



User-Centered Design of Shape-Changing Controls

Hyunyoung Kim

► To cite this version:

Hyunyoung Kim. User-Centered Design of Shape-Changing Controls. Human-Computer Interaction [cs.HC]. Université Grenoble Alpes, 2020. English. NNT: . tel-03364926

HAL Id: tel-03364926

<https://theses.hal.science/tel-03364926>

Submitted on 5 Oct 2021

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

Spécialité : Informatique

Arrêté ministériel : 25 mai 2016

Présentée par

Hyunyoung KIM

Thèse dirigée par **Céline COUTRIX**, CR1, CNRS,
et codirigée par **Anne ROUDAUT**,
PROFESSEUR ASSOCIE, UNIVERSITE DE BRISTOL

préparée au sein du **Laboratoire d'Informatique de Grenoble**
dans l'**École Doctorale Mathématiques, Sciences et**
technologies de l'information, Informatique

Conception centrée sur l'utilisateur des
commandes de changement de forme

User-Centered Design of Shape-Changing
Controls

Thèse soutenue publiquement le **28 janvier 2020**,
devant le jury composé de :

Monsieur SRIRAM SUBRAMANIAN

PROFESSEUR, UNIVERSITE DE SUSSEX - GRANDE BRETAGNE,
Rapporteur

Monsieur MIGUEL BRUNS

PROFESSEUR ASSOCIE, UNIVERSITE TECH. EINDHOVEN - PAYS-
BAS, Rapporteur

Madame LAURENCE NIGAY

PROFESSEUR, UNIVERSITE GRENOBLE ALPES, Président

Monsieur DANIEL ASHBROOK

PROFESSEUR ASSOCIE, UNIVERSITE DE COPENHAGUE -
DANEMARK, Examineur





Acknowledgments

I would like to express my sincere appreciation to my supervisors, Céline Coutrix and Anne Roudaut. It has been a great journey to work with them. I learned how to do research while having fun with and around it. I sometimes look back to the day we had our first in-person meeting. I knew little about research. I was so nervous, and worrying about the unknown future. Thanks to them, now I have confidence and look forward to my academic future.

I had not visited France before my PhD and had not known what it would bring to my life. I have met so many nice people, had rich cultural exchanges, and picked up new hobbies. They made my life rich. I first want to mention my PhD brother Juan. We had lots of things in common: research interests, the same supervisor, and the fact that we were both foreigners. We could discuss whenever there was a problem, whether work-related or personal. He helped me see things balanced by providing a different point of view. I also thank my office mates, Raquel, Laura, Tanguy, Mina, Van bao, Julian, and Marine, for understanding me messing around the office with prototypes and sticky notes. I had a lot of fun jamming and dancing with Ying, Belen, and Julius. I appreciate my bouldering friends, Romain, Manon, Alix, Zhuzhi, and Anuvabh for helping me keep in a good shape. Jérémy, Charles, Elie, Jose, Hayet, and Carole, I will miss Dr. D and our board game nights. We did not shared an office, but I appreciate Mike for making me feel welcome. I thank François and George for sharing their apartments with me and Fabian.

I had a luck to visit two universities during my PhD: the University of Stuttgart and the University of Bristol. In Stuttgart, Huy and I shared an office, which was called Little Asia (readers can guess why it was called so). We shared lots of Swabian jokes and serious discussions about how to work. Niels spared lots of his time to give me feedback on my papers. He was also fun to hangout with. Alex, Rufat, Dominik, and I went to Halsi (a convenience store in the university) almost everyday to survive the afternoon. I miss their Leberkäse. It was a nice experience to write a paper with

Acknowledgments

Miriam, Andreas, and Albrecht. I am happy that we got an award with the paper. I thank Paweł for sharing the challenges he had in his academic life. It gave me a lot of courage. I also appreciate Romina, Tonja, Thomas, Francisco, Sven, Lars, Anja, and Dirk for being nice to me. I was too shy to express all my thoughts, but I do appreciate them.

In Bristol, I was lucky to have Isabel to host me. I enjoyed my time in her apartment and learning from her about how to build up muscles. We also presented papers at the same CHI session. Kathy was one of the most organized and brightest people I have ever met. The book she lent me, "The Professor Is In," sharpened my professional attitude. Lulu and I shared the pain of the PhD life. It made me feel that I was not the only one who suffered. I appreciate Asier, Gareth, and Jess for feeding me all the technical and nerdy knowledge.

My family and friends in Korea supported me a lot in the decision making of leaving Korea for my PhD. My dad always supported me whatever decision I make. He also taught me work ethics. I appreciate my mom showing her work around home since I was young; I am still fascinated by blue prints and architects. I was not the nicest sister to Soyoung and Hyeyoung, but they liked me anyways and always worried about me. Hani, Jihye, and Misol have been great friends since high school. I appreciate that we still share lots of parts of our lives.

Lastly, I appreciate my fiancé Fabian for supporting me by visiting me in Stuttgart and Bristol, cooking, and being there for me.




Abstract

Shape-changing interfaces bring flexibility in physical interfaces through by transforming computational devices into any shape or materiality. Shape-changing interfaces will be increasingly available to end-users in the future, along with technology development. However, we know little about design criteria of shape-changing interfaces for end-users, especially for whom use parameter control interfaces. Parameter control interfaces are often designed based on existing examples such as dials and sliders, and there were few studies to understand user needs behind their usage. On the other hand, there are shape-changing interface taxonomies that allow designers to explore design ideas of shape-changing interfaces systematically, but they are hardly evaluated. In this thesis, I discuss my Ph.D. work investigating the two areas of HCI: parameter control interfaces and shape-changing interfaces. I first conduct a formative study to suggest design requirements for parameter control interfaces based on users' current practice. Second, I refine a shape-changing interface taxonomy by evaluating its descriptive power by using everyday reconfigurable objects. Lastly, I look into the intersection of the parameter control interfaces and shape-changing interfaces. I develop two case studies: KnobSlider, a shape-changing interface that can be a knob or a slider, and ExpanDial, a rotational control that extends the interaction modality through shape-changes.



Résumé

Les interfaces à changement de forme apportent de la flexibilité aux interfaces physiques en transformant les dispositifs de calcul en n'importe quelle forme ou matérialité. Les interfaces à changement de forme seront de plus en plus accessibles aux utilisateurs finaux à l'avenir, parallèlement au développement technologique. Cependant, nous savons peu de choses sur les critères de conception des interfaces à changement de forme pour les utilisateurs finaux, en particulier pour ceux qui utilisent des interfaces de contrôle des paramètres. Les interfaces de contrôle des paramètres sont souvent conçues sur la base d'exemples existants tels que des cadrans et des curseurs, et peu d'études ont été menées pour comprendre les besoins des utilisateurs derrière leur utilisation. D'autre part, il existe des taxonomies d'interfaces à changement de forme qui permettent aux concepteurs d'explorer systématiquement les idées de conception d'interfaces à changement de forme, mais elles ne sont guère évaluées. Dans cette thèse, je discute de mon travail de doctorat qui étudie les deux domaines de l'IHM : les interfaces de contrôle des paramètres et les interfaces à changement de forme. Je mène d'abord une étude formative pour suggérer des exigences de conception pour les interfaces de contrôle des paramètres en fonction de la pratique actuelle des utilisateurs. Ensuite, j'affine une taxonomie d'interface à changement de forme en évaluant son pouvoir descriptif à l'aide d'objets quotidiens reconfigurables. Enfin, j'étudie l'intersection des interfaces de contrôle des paramètres et des interfaces à changement de forme. Je développe deux études de cas : KnobSlider, une interface à changement de forme qui peut être un bouton ou un curseur, et ExpanDial, une commande de rotation qui étend la modalité d'interaction par des changements de forme.



Statement on Multiple Authorship and Prior Publication

The thesis is based on my previous publications in ACM proceedings and a journal. They are KnobSlider [101, 99, 100], Morphees+[97], and ExpanDial [102]. I am the first author of those publications and the main contributor.

Here I specifically state where I contributed in the publications. For KnobSlider, I collaborated in the analysis of the formative study. I lead the implementation of the KnobSlider prototype, and I collaborated on the analysis of the qualitative study. I lead the design, execution, and analysis of the controlled study. For Morphees+, I lead the focus group interview to collect everyday reconfigurable objects. I contributed to the data analysis and visualization. For ExpanDial, helped the analysis of grasp study results. I lead the implementation of the prototype, the focus group interview, and its analysis.



Contents

Acknowledgments	iii
Abstract	v
Résumé	vii
Statement on Multiple Authorship and Prior Publication	ix
Contents	x
List of Figures	xii
List of Tables	xx
1 Introduction	1
1.1 Context	2
1.2 Problem Statement	6
1.3 Methodology	8
1.4 Thesis Contributions	11
2 Related Work	15
2.1 Evolution of the Types of Interfaces	16
2.2 Shape-Changing Interfaces as a Research Field	24
2.3 Design of Control Interfaces	29
2.4 Flexibility in Physical Control Interfaces	35
2.5 Conclusion	40
3 Design Requirements for Control Interfaces	43
3.1 Introduction	43
3.2 Contextual Interviews	45
3.3 Results	55
3.4 Design Requirements for Control Interfaces	64
3.5 Conclusion	66

4	Design Tools for Shape-Changing Interfaces	69
4.1	Introduction	69
4.2	Getting Inspirations from Users' Everyday Life	71
4.3	Rasmussen's and Roudaut's Taxonomy	72
4.4	Method	76
4.5	Analysis of the Current Taxonomies	82
4.6	Morphees Taxonomy Refinement	86
4.7	Discussions on Implementing the Features	90
4.8	Conclusion	94
5	KnobSlider: Design of Shape-Change for Heterogeneous Controls	97
5.1	Introduction	97
5.2	KnobSlider Design	100
5.3	Implementing the Working Prototype	114
5.4	Qualitative Study with Professional Users	118
5.5	Controlled Experiment: Pairwise Comparison of Speed Properties	125
5.6	Conclusion	132
6	ExpanDial: Design of a Shape-Changing Dial Based on a Grasp Study	135
6.1	Introduction	135
6.2	Grasp Study	137
6.3	ExpanDial Prototype Implementation	145
6.4	Design of Applications and Gestures	148
6.5	Results	149
6.6	Comparison with KnobSlider	155
6.7	Conclusion	156
7	Conclusion	159
7.1	Thesis Contributions	159
7.2	Limitations and Short-term Future Work	161
7.3	Perspectives for Future Shape-Changing Interfaces	166
8	Résumé en français	169
8.1	Contexte	171
8.2	Énoncé du problème	176
8.3	Méthodologie	178
8.4	Contributions de la thèse	182
	Bibliography	185



List of Figures

1.1	Touchscreen and physical audio mixers. (A) A touchscreen audio mixer, Matrix DJ Touchscreen System [33]. It allows users to preset several "windows" with interface elements and switch between windows on demand. (B) A physical audio mixer, which users can control multiple parameters simultaneously by using passive haptic feedback.	2
1.2	The two research areas we investigate in the thesis: control interfaces and shape-changing interfaces. The intersection is shape-changing controls, our main focus of the thesis.	8
1.3	The detailed view of our research focus showing the four-step approach: (1) We first study underlying user needs and design requirements for control interfaces. (2) We then provide design tools for shape-changing interfaces by refining an existing taxonomy and generating a collection of everyday reconfigurable objects. (3, 4) Lastly, we conduct two case studies that explore designs of shape-changing control interfaces that are driven by the understanding of control interfaces and design tools for shape-changing interfaces.	8
2.1	Scope of the literature we review in the thesis. We first briefly go through the types of interfaces, to show how shape-changing interfaces are positioned comparing to traditional interfaces. We then discuss shape-changing interfaces as a research field by referring literature that defines their taxonomies and design approaches for them. We then study designs of traditional design control interfaces. Lastly, we review how literature have implemented flexibility in physical control interfaces in terms of time- and space-multiplexing.	14
2.2	Three types of interfaces (GUIs, PUIs, and shape-changing interfaces) arranged on the axes of physicality and flexibility.	17
2.3	Examples of early GUIs. Still from Kenneth Friedman [53].	18
2.4	Videoplace by Krueger et al. [106]. The user can have different interactions on the same interface, as in (A) and (B). Still from VintageCG [198]. . . .	18

2.5	MusicBottles, a PUI for playing jazz music. Users can control which instrument of the music is played by opening and closing the bottle lids [83]. Courtesy of Tangible Media Group, MIT Media Lab [175].	20
2.6	The Marble Answering Machine, a conceptual physical interface by Bishop [14]. Still from Luckybite [118].	20
2.7	(Left) The metaDESK with tangible elements: lenses, phicons, and instrument [191]. (Right top) Demonstration of the activeLENS. The device provides a bird's-eye view of a place where it is over the map. (Right bottom) The instrument can scale and rotate the map. Courtesy of Tangible Media Group, MIT Media Lab.	21
2.8	PaperPhone, an Organic UI example [108]. The user is bending the corner of the flexible phone to input a gesture. Courtesy of Byron Lahey.	22
2.9	A storyboard of using the Perfect Red to create a speaker. Courtesy of Tangible Media Group, MIT Media Lab.	23
2.10	Examples of binary controls. (A) Buttons are controls that are pushed towards to their surface. They are "on" only when pressed (also called as keys), or can keep their "on" states (often called push-buttons). (B) Switches can be also pressed towards surface. However, they have two distinct pushing points, which represent "on" and "off" [8].	30
2.11	Continuous and discrete dial examples. (A) A continuous dial can control continuous parameters such as volume of sound. It does not have detents. (B) A discrete dial can set a cooking mode of an oven. The dial also has detents where the visual signs are.	31
2.12	Examples of continuous and discrete linear controls. (A) The cursor of the continuous slider can be moved smoothly. (B) The sliding switch has limited number of detents, which can guide users to use it without seeing the interface.	32
2.13	Button- or dial-based physical control interfaces that provide flexibility. (A) A shape-changing button [76]. (B, C) height- and shape-changing dials [170, 119]. (D) A dial with variable detent [7]. (E, F) Width- and shape-changing dials [133, 134]. Courtesy of Fabian Hemmert, Jihoon Suh, Stefan Rapp, Nicolas Villar, and Anke van Oosterhout (E,F).	35
2.14	Slider-based physical interfaces that provide flexibility. (A) A slider with an actuated cursor to physically render sound wave [174]. (B,C,D,E) Sliders with different haptic feedback (detent) [162, 56, 117, 193]. (F) A slider that users can change its length [32]. (G) A slider that users can change the number of the cursor [63]. Courtesy of Atau Tanaka, Morten Fjeld (B,C), Lars Lischke, Marynel Vázquez, Céline Coutrix, and Andreas Korge.	36
2.15	Examples for space-multiplexing control interfaces. (A) A set of mechanical widgets including rotational and linear joints [15]. (B) Two vertically stacked dials [25]. (C) a dial on a slider [40]. Courtesy of Alan Blackwell, Liwei Chan, and Tom Djajadiningrat.	37

2.16	Examples of time-multiplexing control interfaces. (A) Paddle, a deformable device that can make a round shape or flat linear shape [142]. (B) A user is demonstrating the rotational interaction with inFORM [51]. inFORM can also make touch surface for slider interaction. (C) A rod is being used as dial in Emergeables [148], while it can be used as a part of a linear control. (D) The user is forming the surface of ForceForm. She/he can create round or linear grooves for rotational or linear interactions [188]. (E) With ChainFORM, users can also create round or linear shapes [124]. Courtesy of Raf Ramakers, Tangible Media Group, MIT Media Lab (B, E), Céline Coutrix, and Tom Gedeon.	38
2.17	Examples of widgets on touch surfaces. (A) Tangible remote controllers for wall-sized displays [88]. (B) SLAP Widgets [201]. Courtesy of Yvonne Jansen and Malte Weiss.	39
3.1	Contribution of this chapter: Understanding user needs in control interfaces by conducting contextual interviews and deriving design requirements for control interfaces.	42
3.2	The control widgets in professional control interfaces have little changed for 30 years. Although touchscreens and background lights in control widgets are added, the widgets such sliders and buttons stay the same. (A) LCD 120. (B) grandMA3 full-size. Courtesy of MA Lighting International GmbH [59].	44
3.3	The participants and their interfaces observed in our contextual interviews. (P1) Movie operator. (P2) Graphic designer. (P3) Light artist. (P4) Light engineer. (P5-6) Sound engineers. (P7-8) Private pilots. We went to their workplaces to observe their workflows and interview them.	46
3.4	(A) P1 movie operator is adjusting a camera parameter with her hand held control interface while looking at a screen. (B) She is using the same interface to edit a video.	47
3.5	(A) P2 graphic designer is editing the drawing on the left screen. She has the second screen on the right side to access the conversation with clients. (B) An example drawing from her portfolio, showing the original sket on the left and the final version on the right. The more examples can be found in her online portfolio: http://hfournie.free.fr/	48
3.6	P3 light artist and his work environment. (A) the stage arrangement with his desk. The audience sat between the stage and the sound and light engineers' desk (not visible in the figure). (B) P3 is using his laptop to control lights before the show. (C) P3 is controlling the laptop and iPad while looking at the stage during the show, in the dark.	49
3.7	P4 light engineer and his work environment. (A) He is writing down the mapping of the controls on paper. (B) He is setting up the lights in the daylight for a night show.	50
3.8	P5 sound engineer and his work environment. (A) P5 sound engineer is communicating with a musician on the stage while controlling a slider. (B) He set up parameters on his laptop software which was connected to the mixing console. He gave color codes and parameter names on the software (see left top corner of the screen).	51

3.9	P6 sound engineer and his work environment.	52
3.10	P7 a pilot and his flight simulator	53
3.11	P8 controlling his cockpit interface.	54
3.12	Examples of binary controls we observed during the contextual interviews. (A) Tab buttons to navigate to different UI screens. (B) Buttons on a mixing console to change assigned parameters or values of a set of slid- ers. (C,D) Switches in a cockpit. Similar to (A) and (B), they can show which parameter values are currently chosen. (E) Two "RNG" buttons to increase and decrease zoom on a map. A "ENT" button to finalize input of the co-axial dials below. (F) A button to trigger a sequence of changes in light. (G) buttons on a tablet pen to trigger functions (from sketch during the interview). (H) Buttons next to a display. The functions of the buttons are flexible thanks to the display.	57
3.13	Examples of rotational controls we observed in the contextual interviews. (A) Continuous dials with infinite ranges. (B) Dials with discrete visual markers. (C) Two-leveled dials with detents, enabling both coarse and precise controls depending on which level users are controlling. (D) a shuttle dial with a smooth concave notch. (E) an arrow-shaped dial with a limited control range. (F) a tactile dial on a graphic tablet. The round groove allows users to place and move fingers on it. (G) tactile dials on a touchscreen tablet. They control continuous and bounded parameters. . .	58
3.14	Examples of linear controls we observed in the contextual interviews. A) Slider with a visual marker (red tape). B) Slider with an associated button. C) Sliders with color codes. D) Tactile slider with a place holder. E) Touch slider on a tablet. F) Side control yoke in a cockpit. Users can pull and push it to change the elevation during flight or brake during taxi. G) Throttle in a cockpit. By pushing it, users can control the amount of fuel going to the engine to change the speed.	59
3.15	P6 using haptic feedback to slightly move the slider cursor.	61
4.1	Contribution of this chapter: a refined taxonomy of shape-changing inter- faces and a collection of everyday reconfigurable object as an inspirational tool.	68
4.2	Rasmussen's taxonomy on types of change in shape.	72
4.3	Morphees taxonomy.	73
4.4	The workshop to add missing reconfigurable objects and find future design ideas.	76
4.5	Examples of collected everyday reconfigurable objects. The full collection of 82 objects with pictures is available at [98]. Photo credits (from left top to right bottom): Hyunyoung Kim, SparkFun Electronics, Paul Goyette, Minnesota Historical Society, Counselling, Unsplash.	77
4.6	Everyday objects (left column) and the taxonomies' features (right col- umn) they belong to. The thickness of each node shows how many con- nections it has. Rasmussen's features are blue, and Roudaut's features are red.	80

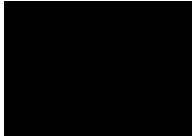
4.7	Number of objects that taxonomy features share. (Left, Heatmap) The diagonal shows how many objects are in each feature; The upper-right triangle (equivalent to the lower-left) shows how many objects the features share. (Right, Dendrogram) Clusters of similar features at different levels of the tree; The shorter length of branch (A) means the two features are more similar than the other clusters are (B-F).	81
4.8	Refinement of the Shape Resolution features after analyzing everyday reconfigurable objects. We add (A) Size and Modularity to complete the (B) previous features. Size is an extended feature from the original definition of Area. Modularity is a new feature measuring the ability to be split into several parts that can be recombined.	86
4.9	Example objects of Elastic, Stiff and Hybrid material. Elastic: #92 balloon, #44 map. Stiff: #38 carabiner, #88 Lego. Hybrid: #14 canopy on a window, #67 tent poles. Photo credits: Cookelma, Nikolaj, Poly-paradigm, Max Pixel, Lilsarahp, chaoticandrandom.	90
4.10	Relative numbers of objects with a certain reconfigurable feature. Counted and accumulated within each material type.	91
4.11	Examples of stiff objects and lower pairs [73]. From left to right: #145 Swiss army knife, #148 telescopic ladder, a screw pair, #23 telescopic radio antenna, #11 tripod, #1 modular sofa. Photo credits: Andy Rennie, markus53, SparkFun Electronics, Evan-amos.	93
5.1	Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by designing, implementing, and evaluating a shape-changing control interface.	96
5.2	Idea 1. Slap Bracelet	103
5.3	Idea 2. Party Whistle	104
5.4	Idea 3. Accordion	105
5.5	Idea 4. Roly-Poly	106
5.6	Idea 5. Twisty Toy	107
5.7	Idea 6. Origami	109
5.8	Idea 7. Stackable Disks	110
5.9	Idea 8. Zip-Line	111
5.10	Idea 9. Fish Bone	112
5.11	Idea 10. Dukta pattern	113
5.12	(A-C) KnobSlider working prototype without the top cover to expose the slider's timing belt and the slider mechanism. (A) In slider shape, the movement of timing belt is conveyed through the gears, (B) during transformation, the edges of blocks start to lock the bottom central gear, (C) the edges completely lock the bottom central gear, the rotation of the knob does not affect the timing belt.	114
5.13	Elements of KnobSlider, here without the top cover to expose the slider's timing belt.	114

5.14	The assembly view of KnobSlider. The device consists of forty pieces of the printed case (yellow), five pulleys, a timing belt, a rotational sensor, five servo motors (blue). The method we used to connect the three pieces in the red line is illustrated in Figure 5.15.	115
5.15	A closer look at the piece in the red box in Figure 5.14, to show how two motor holders are connected through the connecting piece. They are showing the bottoms of the motor holders and top of the connecting piece. The connecting piece is showing the top to show the grooves for connection. The dots on the red lines indicate which part should meet which part when assembled. (1) The prominent part of the motor holder 2 goes under the servo motor arm on the motor holder 1. (2) The groove on the connecting piece looking like the servo motor arm locks the prominent part and the servo motor arm. (3) The second groove on the connecting piece additionally holds the motor holder 2.	116
5.16	The system diagram of KnobSlider. Five servo motors are powered by an external source (5V). They are controlled by an Arduino, and the Arduino communicates with a PC. The rotary sensor in KnobSlider communicates with the PC separately.	116
5.17	Seven out of the ten participants interacting with the probe. P2, PII and PIX are using the slider status. P3 and P5 are about the change the shape by clicking on the central button. P6 and P8 are using the dial status. . .	118
5.18	The speed variables explored in the experiment. <i>Max speed</i> is the maximum speed that the motors will have over shape-changes. We use three amounts of <i>max speed</i> : 50, 200, and 400°/s. <i>Speed profile</i> is the changes in the speed during shape-changes. <i>Square</i> : the speed of shape-change is constant over time. <i>Mountain</i> : the speed increases with a constant amount of acceleration until it reaches the maximum speed and then decreases with the same absolute amount of the acceleration.	127
5.19	A participant in the <i>video</i> condition. He is looking at a video of KnobSlider changing its shape on a screen. The size of the device on the screen is controlled to have the same size in the <i>device</i> condition.	128
5.20	The Bradley-Terry-Luce model output of different max speed and tangibility variables. The red bars show the preference ability of physical <i>device</i> (<i>physical</i>) condition with different conditions of max speed, and the green bars show the preference ability of <i>video</i> (<i>virtual</i>) condition of the same device with different conditions of max speed.	130
5.21	The Bradley-Terry-Luce model output of <i>speed profile</i> variable. The participants preferred the <i>square</i> profile over the <i>mountain</i> profile, when the <i>max speed</i> conditions were accumulated.	131
6.1	Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by looking at the design space of shape-changing dials. We look into grasps of dials and future applications and gestures for shape-changing dials.	134
6.2	The dials used in the study: four widths (1, 2, 4, 8 cm from left to right) and two heights (1, 8 cm, from bottom to top).	137

List of Figures

6.3	The study setup with two RGB cameras and one thermal camera above the dial placed on a Lazy Susan. Participants were sitting in front of the setup and were asked to stay seated.	138
6.4	Hand yaw, roll, and pitch.	139
6.5	Thermal camera images from the beginning (left) to the end (right) of the Lazy Suzan rotation. The angle shows the hand yaw computed from the thumb to the centroid of the other fingers relatively to the user's position.	140
6.6	Images from the RGB camera. Here the hand comes from the top (hand roll).	141
6.7	Overall postures observed.	141
6.8	Hand rolls per dial Height, Width and Angle of rotation.	142
6.9	(Left) Hand yaws per Width and Height of the dials and Angle of rotation. (Right) Number of fingers per Width and Height of the dials.	143
6.10	Placement of the fingers on the length of the 8cm dials per Width and Angle of rotation.	143
6.11	The ExpanDial, a shape-changing dial prototype using expandable origami.	145
6.12	Left) The folding pattern of a paper piece layer of ExpanDial. Right) The paper pieces folded along the pattern, stacked, and connected through 3D printed connectors.	146
6.13	The schematic of ExpanDial showing the shape-change mechanism. Three motors control the width (orange) and three motors control the height (blue). A rotational sensor (green) captures the rotation and click of the dial.	146
6.14	The application areas and control/display modality of envisioned application ideas.	150
6.15	Examples of envisioned applications of ExpanDial. (A) timer and temperature setting for an oven. (B) An alarm clock that gets bigger and brighter as the set time comes. (C) Using the dial to explore a color space. (D) A rehabilitation game.	151
6.16	Suggested gestures to increase/decrease circumference and height of dials. The numbers in the parenthesis show how many participants suggested the gesture. Left column: targeted shape-changes of the dial. Right columns: suggested gestures and how frequently they were suggested (in parenthesis). They are vertically aligned by their similarity with other shape-change gestures (e.g., Squeeze & Let Go for width increase and Squeeze for width decrease were suggested together).	153
7.1	Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by looking at the design space of shape-changing dials. We look into grasps of dials and future applications and gestures for shape-changing dials.	158

8.1	Mélangeurs audio (A) virtuel et (B) physique. (A) <i>Matrix DJ Touchscreen System</i> , un mélangeur audio à écran tactile, fournit de la flexibilité à ses utilisateurs. Il permet à l'utilisateur de prérégler plusieurs "fenêtres" avec des éléments d'interface, et de passer d'une fenêtre à l'autre pendant la lecture audio. Image utilisée ici avec l'aimable autorisation de Cal Blanco. (B) un mélangeur audio physique : les utilisateurs peuvent contrôler plusieurs paramètres simultanément grâce à retour haptique passif des éléments de contrôle.	171
8.2	Les deux domaines de recherche que nous étudions dans la thèse : les interfaces de contrôle et les interfaces à forme variable. L'intersection est le changement de forme des interface de contrôle, notre principal centre d'intérêt dans la thèse.	178
8.3	La vue détaillée de nos recherches montre l'approche en quatre étapes : (1) Nous étudions d'abord les besoins sous-jacents des utilisateurs et les exigences de conception des interfaces de contrôle. (2) Nous fournissons ensuite des outils de conception d'interfaces changeant de forme en affinant une taxonomie existante et en fournissant une collection d'objets reconfigurables du quotidien. (3, 4) Enfin, nous menons deux études de cas qui explorent la conception d'interfaces de commande à forme variable. Ces deux études s'appuient sur la compréhension des interfaces de commande et les outils de conception d'interfaces de changement de forme.	178



List of Tables

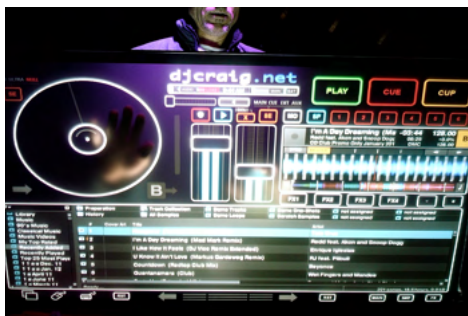
2.1	Shape-changing interface researches involving user studies.	26
2.2	Shape-changing interface design researches using taxonomies for systematic inspiration. Some of them implemented working or low-fidelity prototypes and one of them created sketches.	27
4.1	Metrics of the ten features of Morphees taxonomy.	75
4.2	Metrics of the eleven features of Morphees+ taxonomy.	87
5.1	Design space of control interfaces, in the perspectives of time- and space-multiplexing.	101
5.2	Summary of the low-fidelity prototype analysis based on the design requirements from the formative study in Chapter 3.	102
5.3	Summary of how KnobSlider fulfills the design requirements. The text in bold highlights what features KnobSlider support the requirements. . . .	117
5.4	Tasks performed in the qualitative study.	119
5.5	The variable and conditions of the controlled study. For the <i>physicality</i> variable, we use between-subjects design to remove the learning effect. For the <i>max speed</i> and <i>speed profile</i> variables, we use within-subjects design to eliminate individual differences by participants on the variables.	126
6.1	Comparison of KnobSlider and ExpanDial based on the design requirements from Chapter 3. Understanding interactions with control interfaces.	155

Introduction

This thesis contributes to the field of HCI—Human-Computer Interaction, a field in computer science focusing on the design and technology for the interaction between users and computers. The main goal of the thesis is to advance flexibility in physical control interfaces through shape-change. Flexibility—an interface’s ability to provide multiple means for users and the system to exchange information [39]—can be often found in Graphical User Interfaces (GUIs). For instance, users can customize the tool palette in Photoshop[®], and the system can adjust windows to fit them in a display. Flexibility of interfaces is the key to express the readily changing digital information. On the other hand, physicality of Physical User Interfaces (PUIs)¹ provide rich haptic feedback, affordances through their shapes, and eyes-free control to users [161]. It enhances spatial memory [29], increases directness of interaction [10, 161], and exploits humans’ dexterity [40]. However, PUIs often lack flexibility. For instance, phicons—physical icons, physical representatives of digital information that can replace graphical icons [85]—often remain static, and users need to use other phicons when they change tasks or parameters to control [161]. This happens in particular with common control interfaces such as dials and sliders: they keep their shapes throughout interactions. They do not adapt to the current parameters users are controlling, users’ work environment, or users themselves. In this thesis, we tackle the problem of the lack of flexibility in physical control interfaces through shape-changing interfaces. Shape-changing interfaces can take and/or display deformations of interfaces, and thus provide flexibility in physical interfaces. To embed flexibility in control interfaces, we take three steps: (1) we study the advantages and limitations of current control interfaces through an empirical study; (2) we propose design tools for shape-changing interfaces; and (3) we demonstrate and evaluate two case studies based on the lessons from the empirical study and the design tools.

