jean Vanderdonckt, Philippe Palanque, and Marco Winckler, editors, *Handbook of Human Computer Interaction*, pages 1–51. Springer International Publishing.
- [69] Frederick Ducatelle, Gianni A. Di Caro, and Luca M. Gambardella. Cooperative self-organization in a heterogeneous swarm robotic system. In *Proceedings of the 12th annual conference on Genetic and evolutionary computation, GECCO '10*, pages 87–94. Association for Computing Machinery, 2010.
- [70] Gregory Dudek, Michael Jenkin, Evangelos Milios, and David Wilkes. A taxonomy for swarm robots. In *Proceedings of 1993 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'93)*, volume 1, pages 441–447. IEEE, 1993.
- [71] Rainer Ebner, Gunter Haring, Franz Penz, and Gerhard Weichselberger. A comparative evaluation of graphical user interfaces. 22(1):12–15.
- [72] Gary R. VandenBos (Ed.). Publication manual of the american psychological association (6th ed.), 2009.
- [73] European Committee for Standardization. Safety of machinery - ergonomics requirements for the design of displays and control actuators - part 3: Control actuators, 2008.
- [74] Thomas Feix, Javier Romero, Heinz-Bodo Schmiedmayer, Aaron M. Dollar, and Danica Kragic. The GRASP taxonomy of human grasp types. 46(1):66–77.
- [75] George W Fitzmaurice and William Buxton. An empirical evaluation of graspable user interfaces. In *CHI*, pages 43–50, New York, New York, USA, 1997. ACM Press.
- [76] George W. Fitzmaurice, Hiroshi Ishii, and William A. S. Buxton. Bricks: Laying the foundations for graspable user interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI '95*, page 442–449, USA, 1995. ACM Press/Addison-Wesley Publishing Co.

- 
- [77] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. inFORM: dynamic physical affordances and constraints through shape and object actuation. In *UIST '13: Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 417–426, New York, New York, USA, October 2013. ACM.
- [78] Clifton Forlines, Daniel Wigdor, Chia Shen, and Ravin Balakrishnan. Direct-touch vs. mouse input for tabletop displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems - CHI '07*, pages 647–656. ACM Press, 2007.
- [79] Jack Forman, Taylor Tabb, Youngwook Do, Meng-Han Yeh, Adrian Galvin, and Lining Yao. Modifiber: Two-way morphing soft thread actuators for tangible interaction. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–11, New York, NY, USA, 2019. Association for Computing Machinery.
- [80] Bruno Fruchard. Squish this: Force input on soft surfaces for visual targeting tasks. page 9.
- [81] Toshio Fukuda and Yoshio Kawauchi. Cellular robotic system (CEBOT) as one of the realization of self-organizing intelligent universal manipulator. In *Proceedings of the 1990 IEEE International Conference on Robotics and Automation, Cincinnati, Ohio, USA, May 13-18, 1990*, pages 662–667, 1990.
- [82] Marwan Gharbia, Alice Chang-Richards, Yuqian Lu, Ray Y. Zhong, and Heng Li. Robotic technologies for on-site building construction: A systematic review. *Journal of Building Engineering*, 32:101584, November 2020.
- [83] Kyle Gilpin, Ara Knaian, and Daniela Rus. Robot pebbles: One centimeter modules for programmable matter through self-disassembly. In *2010 IEEE International Conference on Robotics and Automation*, pages 2485–2492. IEEE, 2010.
- [84] Kyle Gilpin, Keith Kotay, Daniela Rus, and Iuliu Vasilescu. Miche: Modular shape formation by self-disassembly. *The International Journal of Robotics Research*, 27(3):345–372, 2008.
- [85] Kyle Gilpin and Daniela Rus. Modular robot systems. *IEEE Robotics Automation Magazine*, 17(3):38–55. Conference Name: IEEE Robotics Automation Magazine.
- [86] A Goguey, C Steer, A Lucero, L Nigay, Deepak Ranjan Sahoo, Céline Coutrix, Anne Roudaut, Sriram Subramanian, Yutaka Tokuda, Timothy Neate, Jennifer Pearson, Simon Robinson, and Matt Jones. PickCells: A Physically Reconfigurable Cell-composed Touchscreen. In *CHI '19: Proceedings of the 37th Annual ACM Conference on Human Factors in Computing Systems*, 2019.

- 
- [87] Alix Goguey, Cameron Steer, Andrés Lucero, Laurence Nigay, Deepak Ranjan Sahoo, Céline Coutrix, Anne Roudaut, Sriram Subramanian, Yutaka Tokuda, Timothy Neate, and et al. Pickcells: A physically reconfigurable cell-composed touchscreen. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, New York, NY, USA, 2019. Association for Computing Machinery.
- [88] Antonio Gomes, Andrea Nesbitt, and Roel Vertegaal. MorePhone: a study of actuated shape deformations for flexible thin-film smartphone notifications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 583–592, Paris France, April 2013. ACM.
- [89] Antonio Gomes, Lahiru Lakmal Priyadarshana, Aaron Visser, Juan Pablo Carrascal, and Roel Vertegaal. Magicscroll: a rollable display device with flexible screen real estate and gestural input. In *Proceedings of the 20th International Conference on Human-Computer Interaction with Mobile Devices and Services*, pages 1–11, Barcelona Spain, September 2018. ACM.
- [90] Antonio Gomes, Calvin Rubens, Sean Braley, and Roel Vertegaal. Bitdrones: Towards using 3d nanocopter displays as interactive self-levitating programmable matter. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 770–780, New York, NY, USA, 2016. ACM.
- [91] Antony W Goodwin and Heather E Wheat. Sensory signals in neural populations underlying tactile perception and manipulation. *Annual review of neuroscience*, 27:53–77, 2004.
- [92] Chase Greenhagen, Timothy Krentz, Janelle Wigal, and Sami Khorbotly. A real-life robotic application of the particle swarm optimization algorithm. In *2016 Swarm/Human Blended Intelligence Workshop (SHBI)*, pages 1–5, 2016.
- [93] Jens Emil Grønbaek, Majken Kirkegaard Rasmussen, Kim Halskov, and Marianne Graves Petersen. Kirigamitable: Designing for proxemic transitions with a shape-changing tabletop. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–15, New York, NY, USA, 2020. Association for Computing Machinery.
- [94] The LEGO group, 2021.
- [95] Roderich Groß and Marco Dorigo. Self-assembly at the macroscopic scale. 96:1490–1508, 2008.
- [96] Grünbaum. Uniform tilings of 3-space. *Geombinatorics*, 4, 1994.

- 
- [97] Hongri Gu, Quentin Boehler, Daniel Ahmed, and Bradley J. Nelson. Magnetic quadrupole assemblies with arbitrary shapes and magnetizations. *Science Robotics*, 4(35):eaax8977, October 2019.
- [98] Bahar Haghghat, Emmanuel Droz, and Alcherio Martinoli. Lily: A miniature floating robotic platform for programmable stochastic self-assembly. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1941–1948, 2015. ISSN: 1050-4729.
- [99] G.J. Hamlin and A.C. Sanderson. TETROBOT modular robotics: prototype and experiments. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems. IROS '96*, volume 2, pages 390–395 vol.2.
- [100] Sandra G Hart and Moffett Field. NASA-TASK LOAD INDEX (NASA-TLX); 20 YEARS LATER. page 5, 2006.
- [101] Sandra G. Hart and Lowell E. Staveland. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In *Advances in Psychology*, volume 52, pages 139–183. Elsevier, 1988.
- [102] Simon Hauser, Mehmet Mutlu, and Auke J. Ijspeert. Kubits: Solid-state self-reconfiguration with programmable magnets. *IEEE Robotics and Automation Letters*, 5(4):6443–6450, 2020.
- [103] Takefumi Hiraki, Shogo Fukushima, and Takeshi Naemura. Phygital field: an integrated field with a swarm of physical robots and digital images. In *SIGGRAPH ASIA 2016 Emerging Technologies*, SA '16, pages 1–2. Association for Computing Machinery, 2016.
- [104] Mark Hollins, Richard Faldowski, Suman Rao, and Forrest Young. Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis. *Perception & Psychophysics*, 54(6):697–705, 1993.
- [105] M Hollins and S R Risner. Evidence for the duplex theory of tactile texture perception. *Perception & psychophysics*, 62(4):695–705, May 2000.
- [106] D. Holman, A. Girouard, H. Benko, and R. Vertegaal. The design of organic user interfaces: Shape, sketching and hypercontext. 25(2):133–142.
- [107] David Holman and Roel Vertegaal. Organic user interfaces: designing computers in any way, shape, or form. 51(6):48, 2008.
- [108] Hongxing Wei, Yingpeng Cai, Haiyuan Li, Dezhong Li, and Tianmiao Wang. Sambot: A self-assembly modular robot for swarm robot. In *2010 IEEE International Conference on Robotics and Automation*, pages 66–71. IEEE, 2010.