¹In this thesis, we choose to use the term PUIs instead of Tangible User Interfaces (TUIs), which is more widely used in the HCI field. We use PUIs to include any interfaces that have physical forms and characteristics, as the original notion of TUIs do not necessarily include them [85].

1. Introduction



(A) A touchscreen audio mixer.
Courtesy of Cal Blanco [16].



(B) A physical audio mixer.
Courtesy of tdjgordon [177].

Figure 1.1: Touchscreen and physical audio mixers. (A) A touchscreen audio mixer, Matrix DJ Touchscreen System [33]. It allows users to preset several "windows" with interface elements and switch between windows on demand. (B) A physical audio mixer, which users can control multiple parameters simultaneously by using passive haptic feedback.

1.1 Context

1.1.1 Control interfaces

Control interfaces refer to parameter control widgets such as buttons, sliders, and dials [88]. They are also named as controls or control elements [8]. They roughly come in three interaction types: binary (e.g., push buttons), rotational (dials), and linear interaction (e.g., sliders). Control interfaces are widely used in professional tasks such as audio mixing² and light control³. They existed even before digitalization of analog data such as sound⁴, thus users are used to the interfaces. Each widget can be mapped to one or multiple parameters at a task, and the mappings are supposed to stay the same during the task. They are distinguished from other interfaces that are designed to change the mappings over a task such as mouse, keyboard, and gestural interfaces.

Control interfaces can be found in both GUIs and physical user interfaces (see Figure 1.1). Control interfaces in GUIs provide great flexibility, such as changing the interfaces throughout a task. For instance, a touchscreen audio mixer can show only a few virtual sliders for simple audio control when users need other widgets at the same time, and then show many more sliders when they need to control more audio parameters (Figure 1.1A). On the other hand, physicality allows richer physical interactions in interfaces than touchscreens or mouse. For instance, users can grab the widgets and have haptic feedback on how they are controlling the widgets (Figure 1.1B).

While having the long history and being wide spread, control interfaces have been

²<https://www.bax-shop.co.uk/digital-mixing-desk/behringer-x32-digital-mixer-and-usb-midi-controller>

³<https://www.bax-shop.co.uk/dmx-lighting-controllers/eurolite-color-chief-dmx-controller>

⁴https://en.wikipedia.org/wiki/Mixing_console

giving users few options about flexibility and physicality: users are forced to choose either flexibility in GUIs or physicality in physical user interfaces. Therefore they have to give up some of the values in flexibility and physicality. Recently, there have been research papers embedding both flexibility and physicality in control interfaces [133, 134, 32, 148]. The thesis goal is aligned with those papers, while we take a user-centered approach. We first want to know the values of flexibility and physicality are, and if we can take those values in new control interfaces.

1.1.2 The value of flexibility in user interfaces

Flexibility of interfaces describes the ability of an interface to change their form to adapt to various tasks and users' needs and preferences [156]. Flexibility is a typical benefit of Graphical User Interfaces (GUIs), and it allows using many different application on a single device. For instance, an average user uses 40 mobile apps each month [180]. Flexibility also enables personalization. For example, GUIs often provide lots of customization options such as a touchscreen audio mixer allowing users to choose among different input ranges and visualizations that suit their tasks [45]. The interface can also provide many widgets such as sliders, buttons, and a list of songs, which can be relocated on a screen as anyone wishes.

Contrary to GUIs, Physical User Interfaces (PUIs) are real world (i.e., physical) objects that allow users interact with digital world [36]. PUIs, despite allowing for some flexibility, are much less flexible than GUIs. One of a few examples of flexibility in physical interfaces is modular interfaces such as Palette[®]⁵. Users can arrange dials, sliders, buttons, and screens to create customized interfaces that suit their workflows. Physical interfaces can also allow flexibility through flexible mappings of parameters. Audio mixing boards can have multiple banks—sound engineers assign multiple parameters on a single slider. They switch between different sets of parameters by pressing buttons next to the sliders. Physical interfaces are recommended to be task-specific [47]. However, the specificity and physicality of physical interfaces currently limit their flexibility: dials stay as dials, and sliders stay as sliders. Because of this intrinsic physical limitation, a physical interface usually focuses on a limited set of tasks [161]. For example, a physical interface for urban planning performs limited functions such as simulating shadows and wind [192]. When users switch tasks, they would need to switch the physical interfaces as well. It increases physical clutter [190], bulkiness [41], and risk of losing the physical interfaces [104].

1.1.3 The value of physicality in user interfaces

Physicality in user interfaces describes the ability of an interface to provide physical features (particular form factors or physical widgets) that helps users with specific tasks they need to accomplish, such as browsing MRI images [60] and zooming a map [85]. Physicality is a typical benefit of PUIs and bring many advantages in interactions:

⁵<https://palettegear.com/>

1. Introduction

- Physicality enables eyes-free control. For instance, even when target parameters are distant, users can control the parameters with physical controls without looking at the controls. The physicality of the controls can tell users whether their hands are on the controls and manipulating them. It allows users to reduce the mean time for reacquiring the interfaces and the error rate of pursuit tasks [88, 148].
- Physicality leverages human dexterity and encourages users to use various gestures and body parts in addition to fingertips [161]. In Bricks [49], users used their entire hands and arms to perform a Lego sorting task without any instructions given. Tuddenham et al. elaborated the findings further by comparing physical interfaces and a touchscreen: users used various numbers of fingers, grasps, hand movements on physical interfaces, while they mostly used two fingertips on the touchscreen [189]. This type of physicality of interfaces contribute to flexibility as they allow diverse means of input.
- Physicality encourages space-multiplexing rather than time-multiplexing of input widgets. I.e., a physical widget controls a single function or data entity. It allows persistent mappings between control widgets and functions [161]. Space-multiplexing thus exploits "our spatial memory (or 'muscle memory')" [47]. It reduces the cost of acquiring (i.e., choosing) an input widget or function [161] and enables users to better perform than with time-multiplexing interfaces [47].

Flexibility and physicality are often exclusively found in GUIs and PUIs: PUIs lack flexibility (e.g., time-multiplexing) and GUIs lack physicality (c.f., vibrotactile feedback) It leads us to the next category of interfaces, shape-changing interfaces, which offer both.

1.1.4 Shape-changing interfaces, embodying both flexibility and physicality in interfaces

Shape-Changing Interfaces are "interactive computational devices to transform into any shape or materiality relevant to the context of use" [4]. They combine flexibility and physicality within a single interface and thus demonstrate many benefits:

- Shape-changing interfaces provide interaction widgets on demand. For example, when users need to paint a 3D model, the model can be physically rendered [51]. When users need to scale the 3D model, a slider emerges on the surface and allows users to physically scale the model. Another example is self-actuated flexible mobile devices that can provide appropriate shapes for different applications, such as a wide flat shape for a map and a console-like shape for a game [149, 151].
- Shape-changing interfaces provide dynamic affordances, i.e., the interfaces can change their physical features such as shape, size, and location [51]. They adapt the shape of a device to the function that this same device must deliver.

For example, a flat tablet turns into a curved shape to indicate its use as a phone and then turns into a ring suggesting its use as a bracelet [204]. Shape-changing interfaces also allow users to transform affordances of devices. For instance, Jamming User Interfaces enable users to deform the interface to a phone, remote control, watch, and game controller to change the perceived functionalities of the interface [52].

- Personalization is easier with shape-changing interfaces thanks to their flexibility. Although it is not fully investigated how the personalization of shape-changing interfaces should be designed, some literature shows the possibility of personalization with shape-changing interfaces. For example, Ripple Thermostat [133] proposed to change the size and force feedback of a thermostat dial to adapt to users' energy consumption policy. While the authors did not suggest personalization, Inflatable Mouse [103] could change its size to adapt to users' hand sizes.
- Shape-changing interfaces also enable eyes-free control as physical interfaces. Emergeables [148] show that shape-changing controls require less visual attention from the users to the control interface than touchscreen controls. The shape-changing controls required less number and duration of eye-fixations during a task comparing to touchscreen controls. Tangible drops [152] show that even liquid materials can enable eyes-free control through locomotion or vibration around users' fingertips.
- Shape-changing interfaces inherit from PUIs the possibilities of using human dexterity and various gestures. In LineFORM [123], a user wrap the chained device around his arm and can learn boxing from a remote boxer through the movement and force feedback of the chained device around his arm. Materiable [125] shows that some users use their arms and upper bodies instead of hands to press the interface and feel the force feedback.

1.2 Problem Statement

As shown previously, shape-changing interfaces have the potential to embody both flexibility and physicality in interfaces. We believe that this dual feature is particularly relevant for control interfaces. However, there are limited work on shape-changing control interfaces, and we wonder why it is the case given the advantage we can gain from such interfaces. We believe that this is due to two main challenges that need to be tackled: (1) on the control interface side we need to better understand what the end user requirements are for such interfaces; (2) on the shape-changing interfaces side there is a lack of tools to help the design of new devices. For instance the design space of shape-changing interfaces is enormously large: the interfaces can have one of, some of, or all of ten different shape features, and each feature has infinite range of deviations [149]. It can make designers to take lots of iterations while designing them. The goal of this thesis is thus to tackle these two challenges to enable the (3) creation of new shape-changing control interfaces.

Problem I: lack of design guidelines for control interfaces

Currently it is not clear what kind of design guidelines can be used when designing shape-changing controls. Design guidelines enable designers to explore different ideas efficiently. E.g., they use design guidelines for web design⁶, game design⁷ and user study design⁸. There have been a few design guidelines for shape-changing controls, combined with haptic stimuli [134], providing different access levels to a system [170], and providing audio navigational tool for visually impaired people [174]. However, those approaches are (1) focusing on particular users and applications, and (2) using particular shape-changing controls. We need design guidelines based on a broader set of applications of control interfaces to bring common knowledge grounded on what users need from shape-changing controls. From these perspectives, we see two research objectives to be addressed:

Objective 1 Understand a broad set of end users in the wild.

Objective 2 Generate design requirements for shape-changing controls.

Problem II: Lack of up-to-date design tools for shape-changing interfaces

There are tools for shape-changing interfaces that can describe and inspire different types of shape-changes [149, 145]. However, these tools are built up upon existing shape-changing interfaces, and their descriptive power is not often tested in real cases. Thus we do not know their strength to generate new interfaces as well. We want to evaluate their descriptive power.

⁶<https://html5forwebdesigners.com/design/>

⁷<https://www.giantbomb.com/profile/therpgfanatic/blog/10-simple-rules-for-good-game-design/61994/>

⁸<https://uxplanet.org/ultimate-guide-to-user-research-bed4a57d260>

Objective 3 Evaluate and refine current shape-changing interface design tools.

Additionally, we see a lack of variety in the type of design tools that currently exist. Current approaches of designing new shape-changing interfaces are either using taxonomy-based tools [130, 146], taking inspirations from users [168], or taking partial inspirations such as from nature [195] and materials [184]. We want to add a new type of tool that can be systematically used for designing shape-changing interfaces. From this problem, we see another objective to be addressed:

Objective 4 Generate a new design tool for shape-changing interfaces.

Problem III: Lack of shape-changing control interfaces

At the crossroad of these two areas (control interfaces and shape-changing interfaces), there is a lack of examples of shape-changing control interfaces. For instance, current shape-changing controls focus on pin-based actuation [51, 148], changing height or width of dials [170, 133], changing the circumference shape of a dial [134], changing length of a slider [32], or actuating sliders [174, 56]. The design space of shape-changing interfaces is vast, and we need more examples to understand characteristics of shape-changing controls and suggest general design guidelines for them. The final objective of this thesis is thus to:

Objective 5 Design and evaluate new forms of shape-changing control interfaces.

1.3 Methodology

Figure 1.2 illustrates the two research areas we focus on in this thesis: control interfaces and shape-changing interfaces. Before jumping into the main research focus of the thesis—shape-changing controls, which is the intersection of the two research areas—we take a step back and look at the two most related research areas.

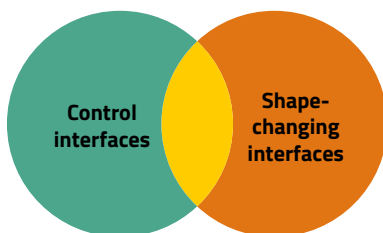


Figure 1.2: The two research areas we investigate in the thesis: control interfaces and shape-changing interfaces. The intersection is shape-changing controls, our main focus of the thesis.

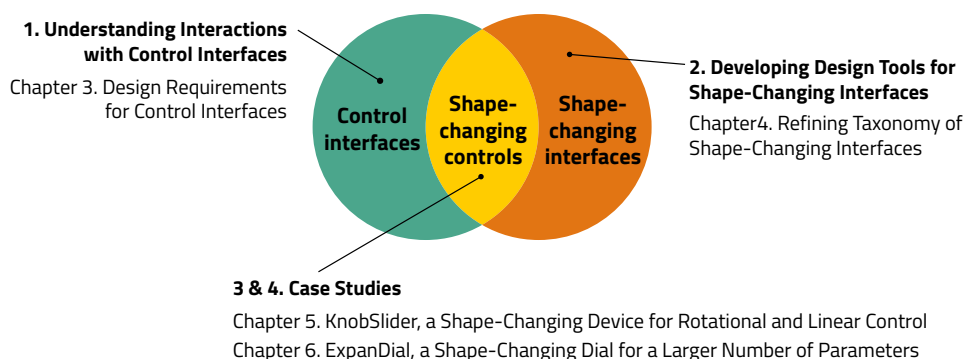


Figure 1.3: The detailed view of our research focus showing the four-step approach: (1) We first study underlying user needs and design requirements for control interfaces. (2) We then provide design tools for shape-changing interfaces by refining an existing taxonomy and generating a collection of everyday reconfigurable objects. (3, 4) Lastly, we conduct two case studies that explore designs of shape-changing control interfaces that are driven by the understanding of control interfaces and design tools for shape-changing interfaces.

Figure 1.3 shows the four steps we took throughout this thesis. In the first step, we investigate users’ current interaction methods to provide design guidelines for future shape-changing controls. In the second step, we look into design tools for shape-changing interfaces to enable ourselves to design shape-changing controls in a systematic way. For the third and fourth steps, we use the lessons from users’ current interaction methods and design tools to design and implement two shape-changing controls: KnobSlider and ExpanDial. Below we detail the four steps we took one by one.

1. Design requirements for control interfaces

The first step of our approach is to look at the control interface area: we study how professional users interact with control interfaces. As shape-changing controls are a new type of control interfaces, we should take a user-centered approach to increase users' acceptance of shape-changing controls. However, we do not have design guidelines for control interfaces, especially focusing on the flexibility and physicality issues. We hence study users' interaction with current control interfaces to provide design guidelines. In the first step of our methodology, we conduct contextual interviews with professionals who use control interfaces for their work. We focus on rotational and linear control interfaces as they are typical types of control interfaces. We also want to know if the flexibility and physicality issue can be found across professions, so we include five professions that require intensive use of control interfaces. This provides us design requirements to guide the design of shape-changing controls, embodying both flexibility and physicality in them.

2. Design tools for shape-changing interfaces

The second step was to look at the other research area: shape-changing interfaces. Before designing any shape-changing controls based on the design requirements from the first step, we revisit design frameworks for shape-changing interfaces. To systematically explore designs of shape-changing interfaces, researchers use taxonomies. The taxonomies can describe features of shape-changing interfaces and have been used as a design framework. However, they were independently suggested, and there was no global approach to unify and test their descriptive power. Hence, before using the taxonomies to suggest new shape-changing controls, we evaluate and improve the them. In the evaluation process, we use everyday reconfigurable objects to test the taxonomies. This allows us to provide two design tools. The first tool is Morphees+, a refined taxonomy for shape-changing interfaces. The second tool is a collection of everyday reconfigurable objects that can generate ideas of new shape-changing interfaces.

3 & 4. Case Studies

The third and fourth steps combine the area of control interfaces and shape-changing interfaces for the design of shape-changing controls. We conducted two case studies: (1) KnobSlider, a shape-changing control that can be dial or slider and (2) ExpanDial, a height- and width changing dial.

3. Case study I: KnobSlider, implementation of shape-change for heterogeneous controls

In the third step, we use the design requirements from the control interface area and the design tools from the shape-changing interface area, and implement a shape-

1. Introduction

changing control. We suggest KnobSlider, a shape-changing interface that can switch between a dial and a slider. Not to bias ourselves and to extensively explore the design space, we first use the design tools to generate design ideas and then use the design requirements to evaluate them. It reveals the best design, KnobSlider. To evaluate the design of KnobSlider, we bring it back to users. The qualitative study reconfirms the design requirements and shows that KnobSlider can cause negative feelings from users, such as surprise. It motivates us to conduct the second study to explore users' preference on shape-change speed. The analysis shows users prefer a certain range of speed and their preferences depend on the physicality on the interface.

4. Case study II: ExpanDial, design of a shape-changing dial based on a grasp study

In the last step, we suggest another case study to cope with the shortcoming of KnobSlider. Although KnobSlider enables users to choose their preferred control interface and to control at least two parameters on one device, it lacks some flexibility: users cannot use both the knob and slider states simultaneously with one KnobSlider. It motivates us to conduct the second case study, ExpanDial. ExpanDial allows users to control multiple parameters at the same time with its rotation, width and height changes. In this case study, we introduce flexibility into one type of control interface instead of combining two control interfaces into one device. We also use other shape-change features not used for KnobSlider. We first conduct a grasp study to investigate the current grasps of dials to take human factors into account in the design of ExpanDial. We then use ExpanDial in a focus group study to learn its future applications and gestures to activate shape-changes.

1.4 Thesis Contributions

The thesis contributes to HCI in fourfold:

1. Design requirements of rotational and linear control interfaces⁹ (Chapter 3)
 - a) Through contextual interviews, we gain an understanding of professional users' needs regarding parameter control. The results show benefits and limitations of physical and touchscreen controllers.
 - b) We derive design requirements for a flexible physical interface element based on the formative study: users need fast, precise, eyes-free and mobile interaction with a large number of parameters. They also need retro-compatibility with current interaction.
2. Design tools for shape-changing interfaces¹⁰ (Chapter 4)
 - a) We provide a collection of 82 everyday reconfigurable objects [98] that is reusable and extendable by other researchers. The collection includes pictures and descriptions and can inspire new shape-changing interfaces.
 - b) We reveal the relationships between the two most widely used taxonomies [145, 149] for shape-changing interfaces and show areas for improvement.
 - c) We add Size and Modularity features to the "shape resolution" taxonomy [149] which turned out to be the most complete and referenced taxonomy to describe shapes and quantities of shape-changes.
 - d) We go one step further and reveal how the reconfigurable features of everyday objects were implemented. It can inform implementation of Morphees+ features and help fast prototype of certain features by using corresponding objects.
3. Implementation of a shape-changing control for a rotational and linear control¹¹ (Chapter 5)
 - a) We generate ten different low-fidelity prototypes that can have linear and rotational inputs based on Morphees+ features, and evaluate the prototypes based on the design requirements from the contextual interviews.
 - b) Based on the best low-fidelity prototype, we implement KnobSlider, a shape-changing device that can be a dial or a slider.
 - c) The qualitative study with professional users using KnobSlider confirms the design requirements from the formative study. It also reveals challenges for shape-changing controls, such as surprising feelings from shape-changes.

⁹The results and design requirements from the contextual interviews are published as a part of KnobSlider publications. See ¹¹ for details.

¹⁰The work is published at ACM CHI 2018 [97] and got the Honourable Mention Award (top 5% among over 2500 submissions)

¹¹KnobSlider is published at CHI 2018 [101] and IHM 2016 [99], along with the design requirements for rotational and linear control interfaces. The extended version of the paper with the controlled study is published at Frontiers in Robotics and AI Journal [100]. The device was also demonstrated at IROS 2018, a robotics conference.

1. Introduction

- d) The pairwise comparison study on shape-change speed of KnobSlider shows that users prefer a certain range of speed and their speed preferences change depending on whether the device is shown in the real world or on a video.
- 4. Increasing the number of parameters controlled by a rotational control interface¹² (Chapter 6)
 - a) We conduct a grasp study on differently sized dials and present design implications for shape-changing dials.
 - b) Based on the design requirements from the contextual interviews and the design implications from the grasp study, we implement ExpanDial. ExpanDial is a shape-changing dial that can also change its height and width, hence enable control of three parameters at the same time. ExpanDial uses Size feature of Morphees+, which was not used in KnobSlider.
 - c) The focus group study with ExpanDial suggests future applications of shape-changing dials and gestures to activate shape-changes of dials.

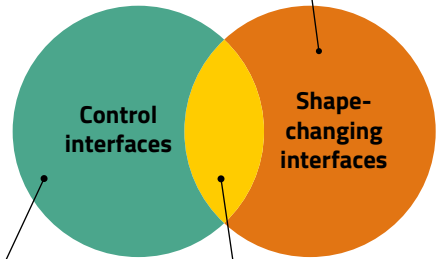
¹²ExpanDial is published at DIS 2019 [102].

1.4. Thesis Contributions

2.1 Evolution of the Types of Interfaces

2.2 Shape-Changing Interfaces as a Research Field

• Interfaces



2.3 Design of Control Interfaces

2.4 Flexibility in Physical Control Interfaces

Figure 2.1: Scope of the literature we review in the thesis. We first briefly go through the types of interfaces, to show how shape-changing interfaces are positioned comparing to traditional interfaces. We then discuss shape-changing interfaces as a research field by referring literature that defines their taxonomies and design approaches for them. We then study designs of traditional design control interfaces. Lastly, we review how literature have implemented flexibility in physical control interfaces in terms of time- and space-multiplexing.

Related Work

In this chapter we review literature related to the flexibility and physicality of control interfaces and shape-changing interfaces (see Figure 2.1 on page 14). We focus on four areas in HCI: (1) interfaces, (2) shape-changing interfaces, (3) control interfaces, (4) shape-changing controls. To introduce shape-changing interfaces, we first look into two types of traditional interfaces (GUIs and PUIs) and show how shape-changing interfaces are similar or different from them. We then go into the detail of shape-changing interfaces, by reviewing their taxonomies and current design approaches. To understand control interface area, we review literature that discuss design requirements for conventional and also novel control interfaces. Lastly, we go through the literature of control interfaces in the viewpoint of flexibility. We provide an overview of how previous work provide or do not provide time- and space-multiplexing and show where our work positioned in this area.

2.1 Evolution of the Types of Interfaces

In this section, we review the evolution of the types of interfaces. There are lots of types of interfaces, and here we are interested in GUIs, Physical User Interfaces (PUIs), and shape-changing interfaces. To understand their differences, we propose to organize them in the following two axes: physicality and flexibility.

Physicality describes interfaces' capability of being touched and interact with users through their physical properties such as shape [119], texture [67], material [67], and deformability [142]. Literature often describe it as tangibility [67, 85], which in dictionaries means being able to perceive interfaces through touch¹. We decide to use the term physicality instead of tangibility, because physical interfaces are not necessarily tangible. For instance, PinWheels is an interfaces that renders weather information through the spin of pinwheels [84]. However, it was installed at the ceiling of a gallery and was not reachable by the audience, and therefore not tangible. We believe the term physicality is more inclusive than tangibility and better capture the quality of physical (or tangible) interfaces, hence use the term physicality in this thesis.

Flexibility is used in various meanings in literature. Scapin and Bastien defined flexibility as the capability of interfaces providing means to users to customize the interfaces according to their work strategies, habits, and the task requirements [156]. It was suggested as one of the ergonomic criteria for the evaluation of interfaces. Dix et al. broadened the definition as "the multiplicity of ways in which the user and system exchange information" [39]. It not only includes users' ability to customize interfaces but also includes the ability of system to adapt interfaces to users. It can also describe the capability of system to provide alternative ways for input and output. Lastly, it can illustrate the capability of system to give interaction initiatives to users rather than keeping it for itself, e.g., providing strict step-by-step dialog interactions. The latter definition of flexibility well describes shape-changing interface features, i.e., (1) shape-changes can be triggered both by the system and users [4]; (2) shape-changing interfaces allow users to use other body parts than fingertips for interaction [125]; and (3) the interaction initiatives can be transferred to users, e.g., through negotiation [144]. In the rest of the thesis, we use Dix et al.'s definition of flexibility.