- 
- [109] J.R. Hook and H.E. Hall. *Solid State Physics, 2nd Edition*. Wiley, July 1991.
- [110] Oren Horev. Talking to the hand: An exploration into shape shifting objects and morphing interfaces. Master’s thesis, Interaction Design Institute Ivrea, 2006.
- [111] Eva Hornecker and Jacob Buur. Getting a grip on tangible interaction: A framework on physical space and social interaction. page 10, 2006.
- [112] K. Hosokawa, T. Tsujimori, T. Fujii, H. Kaetsu, H. Asama, Y. Kuroda, and I. Endo. Self-organizing collective robots with morphogenesis in a vertical plane. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, volume 4, pages 2858–2863 vol.4, 1998. ISSN: 1050-4729.
- [113] Feili Hou and Wei-Min Shen. Graph-based optimal reconfiguration planning for self-reconfigurable robots. 62(7):1047–1059.
- [114] James M. D. Hunter, Evelyn P. T. Mackin, and Anne M. S. Callahan. *Rehabilitation of the Hand: Surgery and Therapy*, volume 1. Mosby, 1995.
- [115] Jörn Hurtienne and Daniel Reinhardt. Texture metaphors and tangible interaction: No smooth relationship? In *Proceedings of the Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '17*, pages 79–87. ACM Press, 2017.
- [116] Irfan Hussain, Gionata Salvietti, and Domenico Prattichizzo. On control interfaces for the robotic sixth finger. In *Proceedings of the 7th Augmented Human International Conference 2016, AH '16*, pages 1–2. Association for Computing Machinery.
- [117] Sungjae Hwang, Myungwook Ahn, and Kwang-yun Wohn. MagGetz: customizable passive tangible controllers on and around conventional mobile devices. In *Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 411–416, St. Andrews Scotland, United Kingdom, October 2013. ACM.
- [118] H Ishii, C Ratti, B Piper, Y Wang, A Biderman, and E Ben-Joseph. Bringing clay and sand into digital design — continuous tangible user interfaces. 22(4):287–299.
- [119] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. Radical atoms: Beyond tangible bits, toward transformable materials. *Interactions*, 19(1):38–51, January 2012.
- [120] Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. Radical atoms: beyond tangible bits, toward transformable materials. *Interactions*, 19(1):38–51, January 2012.



- 
- [121] Hiroshi Ishii and Brygg Ullmer. Tangible bits: towards seamless interfaces between people, bits and atoms. In *Proceedings of the SIGCHI conference on Human factors in computing systems - CHI '97*, pages 234–241. ACM Press.
- [122] ISO. Robots and robotic devices — collaborative robots. Standard, International Organization for Standardization, Geneva, CH, February 2016.
- [123] ISO. Robotics — safety requirements for robot systems in an industrial environment — part 1: Robots. Standard, International Organization for Standardization, Geneva, CH, 2018.
- [124] ISO. Ergonomics of Human-System Interaction – Part 210: Human-Centered Design for Interactive Systems. Standard, International Organization for Standardization, Geneva, CH, July 2019.
- [125] Robert J.K. Jacob, Audrey Girouard, Leanne M. Hirshfield, Michael S. Horn, Orit Shaer, Erin Treacy Solovey, and Jamie Zigelbaum. Reality-based interaction: A framework for post-wimp interfaces. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '08, page 201–210, New York, NY, USA, 2008. Association for Computing Machinery.
- [126] Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. Haptic edge display for mobile tactile interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 3706–3716, New York, NY, USA, 2016. ACM.
- [127] Sungjune Jang, Lawrence H. Kim, Kesler Tanner, Hiroshi Ishii, and Sean Follmer. Haptic Edge Display for Mobile Tactile Interaction. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, pages 3706–3716, New York, NY, USA, May 2016. Association for Computing Machinery.
- [128] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. Tangible remote controllers for wall-size displays. In *CHI '12: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2865–2874, New York, New York, USA, May 2012. ACM.
- [129] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. Evaluating the efficiency of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '13, page 2593–2602, New York, NY, USA, 2013. Association for Computing Machinery.
- [130] Yvonne Jansen and Kasper Hornbaek. A psychophysical investigation of size as a physical variable. 22(1):479–488.

- 
- [131] Yunyao Jiang and Yanning Li. 3d printed chiral cellular solids with amplified auxetic effects due to elevated internal rotation. *Advanced Engineering Materials*, 19(2):1600609, 2017.
- [132] Sergi Jordà, Günter Geiger, Marcos Alonso, and Martin Kaltenbrunner. The reacTable: exploring the synergy between live music performance and tabletop tangible interfaces. In *Proceedings of the 1st international conference on Tangible and embedded interaction - TEI '07*, page 139. ACM Press.
- [133] Akiya Kamimura, Eiichi Yoshida, Satoshi Murata, Haruhisa Kurokawa, Kohji Tomita, and Shigeru Kokaji. A self-reconfigurable modular robot (MTRAN) — hardware and motion planning software —. In Hajime Asama, Tamio Arai, Toshio Fukuda, and Tsutomu Hasegawa, editors, *Distributed Autonomous Robotic Systems 5*, pages 17–26. Springer Japan, 2002.
- [134] M. E. Karagozler, J. D. Campbell, G. K. Fedder, S. C. Goldstein, M. P. Weller, and B. W. Yoon. Electrostatic latching for inter-module adhesion, power transfer, and communication in modular robots. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2779–2786, 2007. ISSN: 2153-0866.
- [135] M. E. Karagozler, S. C. Goldstein, and J. R. Reid. Stress-driven mems assembly + electrostatic forces = 1mm diameter robot. In *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2763–2769, Oct 2009.
- [136] Mustafa E Karagozler, Brian Kirby, Wei Jie Lee, Eugene Marinelli, Tze Chang Ng, Michael P Weller, and Seth C Goldstein. Ultralight modular robotic building blocks for the rapid deployment of planetary outposts. page 15, 2006.
- [137] Hamidreza Karbasi, Jan Paul Huissoon, and Amir Khajepour. Uni-drive modular robots: theory, design, and experiments. 39(2):183–200, 2004.
- [138] Elio Keddisseh, Marcos Serrano, and Emmanuel Dubois. KeyTch: Combining the keyboard with a touchscreen for rapid command selection on toolbars. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–13. ACM, 2021.
- [139] Michael Kenward and James Roger. An improved approximation to the precision of fixed effects from restricted maximum likelihood. *Computational Statistics & Data Analysis*, 53:2583–2595, 05 2009.
- [140] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. KnobSlider: Design of a Shape-Changing UI for Parameter Control. In *CHI '18*, 2018.