Figure 2.2 illustrates the three types of interfaces arranged on these axes. GUIs provide flexibility as they can freely change their form, but they lack physicality. PUIs provide physicality with their physical forms—they come in various shapes that suit tasks, and users can interact with them in the real world. Then shape-changing interfaces have emerged to support both flexibility and physicality. They can change their shape along time, and users can interact with them beyond their fingertips. In the rest of this section, we introduce the brief history of the types of interfaces and discuss how they bring flexibility and physicality.

¹<https://www.lexico.com/en/definition/tangible>

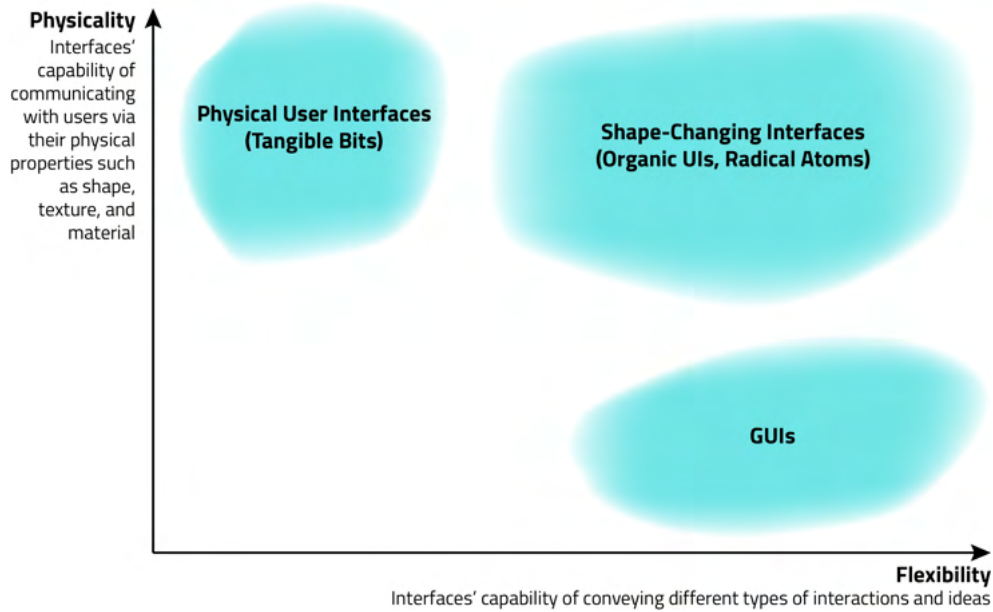


Figure 2.2: Three types of interfaces (GUIs, PUIs, and shape-changing interfaces) arranged on the axes of physicality and flexibility.

2.1.1 GUIs

GUIs are a type of interfaces that can communicate with users through graphical elements such as icons and windows. They were introduced in 1960s to overcome the long learning curve of Command-Line Interfaces (CLIs). Here we describe a few examples of GUIs that were a breakthrough and impacted the current interaction design.

In 1963, Ivan Sutherland developed the first computer-aided design program, Sketchpad. With a light pen, an input device that can detect the position of pen tip on a CRT screen, he could directly draw and manipulate graphical objects on a screen (Figure 2.3A) [171]. Sketchpad inspired Douglas Engelbart to build oN-Line System that was an early version hypertext links. When demonstrating the oN-Line System, he also demonstrated the first mouse to accelerate interaction with the hypertexts and other interface elements.

The modern concept of GUIs took metaphors from a physical desktop and its surrounding equipment such as file folders [165]. It contributed to personalize computers with the development of computer mouse in 1968 [42] (Figure 2.3B²). The mouse decreased movement time and error rate of pointing tasks [44]. GUIs allowed greater flexibility in interactions comparing to the text-based interfaces. For example, they provided interactions with visual icons and windows with a mouse while allowing keyboard input.

Although Sketchpad and mouse increased the flexibility of interfaces, their input was

²DARPA, <https://www.darpa.mil/about-us/timeline/the-mother-of-all-demos>

2. Related Work

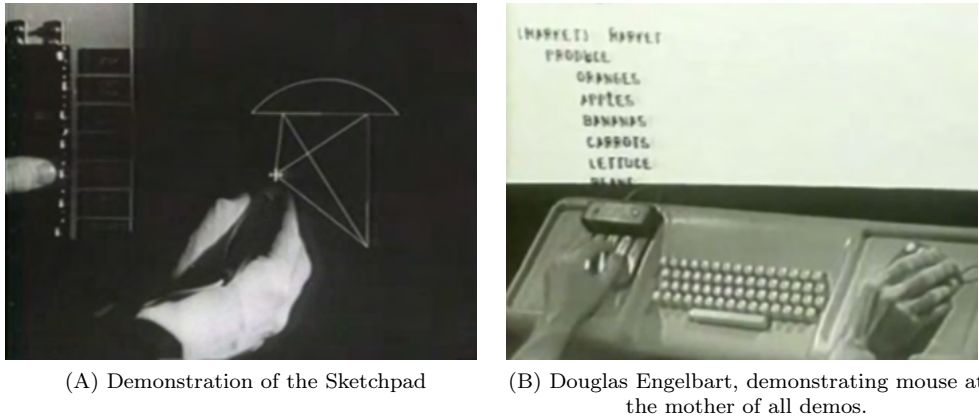


Figure 2.3: Examples of early GUIs. Still from Kenneth Friedman [53].

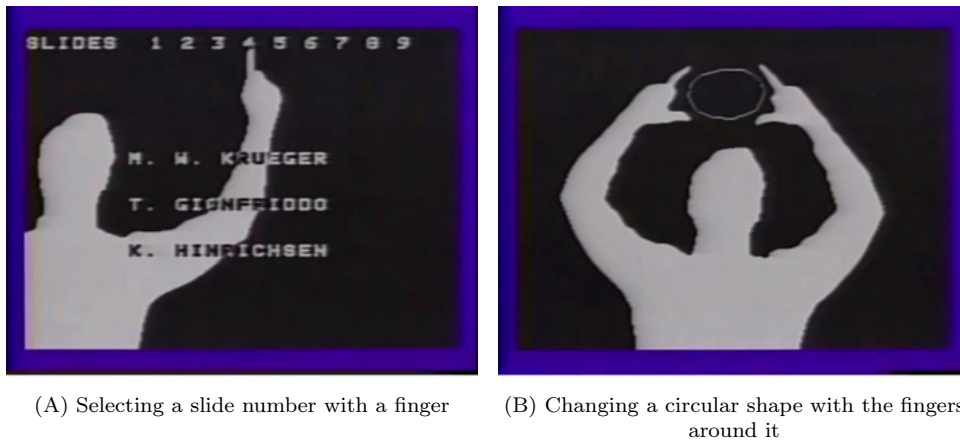


Figure 2.4: Videoplace by Krueger et al. [106]. The user can have different interactions on the same interface, as in (A) and (B). Still from VintageCG [198].

limited to one point. Then Krueger et al. [106] in 1985 extended the input space of GUIs by combining live video of a user and a GUI in Videoplace (Figure 2.4). They demonstrated interactions such as selecting a button with a fingertip (Figure 2.4A) and changing an object size with two hands (Figure 2.4B). Such interactions are widely used in nowadays touchscreen interfaces. They significantly increased the input vocabulary of GUIs, hence the flexibility.

Flexibility of GUIs has been improved thanks to many research papers and industrial practitioners. For instance, plasticity—capability of interfaces to provide variations depending on the context of use while preserving usability [154, 23]—belongs to flexibility, and it is standardized and implemented in many interactive system. There are three examples of standardization of GUI flexibility. First, many web development platforms³ enable users to create websites that responsively change their layouts depending on the screen size. It saves web development cost and time. Second,

³E.g., Wix.com <https://www.wix.com/>, Squarespace <https://www.squarespace.com/>

Youtube changes the quality of streaming video based on the viewers' Internet condition⁴. Lastly, smartphones automatically adjust the screen brightness according to the room brightness. These kinds of flexibility are hardly observed in PUIs.

GUIs have some physicality *per se*, because the interfaces have physical parts. GUIs often come with physical devices such as mouse, keyboard, and screen. Even touch-screen interfaces provide physicality with the flat screen. However, the flat surfaces do not provide physical shapes for widgets or tell users where to press or slide. Some studies suggest to improve the limitation by providing dynamic haptic feedback through electrostatic friction [10.1145/1866029.1866074] or a vibrotactile actuator [10.1145/3025453.3025812]. While they take an approach of adding physicality on GUIs, we are interested in adding flexibility on PUIs in the scope of the thesis. In the following section, we discuss PUIs, their advantages, and examples.

2.1.2 Physical User Interfaces (PUIs)

Physicality in PUIs benefits users by providing affordances through their physical bodies. The term affordances is coined by Gibson: "The affordances of the environment are what it offers the animal, what it provides or furnishes, either for good or ill" [58]. Affordances are information that environments, objects, or animals provide to humans showing what the humans can do with them. Affordances can be different depending on the observers, and their intention or needs. For instance, a ladder affords ascending and descending locomotion to adults, but not for babies. Norman articulated the notion of affordances by distinguishing "affordances" and "perceived affordances" in interfaces [131]. Affordances of an interface determine what actions are possible with the interface, and perceived affordances are possible actions perceived by users with the interface. He emphasized that interface designers should well design "signifiers," which communicates clues of what actions can be taken by users to interact. An example of embedding physical signifiers in interfaces is musicBottles, which afford opening the lids of the bottles to start interaction. When users open the lid of the bottles, jazz music is played just as fragrance comes out from a perfume bottle [83].

Hartson [74] elaborated the notion of affordances, by subcategorizing them into cognitive affordances (Norman's perceived affordances [131]), physical affordances (i.e., physical constraints, Gibson's affordances [58], and Norman's real affordances [131]), sensory affordances (i.e., visual, auditory, or any design features that help users recognize the interfaces, e.g., big enough font size [194]), and functional affordances (i.e., design features that tell users what functional goals they can achieve, e.g., a button labeled "Sort" afford sorting function). Later Vermeulen et al. [194] noted that feedforward is a cognitive and sensory affordance that tell users what actions they can take, and feedback is a cognitive affordance that interfaces provide after the actions. PUIs are good at providing physical affordances. For instance, the shape of the Marble Answering Machine [14] (Figure 2.6) provides physical affordances that

⁴<https://support.google.com/youtube/answer/91449?hl=en>, retrieved on 18/07/2019.

2. Related Work



Figure 2.5: MusicBottles, a PUI for playing jazz music. Users can control which instrument of the music is played by opening and closing the bottle lids [83].
Courtesy of Tangible Media Group, MIT Media Lab [175].

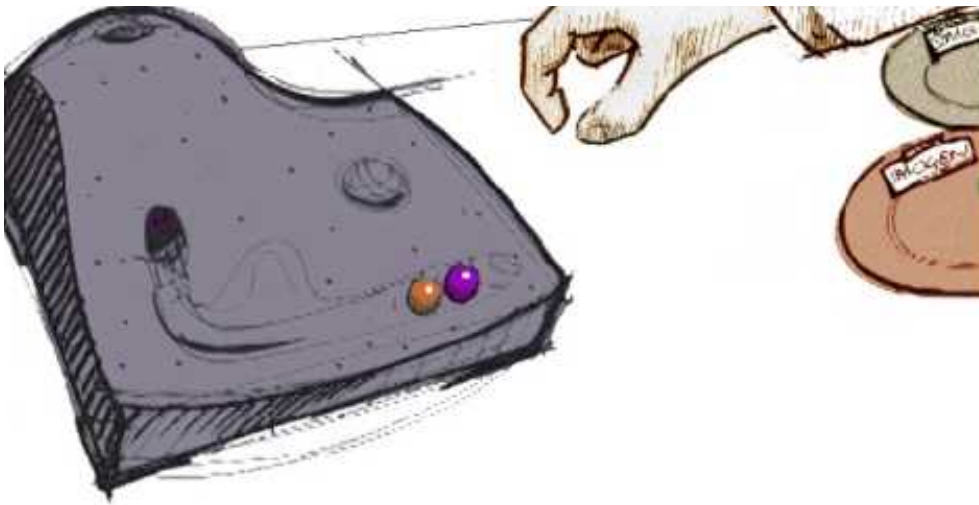


Figure 2.6: The Marble Answering Machine, a conceptual physical interface by Bishop [14]. Still from Luckybite [118].

marbles should be inserted to the left top hole, as the size of the hole is larger than the marbles and then they would fall into the machine.

A similar concept of physical user interfaces was suggested by Ishii and Ullmer and called Tangible User Interfaces (TUIs) [85]. TUIs aim to "augment the real physical world by coupling digital information to everyday physical objects and environments." We consider TUIs as a part of PUIs, as TUIs are suggested to have unique characteristics: "interactive surfaces", "coupling of bits with graspable physical objects", and



Figure 2.7: (Left) The metaDESK with tangible elements: lenses, phicons, and instrument [191]. (Right top) Demonstration of the activeLENS. The device provides a bird's-eye view of a place where it is over the map. (Right bottom) The instrument can scale and rotate the map. Courtesy of Tangible Media Group, MIT Media Lab.

"ambient media for background awareness" [85]. TUIs attempt to reduce the distinction between input devices (keyboard and mouse) and output devices (monitors and head-mounted displays) [190]. TUIs also attempt to diversify the input/output media in addition to the GUIs. For example, the case study metaDESK shows how TUIs can replace some of the GUIs elements [191]. It provides a physical widget that can scale and rotate a map (Figure 2.7 bottom right). The widget has two pucks on a linear axis, which provides physical constraints.

GUIs allow limited flexibility in input methods, compared to PUIs. For instance on touchscreens, only fingertips are practical to input and not hands or arms. Keyboard and mouse are efficient in certain tasks, but rarely allow other interactions than pressing the buttons or moving the mouse, thus limit flexibility. There are a few exceptions that extend interactions with the interfaces by allowing gestures [176, 196]. On the contrary, PUIs can allow different input methods depending on users' strategies. For instance, users can slide physical objects such as bricks instead of picking them up and putting them down [49]. They can also stack physical objects. Another way for PUIs to provide flexibility is through mapping with digital parameters. Audio mixing boards can have multiple banks, and sound engineers assign multiple parameters on a single slider. They switch between different sets of parameters by pressing buttons next to the sliders⁵.

PUIs generally lack flexibility, although some PUIs provide dynamic interaction such as ejecting paper documents according to user input [10.1145/1056808.1057072]. Dials stay as dials, and sliders stay as sliders. Because of this intrinsic physical limitation, a physical interface usually focuses on a limited set of tasks [161]. For

⁵e.g., see 1.3.2 Layers and banks in http://www.digico.org/DiGiCo_Manuals/SD5_Getting_Started.pdf.

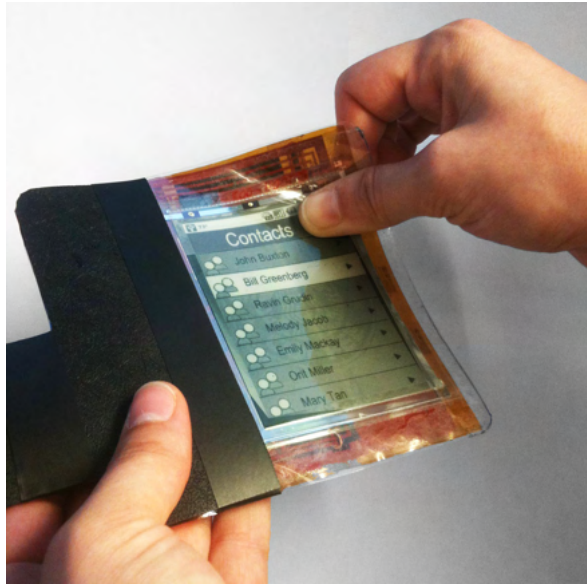


Figure 2.8: PaperPhone, an Organic UI example [108]. The user is bending the corner of the flexible phone to input a gesture. Courtesy of Byron Lahey.

example, the physical widget of the metaDESK [192] would function only for scaling and rotating. When users switch tasks, they would need to switch the physical widget. It increases physical clutter [190], bulkiness [41], and risk of losing the physical interfaces [104]. Although PUIs have great advantages, they often stay rigid, and cannot replicate the flexibility of GUIs.

2.1.3 Shape-Changing Interfaces

To overcome the limitation of PUIs, shape-changing interfaces were suggested. While widely called shape-changing interfaces in the HCI community, the notion of shape-changing interfaces was previously proposed with different names: Organic User Interfaces and Radical Atoms.

Vertegaal and Poupyrev suggested the concept of Organic UIs [195] (Figure 2.8), which added flexibility of input to PUIs. Organic UIs have three key interaction themes: 1) Input Equals Output, 2) Function Equals Form, and 3) Form Follows Flow. They premised that devices can be in any form, and the input can be continuous rather than discrete, such as bending a display rather than pushing a button. They also emphasized that interfaces should be able to change its form or move to support user interactions, which is greatly distinguished from PUIs.

Later, Radical Atoms vision [86] refined the concept of Organic UIs (Figure 2.9). The conceptual shape-memory clay interface Perfect Red well demonstrates the features of the Radical Atoms. It takes deformations as input like Organic UIs, but it takes deformations rather as gestures than exact deformations. For instance, rolling a ball of the clay will make it snap to a perfect sphere. It also encourages using additional

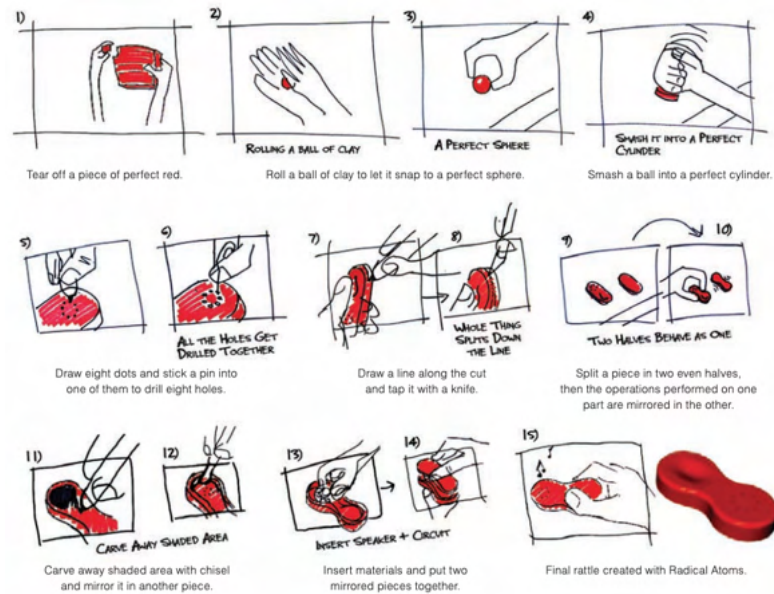


Figure 2.9: A storyboard of using the Perfect Red to create a speaker.
Courtesy of Tangible Media Group, MIT Media Lab.

tools in addition to human hands. For instance, users can use pens, sticks, knives, and chisels to specify and activate shape-changes. Lastly, it takes the advantage of digital interface: it can make a copy of itself and mirror the behavior or the main copy.

The elaborated concepts encouraged many researchers to investigate flexibility of physical interfaces. Such interfaces are now called shape-changing interfaces [4]. As the concepts and implementations are relatively new, the definition of shape-changing interfaces is not consensual. On the one hand, some research papers try to divide shape-changing interfaces into two categories: one that system actuate the shape-changes (often called shape-changing interfaces [52, 145, 130, 186], shape displays [51], or actuatable displays [3]), and the other that user actuate the shape-changes (called deformable interfaces [17, 22, 96, 184, 111, 159, 126] or malleable interfaces [52, 64, 120]). On the other hand, research papers discuss using shape-changes for both input and output [31, 204, 149, 4]. In this thesis, we use the term "shape-changing interfaces" for interfaces that can use shape-changes as input and/or output. This is because we believe that having one-sided interaction cannot fully provide an entire picture on types of interfaces. It would also allow us to consider both input and output aspects of shape-changing interfaces and their correlations. Also, having one coherent term would help communication among researchers and mature the field.

2.2 Shape-Changing Interfaces as a Research Field

Shape-changing interfaces are relatively new interfaces, and thus there are efforts to define them as a research field and encourage researchers to further investigate them. Alexander et al. recently defined empty spaces in the field and pointed future research directions [4]. They discuss four types of challenges that need to be addressed: user behavior, design, technological, and societal challenges. This thesis tackles the first three challenges through conducting user studies, and designing and implementing shape-changing interfaces.

In this section, we review literature that suggest taxonomies, and define terminologies and features of shape-changing interfaces. We also review how literature has contributed to the design of shape-changing interfaces and how the thesis is related to them.

2.2.1 Taxonomy, Shaping Shape-changing Interfaces as a Research Field

Early shape-changing interface taxonomies often focus on technologies, as implementation were one of the first barriers for advancing the field. In 2011, Coelho et al. [31] proposed such a taxonomy in which they describe the technological features of shape-changing devices. Examples included power requirement, ability to memorize new shapes, input stimuli such as voltage potential, and ability to sense deformations. The approach was technologically driven and described materials and implementations rather than possible deformations of the objects.

Rasmussen et al. [145] presented a review of 44 existing studies prior to 2008 on shape-changing interfaces. Instead of technical features, they focused on four new types of features in shape-changing interfaces: change in shape, transformation, interaction, and purposes of shape-changes. Change in shape describes the difference between distinct shapes of an interface. Change in shape includes eight features such as orientation, form, and volume, and they have inspired other research on the design of shape-changing interfaces [130, 107, 146]. Transformation can describe how an interface changes from one to another shape. It includes kinetic features such as velocity and expressive features such as organic or mechanical. The authors also analyzed how shape-changing interfaces interact with users, e.g., whether the interfaces allow direct touch and manipulation or not. Lastly, they identified four purposes of shape-changing interface research, which are functional, hedonic, explorative, providing toolkits. In this thesis, we first focus on "change in shape" rather than the "transformation," because we think providing proper shapes for control tasks is most important. We also focus on "direct interaction" with users and implementing "functional" shape-changing interfaces.

Roudaut et al. [149] proposed the term shape-resolution that extends the definition of display resolution to shape-changing interfaces. It is based on the mathematical model of Non-Uniform Rational B-splines (NURBS) and has ten features that the

authors used to classify shape changing prototypes from previous work. They also provide specific metric to compute them.

Troiano et al. [186] suggested four behavioral patterns of shape-change from Sci-Fi movies. The authors collected 101 shape-changing instances from 340 movies and identified the functional behavioral patterns using thematic analysis.

Lastly, Boem and Troiano [17] surveyed 131 papers that focus on non-rigid deformable interfaces. They categorized the design elements of the interfaces based on input method, shape, material, etc. When analyzing the shapes of the interfaces, they considered the initial shapes before users' deformation. They largely grouped them into "volumetric" or "flat" shapes, which have subcategories such as "geometric" and "organic."

As we have shown, there are many taxonomies for shape-changing interfaces. They were rarely merged or evaluated. One merged and evaluated taxonomy would benefit designers and researchers to generate new shape-changing interface ideas or extend it. In this thesis, we hence aim to merge and evaluate two of the taxonomies [145, 149] that are most widely used.

2.2.2 Design Approaches for Shape-Changing Interfaces

In this section, we review literature that has contributed to the design of shape-changing interfaces. We see three axes in the design approaches in the literature: user-driven, taxonomy-driven, and technology-driven. The literature in this section is examples for the design approaches and not exhaustive. The design approaches are not mutually exclusive, e.g., a research with the user-driven approach can also use taxonomies for design.

Having Users in the Studies

We observe literature that involved users in the studies. We largely observed two axes in the approaches: (1) conducting user study before implementation or after the implementation of prototypes, (2) conducting lab study or field study (Table 2.1). The researches that conducted user studies before implementation of prototypes had user-centered design: they had target users at the beginning of the researches and applied the learnings from the user studies to the design of the prototypes [138, 174]. The researches that conducted user studies after implementation focused on implementation of novel shape-changing interfaces and then conducted user studies to validate the prototype design [138, 174, 136], to find applications and interaction ideas for them [3, 71, 46, 168], to discover their benefits compared to other interfaces [32], and to fine-tune interaction variables [133, 134]. Most of the researches conducted lab studies Multi-plié [138], Haptic Wave [174], Tilt displays [3, 71, 32, 133, 134, 54, 169] rather than field studies [136, 46, 168]. We did not find research that conducted field study before implementation. In this section, we review some of the literature in terms of the axes.

Table 2.1: Shape-changing interface researches involving user studies.

	User study before implementation	User study after implementation
Lab study	Multi-plié [138], Haptic Wave [174]	Multi-plié [138], Haptic Wave [174], Tilt displays [3], ShapeClip [71], Ripple Thermostat [133], DynaKnob [134], Zoomable TUIs [32], Foldwatch [54], Sturdee et al. [169]
Field study		Bendi [136], ShapeCanvas [46], Sturdee et al. [168]

An example of having user studies before implementing working prototypes is Multi-plié [138]. The authors first decided to improve the Standard Operating Procedures, flows, and checklists in a cockpit. To improve the interactions, they invited pilots to the lab and conducted user studies with accordion-like low-fidelity prototypes. Then the authors implemented working prototypes. They could change the folding pattern (e.g., crease up or pulse-like movement) for notification. Users could press down a crease to mark an action on a checklist is done or to see additional information. The study with the prototypes showed that the interface can increase safety, efficiency, and collaboration between two pilots.

An example of the implementing prototypes before conducting user studies is Tilt Displays [3]. The prototype consisted of 3×3 modular screens, and each screen can change its height and tilt to four directions. The authors conducted two controlled user studies: the first to see users' impressions of the prototype and explore potential interactions and applications; and the second to suggest gestures to manually and automatically change the shape of the prototype.

Unlike Multi-plié [138], Bendi [136] was first implemented and then used in a user study. Unlike Tilt Displays [3], the authors conducted a field study. Bendi was a mobile device that uses shape-changes to promote communication between couples. The authors first implemented the prototype by experimenting different movements and device designs. They then evaluated the prototypes by giving them to actual couples in a cafe. The results showed that the prototypes could convey emotions in a light manner, through the visual and tactile stimuli.

In this thesis, we conduct a field study to learn user needs in control interfaces in ecologically valid settings. We apply the user needs in the design process of a shape-changing controls. We also use the implemented shape-changing controls in further user studies to validate the design and elicit applications and interaction gestures.

Using Taxonomies to Generate Design Ideas

Researchers used the taxonomies to generate ideas by themselves or to inspire others to do it. Some of them implemented working or low-fidelity prototypes [130, 107, 63]

Table 2.2: Shape-changing interface design researches using taxonomies for systematic inspiration. Some of them implemented working or low-fidelity prototypes and one of them created sketches.

Prototypes	Nørgaard et al. [130], Kwak et al. [107], SplitSlider [63]
Sketches	Rasmussen et al. [146]

and one of them created sketches instead of prototypes [146] (Table 2.2).

The work of Nørgaard et al. [130] is an example of designing prototypes based on taxonomies. They asked eight groups of designers to design shape-changing toys where each has a feature from the taxonomy from Rasmussen et al. [145]. The results suggested how future shape-changing interfaces can interact with users. For instance, the interface could move first to invite users, augment users' action, or use movement from animals. More importantly, they suggest to consider temporality when designing shape-changing interfaces, as the interfaces always involve movement unlike GUIs that instantly change the appearance according to user input and stay the same until the next input. The results also suggested the delay of movement as well as the speed of movement as new design parameters.