- 
- [141] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. Morphees+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs. In *CHI '18*, pages 1–14, New York, New York, USA, 2018. ACM Press.
- [142] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. KnobSlider: Design of a shape-changing parameter control UI and study of user preferences on its speed and tangibility. *Frontiers in Robotics and AI*, 6:79, 2019.
- [143] Hyunyoung Kim, Patrícia Deud Guimarães, Céline Coutrix, and Anne Roudaut. Expandial: Designing a shape-changing dial. In *Proceedings of the 2019 on Designing Interactive Systems Conference, DIS '19*, page 949–961, New York, NY, USA, 2019. Association for Computing Machinery.
- [144] Lawrence H Kim, Daniel S Drew, Veronika Domova, and Sean Follmer. User-defined swarm robot control. page 13, 2020.
- [145] Lawrence H. Kim and Sean Follmer. UbiSwarm: Ubiquitous robotic interfaces and investigation of abstract motion as a display. 1(3):1–20, 2017.
- [146] Lawrence H. Kim and Sean Follmer. SwarmHaptics: Haptic display with swarm robots. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–13. ACM Press, 2019.
- [147] Brian T. Kirby, Michael Ashley-Rollman, and Seth Copen Goldstein. Blinky blocks: a physical ensemble programming platform. In *Proceedings of the 2011 annual conference extended abstracts on Human factors in computing systems - CHI EA '11*, page 1111. ACM Press, 2011.
- [148] Roberta L. Klatzky, Susan J. Lederman, Cheryl Hamilton, Molly Grindley, and Robert H. Swendsen. Feeling textures through a probe: Effects of probe and surface geometry and exploratory factors. *Perception & Psychophysics*, 65(4):613–631, 2003.
- [149] Hendrik Knoche, John D. McCarthy, and M. Angela Sasse. How low can you go? the effect of low resolutions on shot types in mobile tv. *Multimedia Tools and Applications*, 36(1):145–166, Jan 2008.
- [150] Amy J. Ko, Brad A. Myers, and Htet Htet Aung. Six learning barriers in end-user programming systems. In *2004 IEEE Symposium on Visual Languages - Human Centric Computing*, pages 199–206.
- [151] Kurt Konolige, Charlie Ortiz, Regis Vincent, Benoit Morisset, Andrew Agno, Michael Eriksen, Dieter Fox, Benson Limketkai, Jonathan Ko, Benjamin Stewart, and Dirk Schulz.

- 
- Centibots: Very large scale distributed robotic teams. In Renè Jacquot, editor, *Building the Information Society*, volume 156, pages 761–761. Springer US, 2004. Series Title: IFIP International Federation for Information Processing.
- [152] K.D. Kotay and D.L. Rus. Motion synthesis for the self-reconfiguring molecule. In *Proceedings. 1998 IEEE/RSJ International Conference on Intelligent Robots and Systems. Innovations in Theory, Practice and Applications (Cat. No.98CH36190)*, volume 2, pages 843–851. IEEE, 1998.
- [153] Martin Krzywinski and Naomi Altman. Error bars. 10(10):921–922, 2013.
- [154] Caitlin Kuhlman, Diana Doherty, Malika Nurbekova, Goutham Deva, Zarni Phyto, Paul-Henry Schoenhagen, MaryAnn VanValkenburg, Elke Rundensteiner, and Lane Harrison. Evaluating preference collection methods for interactive ranking analytics. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–11. ACM, 2019.
- [155] H. Kurokawa, E. Yoshida, K. Tomita, A. Kamimura, S. Murata, and S. Kokaji. Self-reconfigurable m-TRAN structures and walker generation. *Robotics and Autonomous Systems*, 54(2):142–149, 2006.
- [156] Haruhisa Kurokawa, Akiya Kamimura, and Kohji Tomita. Self-assembly and Self-reproduction by an M-TRAN Modular Robotic System. In M. Ani Hsieh and Gregory Chirikjian, editors, *Distributed Autonomous Robotic Systems*, Springer Tracts in Advanced Robotics, pages 205–218, Berlin, Heidelberg, 2014. Springer.
- [157] Michael A Lawrence, Ryo Kitada, Roberta L Klatzky, and Susan J Lederman. Haptic roughness perception of linear gratings via bare finger or rigid probe. *Perception*, 36(4):547–557, 2007.
- [158] Mathieu Le Goc, Pierre Dragicevic, Samuel Huron, Jeremy Boy, and Jean-Daniel Fekete. A Better Grasp on Pictures Under Glass: Comparing Touch and Tangible Object Manipulation using Physical Proxies. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, pages 76–83, Bari Italy, June 2016. ACM.
- [159] Mathieu Le Goc, Lawrence H Kim, Ali Parsaei, Jean-Daniel Fekete, Pierre Dragicevic, and Sean Follmer. Zooids: Building Blocks for Swarm User Interfaces. In *UIST’16*, pages 1–13, August 2016.
- [160] S. J. Lederman and R. L. Klatzky. Haptic perception: A tutorial. *Attention, Perception & Psychophysics*, 71(7):1439–1459, 2009.

- 
- [161] Kyung Min Lee, Hilmar Koerner, Richard A. Vaia, Timothy J. Bunning, and Timothy J. White. Light-activated shape memory of glassy, azobenzene liquid crystalline polymer networks. 7(9):4318, 2011.
- [162] Yujin Lee, Myeongseong Kim, and Hyunjung Kim. Rolling pixels: Robotic steinmetz solids for creating physical animations. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '20, pages 557–564. Association for Computing Machinery, 2020.
- [163] Vincent Levesque, Louise Oram, Karon MacLean, Andy Cockburn, Nicholas D. Marchuk, Dan Johnson, J. Edward Colgate, and Michael A. Peshkin. Enhancing physicality in touch interaction with programmable friction. In *Proceedings of the 2011 annual conference on Human factors in computing systems - CHI '11*, page 2481. ACM Press, 2011.
- [164] Dazhai Li, Hualei Fu, and Wei Wang. Ultrasonic based autonomous docking on plane for mobile robot. In *2008 IEEE International Conference on Automation and Logistics*, pages 1396–1401, 2008. ISSN: 2161-816X.
- [165] Rong-Hao Liang. GaussBricks: Magnetic Building Blocks for Constructive Tangible Interactions on Portable Displays. page 9, 2014.
- [166] Rong-Hao Liang, Liwei Chan, Hung-Yu Tseng, Han-Chih Kuo, Da-Yuan Huang, De-Nian Yang, and Bing-Yu Chen. Gaussbricks: Magnetic building blocks for constructive tangible interactions on portable displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '14, page 3153–3162, New York, NY, USA, 2014. Association for Computing Machinery.
- [167] Alessandro Liberati, Douglas G. Altman, Jennifer Tetzlaff, Cynthia Mulrow, Peter C. Gøtzsche, John P. A. Ioannidis, Mike Clarke, P. J. Devereaux, Jos Kleijnen, and David Moher. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: Explanation and elaboration. *PLoS Medicine*, 6(7):e1000100, 2009.
- [168] David Lindlbauer, Jens Emil Grønbaek, Morten Birk, Kim Halskov, Marc Alexa, and Jörg Müller. Combining shape-changing interfaces and spatial augmented reality enables extended object appearance. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 791–802. ACM.
- [169] Lars Lischke, Paweł W. Woźniak, Sven Mayer, Andreas Preikschat, and Morten Fjeld. Using variable movement resistance sliders for remote discrete input. In *Proceedings of the Interactive Surfaces and Spaces on ZZZ - ISS '17*, pages 116–125. ACM Press, 2017.