Rasmussen et al. [146] rather focused on visual sketches rather than working prototypes. It allowed them to analyze lots of sketches and analyze design vocabularies in them. They asked researchers to draw sketches of shape-changing radios and mobile phones by based on a shape-changing interface taxonomy [145]. They showed which features are most often used in general or for certain devices (e.g., Spatiality used only for radio, and Adding/Subtracting used only for mobile phone).

The research papers in this section demonstrated the generative power of taxonomies. We also use a taxonomy to generate ideas for new shape-changing controls.

Exploring Novel Implementation Technologies

The material and implementation oriented research introduce new technologies for shape-changing interfaces. For instance, Jamming UI [52] used small particles such as plastic balls in a malleable air chamber, and controlled the stiffness of the bag by letting air in or suck the air out. This work allowed manual shape-changes. It inspired other research papers, such as [1]. PneuUI [204] also used pneumatic actuation, but focused on the design of chambers and interactions with the prototypes. Additionally, Bendi [136] and Roudaut et al. [149] have demonstrated using SMAs to implement shape-changing mobile phones. In this thesis, we apply some of the actuation methods when exploring low-fidelity prototype ideas.

In this thesis, we use some of the implementation technologies in the design process. We use them as envisioned implementation methods to make low-fidelity prototype ideas realistic and consider the advantages and disadvantages of the implementation technologies in the evaluation of the ideas.

2. Related Work

To summarize, we reviewed the design approaches in shape-changing interfaces: user-driven, taxonomy-driven, and technology-driven. We conduct contextual interviews to learn design requirements for control interfaces, before designing new shape-changing controls. We use a shape-changing interface taxonomy to systematically generate design ideas. Lastly, we use some of the suggested implementation technologies in the design and implementation of shape-changing controls.

2.3 Design of Control Interfaces

In the HCI field, control interfaces are interfaces that can manipulate computer parameters to accomplish tasks. They are also called parameter control widgets [88], controls [8], or control elements [8]. In this thesis, we focus on control interfaces that control one dimensional parameters (unlike joysticks and mice). There are many kinds of control interfaces [8], and here we roughly categorize them into three types according to their parameters and interactions: (1) binary control (e.g., buttons), (2) rotational control (e.g., dials), and linear control (e.g., sliders). In this section, we want to present design guidelines for control interfaces. We first look into the design of existing control interfaces. We then go through design implications for future control interfaces.

2.3.1 Design Guidelines for the Current Control Interfaces

Binary controls

Binary control interfaces are largely categorized into two types: button and switches [8]. Buttons (also called keys) have one control point to place a finger to interact, and they support vertical linear displacement (e.g., Figure 2.10A). Buttons are desired to be physically displaced by pressed down and produce a clear haptic and acoustic feedback for clicked [8]. Researchers suggest the width of a button between 12 mm and 20mm, and the distance between the centers of neighboring buttons between 18 mm and 20mm [21, 61, 8]. The distance for vertical displacement is recommended between 1.3 mm and 6.4 mm [21, 8]. Most buttons go back to the initial (raised) state when not pressed, but bistable push-buttons keep the pressed state. Users need to press them again to make it to go to the initial state [8].

Switches have two control points, i.e., one for 'on' and the other for 'off' (e.g., Figure 2.10B). Switches are mostly bistable and provide clear visual feedback on their states by showing which side of the switch is pressed (Figure 2.10B, the upper side of the switch is pressed). According to Baumann and Thomas, American convention of switches is to have the 'on' position on the right or upward or away from users, and European convention is to have the 'on' position on the right or downward [8]. Switches can have lever-arms instead of tilted buttons [8].

Rotational controls

Rotational controls are interfaces that control parameters through rotation. They are also called control knobs [8], rotary control [43], or dials [25]. In this thesis, we call them dials for simplicity. Dials can be divided into two categories by their parameter properties: continuous and discrete [8] (Figure 2.11). Continuous dials often have a size that can be rotated by two or three fingers. Baumann and Thomas suggest that the diameter and height of a dial should be between 10 mm and 30 mm.

2. Related Work

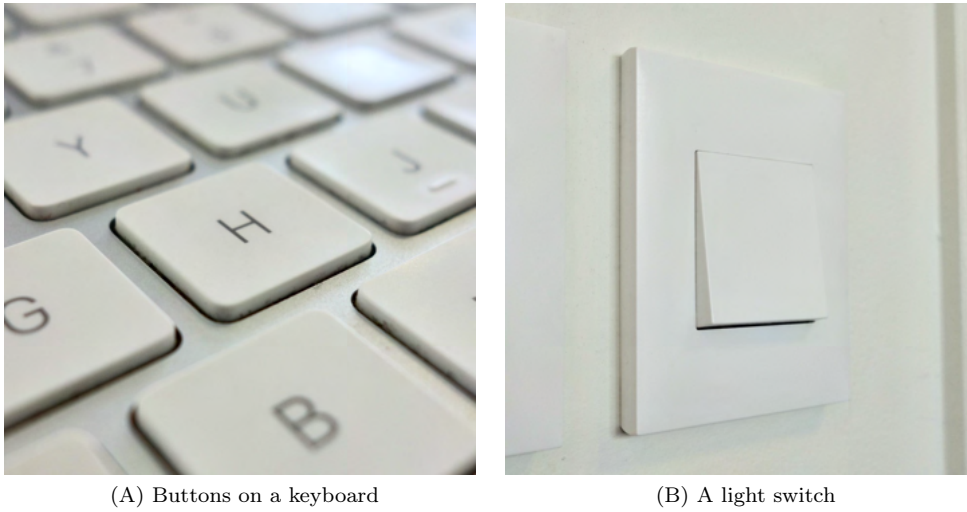


Figure 2.10: Examples of binary controls. (A) Buttons are controls that are pushed towards to their surface. They are "on" only when pressed (also called as keys), or can keep their "on" states (often called push-buttons). (B) Switches can be also pressed towards surface. However, they have two distinct pushing points, which represent "on" and "off" [8].

They say that a single gesture rotation is possible up to 120° . They also suggest that the clockwise rotation should increase the corresponding parameter, not decrease. The minimum end of the input range should be placed between six and nine o'clock positions. Gelineck and Serafin suggest that dials can be used to control parameters that are little related to each other based on their observations [57]. Compared to sliders, dials take more time for users to know their status as they need to check each dial at a time. However, dials can take less space than sliders and enables fine tuning.

Discrete rotational controls, "discrete control knobs," or "rotary switches" [8] (Figure 2.11) control parameters that have three or more discrete states. When there are more than three states, the controls can have a round shape as the continuous dials. However, they should provide higher rotational force feedback between the states than at the states. Hence, grooved or arrow-shaped controls are preferred to cope with the force feedback. The angular travel between two states should be at least 30° when it requires eyes-free interaction. Otherwise 15° should work as well [8].

Bradley [18] further investigated the correlation between rotational friction, dial diameter, time to reach a dial, and time to turn the dial. The results showed that the time to reach the dial significantly increases when the diameter is 1.25 in (3.17 cm) or less. On the other hand, the time to turn the dial is significantly increased when the diameter is less than 1 in (2.54 cm) and the friction is moderate (60 - 90 g/in, 23 - 35 N/m). The time to turn the dial significantly increases if the diameter is less than 1.75 in or more than 2.5 in when the friction is high (150 - 200 g/in, 58 - 77 N/m). Future studies can refer the study when they design the rotational friction and diameter for different purposes (e.g., fast or slow interactions).

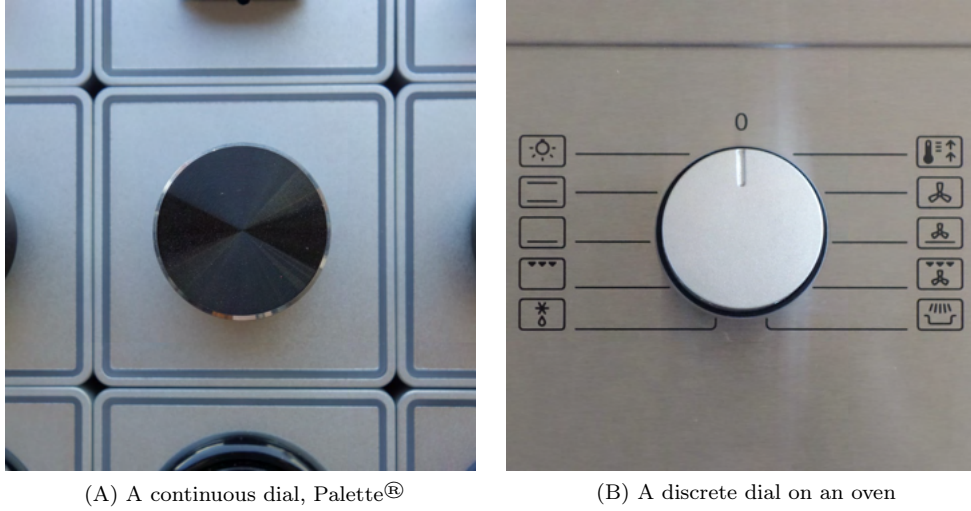


Figure 2.11: Continuous and discrete dial examples. (A) A continuous dial can control continuous parameters such as volume of sound. It does not have detents. (B) A discrete dial can set a cooking mode of an oven. The dial also has detents where the visual signs are.

Linear controls

In this thesis, we call linear controls for interfaces that require linear movement of a physical cursor (or thumb) either physical or virtual. We see largely two types of linear controls, which are continuous and discrete. Continuous linear control, often called sliders (Figure 2.12A) [8, 88, 183], can adjust parameters in a limited range. Gelineck and Serafin [57] suggest that multiple sliders can be used to control parameters that are associated with each other, while is hard with dials. Multiple sliders can be operated with one hand, and their status is easily observed [57, 8]. Sliders are usually placed on a horizontal or slightly inclined surface toward users, the sliding direction is aligned with users' line of sight. It is because sliding on a vertical surface or sliding sideways is less accurate [8].

There are also discrete linear controls (see Figure 2.12B). Similar to discrete dials, they have a limited number of input ranges. However, their control is more difficult than discrete dials. The position of the cursor is harder to glance or to sense through tactile feedback, while discrete dials have clear angular pointers [8].

In this thesis, we try to apply the design guidelines when we design new shape-changing controls when applicable. Also, we derive design requirements independent from the widgets.

2.3.2 Design Implications for Future Control Interfaces

Literature suggests design requirements for control interfaces through user studies. Since they are based on user studies, the design requirements are not restricted to cer-

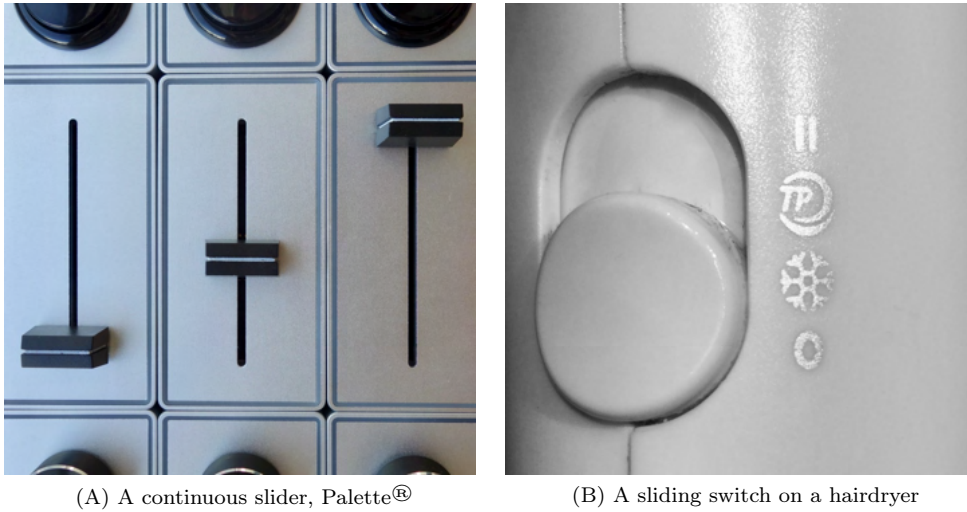


Figure 2.12: Examples of continuous and discrete linear controls. (A) The cursor of the continuous slider can be moved smoothly. (B) The sliding switch has limited number of detents, which can guide users to use it without seeing the interface.

tain types or dimensions of control interfaces. We can apply them when designing new control interfaces. Here we review the literature based on the type of control widgets suggested (rotational controls, linear controls, or regardless of types of controls).

Implications for rotational controls

Ripple Thermostat [133] explored the design of force feedback and width-change of dials to convey emotions on thermostats. The study results show that the force feedback of the dial is effective to communicate "disagreement" of the system, i.e., the thermostat refuses to change the temperature that users input. Also, the width-change increased users' perceived arousal. While the study focused on the single type of shape change (width change), DynaKnob [134] went one step further by exploring the perceived correlation between six dial shapes and twelve force feedback patterns (e.g., different numbers of detents, rotation range, amplitude of acceleration or friction). The study demonstrated the best force feedback pattern for each dial shape. The study not only confirmed previous design requirements, e.g., low friction is recommended for smooth-surfaced dials [163, 8], but also show that mismatching the dial shapes and force feedbacks can make users feel the interfaces are "broken."

On the other hand, Pauchet et al. [137] investigated GazeForm, a touchscreen interface, which has physical dials coming up when there is no (or very short) gaze at the interface. The interface was to support eyes-free control in cockpits, e.g., controlling control widgets while monitoring flight status, and also allow direct control on the touchscreen if needed. They compared the dials with a regular touchscreen. The results show that eye tracking is a valid way to activate shape-changes, i.e., the participants in the study learned to shortly glance at the interface without retracting the dials. The results also show that the gaze-responsive physical interface is superior

to the touchscreen regarding execution time, reaction time, gazing time at the interface, and task recovery time. The notable exception was when there was a sliding task; the touchscreen performed better because the surface with the physical dials had discontinuous area when the dials were retracted.

Implications for linear controls

Zoomable TUIs [32] took a quantitative approach to find a compromise between a slider's size and its performance in a pursuit task. The authors showed that the larger slider status (8 cm) performs better than the shorter ones (2, 4 cm) when the task is difficult, which reassured that increasing the motor movement and visual size of an interface could increase task precision [27]. They went one step further by evaluating the gain in task performance while users have to change the slider size periodically. The results show that the resizable slider provides better precision than a small slider (2 cm) when users change the slider size less often than every nine seconds.

Haptic Wave [174] focused on physically rendering sound waveforms for visually impaired audio producers and engineers. The first study with a 6 DOF haptic device showed that users prefer the rendering in 2D than 3D, as waveforms are time-based media and they do not like having "too many degrees of freedom" for the data. Based on the study, the authors implemented a slider that has an actuated cursor to render waveforms, which was similar to literature that had actuated slider cursors [162, 5, 56, 117]. However for Haptic Wave, the authors place the slider is on a horizontal rail. Users could sweep the slider horizontally to navigate in a waveform, and the slider cursor moved to render the peak of the selected point of the waveform. They could feel the movement of the cursor with their hands. The direct manipulation (using their hands for both input and output) allowed the users to edit sound more efficiently and helped them put the image of a waveform in their head.

Implications regardless of types of controls

Vinot et al. [197] suggest eleven design requirements for cockpit interfaces, regardless of the types of control widgets. They focused on three themes: usability, safety, and industrial requirements. Some requirements focus on functions (e.g., situation awareness) and cost effectiveness. The other control interfaces related requirements suggest that the cockpit interfaces should provide various modalities (e.g., haptic and force feedback in addition to visual feedback) to reduce cognitive load even in degraded conditions (e.g., physical and mental fatigue, smoke, turbulence, etc.). The authors also suggest that the interfaces should not be detachable for safety issues and flexibility for suppliers to reconfigure the interfaces for aircraft manufacturers.

Letondal et al. [116] continued the direction by observing and interviewing eight pilots during actual flights or using simulators. Their design requirements for future cockpit are more focusing on interactions than functions or cost effectiveness. For instance, they do not recommend gestural interfaces as pilots use lots of gestures to

2. Related Work

help perceive data, e.g., touching a panel when reading data on it. It was related to that pilots learn the positions of control panels, hence spatial-based design is recommended. The pilots also externalized their control actions by speaking in a standardized way, to communicate with copilots.

In this thesis, we first conduct contextual interviews to understand users' interaction with current control interfaces. We think that is more generally applicable in new shape-changing controls. We also conduct some user studies with shape-changing controls we implemented, to see the design requirements are also applicable to shape-changing interfaces.

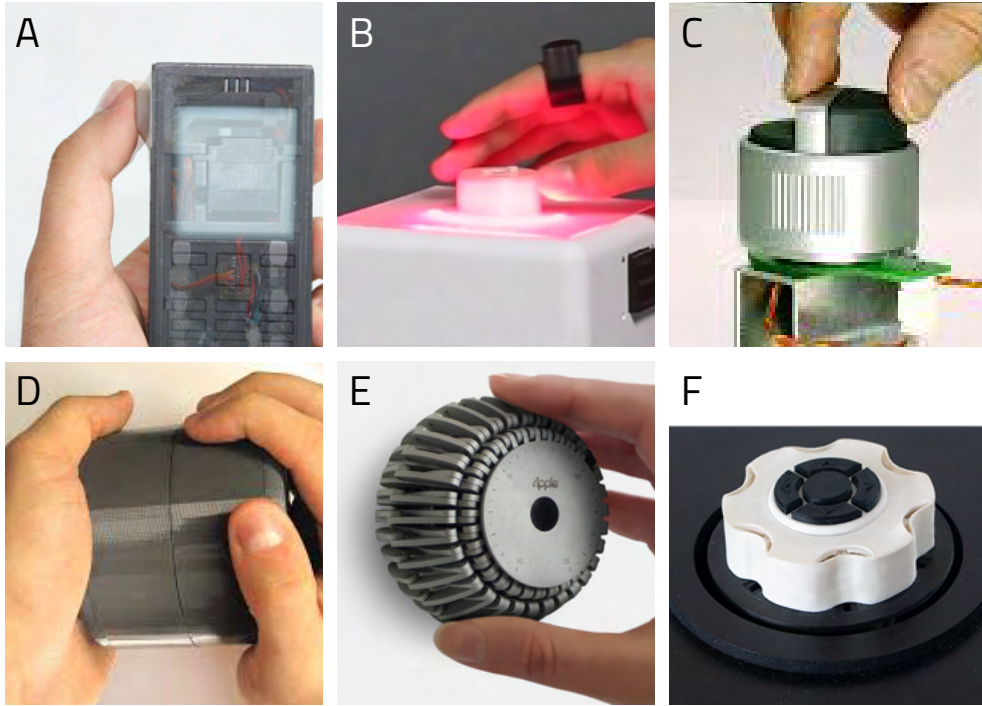


Figure 2.13: Button- or dial-based physical control interfaces that provide flexibility.

(A) A shape-changing button [76]. (B, C) height- and shape-changing dials [170, 119]. (D) A dial with variable detent [7]. (E, F) Width- and shape-changing dials [133, 134]. Courtesy of Fabian Hemmert, Jihoon Suh, Stefan Rapp, Nicolas Villar, and Anke van Oosterhout (E,F).

2.4 Flexibility in Physical Control Interfaces

Our work aims to provide flexible physical interaction in control interfaces. We survey previous works that investigated flexible and physical control input devices.

2.4.1 Flexibility of a Single Device

There have been many button- and dial based devices that provide flexibility through shape-changes. An early height-changing button was proposed by Hemmert et al. [76] (Figure 2.13 A). It was dedicated to cell phone notifications such as missed calls. Button+ could change the dial height to give different control access to different sets of users, or to change the level of control difficulty for games [170] (Figure 2.13 B). Haptic Chameleon was a shape-changing dial that changed its function according to its deformed shape to control videos [119] (Figure 2.13 C). InGen was a passive dial with dynamic detent, stiffness and abrupt stops to help users scroll a list [7] (Figure 2.13 D). More recently, Ripple Thermostat explored a dial that changes its height and width associated with the rotational force feedback to help users save heating energy [133] (Figure 2.13 E). DynaKnob could change between four different dial shapes and provide appropriate rotational resistance for each shape [134] (Figure 2.13 F).

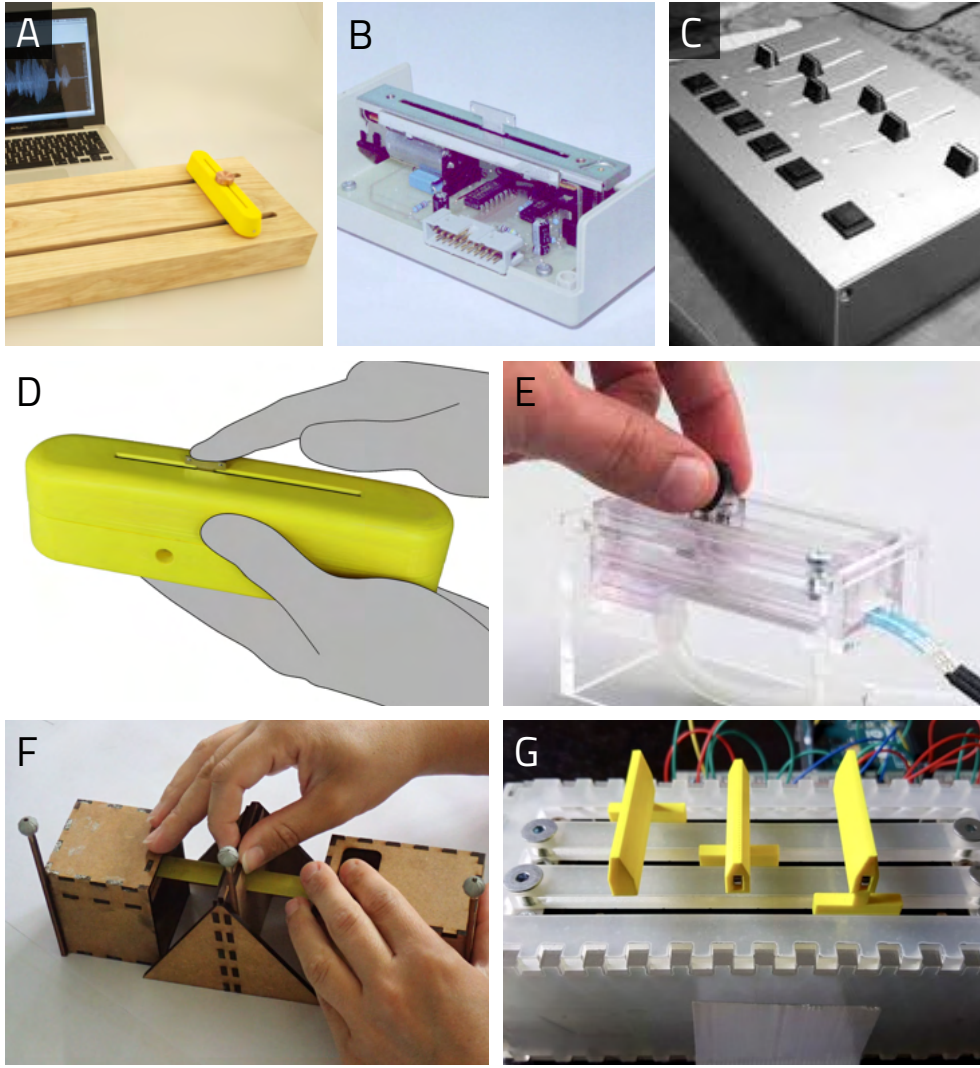


Figure 2.14: Slider-based physical interfaces that provide flexibility. (A) A slider with an actuated cursor to physically render sound wave [174]. (B,C,D,E) Sliders with different haptic feedback (detent) [162, 56, 117, 193]. (F) A slider that users can change its length [32]. (G) A slider that users can change the number of the cursor [63]. Courtesy of Atau Tanaka, Morten Fjeld (B,C), Lars Lischke, Marynel Vázquez, Céline Coutrix, and Andreas Korge.

Many studies on the flexibility of sliders mostly focused on dynamic haptic/force feedback. Some motorized slider cursors have been proposed for physics education [162] (Figure 2.14 A), haptic cues of sound amplitude [162, 174] (Figure 2.14 A,B), creating music loop [56] (Figure 2.14 C), and remote display input [117] (Figure 2.14 D). Vázquez et al. changed the haptic feedback of sliders and dials by changing pressure in air chambers around the slider/dial axes [193] (Figure 2.14 E). Unlike the work focusing on haptic/force feedback, Zoomable TUIs explored physically zoomable sliders to balance between device footprint and pointing performance [32] (Figure 2.14 F). SplitSlider explored designs of reconfigurable dials and sliders to allow uncertain input on physical interfaces [63] (Figure 2.14 G).

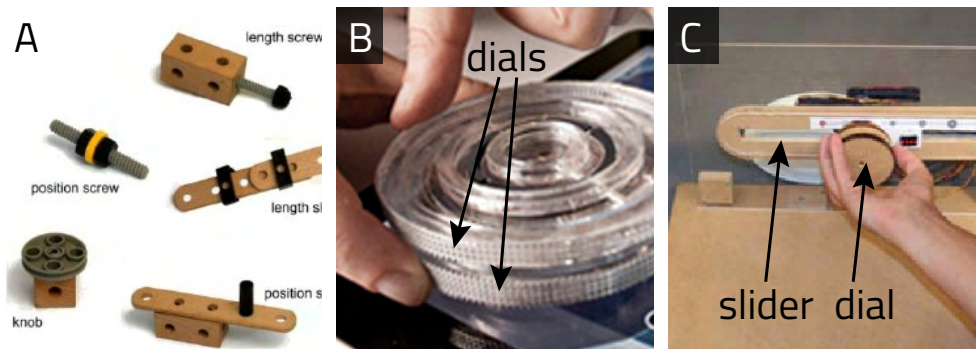


Figure 2.15: Examples for space-multiplexing control interfaces. (A) A set of mechanical widgets including rotational and linear joints [15]. (B) Two vertically stacked dials [25]. (C) a dial on a slider [40]. Courtesy of Alan Blackwell, Liwei Chan, and Tom Djajadiningrat.

2.4.2 Space-Multiplexing

One approach to enable flexibility is to provide multiple devices in different locations simultaneously. There have been two approaches taken in spatially arranging controls. First, next to each other, like on sound mixing boards. Here, users manipulate sets of physical controls, including sliding and rotating joints [15] (Figure 2.15 A). Their drawback is their footprint when space is a critical resource. Second, on top of each other, like in Zebra Widgets [25] (Figure 2.15 B) and a rotary dial control for microwave oven [40] (Figure 2.15 C). They required less surface than the first arrangement. However, Zebra Widgets do not allow stacking a dial on a slider or vice versa. With the microwave control, moving one device might cause unwanted movement of the other device.

2.4.3 Time-Multiplexing

Another approach is to have dials and sliders in a sequence at the same location. With Paddle, users can make a flat surface for swipe (linear input), then deform it to a ring for rotational input [142] (Figure 2.16 A). inFORM [51] (Figure 2.16 B) could provide a touch slider and rotational control with a physical token (the red ball in the Figure) at the same place on by one. Emergeables [148] (Figure 2.16 C) also provided a slider and a dial at the very same location. With ForceForm [188] (Figure 2.16 D), users molded a placeholder to make a slider or dial on a touch surface. ChainFORM [124] (Figure 2.16 E) provided a linear or a round shape with actuation and touch sensing. However, in these implementations, the manipulation of the sliders was very different from that of the physical sliders, either lacking a physical cursor [51, 124, 142, 188] or continuity [148].