- 
- [170] Chao Liu, Sencheng Yu, and Mark Yim. Motion planning for variable topology truss modular robot. In *Robotics: Science and Systems XVI*. Robotics: Science and Systems Foundation.
- [171] Sara Ljungblad and Lars Erik Holmquist. Designing robot applications for everyday environments. In *Proceedings of the 2005 joint conference on Smart objects and ambient intelligence: innovative context-aware services: usages and technologies*, sOc-EUSAI '05, pages 65–68. Association for Computing Machinery, 2005.
- [172] Pedro Lopes, Patrik Jonell, and Patrick Baudisch. Affordance++: Allowing objects to communicate dynamic use. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*, CHI '15, pages 2515–2524. Association for Computing Machinery, 2015.
- [173] Henrik Hautop Lund. Anybody, anywhere, anytime - Robotics with a social impact through a building block approach. In *Advanced Robotics and its Social Impacts*, pages 2–7, October 2011. ISSN: 2162-7576.
- [174] Henrik Hautop Lund. Lessons learned in designing user-configurable modular robotics. In Jong-Hwan Kim, Eric T . Matson, Hyun Myung, Peter Xu, and Fakhri Karray, editors, *Robot Intelligence Technology and Applications 2: Results from the 2nd International Conference on Robot Intelligence Technology and Applications*, Advances in Intelligent Systems and Computing, pages 279–286. Springer International Publishing, 2014.
- [175] Andreas Lyder, Ricardo Franco Mendoza Garcia, and Kasper Stoy. Mechanical design of odin, an extendable heterogeneous deformable modular robot. In *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 883–888, 2008. ISSN: 2153-0866.
- [176] Jock Mackinlay. Applying a theory of graphical presentation to the graphic design of user interfaces. In *Proceedings of the 1st annual ACM SIGGRAPH symposium on User Interface Software - UIST '88*, pages 179–189. ACM Press.
- [177] B. Madhevan and M. Sreekumar. Structures and characteristics in reconfigurable modular robots. In Jian S Dai, Matteo Zoppi, and Xianwen Kong, editors, *Advances in Reconfigurable Mechanisms and Robots I*, pages 525–534. Springer.
- [178] Atsushi Matsubayashi, Yasutoshi Makino, and Hiroyuki Shinoda. Direct finger manipulation of 3d object image with ultrasound haptic feedback. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–11. ACM Press.

- 
- [179] David Merrill, Jeevan J Kalanithi, and Pattie Maes. Siftables - towards sensor network user interfaces. In *Tangible and Embedded Interaction*, 2007.
- [180] David Merrill, Emily Sun, and Jeevan Kalanithi. Sifteo cubes. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '12, page 1015–1018, New York, NY, USA, 2012. Association for Computing Machinery.
- [181] G. Michelitsch, J. Williams, M. Osen, B. Jimenez, and S. Rapp. Haptic chameleon: A new concept of shape-changing user interface controls with force feedback. In *CHI '04 Extended Abstracts on Human Factors in Computing Systems*, CHI EA '04, page 1305–1308, New York, NY, USA, 2004. Association for Computing Machinery.
- [182] Kei Misumi, Gwenn Ulliac, Naoto Usami, Benoit Piranda, Yoshio Mita, Akio Higo, and Julien Bourgeois. Micro-scale Electrostatic Attach-detach Device for Self-reconfigurable Modular Robotic System. In *2020 Symposium on Design, Test, Integration Packaging of MEMS and MOEMS (DTIP)*, pages 1–4, June 2020.
- [183] Shuhei Miyashita, Max Lungarella, and Rolf Pfeifer. Tribolon: Water-based self-assembly robots. In Andrew Adamatzky and Maciej Komosinski, editors, *Artificial Life Models in Hardware*, pages 161–184. Springer, 2009.
- [184] Rico Moeckel, Cyril Jaquier, Kevin Drapel, Elmar Dittrich, Andres Upegui, and Auke Jan Ijspeert. Exploring adaptive locomotion with YaMoR, a novel autonomous modular robot with bluetooth interface. 33(4):285–290, 2006.
- [185] Francesco Mondada, Giovanni C. Pettinaro, Andre Guignard, Ivo W. Kwee, Dario Floreano, Jean-Louis Deneubourg, Stefano Nolfi, Luca Maria Gambardella, and Marco Dorigo. Swarm-bot: A new distributed robotic concept. *Autonomous Robots*, 17(2):193–221, 2004.
- [186] Rafael Morales González, Caroline Appert, Gilles Bailly, and Emmanuel Pietriga. Touch-tokens: Guiding touch patterns with passive tokens. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, page 4189–4202, New York, NY, USA, 2016. Association for Computing Machinery.
- [187] Rodrigo Moreno, Frank Veenstra, David Silvera, Julian Franco, Oscar Gracia, Ernesto Cordoba, Jonatan Gomez, and Andres Faina. Automated Reconfiguration of Modular Robots Using Robot Manipulators. In *2018 IEEE Symposium Series on Computational Intelligence (SSCI)*, pages 884–891, November 2018.
- [188] J.W. Morley, A.W. Goodwin, and I. Darian-Smith. Tactile discrimination of gratings. *Experimental Brain Research*, 49(2), 1983.

- 
- [189] W. F. Moroney, D. W. Biers, F. T. Eggemeier, and J. A. Mitchell. A comparison of two scoring procedures with the nasa task load index in a simulated flight task. In *Proceedings of the IEEE 1992 National Aerospace and Electronics Conference*, pages 734–740 vol.2, May 1992.
- [190] S. Murata, H. Kurokawa, E. Yoshida, K. Tomita, and S. Kokaji. A 3-d self-reconfigurable structure. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No.98CH36146)*, volume 1, pages 432–439. IEEE, 1998.
- [191] Satoshi Murata, Eiichi Yoshida, Akiya Kamimura, Kohji Tomita, Haruhisa Kurokawa, and Shigeru Kokaji. Homogeneous distributed mechanical systems. In Fumio Hara and Rolf Pfeifer, editors, *Morpho-functional Machines: The New Species*, pages 167–193. Springer Japan, 2003.
- [192] Satoshi Murata, Eiichi Yoshida, Haruhisa Kurokawa, Kohji Tomita, and Shigeru Kokaji. Concept of self-reconfigurable modular robotic system. *Artificial Intelligence in Engineering*, 15(4):383–387, 2001.
- [193] Pranathi Mylavarapu, Adil Yalcin, Xan Gregg, and Niklas Elmqvist. Ranked-list visualization: A graphical perception study. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–12. ACM, 2019.
- [194] Hikaru Nagano, Shogo Okamoto, and Yoji Yamada. Haptic invitation of textures: Perceptually prominent properties of materials determine human touch motions. *IEEE Transactions on Haptics*, 7(3):345–355, 2014.
- [195] K Nakagaki, S Follmer, and H Ishii. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In *Proceedings of the 28th Annual ACM Conference on Human Factors in Computing*, 2015.
- [196] Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, and Hiroshi Ishii. ChainFORM: A linear integrated modular hardware system for shape changing interfaces. In *Proceedings of the 29th Annual Symposium on User Interface Software and Technology, UIST '16*, pages 87–96. Association for Computing Machinery, 2016.
- [197] Ken Nakagaki, Luke Vink, Jared Counts, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. Materiable: Rendering dynamic material properties in response to direct physical touch with shape changing interfaces. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, CHI '16*, pages 2764–2772. Association for Computing Machinery.



- 
- [198] Changjoo Nam, Huao Li, Shen Li, Michael Lewis, and Katia Sycara. Trust of humans in supervisory control of swarm robots with varied levels of autonomy. In *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 825–830, 2018. ISSN: 2577-1655.
- [199] Koya Narumi, Fang Qin, Siyuan Liu, Huai-Yu Cheng, Jianzhe Gu, Yoshihiro Kawahara, Mohammad Islam, and Lining Yao. Self-healing ui: Mechanically and electrically self-healing materials for sensing and actuation interfaces. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, page 293–306, New York, NY, USA, 2019. Association for Computing Machinery.
- [200] Jonas Neubert and Hod Lipson. Soldercubes: a self-soldering self-reconfiguring modular robot system. *Autonomous Robots*, 40(1):139–158, January 2016.
- [201] Laurence Nigay and Joëlle Coutaz. A generic platform for addressing the multimodal challenge. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '95, page 98–105, USA, 1995. ACM Press/Addison-Wesley Publishing Co.
- [202] Martin Nisser, Leon Cheng, Yashaswini Makaram, Ryo Suzuki, and Stefanie Mueller. Programmable polarities: Actuating interactive prototypes with programmable electromagnets. In *The Adjunct Publication of the 34th Annual ACM Symposium on User Interface Software and Technology*, pages 121–123. ACM, 2021.
- [203] Chris North, Tim Dwyer, Bongshin Lee, Danyel Fisher, Petra Isenberg, George Robertson, and Kori Inkpen. Understanding Multi-touch Manipulation for Surface Computing. In Tom Gross, Jan Gulliksen, Paula Kotzé, Lars Oestreicher, Philippe Palanque, Raquel Oliveira Prates, and Marco Winckler, editors, *Human-Computer Interaction – INTERACT 2009*, volume 5727, pages 236–249. Springer Berlin Heidelberg, Berlin, Heidelberg, 2009. Series Title: Lecture Notes in Computer Science.
- [204] Shogo Okamoto, Hikaru Nagano, and Yoji Yamada. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics*, 6(1):81–93, 2013.
- [205] Michael Ortega and Alix Goguy. BEXHI: A Mechanical Structure for Prototyping Bendable and EXpandable Handheld Interfaces. In *Proceedings of the 2019 ACM International Conference on Interactive Surfaces and Spaces*, pages 269–273, Daejeon Republic of Korea, November 2019. ACM.
- [206] Esben Hallundbæk Østergaard, Kristian Kassow, Richard Beck, and Henrik Hautop Lund. Design of the atron lattice-based self-reconfigurable robot. *Autonomous Robots*, 21(2):165–183, Sep 2006.

- 
- [207] Antti Oulasvirta and Kasper Hornbæk. Hci research as problem-solving. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, page 4956–4967, New York, NY, USA, 2016. Association for Computing Machinery.
- [208] Amit Pamecha and Chih-Jung Chiang. DESIGN AND IMPLEMENTATION OF META-MORPHIC ROBOTS. page 11, 1996.
- [209] Pat Pannuto, Yoonmyung Lee, ZhiYoong Foo, Gyouho Kim, David Blaauw, and Prabal Dutta. Lessons from five years of making michigan micro motes. page 2, 2015.
- [210] Rizuwana Parween, Anh Vu Le, Yuyao Shi, and Mohan Rajesh Elara. System Level Modeling and Control Design of hTetrakis–A Polyiamond Inspired Self-Reconfigurable Floor Tiling Robot. *IEEE Access*, 8:88177–88187, 2020. Conference Name: IEEE Access.
- [211] Fabio Paternò and Carmen Santoro. End-user development for personalizing applications, things, and robots. 131:120–130.
- [212] James Patten and Hiroshi Ishii. A comparison of spatial organization strategies in graphical and tangible user interfaces. In *Proceedings of DARE 2000 on Designing augmented reality environments - DARE '00*, pages 41–50. ACM Press.
- [213] Sylvain Pauchet, Catherine Letondal, Jean-Luc Vinot, Mickaël Causse, Mathieu Cousy, Valentin Becquet, and Guillaume Crouzet. GazeForm: Dynamic gaze-adaptive touch surface for eyes-free interaction in airliner cockpits. In *Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS '18*, pages 1193–1205. ACM Press, 2018.
- [214] Sylvain Pauchet, Jean-Luc Vinot, Catherine Letondal, Alexandre Lemort, Claire Lavenir, Timothée Lecomte, Stéphanie Rey, Valentin Becquet, and Guillaume Crouzet. Multiplié: A linear foldable and flattenable interactive display to support efficiency, safety and collaboration. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–13, New York, NY, USA, 2019. Association for Computing Machinery.
- [215] Sylvain Pauchet, Jean-Luc Vinot, Catherine Letondal, Alexandre Lemort, Claire Lavenir, Timothée Lecomte, Stéphanie Rey, Valentin Becquet, and Guillaume Crouzet. Multiplié: A linear foldable and flattenable interactive display to support efficiency, safety and collaboration. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems - CHI '19*, pages 1–13. ACM Press, 2019.
- [216] Florian Perteneder, Kathrin Probst, Joanne Leong, Sebastian Gassler, Christian Rendl, Patrick Parzer, Katharina Fluch, Sophie Gahleitner, Sean Follmer, Hideki Koike, and

- 
- Michael Haller. Foxels: Build your own smart furniture. In *Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '20, pages 111–122. Association for Computing Machinery, 2020.
- [217] Marianne Graves Petersen, Majken Kirkegaard Rasmussen, and Johan Trettvik. Affordances of shape-changing interfaces: An information perspective on transformability and movement. In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, pages 1959–1971. ACM.
- [218] Tri Pham and Nicholas Kelling. Mechanical and membrane keyboard typing assessment using surface electromyography (sEMG). 59(1):912–915.
- [219] Delphine Picard, Catherine Dacremont, Dominique Valentin, and Agnès Giboreau. Perceptual dimensions of tactile textures. *Acta Psychologica*, 114(2):165–184, 2003.
- [220] Ben Piper, Carlo Ratti, and Hiroshi Ishii. Illuminating clay: A 3-d tangible interface for landscape analysis. (1):8.
- [221] Benoit Piranda and Julien Bourgeois. Geometrical study of a quasi-spherical module for building programmable matter. In *DARS 2016, 13th International Symposium on Distributed Autonomous Robotic Systems*, 2016.
- [222] Benoit Piranda and Julien Bourgeois. Designing a quasi-spherical module for a huge modular robot to create programmable matter. *Autonomous Robot Journal, Special Issue: Distributed Robotics: From Fundamentals to Applications*, 42(8):1619–1633, 2018.
- [223] Benoit Piranda and Julien Bourgeois. Designing a quasi-spherical module for a huge modular robot to create programmable matter. page 16, 2018.
- [224] Benoît Piranda and Julien Bourgeois. Datom: A deformable modular robot for building self-reconfigurable programmable matter. In Fumitoshi Matsuno, Shun-ichi Azuma, and Masahito Yamamoto, editors, *Distributed Autonomous Robotic Systems*, pages 70–81, Cham, 2022. Springer International Publishing.
- [225] Benoit Piranda, Guillaume J. Laurent, Julien Bourgeois, Cédric Clévy, Sebastian Moebes, and Nadine Le Fort-Piat. A new concept of planar self-reconfigurable modular robot for conveying microparts. *Mechatronics*, 23(7):906 – 915, 2013. 1. Fractional Order Modeling and Control in Mechatronics 2. Design, control, and software implementation for distributed MEMS (dMEMS).
- [226] Benoît Piranda and Julien Bourgeois. Geometrical study of a quasi-spherical module for building programmable matter. In Roderich Groß, Andreas Kolling, Spring Berman, Emilio

- 
- Frazzoli, Alcherio Martinoli, Fumitoshi Matsuno, and Melvin Gauci, editors, *Distributed Autonomous Robotic Systems*, volume 6, pages 387–400. Springer International Publishing, 2018. Series Title: Springer Proceedings in Advanced Robotics.
- [227] Ingrid Maria Pohl and Lian Loke. Touch toolkit: a method to convey touch-based design knowledge and skills. In *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction - TEI '14*, pages 251–258. ACM Press, 2013.
- [228] Ivan Poupyrev, Tatsushi Nashida, Shigeaki Maruyama, Jun Rekimoto, and Yasufumi Yamaji. Lumen: interactive visual and shape display for calm computing. In *ACM SIGGRAPH 2004 Emerging technologies on - SIGGRAPH '04*, page 17, Los Angeles, California, 2004. ACM Press.
- [229] Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. Actuation and tangible user interfaces: the vaucanson duck, robots, and shape displays. page 8, 2007.
- [230] James A. Preiss, Wolfgang Honig, Gaurav S. Sukhatme, and Nora Ayanian. CrazySwarm: A large nano-quadcopter swarm. In *2017 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3299–3304. IEEE.
- [231] Halley P Profita, James Clawson, Scott Gilliland, Clint Zeagler, Thad Starner, Jim Budd, and Ellen Yi-Luen Do. Don't mind me touching my wrist: a case study of interacting with on-body technology in public. page 8, 2013.
- [232] Laura Pruszko, Céline Coutrix, Yann Laurillau, Benoît Piranda, and Julien Bourgeois. Molecular HCI: Structuring the Cross-disciplinary Space of Modular Shape-changing User Interfaces. *Proceedings of the ACM on Human-Computer Interaction* , 2021.
- [233] Laura Pruszko, Hongri Gu, Julien Bourgeois, Yann Laurillau, and Céline Coutrix. Modular tangible user interfaces: Impact of module shape and bonding strength on interaction. page 15.
- [234] Laura Pruszko, Yann Laurillau, Benoît Piranda, Julien Bourgeois, and Céline Coutrix. Impact of the size of modules on target acquisition and pursuit for future modular shape-changing physical user interfaces. In *Proceedings of the 2021 International Conference on Multimodal Interaction, ICMI '21*, pages 297–307. Association for Computing Machinery.
- [235] Isabel P. S. Qamar, Rainer Groh, David Holman, and Anne Roudaut. HCI meets material science: A literature review of morphing materials for the design of shape-changing interfaces. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, pages 1–23. ACM Press, 2018.