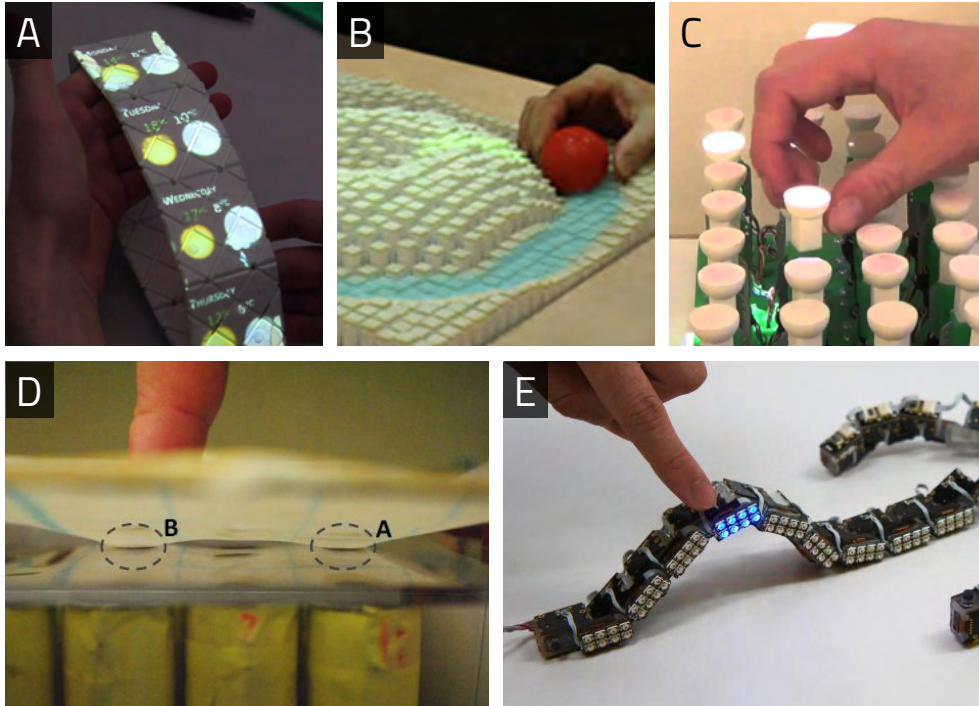


Figure 2.16: Examples of time-multiplexing control interfaces. (A) Paddle, a deformable device that can make a round shape or flat linear shape [142]. (B) A user is demonstrating the rotational interaction with inFORM [51]. inFORM can also make touch surface for slider interaction. (C) A rod is being used as dial in Emergeables [148], while it can be used as a part of a linear control. (D) The user is forming the surface of ForceForm. She/he can create round or linear grooves for rotational or linear interactions [188]. (E) With ChainFORM, users can also create round or linear shapes [124]. Courtesy of Raf Ramakers, Tangible Media Group, MIT Media Lab (B, E), Céline Coutrix, and Tom Gedeon.

2.4.4 Both Space- and Time-Multiplexing

Some research approaches allowed both spatial and temporal multiplexing. With inFORM [51] and ForceForm [188], (Figure 2.16 B,D), it was also possible to provide several buttons, dials, and sliders sequentially in one place and simultaneously in different places. Our approach incorporates a combination of spatial and temporal multiplexing. In contrast to using widgets on touch surfaces [88, 201] (Figure 2.17), we want to avoid the need to manually change types or sizes of widgets on a surface. In contrast of using discrete control points on a slider [51, 148, 188], this thesis aims for both continuous and physical manipulation of the cursor. We also explore continuous shape-changes.

2.4.5 Balancing between Space- and Time-Multiplexing

Space- and time-multiplexing provide different advantages. Space-multiplexing allows spatial arrangements [48], persistence of attachment between devices and parameters

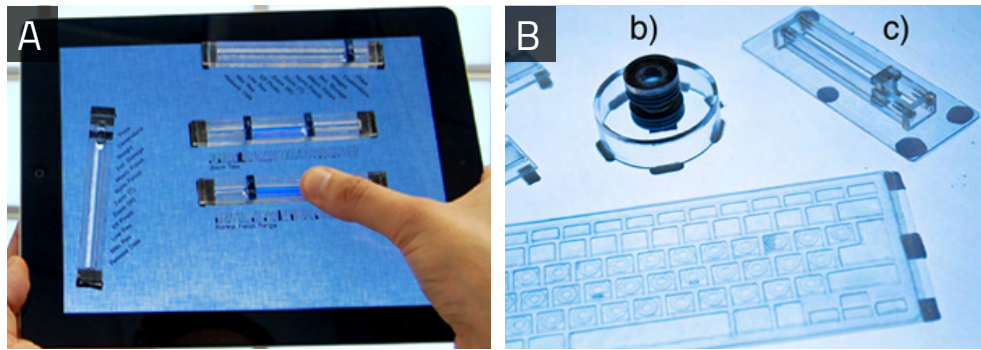


Figure 2.17: Examples of widgets on touch surfaces. (A) Tangible remote controllers for wall-sized displays [88]. (B) SLAP Widgets [201]. Courtesy of Yvonne Jansen and Malte Weiss.

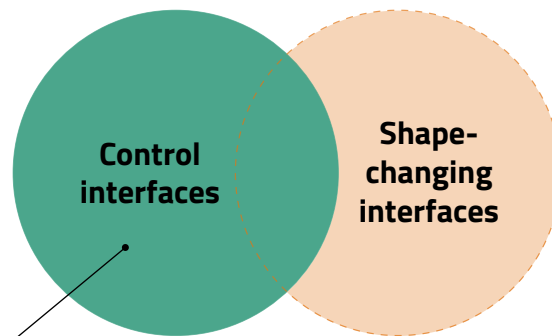
[7, 48], exploiting spatial memory [157, 161], simultaneous control of several parameters [7, 48], and specialized physical form factors [48]. Time-multiplexing lowers hardware and maintenance costs [48] and avoids physical clutter [161]. Two extremes of these different multiplexing approached are "hundreds of potentiometers" and a "single mouse" [10]. Fitzmaurice et al. [48] and Beaudouin-Lafon [10] say that the challenge lies in finding the optimal balance between the two types of multiplexing. We aim to fill in this gap and combine both multiplexing.

2.5 Conclusion

In this chapter, we looked at the evolution of types of interfaces and how shape-changing interfaces contribute to HCI by providing both flexibility and physicality in interfaces. Since shape-changing interfaces is relatively new, we also looked into the efforts to shape the field by reviewing the definitions and taxonomies for them. Lastly, we reviewed how the shape-changing interfaces has been designed for control.

Although many shape-changing controls have been proposed, few of them involve users in the design process. Research papers often build working prototypes and then conduct users studies. We wonder if common design guidelines for control interfaces can help researchers consider users in the design process. Currently, there are a few studies on the usage of control interfaces, and they have focuses on narrow professions such as musicians [184] and pilots [138]. Also, the design guidelines for control interfaces are based on lab studies [18] or existing designs [8], not based on the current practice of broad types of users. To inform researchers the design guidelines for control interfaces, we need studies providing a general perspective and hence include various professions in the studies. It motivates us to conduct a formative study with various professional users including cinema operator, graphic designer, light/sound engineers, and pilots in the next chapter.

2.5. *Conclusion*



Chapter 3. Design Requirements for Control Interfaces



Figure 3.1: Contribution of this chapter: Understanding user needs in control interfaces by conducting contextual interviews and deriving design requirements for control interfaces.

Design Requirements for Control Interfaces

3.1 Introduction

In the Introduction, we discussed the problem of trade-off between flexibility and physicality in current control interfaces. Before designing shape-changing controls to solve the trade-off, we investigate design requirements for control interfaces based on the current practice (see Figure 3.1 on page 42). Another example of the trade-off is Figure 3.2¹, a light control console. To increase flexibility the manufacturer introduced touchscreens on the console. Such touchscreen interfaces could increase flexibility by offering users means to customize the interfaces according to their work strategies/habits and task requirements [156]. For instance, the new console (Figure 3.2B) allows different colors on control widgets that can assist users in recalling and quickly accessing the parameters². Although the console has increased flexibility, the types and shapes of physical control widgets stay the same, and their flexibility has not been increased.

As we reviewed in the previous chapter, control widgets have different physical shapes and advantages. For instance, binary controls are good at instant change of parameters, rotational controls are good at precise manipulation, and linear controls are good at simultaneous manipulation of multiple parameters. Providing different control widgets according to tasks and user habits [57] would increase usability of such consoles.

Shape-changing interfaces can provide flexibility in a single or multiple physical control widgets (e.g., [133, 134, 32, 148]). However, we do not know based on what criteria we should design new shape-changing control interfaces. As we reviewed in the previous chapter, design guidelines for shape-changing controls are focusing on

¹<https://www.malighting.com/company/history/>

²<https://www.malighting.com/grandma3/>

3. Design Requirements for Control Interfaces

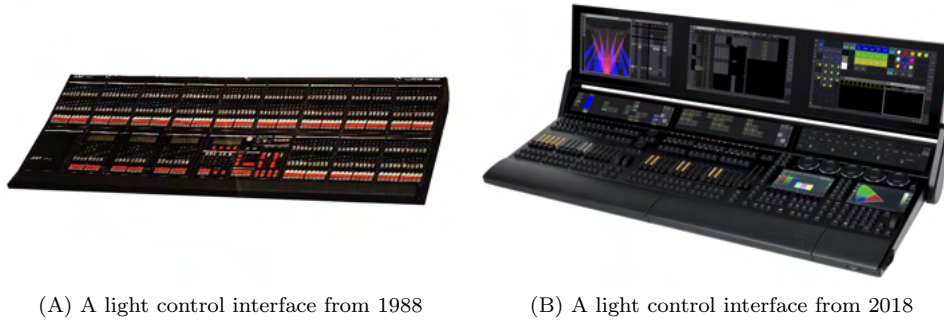


Figure 3.2: The control widgets in professional control interfaces have little changed for 30 years. Although touchscreens and background lights in control widgets are added, the widgets such sliders and buttons stay the same. (A) LCD 120. (B) grandMA3 full-size. Courtesy of MA Lighting International GmbH [59].

specific users [138, 174], implementing taxonomy features [130], or specific devices [174, 133]. To efficiently explore the design space of shape-changing controls and increase users’ acceptance of them, we need design guidelines for shape-changing controls, which focusing on flexibility and physicality.

It motivates us to conduct contextual interviews with users who extensively use control interfaces and would most benefit from new shape-changing controls. Understanding their needs and delivering organized design requirements would help researchers and designers improve their interaction methods. This chapter takes a bottom-up approach to understand the needs of using control interfaces and deliver design requirements that can be reused in future research. We take three steps:

1. We conduct contextual interviews with users who use control interfaces for their tasks. They include a camera operator, graphic designer, light artist, light engineer, two sound engineers, and two pilots. We observed their work environments and workflows in the focus of flexibility and physicality. We then interviewed them for raised questions during the observations and need for flexibility and physicality.
2. We illustrate the results of the interviews. We first describe the control widgets we observed and how they were used. We then draft design requirements for control interfaces regarding the observations and interviews.
3. We conclude with the summarized design requirements for control interfaces to help future researchers use them.

3.2 Contextual Interviews

We first aimed to understand user requirements in current practice of using control interfaces. To gather general requirements that encompass different types of tasks, we decided to target various professions that require using control interfaces that are traditionally physical. The professions include sound/light engineering, visual design, piloting, etc. To collect rich raw data regarding their workflows, we conducted contextual inquiry [79]. It is a semi-structured interview method where researchers observe users performing tasks in their real work environments and ask questions that are prepared and also spontaneously raised during the observation. Our observation and interviews of experts targeted specifically unresolved usability problems related to physicality and flexibility of devices for continuous parameters control.

3.2.1 Procedure

We first identified the most widespread professions, which require extensive use of physical control interfaces. To be open to include many professions, we used the US Bureau of Labor Statistics³ and chose our target users. According to them, there were approximately 261,600 graphic designers, 119,200 pilots, 117,200 sound engineers, 20,060 camera operators, 11,930 exhibit designers (including light engineers) in 2014. This approach allowed us to seek importance through a large population of users (e.g., graphic designers) and/or whose performance is critical to others (e.g., pilots); as well as to seek generality through diverse professions.

Through our extended social network and calling/emailing local professionals. We recruited eight participants. All of them were professional users except the pilots, as we could not reach professional pilots. Though, the recruited pilots had experiences of over 1750 hours of piloting together, and we believe the contextual interviews with them have enriched the study results.

After the recruitment, we conducted contextual interviews in ecologically valid settings. We observed all participants doing live activities. E.g., P1 was shooting a movie, P2 was drawing (P2), P3-6 were preparing a show, and P7-8 were piloting on a simulator or an aircraft (Figure 3.3). During the observation, we asked them to explain what was happening each time a sequence of actions was not clear. The activities were sometimes under a lot of pressure, for instance, a preparation of a show for the same night. When the participants required silence and concentration (P1, P3) and it was not possible to ask a question, we asked the action-related questions during the follow-up interviews. During the interview, we asked for situations where they needed to balance flexibility and physicality. When possible, we conducted the interviews right after the activities. When it was not possible, the interviews were in the next morning (P1 and P3). The observations and interviews took approximately two hours. All participants were voluntary and consented to photo and video recording.

³<https://www.bls.gov>

3. Design Requirements for Control Interfaces

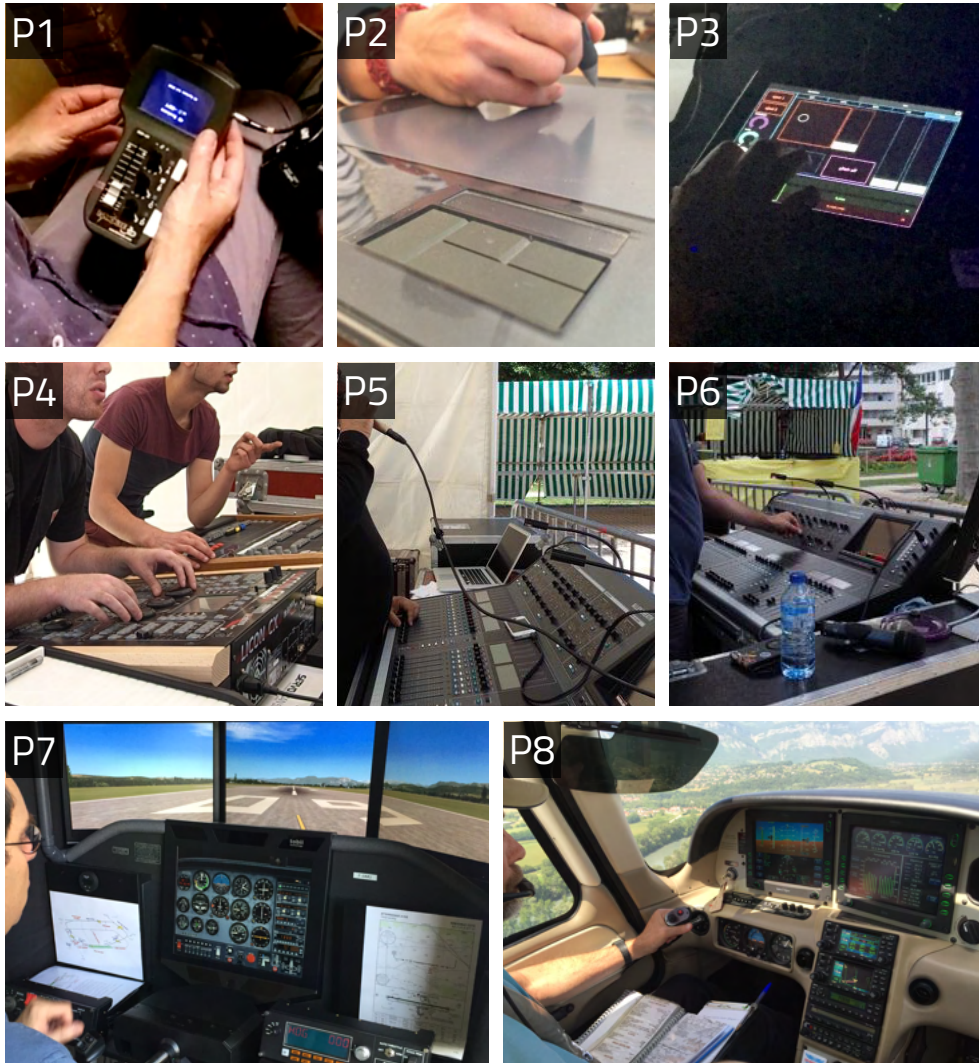


Figure 3.3: The participants and their interfaces observed in our contextual interviews. (P1) Movie operator. (P2) Graphic designer. (P3) Light artist. (P4) Light engineer. (P5-6) Sound engineers. (P7-8) Private pilots. We went to their workplaces to observe their workflows and interview them.

3.2.2 Participants and Context

We had eight participants in the contextual interview. They using control interfaces in their activities (aged 25-63, 2 females, Figure 3.3). They included 1 movie operator (P1), 1 graphic designer (P2), 1 light artist (P3), 1 light engineer (P4), 2 sound engineers (P5, P6), and 2 pilots (P7, P8). As stated before, All of them were professional except the pilots. The pilots were using the interfaces for research or recreational purpose, but had enough hours of flight to share their experiences with us. The interfaces participants were using were mainly physical, although a few recently started using touchscreens. We briefly describe their work experiences and workflows below to provide their overall needs and context of their interactions.

P1. Camera Operator

P1 camera operator (Figure 3.4) had around eight years of experience. She was controlling stereoscopic cameras at the time of observation, and there were other people deciding the frame, etc. The observation took around two hours and was during shooting of an artistic horror movie. During the shooting, she kept a complete silence not to add any additional sound in to the scene. Even between shoots, she talked with her colleagues quietly not to affect the ambiance. She controlled the cameras "live." I.e., she had to control the cameras while a scene was being taken. It was not only to change the stereoscopic depth of the scene but also to express the meaning of the scene (e.g., she told us that she once used a sudden camera depth change from stereoscopic view to flat view, to show the change of the character's mental state). To best express the scene, she tried different camera parameters and discussed with another stereoscopic camera operator who controlled another set of stereoscopic cameras from a different angle.

She explained us that time for shooting can be very limited as they may need specific

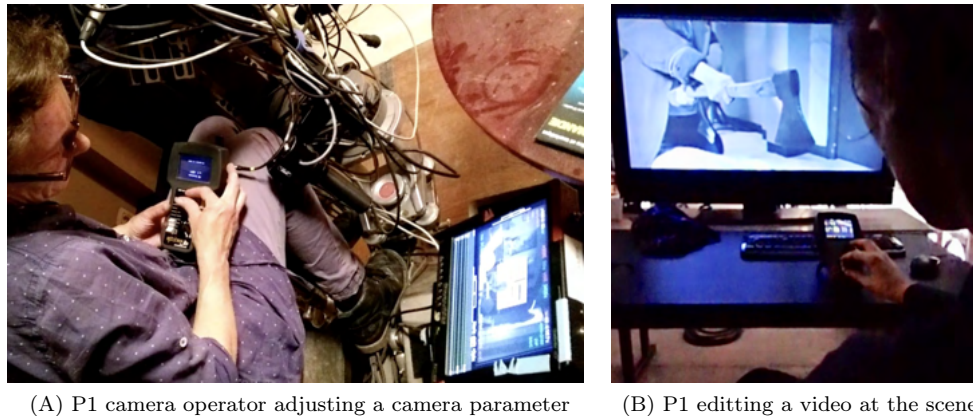


Figure 3.4: (A) P1 movie operator is adjusting a camera parameter with her hand held control interface while looking at a screen. (B) She is using the same interface to edit a video.

3. Design Requirements for Control Interfaces

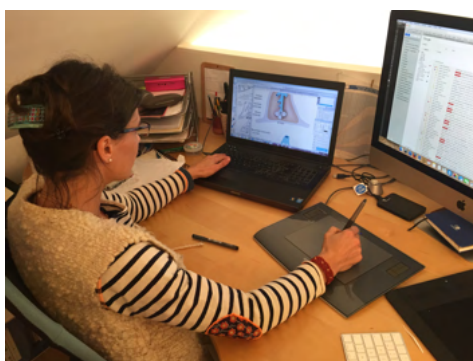
weather and/or natural light. Shooting also involves many people such as directors, actors, and technicians, and delay of shooting would require rearranging those people's schedules, hence can threaten the budget. Although our observation was indoor (an old house) and had less restrictions on natural light, P1 had a lot of pressure of "being ready in time." She did not want to be the last one who delays the schedule. She actually finished all of her technical settings an hour before the planned shooting time.

P2. Graphic Designer

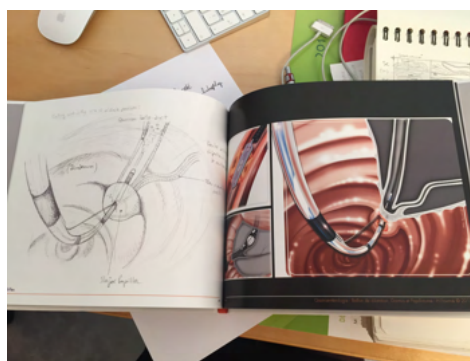
P2 graphic designer (Figure 3.5) had 17 years of work experiences. She worked at home as a freelance medical and scientific illustrator. The observation was at her office and lasted around two hours. She was using a laptop, with keyboard and trackpad (see Figure 3.5A). She used a stylus with a Wacom graphic tablet, which had touch sliders and buttons on the side. She used them as main input devices when she worked on Photoshop.

We observed a separation of workspaces. She said that she usually puts the Photoshop palette on the left screen and tools on the right screen. In Figure 3.5A, the second screen is showing a web browser with emails that she communicated with clients.

She optimized her workflows not to loose time. She said that she usually drew first with pen on paper on a dedicated booklet with the help of her notes from phone meetings with clients. Then she scanned the sketchbook in order to trace it with the computer and kept working on it on the computer as it allowed quick corrections and undos during the several back and forth with her clients. Figure 3.5B shows one of her initial sketches and its digitalized final version.



(A) P2 graphic designer and her work environment

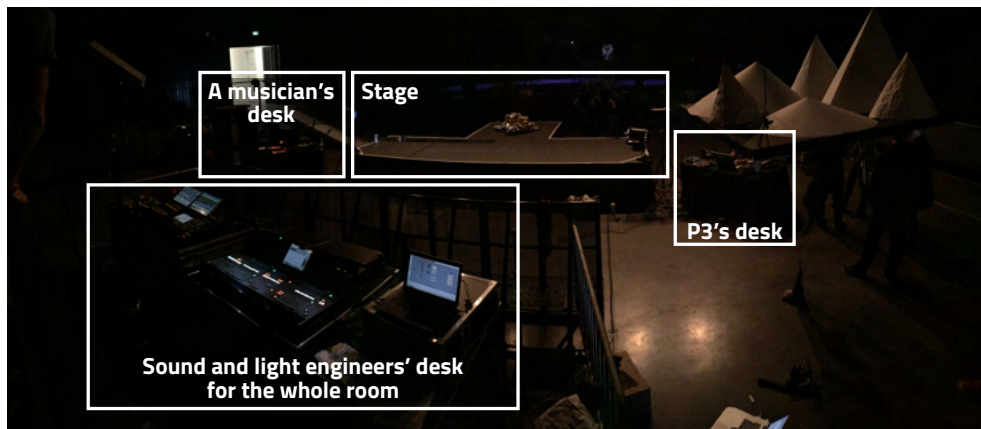


(B) Her original sketch and its final digital version. From her portfolio.

Figure 3.5: (A) P2 graphic designer is editing the drawing on the left screen. She has the second screen on the right side to access the conversation with clients. (B) An example drawing from her portfolio, showing the original sket on the left and the final version on the right. The more examples can be found in her online portfolio: <http://hfournie.free.fr/>

P3. Light Artist

P3 worked as a both light artist and engineer (Figure 3.3, 3.6). During the observation, he was working as a light artist. He used new input technologies in his show, comparing to the other participants. We observed him during the setup and rehearsal of a live art event. For the event, he used his laptop, iPad, and Kinect as input interfaces. He controlled video projectors, laser projectors, a fog machines, and a fan. He wrote text-based code with Xcode to control the laser projectors and the Kinect. He also wrote graphical code with Max/MSP and tapeMovie⁴. He used LEMUR app⁵ on his iPad. He also had Leap Motion⁶ on his desk, but he did not use it during this rehearsal because he did not have time to configure it.



(A) The arrangement of P3 light artist's desk, the stage, and a musician's and engineers' desks.



(B) P3 adjusting parameters before the show.



(C) P3 adjusting parameters during the show.

Figure 3.6: P3 light artist and his work environment. (A) the stage arrangement with his desk. The audience sat between the stage and the sound and light engineers' desk (not visible in the figure). (B) P3 is using his laptop to control lights before the show. (C) P3 is controlling the laptop and iPad while looking at the stage during the show, in the dark.

⁴Programming environment for controlling audio and video instruments in real time. <https://cycling74.com/>

⁵MIDI/OSC control app for iOS. <https://liine.net/en/products/lemur/>

⁶<https://www.leapmotion.com/>

3. Design Requirements for Control Interfaces

Most of the time, he worked in the dark. He performed bimanual [68] and eyes-free tasks: left hand on the laptop's keyboard, right hand on the large pad on the iPad, and eyes on the dancer (see Figure 3.6A). When the rehearsal started, he grabbed the iPad and went in front of the stage (see Figure 3.6B). He sat on the floor with the iPad on his knees. He controlled, i.e., drew the light of the laser. He changed the part, went back to the desk with the iPad, and again went back to in front of the stage with the iPad. He moved back and forth like this many times as they rehearsed the sequence many times. The work environment was very time pressing as it was s preparation for the show at the same night and he did not have every resource he needed, and it increased time pressure. E.g., he lacked one laser project so that he needed to move the projector from the side of the stage to the back. The software handling the Kinect crashed during the rehearsal, so they rehearsed that part again, which added the time pressure.

P4. Light Engineer

We observed P4 light engineer setting up lights for a music concert for the same night (Figure 3.3, 3.7). He used a LICON CX console⁷. His consoles were behind the consoles of sound engineers, and his view was limited by the sound engineers (in Figure 3.7B, there is another console lying between him and the stage). After wiring, he checked that all lines are connected and the signals arrived to the console. He assigned the control to the lights and wrote down assigned lights below the corresponding control widgets (Figure 3.7A). He then programmed light animation sequences to launch during the concert. He moved his head back and forth between the console and the stage all the time to associate his controls on the consoles with the lights on the stage.



(A) (front) P4 light engineer



(B) P4's work environment.

Figure 3.7: P4 light engineer and his work environment. (A) He is writing down the mapping of the controls on paper. (B) He is setting up the lights in the daylight for a night show.

Since it was bright, he could not see his lights well. He sometimes went to the stage

⁷<https://fr.audiofanzine.com/console-eclairage-automatique/jb-lighting/Licon-CX/>

to check the lights, then came back to the console. He also shouted to people on the stage to verify the lighting. It was a windy day, and the wind dropped spotlights. As this could be dangerous, he had to discuss about changing spatial arrangement of spotlights with his colleagues.

P5. Sound Engineer

P5 sound engineer worked both in live and studios, and we observed him working at the live event as P4 (Figure 3.8). He had around 20-30 years of work experience. As the first step of his workflows, he programmed the audio mixing console, mapping the sound parameters on the stage to the controls on the console. To do it, he manipulated the sliders without looking at them, shouted and signed to his colleagues who are on stage to know if it was the right parameter (see Figure 3.8A). To program the console, he used a "patch" (a sheet of paper with instruments and equipment on a stage) from the musicians, given by the organizers of the concert. He associated the instruments and the stage map with the controls of the mixing console. He also used his laptop next to its mixer to name the parameters and sound channels (see Figure 3.8B). He preferred to type the names of the instruments on the keyboard of the laptop rather than on the touch screen of the console. He arranged the instruments by grouping, giving names, and color coding.