- 
- [236] Jorge Peña Queralta, Li Qingqing, Tuan Nguyen Gia, Hong-Linh Truong, and Tomi Westlund. End-to-end design for self-reconfigurable heterogeneous robotic swarms. In *2020 16th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, pages 281–287, 2020. ISSN: 2325-2944.
- [237] Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. Topobo: a constructive assembly system with kinetic memory. In *Proceedings of the 2004 conference on Human factors in computing systems - CHI '04*, pages 647–654. ACM Press.
- [238] Raf Ramakers, Johannes Schöning, and Kris Luyten. Paddle: highly deformable mobile devices with physical controls. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2569–2578, Toronto Ontario Canada, April 2014. ACM.
- [239] Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. Shape-changing interfaces: a review of the design space and open research questions. In *Proceedings of the 2012 ACM annual conference on Human Factors in Computing Systems - CHI '12*, page 735. ACM Press, 2012.
- [240] Majken Kirkegård Rasmussen, Timothy Merritt, Miguel Bruns Alonso, and Marianne Graves Petersen. Balancing user and system control in shape-changing interfaces: A designerly exploration. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '16, page 202–210, New York, NY, USA, 2016. Association for Computing Machinery.
- [241] Christopher Richard and Mark Cutkosky. The effects of real and computer generated friction on human performance in a targeting task. In *Proceedings of the ASME IMECE Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, page 1101–1108. ASME, 2000.
- [242] Julie Rico and Stephen Brewster. Usable gestures for mobile interfaces: evaluating social acceptability. page 10, 2010.
- [243] Michael Rietzler, Florian Geiselhart, Julian Frommel, and Enrico Rukzio. Conveying the perception of kinesthetic feedback in virtual reality using state-of-the-art hardware. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, pages 1–13. ACM Press.
- [244] Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In *CHI '16: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 3793–3805, New York, New York, USA, May 2016. Swansea University, ACM.

- 
- [245] J. W. Romanishin, K. Gilpin, and D. Rus. M-blocks: Momentum-driven, magnetic modular robots. In *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4288–4295, Nov 2013.
- [246] John W. Romanishin, Kyle Gilpin, Sebastian Claiici, and Daniela Rus. 3d m-blocks: Self-reconfiguring robots capable of locomotion via pivoting in three dimensions. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1925–1932. IEEE, 2015.
- [247] A Roudaut, D Krusteva, M McCoy, A Karnik, K Ramani, and S Subramanian. Cubimorph: Designing modular interactive devices. In *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pages 3339–3345. IEEE, 2016.
- [248] Anne Roudaut, Abhijit Karnik, Markus Löchtfeld, and Sriram Subramanian. Morphees: Toward high “shape resolution” in self-actuated flexible mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI ’13, page 593–602, New York, NY, USA, 2013. Association for Computing Machinery.
- [249] Anne Roudaut, Henning Pohl, and Patrick Baudisch. Touch input on curved surfaces. In *CHI ’11: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, May 2011.
- [250] M. Rubenstein, K. Payne, P. Will, and Wei-Min Shen. Docking among independent and autonomous CONRO self-reconfigurable robots. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA ’04. 2004*, pages 2877–2882 Vol.3. IEEE, 2004.
- [251] Michael Rubenstein, Christian Ahler, and Radhika Nagpal. Kilobot: A low cost scalable robot system for collective behaviors. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 3293–3298. IEEE, 2012.
- [252] Daniela Rus and Marsette Vona. Crystalline robots: Self-reconfiguration with compressible unit modules. *Autonomous Robots*, 10(1):107–124, 2001.
- [253] G. G. Ryland and H. H. Cheng. Design of imobot, an intelligent reconfigurable mobile robot with novel locomotion. In *2010 IEEE International Conference on Robotics and Automation*, pages 60–65, 2010.
- [254] David Saldana, Bruno Gabrich, Guanrui Li, Mark Yim, and Vijay Kumar. ModQuad: The flying modular structure that self-assembles in midair. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pages 691–698. IEEE, 2018.

- 
- [255] Behnam Salemi, Mark Moll, and Wei-min Shen. SUPERBOT: A deployable, multi-functional, and modular self-reconfigurable robotic system. In *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3636–3641. IEEE, 2006.
- [256] Jeff Sauro and James R. Lewis. Average task times in usability tests: What to report? In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, pages 2347–2350, New York, NY, USA, 2010. ACM.
- [257] Philipp Schoessler, Daniel Windham, Daniel Leithinger, Sean Follmer, and Hiroshi Ishii. Kinetic Blocks: Actuated Constructive Assembly for Interaction and Display. In *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*, UIST '15, pages 341–349, New York, NY, USA, November 2015. Association for Computing Machinery.
- [258] Orit Shaer and Eva Hornecker. *Tangible User Interfaces: Past, Present and Future Directions*, volume 3. Now Publishers Inc, 2010.
- [259] Orit Shaer, Nancy Leland, Eduardo H Calvillo Gámez, and Robert J K Jacob. The TAC paradigm: specifying tangible user interfaces. *Personal and Ubiquitous Computing*, 8(5):359–369, 2004.
- [260] Florine Simon, Anne Roudaut, Pourang Irani, and Marcos Serrano. Finding information on non-rectangular interfaces. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–8. ACM, 2019.
- [261] Alexa F. Siu, Eric J. Gonzalez, Shenli Yuan, Jason B. Ginsberg, and Sean Follmer. shapeShift: 2d spatial manipulation and self-actuation of tabletop shape displays for tangible and haptic interaction. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, CHI '18, pages 1–13. Association for Computing Machinery.
- [262] Lisa Skedung, Martin Arvidsson, Jun Young Chung, Christopher M. Stafford, Birgitta Berglund, and Mark W. Rutland. Feeling small: Exploring the tactile perception limits. *Scientific Reports*, 3(1):2617, 2013.
- [263] Allan M. Smith, C. Elaine Chapman, Mélanie Deslandes, Jean-Sébastien Langlais, and Marie-Pierre Thibodeau. Role of friction and tangential force variation in the subjective scaling of tactile roughness. 144(2):211–223, 2002.
- [264] Nikita Soni, Ailish Tierney, Katarina Jurczyk, Schuyler Gleaves, Elisabeth Schreiber, Kathryn A. Stofer, and Lisa Anthony. Collaboration around multi-touch spherical displays: A field study at a science museum. 5:1–34.

- 
- [265] R. William Soukoreff and I. Scott MacKenzie. Towards a standard for pointing device evaluation, perspectives on 27 years of fitts' law research in HCI. *International Journal of Human-Computer Studies*, 61(6):751–789, 2004.
- [266] A. Sprowitz, R. Moeckel, M. Vespignani, S. Bonardi, and A.J. Ijspeert. Roombots: A hardware perspective on 3d self-reconfiguration and locomotion with a homogeneous modular robot. *Robotics and Autonomous Systems*, 62(7):1016 – 1033, 2014. Reconfigurable Modular Robotics.
- [267] A. Spröwitz, R. Moeckel, M. Vespignani, S. Bonardi, and A.J. Ijspeert. Roombots: A hardware perspective on 3D self-reconfiguration and locomotion with a homogeneous modular robot. *Robotics and Autonomous Systems*, 62(7):1016–1033, July 2014.
- [268] David St-Onge, Ulysse Côté-Allard, Kyrre Glette, Benoit Gosselin, and Giovanni Beltrame. Engaging with robotic swarms: Commands from expressive motion. 8(2):11:1–11:26, 2019.
- [269] Kasper Stoy and Haruhisa Kurokawa. Current topics in classic self-reconfigurable robot research. In *Proceedings of the IROS Workshop on Reconfigurable Modular Robotics: Challenges of Mechatronic and Bio-Chemo-Hybrid Systems*, 2011.
- [270] Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Versteeg. ReFlex: A flexible smartphone with active haptic feedback for bend input. In *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction - TEI '16*, pages 185–192. ACM Press, 2016.
- [271] Miriam Sturdee and Jason Alexander. Analysis and classification of shape-changing interfaces for design and application-based research. 51(1):1–32, 2018.
- [272] Miriam Sturdee, Aluna Everitt, Joseph Lindley, Paul Coulton, and Jason Alexander. Visual methods for the design of shape-changing interfaces. In David Lamas, Fernando Loizides, Lennart Nacke, Helen Petrie, Marco Winckler, and Panayiotis Zaphiris, editors, *Human-Computer Interaction – INTERACT 2019*, Lecture Notes in Computer Science, pages 337–358. Springer International Publishing, 2019.
- [273] Kasper Støy. Reconfigurable robots. In Janusz Kacprzyk and Witold Pedrycz, editors, *Springer Handbook of Computational Intelligence*, Springer Handbooks, pages 1407–1421. Springer.
- [274] L.R. Sudhakar, R.W. Schoenmarklin, S.A. Lavender, and W.S. Marras. The Effects of Gloves on Grip Strength and Muscle Activity. *Proceedings of the Human Factors Society Annual Meeting*, 32(11):647–650, October 1988.



- 
- [275] Valentina Sumini. SpaceHuman: A soft robotic prosthetic for space exploration. page 8.
- [276] Lingyun Sun, Jiaji Li, Yu Chen, Yue Yang, Zhi Yu, Danli Luo, Jianzhe Gu, Lining Yao, Ye Tao, and Guanyun Wang. FlexTruss: A computational threading method for multi-material, multi-form and multi-use prototyping. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, pages 1–12. ACM.
- [277] Ivan Sutherland. The ultimate display. *Proceedings of the IFIPS Congress 65(2):506-508. New York: IFIP*, 2, 01 1965.
- [278] Ryo Suzuki, Hooman Hedayati, Clement Zheng, James L. Bohn, Daniel Szafir, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger. RoomShift: Room-scale dynamic haptics for VR with furniture-moving swarm robots. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, pages 1–11. Association for Computing Machinery, 2020.
- [279] Ryo Suzuki, Junichi Yamaoka, Daniel Leithinger, Tom Yeh, Mark D. Gross, Yoshihiro Kawahara, and Yasuaki Kakehi. Dynablock: Dynamic 3d printing for instant and reconstructable shape formation. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, UIST '18, pages 99–111, New York, NY, USA, 2018. ACM.
- [280] Ryo Suzuki, Clement Zheng, Yasuaki Kakehi, Tom Yeh, Ellen Yi-Luen Do, Mark D. Gross, and Daniel Leithinger. ShapeBots: Shape-changing Swarm Robots. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, pages 493–505, New York, NY, USA, October 2019. Association for Computing Machinery.
- [281] Ning Tan, Abdullah Aamir Hayat, Mohan Rajesh Elara, and Kristin L. Wood. A framework for taxonomy and evaluation of self-reconfigurable robotic systems. *IEEE Access*, 8:13969–13986, 2020.
- [282] Atau Tanaka and R. Benjamin Knapp. 2002: Multimodal Interaction in Music Using the Electromyogram and Relative Position Sensing. In Alexander Refsum Jensenius and Michael J. Lyons, editors, *A NIME Reader*, volume 3, pages 45–58. Springer International Publishing, Cham, 2017. Series Title: Current Research in Systematic Musicology.
- [283] Atau Tanaka and R. Benjamin Knapp. 2002: Multimodal Interaction in Music Using the Electromyogram and Relative Position Sensing. In Alexander Refsum Jensenius and Michael J. Lyons, editors, *A NIME Reader*, volume 3, pages 45–58. Springer International Publishing, Cham, 2017. Series Title: Current Research in Systematic Musicology.

- 
- [284] Atau Tanaka and Adam Parkinson. *Haptic Wave: A Cross-Modal Interface for Visually Impaired Audio Producers*, page 2150–2161. Association for Computing Machinery, New York, NY, USA, 2016.
- [285] Shan-Yuan Teng, Cheng-Lung Lin, Chi-huan Chiang, Tzu-Sheng Kuo, Liwei Chan, Da-Yuan Huang, and Bing-Yu Chen. TilePoP: Tile-type Pop-up Prop for Virtual Reality. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, UIST '19, pages 639–649, New York, NY, USA, October 2019. Association for Computing Machinery.
- [286] Pierre Thalamy, Benoit Piranda, and Julien Bourgeois. Distributed Self-Reconfiguration using a Deterministic Autonomous Scaffolding Structure. In *Proceedings of the 19th International Conference on Autonomous Agents and MultiAgent Systems*, pages 140–148, Montreal QC, Canada, May 2019.
- [287] Pierre Thalamy, Benoit Piranda, and Julien Bourgeois. 3D Coating Self-Assembly for Modular Robotic Scaffolds. In *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 11688–11695, Las Vegas, NV, USA, October 2020. IEEE.
- [288] Pierre Thalamy, Benoit Piranda, Frederic Lassabe, and Julien Bourgeois. Scaffold-based asynchronous distributed self-reconfiguration by continuous module flow. In *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 4840–4846. IEEE, 2019.
- [289] Pierre Thalamy, Benoit Piranda, Andre Naz, and Julien Bourgeois. Behavioral simulations of lattice modular robots with visiblesim. In *15th International Symposium on Distributed Autonomous Robotic Systems (DARS 2021)*, Kyoto, Japan, jun 2021.
- [290] Pierre Thalamy, Benoît Piranda, and Julien Bourgeois. A survey of autonomous self-reconfiguration methods for robot-based programmable matter. *Robotics and Autonomous Systems*, 120:103242, 2019.
- [291] Pierre Thalamy, Benoît Piranda, Frédéric Lassabe, and Julien Bourgeois. Deterministic scaffold assembly by self-reconfiguring micro-robotic swarms. 58:100722.
- [292] John Tiab and Kasper Hornbæk. Understanding affordance, system state, and feedback in shape-changing buttons. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, CHI '16, page 2752–2763, New York, NY, USA, 2016. Association for Computing Machinery.