He was used to dealing with unexpected last minute troubles. In a playful manner, he said, "[The musician] will arrive, and they will say 'everything has changed!'". Actually, A group of musicians arrived late for the rehearsal, and the schedule was delayed. They provided a new patch different from the one he was given by the organizers, including the addition of new instruments. P5 had to redo the stage plan, remove cables, and re-program the console. He programmed the console for one group of musicians and then for another. During the concert, he switched from



(A) P5 sound engineer



(B) P5 setting up parameters on his laptop

Figure 3.8: P5 sound engineer and his work environment. (A) P5 sound engineer is communicating with a musician on the stage while controlling a slider. (B) He set up parameters on his laptop software which was connected to the mixing console. He gave color codes and parameter names on the software (see left top corner of the screen).

3. Design Requirements for Control Interfaces

one mapping to another by pressing buttons next to each group of 8 sliders, which provided 4 different mappings. When he pressed a button, the sliders instantly moved to preset values.

During the concert, with the second group, he had a problem: sound from an instrument was much louder than the others. To cope with this, he sent someone on the stage to back of the musician, to have a close look at an amp. When the person returned from the stage, this person has finally identified that the musician had not changed the settings. The person went back there with the provided patch to make the settings right. After this, P5 once went out into the audience to check the audio, then came back to his mixing console.

P6. Sound Engineer

P6 sound engineer was a sound engineer of a band in the same event with P4 and P5. He used the mixing console of P5. He did not know the console struggled to use it right away. To become familiar with it, he needed help of P5. He adjusted the sound curve during the balance (adjusting volume and frequency of multiple sound sources⁸), using the knobs and looking at the additional screen beside and listening to the sound (see Figure 3.9). He did this for each instrument and microphone on the stage (around 20 times).

During the balancing, he gave orders to the musicians such as "this time, drum bass." The musician singer then asked him "Wait, you don't want to make all the voices for all of us?" P6 replied no with a wave of his hand and head, and said, "I start with him first, an then one after another." The musician answered "you decide." It was difficult for P5 and the musicians to communicate because on the stage not every musician had a microphone. In this case, they had to shout to be heard by the



(A) P6 sound engineer balancing sound sources while listening the music and looking at a screen.



(B) adjusting a dial and seeing the visual feedback (LED light) around it.

Figure 3.9: P6 sound engineer and his work environment.

⁸https://en.wikipedia.org/wiki/Mixing_engineer

sound engineer. For instance, during the balance, P6 asked the drummer about the audio feedback. The drummer replied but did not have a microphone, so that P6 had to watch the drummer carefully to understand the answer. He asked the drummer, "what kind of change do you want?" The drummer replied, "No need. the drums are not worth it." However, P6 could not hear and asked someone between them to relay the communication.

P7. Private Pilot

P7 has been piloting for 20 years and had 400 hours of flight experience (Figure 3.10A⁹). He flew around 1 or 2 times per month. To control safely even during turbulence, he secured his fingers around the throttle so that he did not make any error controlling engine power while flying (see Figure 3.10B). He used a simulator, that replicates a CESSNA 172, i.e., a standard tourism American light aircraft. The mapping of the controls to the functions can be different depending on the simulated aircraft.

We observed an interface different from interfaces of other professions: co-axial pull+turn buttons with two rings. The larger, bottom ring allowed choosing the number before the decimal point, and the smaller, upper ring allowed choosing the number after the decimal point with a step of 50Hz. The user could pull the smaller, upper ring. The co-axial two-rings buttons allowed pulling the last, upper button to add new layers, i.e., new turnable buttons. However, the participant said that these co-axial pull+turn button do not exist anymore as they are too fragile. He explained that some manufacturers propose four push buttons to enter the same 4 numbers instead of the co-axial buttons.



(A) P7 pilot and his flight simulator



(B) P7 grabbing in the throttle

Figure 3.10: P7 a pilot and his flight simulator

⁹We credit PILOTE2 AGIR Université Joseph Fourier and G-INP for the simulator used in the observation.

P8. Private Pilot

P8 had a commercial pilot license from US Federal Aviation Administration and a private pilot license from European Joint Aviation Authorities. He had an experience of a total 1350 hours of flight including 350 hours of instrument flight¹⁰. The weather was sunny and clear during our observation, and the flight was done with visual flight rules (VFR). He used Cirrus SR20 aircraft with Garmin GNS 430 navigation instrument in it for the observation.

Piloting had high safety risk – maloperations could lead to fatal accidents, and turbulence increased the difficulty of correctly controlling the cockpit interface. Hence, the interface was designed to reduce unintended operations (see Figure 3.11). For instance, he had to confirm a parameter change by pressing a separate "ENT" (Enter) button after rotating the co-axial dials below. Additionally, there was a concave surface for him to grab and to help him position and stabilize his position while not touching the interface by mistake, especially during turbulence.

He developed strategies to control the interfaces smoothly and safely. The physicality of the interface and force feedback also helped him control the interface. For example, the gas/power handle provided dynamic force feedback. It was easy to push up to its detents, and the force feedback of the detents changed depending on the expected speed of the aircraft. Similarly, there were dials with detents.



Figure 3.11: P8 controlling his cockpit interface.

¹⁰Instrument flight is flying in instrument flight rules (IFR), which allows pilots to fly in essentially any weather condition and inside of clouds as long as aircraft can operate safely. Ideally pilots can fly solely referring the instruments and not seeing the outside references such as terrains and nearby buildings, and thus it requires the pilots intensively interact with the instruments (cockpit interface) and more training. The other type of flying is visual flight rules (VFR), flying by referencing outside visual cues only in clear weather. VFR pilots are not allowed to fly in cloud or bad weather.

3.3 Results

In this section, we summarize the method we used to analyze the data from the contextual interviews and the findings from the analysis.

3.3.1 Data Collection and Analysis

We collected 8640 words of written notes, 141 drawings and photos (i.e., finger posture or devices used). We also collected 2h 34m 26s of video and audio recordings of particular sequences of actions or interviews. When possible, we performed the analysis no later than 48 hours after the interview. Our analysis had two focuses: analysis on control widgets and analysis on interactions. For control widgets, we summarized the types of control widgets based on their parameter/interaction types (binary, rotation, and linear).

For the analysis of user interactions, we used the following steps: First, we described every sequence of observed actions. We used the collected notes, photo and video recordings from our observations to help the description. We then used thematic analysis [20] to analyze user needs regarding their controllers. We started with a research question: "what is needed for the users to perform their task?" A coder first labeled the observations with initial categories (codes) answering the question. An additional two coders joined to discuss, and agreed on them as well as identifying particular topics to regroup codes by themes.

3.3.2 Observed Control Widgets

In the contextual interviews, we focuses on three types of control widgets: binary, rotational, and linear controls, which were often observed in the interviews and also in literature (e.g., [183, 88, 148, 193]). Here we illustrate the widgets according to the types and describe their usages and advantages in interactions.

Binary controls

We observed largely three ways of interactions with binary controls: multiple buttons to toggle between parameter values, two buttons to replace rotational or linear controls, and one button to trigger or confirm parameter changes. On the tablet interface of P3, some buttons were used as a tab (toggle buttons, Figure 3.12A). By touching the buttons, P3 could switch between different sets of control widgets. We observed a similar role of buttons on a mixing console of P5 (Figure 3.12B). There were four buttons next to a set of sliders. By pressing a button, he could switch the assigned parameters of the sliders to other parameters or jump to preset values for the parameters. They could show which of the multiple buttons were chosen. A similar but

3. Design Requirements for Control Interfaces

simpler version of such buttons would be the switches (Figure 3.12C). The switches on P7's cockpit simulator could show which of the two parameter values were chosen.

The second type of interaction was using the two "RNG" buttons for continuous value change instead of using rotational or linear controls (Figure 3.12E, Figure 3.11). P8 used the two buttons (the arrows in the figure) to change the zoom of the map. He sometimes wanted to change zoom from the level of 100 to 5 (from localized area to overview of the whole area), and pressed the button repetitively. Lastly, many binary controls were to trigger parameter value changes (Figure 3.12E-G). To list a few, P3 used a large button on the tablet to trigger a sequence of light performances (Figure 3.12F). In this case, he made the button larger than other buttons to press it on time. Unlike any other interfaces, the cockpit interface of P8 had a button to finalize parameter changes. The "ENT" button was used to finalize the input from the co-axial dials (Figure 3.11). The separation of the widgets for parameter value change and confirmation helped him not to make mistakes, especially during turbulences.

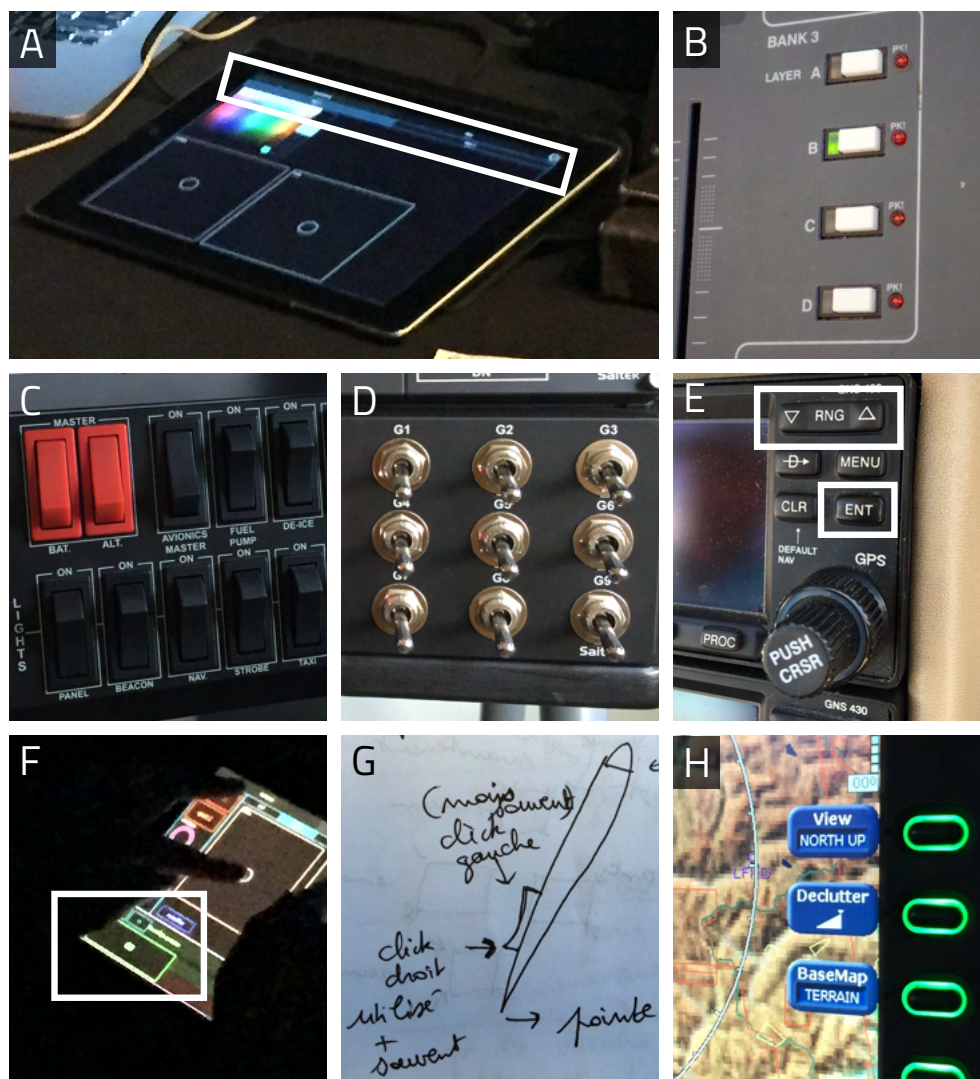


Figure 3.12: Examples of binary controls we observed during the contextual interviews. (A) Tab buttons to navigate to different UI screens. (B) Buttons on a mixing console to change assigned parameters or values of a set of sliders. (C,D) Switches in a cockpit. Similar to (A) and (B), they can show which parameter values are currently chosen. (E) Two "RNG" buttons to increase and decrease zoom on a map. A "ENT" button to finalize input of the co-axial dials below. (F) A button to trigger a sequence of changes in light. (G) buttons on a tablet pen to trigger functions (from sketch during the interview). (H) Buttons next to a display. The functions of the buttons are flexible thanks to the display.

Rotational controls

Most rotational controls were potentiometers with no bounds or detents, of around 1cm diameter with small lobes on their sides (see Figure 3.13A). We observed varied dials, which were less used (Figure 3.13B-G): e.g., with position mark (B, P4), concentric ones (C, P8), large dial with a concave notch for rotation with a single

3. Design Requirements for Control Interfaces



Figure 3.13: Examples of rotational controls we observed in the contextual interviews. (A) Continuous dials with infinite ranges. (B) Dials with discrete visual markers. (C) Two-leveled dials with detents, enabling both coarse and precise controls depending on which level users are controlling. (D) a shuttle dial with a smooth concave notch. (E) an arrow-shaped dial with a limited control range. (F) a tactile dial on a graphic tablet. The round groove allows users to place and move fingers on it. (G) tactile dials on a touchscreen tablet. They control continuous and bounded parameters.

finger (D, P4), arrow-shaped ones (E, P8), tactile dial with grooves on a surface allowing users to rotate it with index fingers[8] (F, P2), or tactile dial on a touchscreen (G, P3). The participants had grips on the dials depending on their designs. E.g., the participants mostly used thumb and index finger to rotate small-sized dials (Figure 3.13A-C), where some of them placed one finger on the concave notch on the shuttle dial and tactile dials (Figure 3.13D, F, G). In general, dials took less space than sliders.

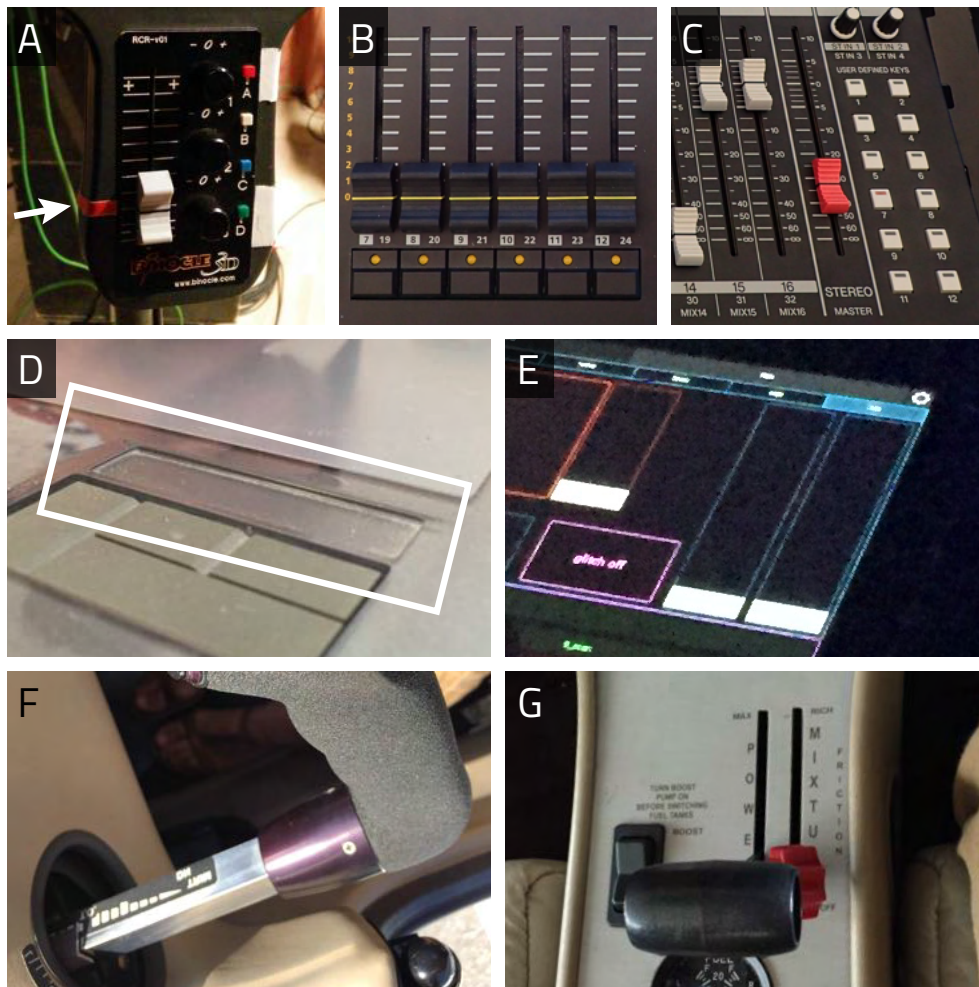


Figure 3.14: Examples of linear controls we observed in the contextual interviews. A) Slider with a visual marker (red tape). B) Slider with an associated button. C) Sliders with color codes. D) Tactile slider with a place holder. E) Touch slider on a tablet. F) Side control yoke in a cockpit. Users can pull and push it to change the elevation during flight or brake during taxi. G) Throttle in a cockpit. By pushing it, users can control the amount of fuel going to the engine to change the speed.

Linear controls

Most of the linear controls were sliders sized around $\sim 8\text{-}10\text{cm}$, with very smooth friction to allow tiny movements. Unlike dials, sliders had less variation in the designs (Figure 3.14A-C). The only small slider we observed was a tactile one with a place-holder (Figure 3.14D), to zoom in on the screen. Other types of linear controls were observed in a cockpit (Figure 3.14F-G).

3.3.3 Frequently Observed Interactions

In the analysis, we also identified six themes of design requirements regarding the interaction with control interfaces. In this section, we illustrate the themes of with examples of actions observed and comments made by the participants.

R1. Interaction with a large number of parameters

All participants interacted with a large number of parameters. For instance, the fewest number of parameters was ten, which P1 used to control stereoscopic cameras' 3D position, 3D orientation, focal length, 1D focus distance, interaxial distance and convergence. P2 used many of the ~60 Photoshop tools and their parameters (e.g., brush size, tip, roundness, hardness, etc.). During his show, P3 adjusted ~50 parameters in total. P4 - P8 (sound and light engineers, and pilots) had more than 100 parameters to deal with.

R2. Fast interaction

The participants needed fast interaction to save time and be efficient, and also to do accurately control their shows or quality of work or to be efficient. We observed three types of circumstances or user needs when they need to access or control parameters quickly.

Fast access to parameters: In many situations, the users needed to quickly acquire the devices. For example, to quickly access the parameters of a fan and a fog machine during the show, P3 (light artist) chose to permanently display two dedicated dials on the left-hand side of his interface (Figure 3.3). P2 explained that her desk is always tidy: she needed a clear space to go from one device to another without losing time. P5 told that he never used the sliders that are too far away, and preferred pressing a button to quickly switch the parameters associated with the sliders that are close to him.

Fast manipulation of parameters: For instance, P7 related that the throttle was used by default for quick, coarse adjustments. P1, P3-P6 worked "live," i.e., during the shooting or show, so they must manipulate the parameters promptly. When working for music concerts, P3-P6 needed to be very reactive as musicians never play the same way. The need for fast manipulation required the participants to use several fingers on sliders or two hands on different devices. P2 explained that she started using the computer to work faster: her work requires several back and forth exchanges with the client who asks for modifications. She used the computer to do quick corrections (e.g., undo) that physical brushes and pens did not support.

Fast observations of parameters: For example, P1 was manipulating interaxial distance between stereoscopic cameras and the bounds of the slider were clearly showing her the physical constraints of cameras. She also used red tape to mark a

particular value of the interaxial distance during the shooting (see Figure 3.3 P1, the left side of the slider). P5 and P6 sometimes quickly glanced at their interfaces to observe a parameter value during the show. During manipulation, the dials of the cockpits (P7-P8) provided haptic feedback through haptic detents. For quick observations of parameters, P7-P8 looked at or touched the corresponding interfaces. P7 explained that in emergency situations, quick observation of parameters is critical. Overall, sliders were preferred for rapid observation of parameters.

R3. Precise interaction

The participants also needed precise interaction as they needed to slightly adjust parameters or to avoid mistakes.

Avoiding mistakes: When operating a slider, P1 placed her hand carefully to avoid mistakenly moving the dials next to it (Figure 3.3).



Figure 3.15: P6 using haptic feedback to slightly move the slider cursor.

Haptic feedback: Users used haptic feedback to slightly adjust parameters. For example, P6 (sound engineer) slightly pushed a slider cursor to precisely change the value of a slider. In this case, the haptic feedback from the physical slider cursor allowed such interaction.

Multi-turn dials: dials, even when small, also offered high precision as most of them were multi-turn. We observed P4 (light engineer) using a dial before the show to very precisely set a projector angle (Figure 3.3, P4). For this, he performed many rotations on a dial with low control-display gain¹¹. Similarly, P7 and P8 (pilots) used dials to accurately input decimal values of radio frequencies. P7 related that the extremity of his aircraft's throttle could be turned for precise adjustments. P1 (movie operator) used a dial to adjust, at pixel precision, the horizontal shift between stereoscopic images, by performing multiple rotations. Overall, dials were preferred for precise interaction.

Large sliders: Most participants used large sliders (8-10cm), and the sliders had very smooth friction (no detent) along the axis. It allowed very subtle movements of the cursors.

¹¹ $CD_{gain} = V_{Display}/V_{Control}$, the proportion between movements in the control space to the movements in the display space

R4. Eyes-free interaction

The participants needed eyes-free interaction often while adjusting parameters. The physicality of their interfaces allowed such interaction, once they grab the interfaces (P1, P2, P4-P6).

P6 needed to adjust the curve of sound level (dB) for each frequency (Hz) of each instrument and microphone on stage. He preferred using the physical dials for this rather than the touchscreen.

P1 needed eyes-free interaction because her screens were not collocated with her dials and sliders. Similarly, P2 focused on her canvas on the screen and looked away to modify her tool, thus lost time finding her object on the canvas again. P3-P6 watched the stage while interacting (Figure 3.3). P5 explained that he preferred physical controllers, and never used the touchscreen of his console, which our observations corroborated. P5 and P6 said that interacting with bounded parameters on multi-turn dials—i.e., unbounded dials—was not comfortable, as they have to look away from the stage to watch the LEDs around the dial to check their boundaries. Bounded dials were not available on the mixing console we observed, and participants said that they also seldom find them on other mixing consoles.

P3's problem with touchscreens was that he felt "blind" as there was no haptic feedback. We observed P3 missing his intended trajectory of a dial on the screen: he started to follow the dial on the tablet. While looking at the stage, he drifted from the dial, losing control of it. When he realized it, he looked down to reacquire the dial. We observed him trying to grasp two touchscreen sliders eyes-free: one with the index finger and the second with the middle finger, both unsuccessfully. He then looked down to re-grasp the sliders. He recouped the lack of physicality with extra-large widgets (Figure 3.3, P3), but it was not satisfactory for him: he lost space, and still lacked physicality, which caused critical errors.

Pilots (P7 and P8) needed eyes-free interaction to figure out current mode of a parameter. They used push/pull handle for power and mixture (of air and fuel) and often placed their hand on the handles to know their status without looking (Figure 3.3, P8), which aligns with the result of [116]. P7 said, "If you put your hand on [the control device], you know in which mode you are." They commented that physical devices were particularly useful when visibility in the cockpit was altered by smoke. P7 and P8 both explained that aircraft manufacturers were introducing touch screen interfaces¹². Both agreed that the idea was dangerous. Their comments strengthened the cockpit design requirements in previous work [24, 197].

R5. Mobile interaction

All users needed mobility. P1 used her cameras and control devices at different locations. P2 sometimes worked away from her desk, e.g., in a van during a vacation.

¹²Thales Avionics 2020, <https://www.ainonline.com/aviation-news/business-aviation/2013-10-22/thales-displays-2020-ready-business-jet-cockpit>

P3 explained that moving around the stage was crucial for him: when not possible, he communicated with someone in front of the stage as a proxy. Unfortunately, this person might not understand what he wanted or did not have the same demand on the final quality. To avoid losing time or quality, he used a tablet, but sub-optimally moved back and forth between his desk and the stage. P4 went on the stage to better see his projectors, and then came back to the console. We observed P5 going on the stage to ease the communication with musicians. He said this was the only reason he used the tablet, as he did not like using the sliders/dials on touch screens. To avoid using the tablet, he communicated with musicians via a microphone (Figure 3.8A), or even shouted or signed. Sometimes a third person was necessary to help communication with drummers who did not have a microphone. Thus, all solutions were suboptimal. Mobility was also necessary during the show: P5 walked around the venue to hear the sound from other locations. He then had to come back to the mixing desk to adjust the parameters. P7 and P8 (pilots) had a compact interface that fits in the cockpit.

R6. Retro-compatibility

The professional users needed to leverage their existing expertise with current interfaces. For example, P2 explicitly commented that she was not keen to change interface because her workflow was efficient and she was not ready to lose income for a short term. Similarly, P5 did not use his tablet as much he used his mixing console, as the tablet lacked retro-compatibility, such as physicality. The only participant that explicitly showed no interest in retro-compatibility was P3. He built a new interface dedicated for each show and improved it with practice. He used the touch-screen interface and laptop, and tried to use new technologies such as Leap motion although she/he did not have time to set it up and use it at our observation. Yet, his touchscreen controllers were mimicking physical ones (dials, sliders, buttons, etc.).

3.4 Design Requirements for Control Interfaces

We derived the following six requirements directly from the themes of our contextual interviews.

- R1. Interaction with a large number of parameters.** All participants needed to control lots of numbers of parameters through their workflows. The cameraman had the least (10). The sound and light engineers can deal with more than 100. Types of parameters were diverse: some were discrete (e.g., tool in Palette) or continuous (e.g., sound volume). Some were bounded (e.g., flaps' angle) or not (e.g., shift between cameras). Some were cyclic (e.g., projector's angle).
- R2. Fast interaction.** The participants needed to control parameters quickly. To do it, they needed quick access to, rapid manipulation, and fast observation of parameters. Quick access to parameters can be supported by placing devices within users' reach. Rapid manipulation of parameters can be supported through smooth trajectories. Fast observation of parameter values can be carried by visual and/or haptic display, including minimum and maximum values or a value of interest.
- R3. Precise interaction.** The participants also needed precise control of parameters. It can be supported through a large interaction area (multi-turn dial or large slider) and little friction. Enough space between devices prevents errors. A stable grip on the device also allows its operation without slipping.
- R4. Eyes-free interaction.** The participants needed to observe how the controlled parameters affect the objects of the task such as stage, video, graphic and sound. while interacting with the interface. Eyes-free access to parameters can be supported by spatial stability of the device to leverage motor-spatial memory. Eyes-free manipulation of parameters can be supported through physical trajectory guide (e.g., slider's rail, dial' rotational axis) and haptic feedback. Eyes-free observation of parameters' value can be supported through a physical cursor or haptic feedback (detent).
- R5. Mobile interaction.** Some of the participants such as the light engineers and camera operator needed to move around the workplace respectively to check the audiences view, and to support scenes where cameras move. Mobile interaction can be supported by small devices, such as the light engineer used his tablet to control some parameters in front of the stage.
- R6. Retro-compatibility.** The participants are professional, and new interfaces need to support them with current interaction: it is arduous for users to give up current UIs—even though new ones can be beneficial in the long term [158]. This can be supported by standard operations of standard devices and options for customization.

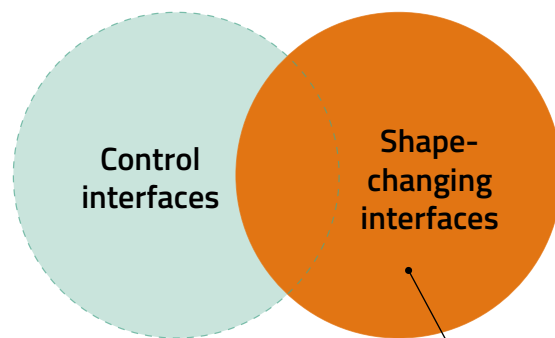
Some of these requirements are incompatible (e.g., a slider should be large for precision and small for mobility). To maximize users' satisfaction of interacting with control

interfaces, a good design needs to find a way to compromise the requirements or to allow user to prioritize the requirements themselves.