- 
- [293] Kohji Tomita, Satoshi Murata, Eiichi Yoshida, Haruhisa Kurokawa, and Shigeru Kokaji. *Reconfiguration Method for a Distributed Mechanical System*, pages 17–25. 01 1996.
- [294] Melanie Tory and Robert Kincaid. Comparing physical, overlay, and touch screen parameter controls. In *Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces - ITS '13*, pages 91–100. ACM Press, 2013.
- [295] E. Tsykunov, R. Agishev, R. Ibrahimov, L. Labazanova, A. Tleugazy, and D. Tsetserukou. SwarmTouch: Guiding a swarm of micro-quadrotors with impedance control using a wearable tactile interface. 12(3):363–374, 2019. Conference Name: IEEE Transactions on Haptics.
- [296] Philip Tuddenham, David Kirk, and Shahram Izadi. Graspables revisited: Multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '10, pages 2223–2232, New York, NY, USA, 2010. ACM.
- [297] Anke van Oosterhout and Eve Hoggan. Deformation techniques for shape changing interfaces. In *Extended Abstracts of the 2021 CHI Conference on Human Factors in Computing Systems*, CHI EA '21, pages 1–7. Association for Computing Machinery.
- [298] Anke van Oosterhout, Eve Hoggan, Majken Kirkegaard Rasmussen, and Miguel Bruns. DynaKnob: Combining haptic force feedback and shape change. In *Proceedings of the 2019 on Designing Interactive Systems Conference - DIS '19*, pages 963–974. ACM Press.
- [299] Luis Vega, Devin Hughes, Camilo Buscaron, Dr Eric M Schwartz, and Dr A Antonio Arroyo. MILyBots: Design and development of swarm-robots. page 9, 2008.
- [300] Benjamin Verdier, Sheldon Andrews, and Paul G. Kry. Human grasping interaction capture and analysis. In *Proceedings of the ACM SIGGRAPH / Eurographics Symposium on Computer Animation*, SCA '17, pages 1–2, New York, NY, USA, July 2017. Association for Computing Machinery.
- [301] Pierre Vermersch. *The explicitation interview*. 05 2018.
- [302] Santiago Villarreal-Narvaez, Jean Vanderdonckt, Radu-Daniel Vatavu, and Jacob O. Wobbrock. A systematic review of gesture elicitation studies: What can we learn from 216 studies? In *Proceedings of the 2020 ACM Designing Interactive Systems Conference*, pages 855–872. ACM, 2020.
- [303] Xiaofeng Wang, Minglu Zhang, and Weimin Ge. A novel docking mechanism design and dynamic performance analysis of self-reconfigurable modular robot. In Xilun Ding, Xianwen Kong, and Jian S. Dai, editors, *Advances in Reconfigurable Mechanisms and Robots*

---

*II*, Mechanisms and Machine Science, pages 681–692. Springer International Publishing, 2016.

- [304] Ryoichi Watanabe, Yuichi Itoh, Masatsugu Asai, Yoshifumi Kitamura, Fumio Kishino, and Hideo Kikuchi. The soul of ActiveCube — implementing a flexible, multimodal, three-dimensional spatial tangible interface. 2(4):13, 2004.
- [305] Michael Philetus Weller, Mark D. Gross, and Seth Copen Goldstein. Hyperform specification: designing and interacting with self-reconfiguring materials. 15(2):133–149, 2011.
- [306] Werner Wetzlinger, Andreas Auinger, and Michael Doerflinger. Comparing effectiveness, efficiency, ease of use, usability and user experience when using tablets and laptops. volume 8517, pages 402–412, 06 2014.
- [307] Paul White, Victor Zykov, Josh Bongard, and Hod Lipson. Three dimensional stochastic reconfiguration of modular robots. In *Robotics: Science and Systems I*. Robotics: Science and Systems Foundation, 2005.
- [308] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 143–146, New York, NY, USA, 2011. ACM.
- [309] Jacob O. Wobbrock, Leah Findlater, Darren Gergle, and James J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, pages 143–146, New York, NY, USA, 2011. ACM.
- [310] Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. PneuUI: pneumatically actuated soft composite materials for shape changing interfaces. In *UIST '13: Proceedings of the 26th annual ACM symposium on User interface software and technology*, pages 13–22, New York, New York, USA, October 2013. ACM.
- [311] Kentaro Yasu. MagneLayer: Force Field Fabrication for Rapid Prototyping of Haptic Interactions. In *ACM SIGGRAPH 2020 Labs*, pages 1–2, Virtual Event USA, August 2020. ACM.
- [312] Kentaro Yasu and Yuichiro Katsumoto. Bump ahead: easy-to-design haptic surface using magnet array. In *SIGGRAPH Asia 2015 Emerging Technologies*, pages 1–3, Kobe Japan, November 2015. ACM.

- 
- [313] M. Yim, D. G. Duff, and K. D. Roufas. Polybot: a modular reconfigurable robot. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, volume 1, pages 514–520 vol.1, April 2000.
- [314] M. Yim, W. Shen, B. Salemi, D. Rus, M. Moll, H. Lipson, E. Klavins, and G. S. Chirikjian. Modular self-reconfigurable robot systems [grand challenges of robotics]. *IEEE Robotics Automation Magazine*, 14(1):43–52, March 2007.
- [315] Mark Yim, Paul White, Michael Park, and Jimmy Sastra. Modular self-reconfigurable robots. In Robert A. Meyers, editor, *Encyclopedia of Complexity and Systems Science*, pages 5618–5631. Springer, 2009.
- [316] Mark H. Yim, John O. Lamping, and Eric W. Mao. Touchable user interface using self movable robotic modules, June 2001.
- [317] Shigeo Yoshida, Yuqian Sun, and Hideaki Kuzuoka. Pocopo: Handheld pin-based shape display for haptic rendering in virtual reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, CHI '20, page 1–13, New York, NY, USA, 2020. Association for Computing Machinery.
- [318] Takashi Yoshioka, James Craig, Graham Beck, and Steven Hsiao. Perceptual constancy of texture roughness in the tactile system. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 31:17603–11, 11 2011.
- [319] Takashi Yoshioka and Julia Zhou. Factors involved in tactile texture perception through probes. *Advanced Robotics*, page 22, 2009.
- [320] H.X. Zhang, J. Gonzalez-Gomez, S.Y. Chen, and J.W. Zhang. Embedded intelligent capability of a modular robotic system. In *2008 IEEE International Conference on Robotics and Biomimetics*, pages 2061–2066. IEEE, 2009.
- [321] Yiwei Zhao, Lawrence H. Kim, Ye Wang, Mathieu Le Goc, and Sean Follmer. Robotic assembly of haptic proxy objects for tangible interaction and virtual reality. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, ISS '17, page 82–91, New York, NY, USA, 2017. Association for Computing Machinery.
- [322] Yiwei Zhao, Lawrence H. Kim, Ye Wang, Mathieu Le Goc, and Sean Follmer. Robotic Assembly of Haptic Proxy Objects for Tangible Interaction and Virtual Reality. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, pages 82–91, Brighton United Kingdom, October 2017. ACM.

- 
- [323] Clement Zheng, Jeeun Kim, Daniel Leithinger, Mark D. Gross, and Ellen Yi-Luen Do. Mechamagnets: Designing and Fabricating Haptic and Functional Physical Inputs with Embedded Magnets. In *Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pages 325–334, Tempe Arizona USA, March 2019. ACM.
- [324] Kening Zhu, Morten Fjeld, and Ayça Ünlüer. WristOrigami: Exploring Foldable Design for Multi-Display Smartwatch. In *Proceedings of the 2018 on Designing Interactive Systems Conference 2018 - DIS '18*, pages 1207–1218, Hong Kong, China, 2018. ACM Press.
- [325] Yanhe Zhu, Jie Zhao, Xindan Cui, Xiaolu Wang, Shufeng Tang, Xueyuan Zhang, and Jingchun Yin. Design and implementation of UBot: A modular self-reconfigurable robot. In *2013 IEEE International Conference on Mechatronics and Automation*, pages 1217–1222. ISSN: 2152-744X.
- [326] Oren Zuckerman, Saeed Arida, and Mitchel Resnick. Extending tangible interfaces for education: Digital montessori-inspired manipulatives. page 10.
- [327] Victor Zykov, Efstathios Mytilinaios, Mark Desnoyer, and Hod Lipson. Evolved and designed self-reproducing modular robotics. *IEEE Transactions on Robotics*, 23(2):308–319, 2007.
- [328] Cem Ünsal, Han Kiliççöte, and Pradeep K. Khosla. A modular self-reconfigurable bipartite robotic system: Implementation and motion planning. 10(1):23–40.