3.5 Conclusion

In this chapter, we conducted contextual interviews with professional users who intensively use control interfaces and summarized their needs as six design requirements throughout the professions. We wish designers and researchers can use the design requirements when they explore the flexibility and physicality problem of control interfaces. Future studies can evaluate the requirements by having other participants from the same kinds of professions or extend the envelop of the requirements by conducting studies with users in other professions. It would be also interesting to clarify the relationships between the requirements, e.g., fast interaction and precise interaction are exclusive when there is no physicality. Lastly, future studies can add sub-requirements under the found requirements, e.g., low CD gain under precise interaction.

3.5. Conclusion



Chapter 4. Design Tools for Shape-Changing Interfaces

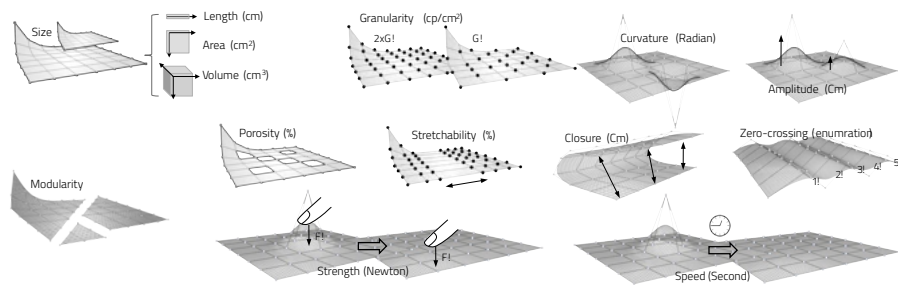


Figure 4.1: Contribution of this chapter: a refined taxonomy of shape-changing interfaces and a collection of everyday reconfigurable object as an inspirational tool.

Design Tools for Shape-Changing Interfaces

4.1 Introduction

In this chapter, we provide design tools to systematically explore design ideas of shape-changing interfaces (Figure 4.1 on page 68). In the Introduction Chapter, we raised the problem of flexibility and physicality of control interfaces. Through the literature study in Chapter 2, we learned that shape-changing interfaces can provide a way to resolve the problem through time- and/or space-multiplexing of physical devices. In the previous chapter, we highlighted six design requirements for control interfaces, which focus on flexibility and physicality of the interfaces.

As we have the design requirements for control interfaces, now we can wonder how to implement them within new devices. Designing shape-changing interfaces is not trivial as the design space of possible shape-change is exponential. To guide design of such interfaces, several taxonomies has been proposed [145, 31, 168, 149, 186]. They can classify possible shapes, dynamics, and functions, and implementation of shape-changing interfaces. The taxonomies have been used to create new shape-changing interfaces and proven to work as a design tool [107, 130, 146, 139]. However, it is not clear which of them is most well-refined and descriptive to clarify the design space of shape-changing interfaces. Additionally, those taxonomies have been proposed by independent groups of researchers, and there has been little effort to unify and sustain them. This chapter is thus not about using one of them, but rather about taking a step back and revisiting the existing taxonomies before using any of them. We evaluate some of the taxonomies and sustain them for the next step of this thesis.

As a first step to sustain the taxonomies, we evaluate their descriptive power with end users' everyday reconfigurable objects. We choose everyday reconfigurable objects, as users are used to manipulating reconfigurable objects in their everyday life, e.g., a knife-changeable blender to prepare a smoothie, a height-adjustable chair at work, a

foldable ladder to reach the attic or an orientation-changeable light to read a book in bed. Their continuously evolved manipulations are handy for users (e.g., being able to open and close a folding fan with only one hand [109]). In addition, these objects have—explicitly or implicitly—inspired the design and taxonomy of shape-changing interfaces (e.g., [94, 95, 109, 142, 150, 166]). Everyday reconfigurable objects allow us not only to inform the taxonomy features that end users are used to, but also can inspire new shape-changing interfaces.

We particularly focus on two taxonomies among previously suggested taxonomies. Roudaut et al. [149] proposed the term "shape resolution" which characterizes shapes as well as deformations in 10 geometrical features used to classify existing manual and automatic shape-changing interfaces. Rasmussen et al. [145] presented a review of existing automatic shape-changing devices and identified eight types of deformations to serve functional and hedonic design purposes. Both taxonomies are widely used within the HCI community¹. Our goal is to study their ability to describe everyday reconfigurable objects, as these continue to inspire new shape-changing interfaces.

In this chapter, we systematically analyze 82 everyday reconfigurable objects by using two shape changing-interface taxonomies. We report our findings to refine one of the taxonomies and inspirations to design new shape-changing interfaces. Our four steps approach provides the following contributions:

1. We collect 82 everyday reconfigurable objects [98] that are reusable by other researchers. The list includes pictures and descriptions. We conducted a collection and brainstorming workshop to have a set of objects.
2. Three shape-changing interface researchers classify the collected items using two taxonomies (Rasmussen's and Roudaut's), which describe topological changes. We reveal the relationship between the taxonomies and areas for improvement.
3. We add Size and Modularity features to "shape resolution" taxonomy (Roudaut), which turned out to be the most descriptive taxonomy to describe shapes and deformations altogether. We also refine its features and call it Morphes+.
4. To help researchers, we also discuss how to implement specific shape-change features using deformation mechanisms of everyday objects. Our goal here is to help to leverage everyday reconfigurable objects to propose new shape-changing interfaces.

¹According to ACM digital library on July 13rd, 2019, Rasmussen's [145] and Roudaut's taxonomy [149] are cited 137 and 87 times each. The other works were cited [31] 66, [130] 8, [107] 13, [146] 6, [186] 3 times.

4.2 Getting Inspirations from Users' Everyday Life

Along with Holman and Vertegaal's [78] vision of organic user interfaces that encourage designers to get inspiration from nature, many shape-changing interfaces take morphologies from nature. Bamboostics [135] demonstrated bamboos bend toward passengers, as they are moved by wind. Some works explored biological motions [92] to express certain emotions of the interface. For instance, a shape-changing phone DEVA [37] presented excitement through ear wiggling, and Animate mobiles [75] moved up its head toward the user to show affection.

While nature-like interfaces convey certain feelings, interfaces using everyday objects tell designers how users interact with certain shapes. [2] et al. conducted a survey of 1515 electronic push buttons in home environments. They proposed a characterization of button properties and how this can inform the design of future shape-changing devices and surfaces.

Everyday reconfigurable objects tell users how to deform them as input. Lee et al. [109] investigated future foldable display using everyday objects such as newspapers and umbrellas. Users change the size of the display by folding the map or turn off the display by completely folding the umbrella. Similarly, a sheet of paper [166], a piece of fabric [167], a book [94], an ancient scroll [95], a Rubik's Magic puzzle [142] and a Rubik's cube [150] were used to design deformable displays.

Considering existing reconfigurable objects enable researchers to use their affordance as well as quickly evaluate interactions with low-cost prototypes. It inspires us to take a closer look at everyday reconfigurable objects. To our best knowledge, there is no systematic study on everyday reconfigurable objects. In this paper, we analyze the objects to inform the design of shape-changing interfaces, in particular through the improvement of their taxonomies.

4.3 Rasmussen's and Roudaut's Taxonomy

Among the seven previously suggested shape-changing interface taxonomies [31, 107, 130, 145, 146, 149, 186], we choose to use Rasmussen's and Roudaut's taxonomies to analyze. They provide general views on shape change features such as orientation and porosity, which are not technology-dependent or purpose-oriented. Moreover, they have the most impact on the field¹. For clarity, We first briefly describe the different features of Rasmussen's Types of Shape Change Taxonomy (Figure 4.2, [145]) and Roudaut's Shape Resolution Taxonomy (Figure 4.3, [149]).

Rasmussen's taxonomy

Rasmussen and her colleagues suggested taxonomy first focusing on shapes rather than the purposes or technologies of shape-changing interfaces [145]. The article reviews 44 shape-changing interfaces and suggest taxonomies for the shape, types of transformation (e.g., kinetic parameters), interaction (e.g., indirect and direct interaction), purposes (e.g., hedonic, functional) of shape-changing interfaces. In this thesis, we only focus on the shape taxonomy, as it is a general tool to generate ideas for shape-changing interfaces regardless of implementation methods[130]. For simplicity, we use R for Rasmussen's taxonomy in this chapter.

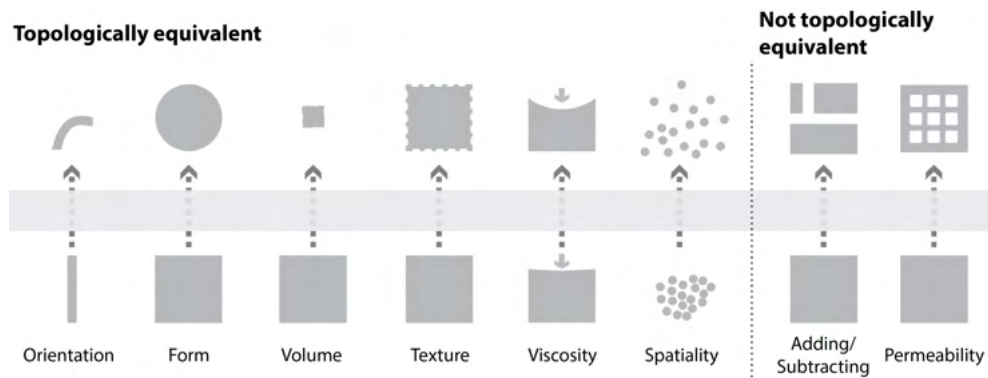


Figure 4.2: Rasmussen's taxonomy on types of change in shape.

- *Orientation* (R.Orientation): distorts the shape through rotational or directional changes.
- *Form* (R.Form): changes the overall form of the shape while preserving the approximate volume.
- *Volume* (R.Volume): changes the overall volume of the shape while maintaining the approximate form.
- *Texture* (R.Texture): adds visual and tactile properties on the surface without affecting the overall form.
- *Viscosity* (R.Viscosity): makes the user perceive the surface as shifting between hard, soft, and vibrating.
- *Spatiality* (R.Spatiality): makes the illusion of shape change through a repositioning of element(s).
- *Adding/Subtracting* (R.Adding/Subtracting): unites or divides elements, while being able to return to the initial shape(s).
- *Permeability* (R.Permeability): alters the shape perforation, but able to return to its initial shape.

Roudaut's Morphees taxonomy

Roudaut and her colleagues suggested "shape resolution" taxonomy to describe and quantify shape-changes [149]. The taxonomy is based on Non-Uniform Rational B-splines (NURBS) and describe shape-changes on a surface (Figure 4.3). In the paper, they used a term Morphees as self-actuated flexible mobile devices. However, it is rather used for the shape resolution features within the community. In this thesis, we keep using the term Morphees for the taxonomy features to keep the consistency in the community. For simplicity's sake, we use M (Morphees) for Roudaut's taxonomy.

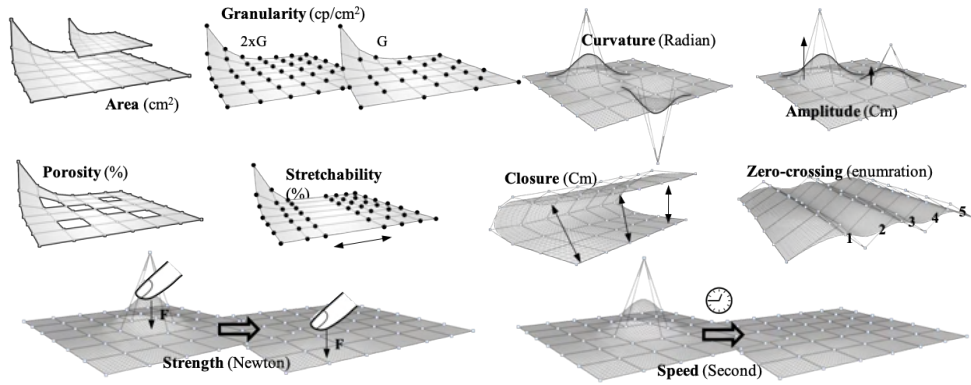


Figure 4.3: Morphees taxonomy.

4. Design Tools for Shape-Changing Interfaces

- *Area* (M.Area) is the surface area of the object computed as the area of the mesh convex hull.
- *Granularity* (M.Granularity) measures the density of physical actuation points.
- *Porosity* (M.Porosity) is the ratio of the Area of perforated parts to the total Area of the shape.
- *Curvature* (M.Curvature) describes the curviness of the surface, computed by removing π from the angle between 3 consecutive control points.
- *Amplitude* (M.Amplitude) describes the range of displacement of control points, computed as the distance between the rest position and the actuated position of a point on the surface.
- *Zero-Crossing* (M.Zero-Crossing) is the number of sign-changes between a pair of consecutive angles across the surface (capability of a shape to have wave-like forms).
- *Closure* (M.Closure) describes how "closed" a shape is, computed as $100 \times (\text{Area} - \text{boundaries Area})$ where boundaries Area is the surface area of the shape created by using the control points situated on the edges.
- *Stretchability* (M.Stretchability) describes how much the surface distorts between two control points.
- *Strength* (M.Strength) is the force needed to move a control point from the minimum Amplitude position to the maximum Amplitude position of the shape.
- *Speed* (M.Speed) is the time needed to move a control point from the rest position to the maximum Amplitude position of the shape under self-actuation.

Morphees also provide metrics to quantify shape-changes (Table 4.1). They allow designers and researchers to compute amount of shape-changes and compare them in an effective way.

Table 4.1: Metrics of the ten features of Morphees taxonomy.

Name	Type, unit	Computation
Area	$[\mathbb{R}^+]$ (cm ²)	surface area of the total convex hull
Granularity	$[\mathbb{R}^+]$ (cp/cm ²)	number of control points / <i>Area</i>
Porosity	$[0;\mathbb{R};100]$ (%)	$100 \times (\sum \text{holes } Area / Area)$
Curvature	$[-\pi;\mathbb{R};\pi]$ (rad)	angle between 3 consecutive control points - π
Amplitude	$[\mathbb{R}^+]$ (cm)	distance between rest and actuated position of a point on the surface
Zero-crossing	$[\mathbb{N}^+]$ (Enum)	\sum sign changes between each consecutive angles
Closure	$[0;\mathbb{R}^+;100]$ (%)	$100 \times (Area\text{-boundaries } Area) / Area$
Stretchability	$[-100;\mathbb{R};\infty]$ (%)	$100 \times (\text{final-initial}) / \text{initial distance between 2 control points}$
Strength	$[\mathbb{R}^+]$ (Newton)	force to move a control point from 0 to max <i>Amplitude</i>
Speed	$[\mathbb{R}^+]$ (Second)	time to automatically move a control point from 0 to max

4.4 Method

We conducted a focus group to (1) collect everyday reconfigurable objects, and (2) find design ideas for future shape-changing interfaces. We then analyzed the collected objects and ideas based on Rasmussen's and Morphees taxonomies [97]. For this thesis, we only use the collected objects and kept the future design interface ideas for future research.

4.4.1 Collecting Reconfigurable Objects

Nine participants (2 female; average age 22) were recruited on a university campus for the focus group. Participants had six different nationalities, with various cultures and customs in relation to different reconfigurable objects (which indeed resulted in custom-related objects). They were also not experts in HCI, in order to avoid any researcher bias.



Figure 4.4: The workshop to add missing reconfigurable objects and find future design ideas.

The focus group had two sessions, having a week interval. In the first session, a moderator explained types of everyday objects that the participants needed to collect. She asked to consider objects that are not only automatically and/or manually reconfigurable; but also objects that are not yet reconfigurable, but the participants wish them to be in the future. We deliberately kept the scope of objects wide to collect a variety of objects. She showed a few examples, e.g., a foldable ruler, sofa bed, etc., to help the participants understand reconfigurable objects. In addition, the moderator answered questions to ensure the instructions were clear.

During the week (7 days) between the two sessions, participants were asked to collect at least 15 pictures of reconfigurable objects from their everyday life. The participants could take pictures with their camera or get pictures from the Web. Some of them overlapped (e.g., Swiss army knife). They collected a total 96 pictures (examples in Figure 4.5). Note that some later examples are only referred to and not shown in pictures due to copyright.



Openable lamps (#18)
change lamp shadows to
change light quality



Telescopic antennas (#23)
are extended to
better capture signals.



Blender (#36) can change
the blades and containers
according to the purpose.



Tea pots and cups (#48)
are combined to store, and
detached to drink tea.



Sword-canes (#52) are
combined to conceal and
walk, and detached to fight.



Sand, Play-doh or Clay (#149)
is molded to make
3D shapes.

Figure 4.5: Examples of collected everyday reconfigurable objects. The full collection of 82 objects with pictures is available at [98]. Photo credits (from left top to right bottom): Hyunyoung Kim, SparkFun Electronics, Paul Goyette, Minnesota Historical Society, Counselling, Unsplash.

4. *Design Tools for Shape-Changing Interfaces*

In the second session, we aimed to gather further existing/future objects. The session lasted around 100 minutes and was divided into three activities.

1. Welcome (20min): At the beginning of the session, two moderators provided hard copies of the pictures collected. A moderator explained the purpose of the focus group and facilitated their idea generation by introducing brainstorming rules and having a brief brainstorming game.
2. First round (40min): participants were divided into two groups. Each participant chose one favorite picture among the pictures collected by the group. All participants were then asked to fill a sheet with (1) the picture; (2) deformation mechanisms in the picture; (3) purpose of the deformation; and (4) a title that shortly describes the object. Then, they explained the sheet to the group members. They were then asked to add further: (1) other objects with similar deformation; (2) other deformation mechanisms for the same object; and (3) other purposes for the same object. When they finished, they passed the sheet to the next participant and continued adding ideas to the initially collected objects. They repeated this procedure three times.
3. Second round (30min): participants were given figures and features of deformations from previous works [145, 149, 168] to prompt ideation. Then the two groups swapped the sheets and pictures and continued the same activity as in the first round. After the second round, we had 149 deformation ideas, including the objects that were collected but not used during the focus group. As a consequence, 90min of focus group allowed us to add 55% more ideas. The focus group enabled us to collect objects that we have not considered before (e.g., #49 detachable bra straps, #133 kayak rudder).

The researchers then named and numbered the 149 objects separating the different parts of an object. For instance, #22 bendable antenna is counted as an idea different from #23 telescopic radio antenna, even though the two can be combined in a single object. Of 149 everyday objects, 82 were currently available to end users. We reserved the other 67 objects for future research, which are natural objects (e.g., armadillo) or not existing yet (e.g., deformable fridge).

We present pictures of example objects in Figure 4.5 and full list in Figure 4.6, left column. The full collection of objects with their picture is accessible to the community [98].

4.4.2 Object Analysis Based on Topological Taxonomies

The three authors independently annotated the 82 reconfigurable objects with Rasmussen's and Roudaut's 18 taxonomy features [145, 149] on a separate spreadsheet. Note that we applied Rasmussen's taxonomy mostly on manual shape change, i.e., outside its intended area of actuated shape change. This was straightforward as its features are focusing on geometrical aspects regardless of actuation. For each object,

we gave a binary value indicating if it has each feature of the taxonomies or not. The features were not exclusive; an object could have several features. Each author added notes to help future discussions if necessary. This work resulted in an average Pearson correlation between raters [38, 50] of 0.319, indicating the annotation *subjective*. The ambiguity of the taxonomies led discussion until a *consensus* was reached (average Pearson correlation = 0.995). We discussed the disagreed features of each object. We iterated the discussion over all 82 objects around three times to keep the consistency for all objects. The discussion took more than 3 hours over two days.

4.4.3 Results

We visualized the agreed classification features of objects in Figure 4.6 and Figure 4.7. We used Google charts² and R³ to create each figure.

Figure 4.6 shows a Sankey diagram with everyday objects (left column) and the taxonomies' features (right column). When an object has a feature, a link is drawn between them. The more links an object or feature has, the thicker its corresponding rectangular node. For instance, #84 Steam/Water/Ice (bottom third) has the thickest node among the objects, because it has the most features. Each column is vertically arranged to show their level of similarity: the more objects/features two items share, the closer they are. Rasmussen's features are blue, and Roudaut's features are red. The feature nodes' color intensities are relative to the number of links that they have. The objects have averaged colors of the linked features.

Figure 4.7 shows a heat map of the everyday objects classified by the features. The diagonal of the matrix shows how many objects were classified in each feature. On the upper-right triangle (equivalent to the lower-left triangle), we see how many objects the features share. As the color key and histogram on the right-side show, red-colored cell gathers the largest number of objects, and white cells gather very few objects (0 at least). The dendrogram on the left-side shows the clusters of similar features, at different levels of the tree. The length of each branch shows how different a cluster is from its neighbors.

These two figures, together with the notes during the annotation and discussion process, reveal three key findings: (1) the two taxonomies' underlying inconsistency and incompatibility; (2) suggestion to strengthen Roudaut's taxonomy; and 3) the relation between the features and object design and material.

²<https://developers.google.com/chart/>

³<https://www.r-project.org/>

4. Design Tools for Shape-Changing Interfaces

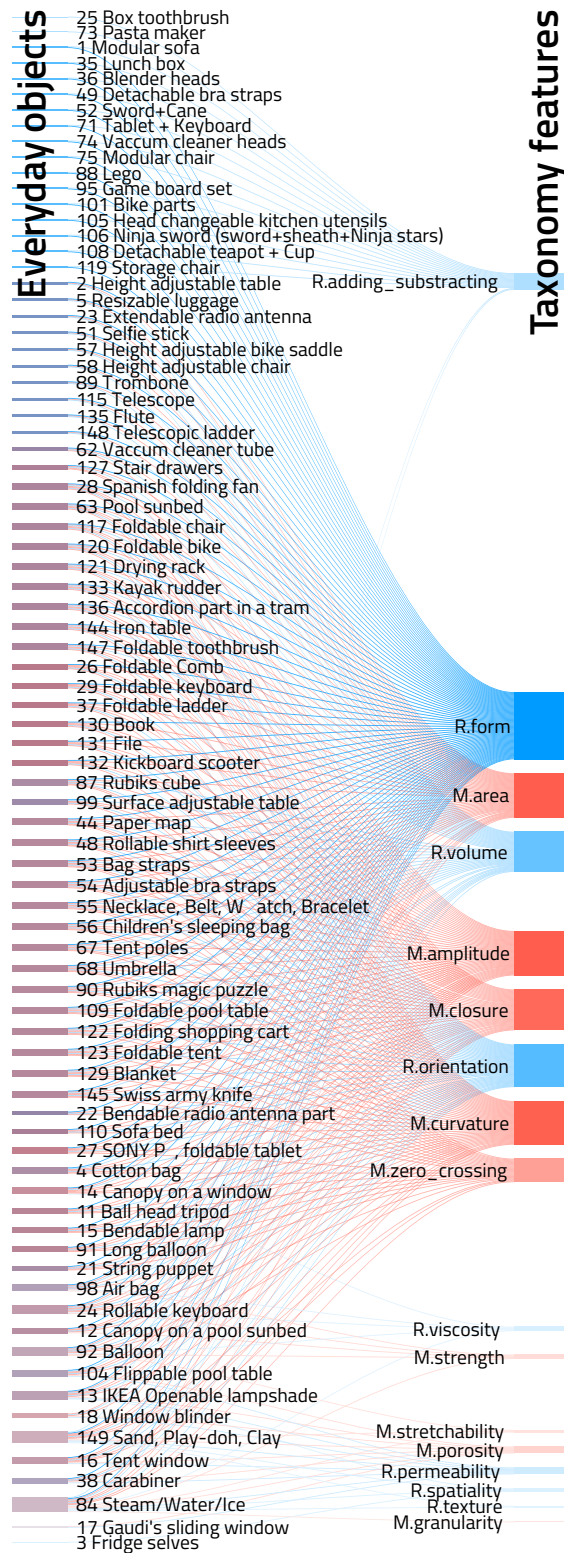


Figure 4.6: Everyday objects (left column) and the taxonomies' features (right column) they belong to. The thickness of each node shows how many connections it has. Rasmussen's features are blue, and Roudaut's features are red.

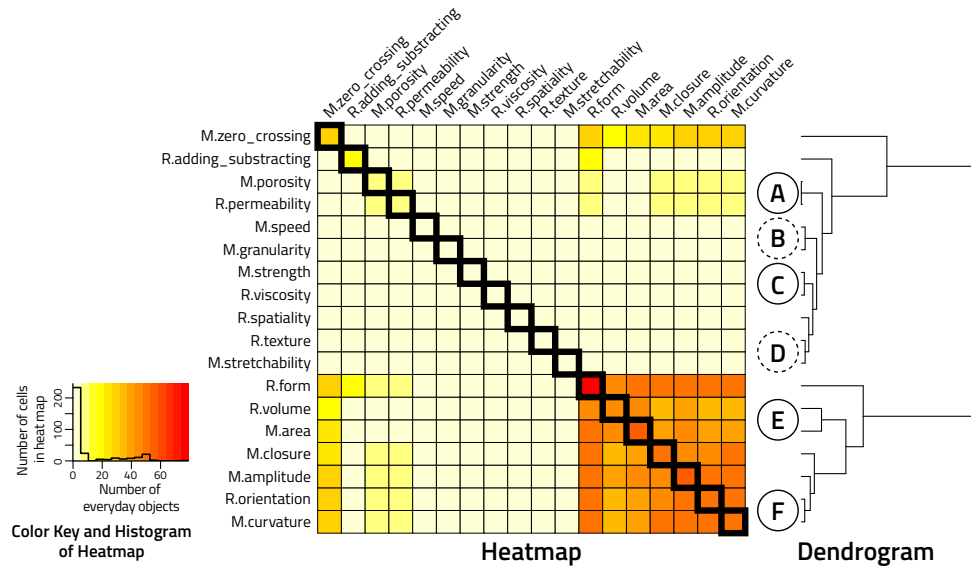


Figure 4.7: Number of objects that taxonomy features share. (Left, Heatmap) The diagonal shows how many objects are in each feature; The upper-right triangle (equivalent to the lower-left) shows how many objects the features share. (Right, Dendrogram) Clusters of similar features at different levels of the tree; The shorter length of branch (A) means the two features are more similar than the other clusters are (B-F).

4.5 Analysis of the Current Taxonomies

From the results, we gathered insights to improve the used taxonomies. We draw insights on homogenization between the taxonomies, and completeness and level of granularity of the features. We also discuss the level of precision in the definition of the features, which is the most important issue.

4.5.1 Similarity and Homogeneity of the Taxonomies

At the dendrogram in Figure 4.7 (right), some features overlap and form clusters from A to F at the leaf level. At cluster F, 49 of the 50 objects in M.Curvature also have the R.Orientation feature, and all the 49 objects that change R.Orientation also change M.Curvature. M.Porosity and R.Permeability (A) perfectly overlap with eight objects. Similarly, (C) four out of the five objects that change in M.Strength also change R.Viscosity, and vice-versa. Even though more data should confirm the overlap between the features, future homogenization of names would be beneficial for the research community.

The second interesting insight is related to the number of dimensions. Of the total 51 objects that have the 2D M.Area and of the 46 objects that have the 3D R.Volume feature, the vast majority (43) is shared between the two features. These two features also form a cluster (E) at the leaf level of the dendrogram, showing they are very similar. They tend to capture the same deformation while considering a different number of dimensions (surface vs. volume). E.g. a foldable chair (#117) increased its surface and volume when unfolded. One might ask then why the 1D extension transformation is not proposed in existing taxonomies.

The third interesting insight is the inclusion of some features in others. For instance, all 27 objects classified in M.zero-crossing also had M.Curvature. As a consequence, for all everyday reconfigurable objects that we studied, it seems that a change in the number of zero crossing points implies the ability to change the curvature too. Positioning taxonomies and their features relative to each other would help the understanding of the design space further.

The number of objects that have M.speed, M.granularity, R.texture, and M.stretchability was too small (0, 1, 2, and 3 respectively) to consider their cluster B and D reliable (in dashed circles). Hence, we did not consider their correlation.

4.5.2 Completeness of the Taxonomies

Everyday reconfigurable objects are all classified in Rasmussen's taxonomy. However, Roudaut's taxonomy, which focuses on the model of Non-Uniform Rational B-splines, does not consider attaching and detaching parts of the object. As a consequence, corresponding objects are not classified in Roudaut's taxonomy, although they are considered reconfigurable by the Rasmussen's taxonomy.

4.5.3 Granularity of the Features

Some features have many objects, while others few. Features with a large number of objects should be further detailed into sub-features in future work to precisely capture what is the deformation proposed to users. E.g. R.Form gathered almost all everyday objects, as we can see in Figure 4.7, the white cell in the heat map and Figure 4.6 is the thickest node (77/82 objects, i.e., 94% of all objects.)

4.5.4 Precision in the Definition of the Features

When classifying, we found it difficult to attribute certain features to objects. In particular:

Ambiguous definitions

R.Orientation, R.Form and R.Spatiality leave room for subjective perception. It was difficult to classify an object objectively. R.Orientation is defined as "distorting the original shape through rotations or changes in direction while preserving the recognisability of the original form." We discussed whether we should agree to classify window blinds (#18) in R.Orientation. As they cannot bend, we chose not to classify them into it, even though users change the orientation of each layer.

R.Form is also lacking precision for us to easily classify many objects (defined as "transformations that preserve the approximate volume of the shape while changing its overall form"). We found that almost all reconfigurable objects (77 of 82, corresponding to 94 %) change in form (white cell in Figure 4.7 and largest nodes in Figure 4.6).

R.Spatiality is also unclear for an object that can attach and detach, where spatial repositioning creates the illusion of shape-change if "individual elements being seen as part of a collective structure." During the discussion, it was difficult to objectively argue for detachable parts of the object being part of the whole.

It is unclear to compute R.Volume (defined as "changes in volume maintaining the approximate form"). We took the inspiration from M.Area, area of the envelope of the object, to compute R.Volume. We considered the envelope of the objects to compute both R.Volume and M.Area. For instance, a Spanish folding fan (#28) and rollable sleeves (#48) can be compacted to a smaller area and volume of their envelope, when they are folded. It thus means that we do not consider hidden surface and space, like inside of the radio antenna where concentric cylinders can be stacked. As a consequence, many objects we gathered changed M.Area (51 of 82, i.e., 62 %) and R.Volume (46 of 82, i.e., 56 %). An interesting possible future improvement would be to characterize how much change in M.Area and/or R.Volume contributes to the overall deformation, i.e., if this is a major or insignificant change.

M.Zero-Crossing is about the change in the number of zero-crossing points. So if a foldable object goes flat, then it can change from 0 zero-crossing points to N (fixed number) zero-crossing points. A future improvement can be to further define if a change in the number of zero-crossing points has to be greater than two (e.g., 0, N1, N2), to better distinguish it from M.Curvature.

Definitions that do not apply human perception

M.Amplitude is sometimes far away from the purpose of the object although they are easier to compute. For instance, a telescopic radio antenna (#23), by definition, changes its M.Area but not its M.Amplitude. However, it felt inappropriate to classify it this way as the purpose of the radio antenna is to change its height to better receive signals. After subsequent discussion, we decided that M.Amplitude was not considered when the extension of an object does not raise a single control point relatively to its neighbors on a surface. As a consequence, all telescopic objects (e.g., selfie stick #51 or extensible bike saddle #57) do not change in M.Amplitude.

Vagueness with modular objects

For M.Area and R.Volume, the difficulty comes from the object that is perceived as a single object and as several objects combined. For instance, the sword-cane (#52) did not have changing M.Area or R.Volume, where the Spanish folding fan (#28) had changing M.Area and R.Volume.

Similarly, M.Closure is difficult to assess with modular objects, like detachable bra straps (#49) or sword-cane (#52). We considered that they do not have M.Closure since the change does not happen on continuous surfaces. However, it needs further investigation since users may perceive the sheath is "closed" when the sword is in the cane, and "open" when the sword is out of the cane.

Shapes that have not been considered in previous literature

When objects have "openness," it is difficult to decide whether M.Porosity and R.Permeability are relevant or not. For instance, carabiner (#38) already has porosity, and we were not sure if its porosity changes. During the discussion, we concluded that its porosity changes because the central space becomes accessible from the side when it is open. We also considered they could show a change in M.Closure.

All raters agreed that objects that can flip parts (like #104 Flippable pool table) were not easy to classify because their deformation was not similar to the ones presented in previous papers. We decided to classify them in a change of M.Curvature and R.Orientation because the exterior skeleton and the central rotating part makes a curved shape when it is being flipped.

In the case of water that can change the state between gas (i.e., steam), liquid and solid (i.e., ice), it is difficult to assess the M.granularity. In other words, it was hard to define what is a control point. One could say it is a molecule but we were not convinced it really makes sense in terms of user deformation. Similarly, it was difficult to decide if a liquid is stretchable because we struggled to define what are the control points.

4.6 Morphees Taxonomy Refinement

Our analysis showed several ways to improve current taxonomies. In this section, we propose refinement on Roudaut’s Morphees taxonomy. We choose to start from Roudaut’s one because the features, being mathematically defined, are more straightforward to apply compared to Rasmussen’s one. Although one critique of Roudaut’s one is that the features are sometimes far away from the purpose of the object, Roudaut’s taxonomy offers a mathematical framework with rigorous metric. We think that the reliable classification through its precision is a good approach, and prefer to build on top of it. We also believe that the taxonomy would enable future studies to computationally generate novel designs.

In the light of the issues revealed in our analysis, we propose to refine Roudaut’s taxonomy by adding two new features (Size and Modularity, Figure 4.8) and refining one (Granularity), and call it Morphees+. We also refine some of the metric definitions to accommodate the changes (Table 4.2).

4.6.1 Adding a Feature: *Size* (1D, 2D and 3D)

Size measures changes in the size of objects and can be split into 3 sub-categories that refine further the original definition of M.Area. We keep using imaginary envelopes

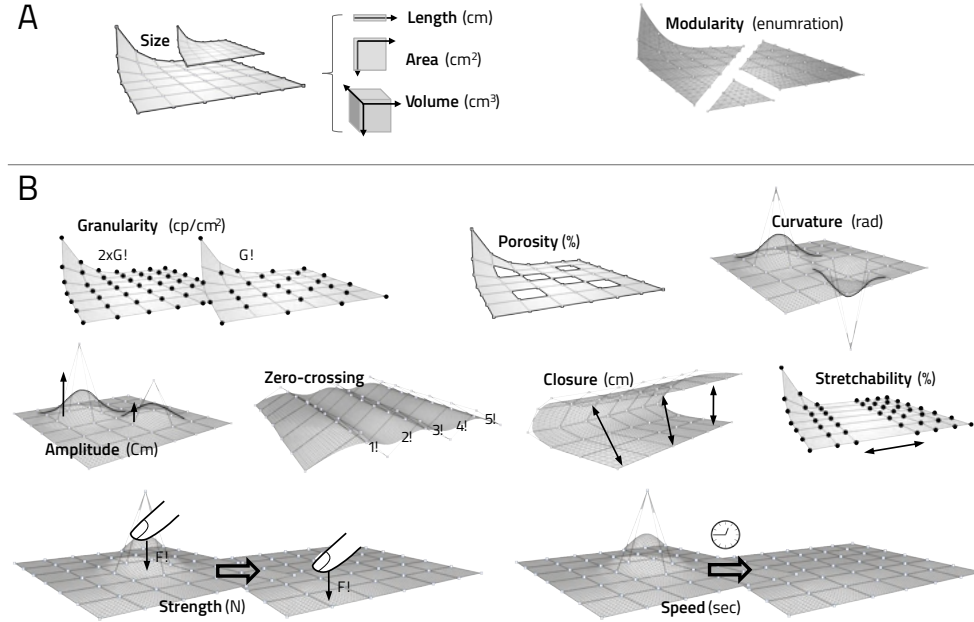


Figure 4.8: Refinement of the Shape Resolution features after analyzing everyday reconfigurable objects. We add (A) Size and Modularity to complete the (B) previous features. Size is an extended feature from the original definition of Area. Modularity is a new feature measuring the ability to be split into several parts that can be recombined.

Table 4.2: Metrics of the eleven features of Morphees+ taxonomy.

Name	Type, unit	Computation
Size	$[\mathbb{R}^+]$ (cm, cm ² , cm ³)	length, surface area, or volume of the total convex hull
Modularity	$[\mathbb{N}^+]$ (Enum)	number of functionally possible combinations
Granularity	$[\mathbb{R}^+]$ (cp/cm ²)	number of control points / <i>Area</i>
Porosity	$[0;\mathbb{R};100]$ (%)	$100 \times (\sum \text{holes } Area / Area)$
Curvature	$[-\pi;\mathbb{R};\pi]$ (rad)	angle between 3 consecutive control points - π
Amplitude	$[\mathbb{R}^+]$ (cm)	distance between rest and actuated position of a point on the surface
Zero-crossing	$[\mathbb{N}^+]$ (Enum)	\sum sign changes between each consecutive angles
Closure	$[0;\mathbb{R}^+;100]$ (%)	$100 \times (Area\text{-boundaries } Area) / Area$
Stretchability	$[-100;\mathbb{R};\infty]$ (%)	$100 \times (\text{final-initial}) / \text{initial distance between 2 control points}$
Strength	$[\mathbb{R}^+]$ (Newton)	force to move a control point from 0 to max <i>Amplitude</i>
Speed	$[\mathbb{R}^+]$ (Second)	time to automatically move a control point from 0 to max

of the objects (convex hull).

- Length (1D) is the length of the object computed as the length of the mesh in one dimension (cm).
- Area (2D) is the surface area of the object computed as the area of the mesh convex hull (cm²).
- Volume (3D) is the volume of the object computed as the volume of the mesh convex hull (cm³).

The sub-categories help the explanation of deformations and give more descriptive power to the taxonomy. Changes in each category would probably affect the other categories.

For instance, Length is good to describe actuated pin displays [51, 71, 115, 114, 125, 172]. In inFORM [51], each pin can extend 100 mm. When all pins are fully extended, the interface volume increases approximately 14,516 cm³. Examples for Area are foldable and rollable displays such as FoldMe [94] and Xpaaand [95]. Xpaaand reduces its Volume when reducing its Area, as the display is hidden in the boxes. When FoldMe has a folded shape, the Volume changes depending on the angles, but the summation of exposed surface area does not.

Some interfaces are better described in Volume, like pneumatic interfaces. For instance, the transformable tablet case [204], Inflatable Mouse [103] and Morphing cube [80] change their volume to notify the user of the device status. Choosing a right sub-category would help designers precisely describe their complex shape-changing devices.

4.6.2 Adding a Feature: *Modularity*

Modularity is the ability of an object to be split into several parts (n) that can be combined while maintaining its original functionality. This feature essentially derives from the adding/subtracting feature of Rasmussen's taxonomy, which did not exist in Roudaut's original taxonomy. It is computed as the number of functionally possible combinations ($C_{possible}$) of k parts among n available parts in total (see formula below). Modularity is defined for objects that can be split into at least two parts ($n > 1$).

$$\sum_{k=1}^{k=n} C_{possible}(n, k), \text{ for } n \in \mathbb{N} \text{ and } n > 1$$

For instance, the Modularity of the vacuum cleaner (#74) that can change between 3 suction heads H_1 , H_2 and H_3 is 4, as it can combine its body B with all three heads (B , BH_1 , BH_2 , BH_3 are possible) where as H_1H_2 , H_2H_3 , H_1H_3 , BH_1H_2 , BH_2H_3 , BH_1H_3 , $H_1H_2H_3$ and $BH_1H_2H_3$ are not possible. Note that we also count B itself as it can serve the cleaning function. Another example is a set of cubelets⁴. Each cubelet has 5 faces that can be connected, 2 cubelets has 100 Modularity ($= 5 \times 5 \times 4 =$ number of connecting faces of the first cubelet \times number of connecting faces of second cubelet \times number of possible connecting directions). An example from research is Topobo [141]. When there are two passive "straights," they have Modularity of 6. Objects that do not have pre-defined modules (#84 steam/water/ice and #149 Sand, Play-doh, Clay) have infinite modularity ∞ .

As with Rasmussen's taxonomy of shape-changing devices, considering this type of reconfiguration of devices is inclusive and does not exclude many types of devices. We think this approach is appropriate given the high number of citations of Rasmussen's taxonomy¹.

4.6.3 Refining Metrics (for Modular Objects)

With the addition of modular objects, we have to refine some mathematical definition of features. For the majority of features, it does not change their computation and can be considered as the sum of the feature values of each part. For instance, the Curvature of an object that can be split in two is the sum of the Curvature of each part. It works similarly for Size, Amplitude and Stretching. However, there are

⁴<http://www.modrobotics.com/cubelets/>

some changes to be applied in the features Closure, Zero-Crossing and Porosity of a modular object; one must first merge mesh of the possible combination of modules before computing these features. As a result, the space between modules becomes holes when modules are combined, thus increasing the value of Porosity. In a similar way, the value of Closure can now change even if the individual value of Closure for each module does not.

4.6.4 Refining Control Points

We ease the classification of features like Granularity, as it was hard to determine the number of control points of a reconfigurable object. Granularity is defined as the ratio between the number of control points and the Area of the object. We now define as control points the joints or points that can control the change of shape of an object. In the case of the foldable toothbrush (#147), we consider only a single control point. Now a change in Granularity means that parts of the object can be grouped (removing a control point) and ungrouped (adding one). Liquid and fabric have an infinite number of control points. When a liquid is frozen, then it is grouped and its granularity lowers.

4.7 Discussions on Implementing the Features

In addition to refining the taxonomy, we use the everyday objects to analyze the different materials and physical links that allows implementing the reconfiguration features, in order to inspire future designs.

Based on Young’s modulus [205], we first identified largely 3 types of materials: elastic (< 4 GPa), stiff (> 11 GPa), and hybrid (consisting of both elastic and stiff materials). We classify the 82 objects according to the material types. There were 13 elastic, 54 stiff and 15 hybrid objects (examples in Figure 4.9).

In order to evaluate reconfiguration capability of each material type, we first count how many objects under a material type have a certain feature (A). For instance, out of 13 elastic objects, 11 objects have M.Area, and 13 objects have R.Orientation. We count the same for other material types. To eliminate the effect of the number of objects per material type, we divide this number (A) by the total number of objects in each material type (B). For instance, elastic objects that have M.Area is 0.846 ($=11/13$, Figure 4.10A), elastic objects with R.Orientation is 1 ($=13/13$, Figure 4.10B).

We then accumulate the relative numbers within materials types in Figure 4.10. We discuss the relations between material types and reconfiguration features using the number of objects per material type and relative numbers (color entities) in the figure.

4.7.1 Elastic vs. Stiff Materials

From the number of objects in material categories, we see that stiff material objects are most common (54 out of 82 objects). The more exposure to stiff objects’ deformation may cause more design ideas on mechanical deformations than organic ones as shown in an exploratory design study [146]. It is also possible that users better perceive deformations of stiff objects, but this is not explored in this study.

Even though there are more stiff objects (54/82), they offer fewer deformation capa-

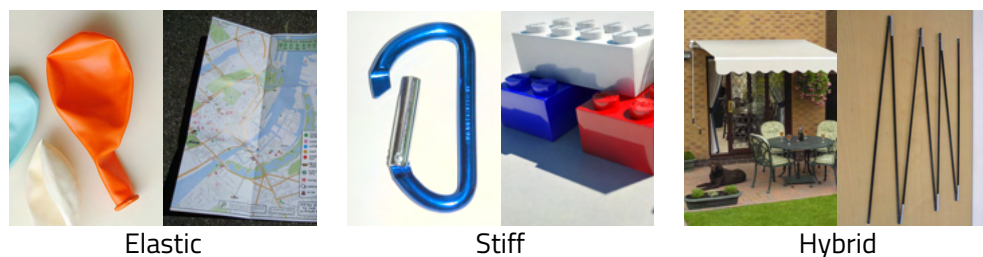


Figure 4.9: Example objects of Elastic, Stiff and Hybrid material. Elastic: #92 balloon, #44 map. Stiff: #38 carabiner, #88 Lego. Hybrid: #14 canopy on a window, #67 tent poles. Photo credits: Cookelma, Nikolaj, Polyparadigm, Max Pixel, Lilsarahp, chaoticandrandom.

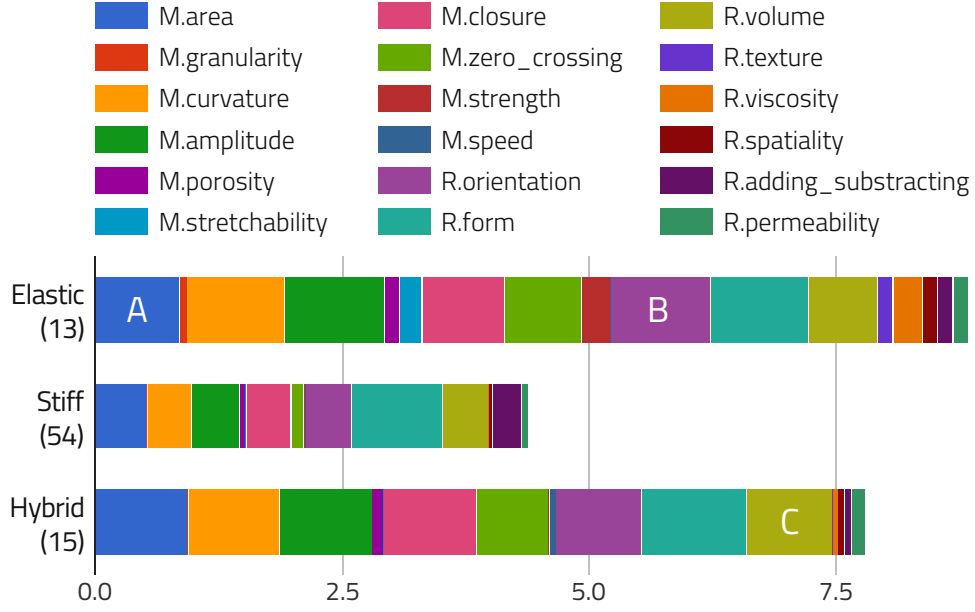


Figure 4.10: Relative numbers of objects with a certain reconfigurable feature. Counted and accumulated within each material type.

bilities than other material type objects. Figure 4.10 shows that stiff objects support fewer features, e.g., they do not have M.Granularity or M.Stretchability. Stiff objects have fewer numbers of reconfiguration features on average; all color entities except R.Adding/Subtracting (second from the last) are smaller than the ones of elastic and hybrid objects.

Contrarily, elastic objects (13/82) have the most features (17 out of 18), because of the materials' intrinsic malleability. Most of them also had the possibility to change M.Granularity, with the notable exception of the ice state of water. Designers can try elastic materials when they need more reconfiguration features on one device.

4.7.2 Hybrid, Between Elastic and Stiff Materials

Not surprisingly, hybrid objects had higher relative numbers of deformation features than stiff objects, and less than elastic objects (Figure 4.10, bottom bar). It is generally because their elastic parts offer elastic materials' features, while stiff parts hinder the deformation. For instance, foldable tent (#123) has high deformability before it is set up. The stiff tent poles define its shape and limit its deformation on purpose.

Stiff parts in hybrid objects help quickly and largely deform elastic parts, and keep the shape (e.g., #14 canopy on a window). Examples from the literature are Obake [34] and morphing cube [80]. Similarly, when hybrid objects are wearable, elastic parts are used for a large surface that touches skin, and stiff parts are used to fix the size (#54 Adjustable bra straps). It contributes to more changes in R.Volume (C in Figure 4.10)

than stiff and elastic objects (same color in middle and top bars). Elastic parts are sometimes used to control stiff parts jointly with gravity (#18 window blinds, BMW kinetic sculpture [6]).

4.7.3 Large Capability of Elastic Materials

There are several features that only elastic objects have. Inflating stretchable material or changing hardness can change M.Stretchability. For instance, balloons (#92) get less elastic after inflation, and (B) clay (#149) gets hard and not stretchable after dry.

When designers aim to change M.Strength and R.Viscosity of elastic objects, they can (1) roll them multiple times (#24 rollable keyboard), (2) inflate (#98 air bag), or (3) change state (#84 steam/water/ice). The steam/water/ice and sand, play-doh, clay are the only objects that could change R.Texture by changing their status. Interestingly, previous works used methods such as using magnetic fluid [90], air pressure [52], and shape memory alloys [126]. Our work shows new mechanisms (1 and 3) to implement M.Strength and R.Viscosity.

Elastic materials can also limit the shape of objects. For instance, when the fan (#28) is unfolded, the covering fabric sets the maximum arc length. Another example is paper: although it is elastic, it better folds along a crease (#44 map). This allows fast prototyping of guided deformation as in Foldio [132].

4.7.4 Guided Deformation with Stiff Materials

Deformation through lower pairs

Objects made of stiff materials have a fixed number of control points and deform only in pre-designed ways. It helps users learn the deformation by visual and force feedback. All stiff objects were classified in lower pair, a type of kinematic pair that constrains movement of a moving body to a matching fixed body through contact between their surfaces [147, 73]. Figure 4.11 shows examples of lower pairs: Revolute (23 out of 54 stiff objects), Prismatic (16/54), Screw (0/54), Cylindrical (12/54), Spherical (2/54) and Planar (1/54).

The revolute, prismatic and screw pairs have 1 degree of freedom (DOF). Revolute (e.g., #145 Swiss army knife) and screw pair have a rotation, and prismatic pair has a translation. The cylindrical and spherical pairs have 2 DOF; i.e. 1 rotation and 1 translation for the cylindrical pair (#23 telescopic antenna), 3 rotations for the spherical pair (#11 tripod). The planar pair has 1 rotation and 2 translations (3 DOF), like an object freely lying on a table. Two pieces of the modular sofa (#1) technically makes the planar pair, but users use only one translation in real life as they do not lift up the sofa.

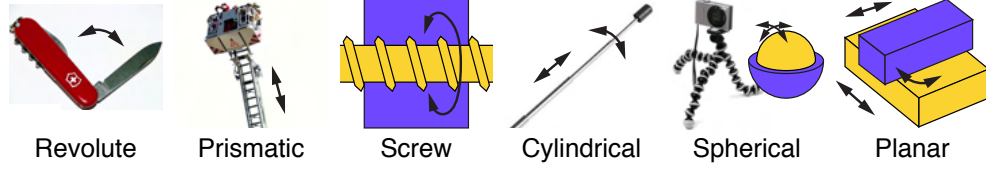


Figure 4.11: Examples of stiff objects and lower pairs [73]. From left to right: #145 Swiss army knife, #148 telescopic ladder, a screw pair, #23 telescopic radio antenna, #11 tripod, #1 modular sofa. Photo credits: Andy Rennie, markus53, SparkFun Electronics, Evan-amos.

Among the collected objects, there was no object with screw pair. We assume that screw pairs are usually used to assemble parts for semi-permanent purposes (e.g., assembling a chair), not for temporal deformation.

Implementing taxonomy features

Of nineteen objects that have the R.Adding/Subtracting, 16 are stiff objects, and they have only prismatic or cylindrical pair (e.g., #23 bike saddle). We assume that the pairs' linear freedom eases the recombination, although it often needs additional systems (e.g., bike saddle clamp) to retain the combination.

The limited deformations of stiff materials can be overcome through careful mechanical designs. For instance, an openable lamp (#13, Figure 4.5 left) uses the same revolute pair as pool sun bed (#63), but it has 3 more features (R.Permeability, R.Spatiality, M.Porosity). On the contrary, a design can reduce a pair's degree of freedom. For instance, a Lego block's (#88) stud has a cylindrical pair, but the multiple studs on a block allow only a vertical translation.

Additionally, we found an additional method to implement M.Porosity and R.Permeability other than the revolute pair that was used in Shutters [30]; a ventilation window (#17) can open holes through a prismatic pair (sliding).

4.8 Conclusion

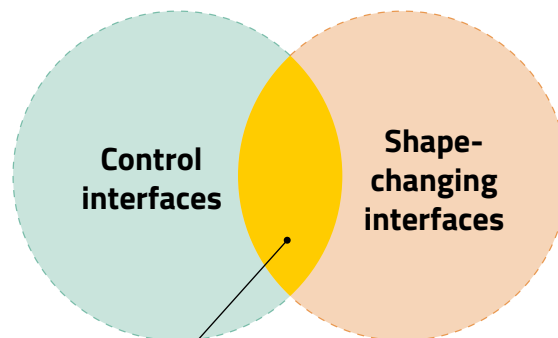
This chapter presented two design tools: the collection of everyday reconfigurable objects and Morphees+. We first presented a collection and analysis of 82 reconfigurable everyday objects to inform the design of shape-changing interfaces. The analysis revealed the similarity between two representative shape-changing interface taxonomies and areas for improvements, such as their subjective comprehension. We then suggested Morphees+, the refined taxonomy based on Morphees taxonomy, by adding the Modularity and Size, and adjusting the other features. By looking at the materials of the objects, we also provided a better understanding of how to implement the reconfiguration features.

Researchers can use the refined taxonomy to systematically get inspired for new shape-changing interfaces. They can also refer the collection of everyday reconfigurable objects and the material analysis when they need to figure out how to implement certain shape-change features. Future studies should further strengthen Morphees+ taxonomy by adding exhaustive set of reconfigurable objects and having other researchers and end users in the analysis process. To extend the design space of shape-changing interfaces, future studies can broaden the collection of reconfigurable objects by adding non-everyday and non-ordinary objects, such as a plasma globe⁵.

In the next chapter, we go back to the problem of flexibility and physicality of control interfaces and explore design solutions. We use the collection of everyday reconfigurable objects and Morphees+ to extensively explore the design space of shape-changing interfaces that can provide flexibility between two different physical controls.

⁵https://en.wikipedia.org/wiki/Plasma_globe

4.8. *Conclusion*



**Chapter 5. KnobSlider: Implementation of Shape-Change
for Heterogeneous Controls**

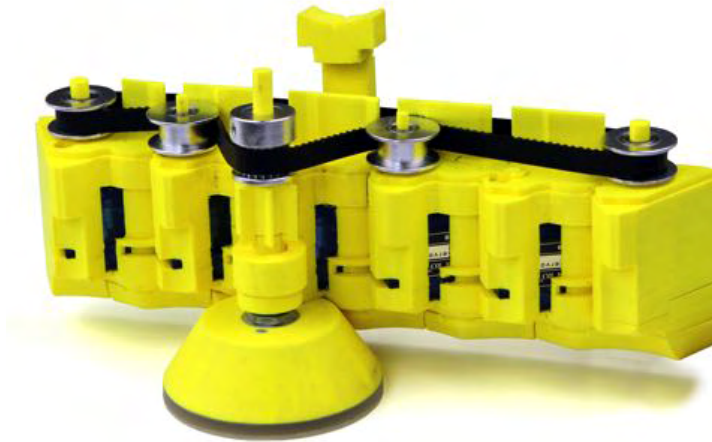
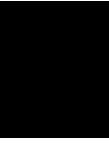


Figure 5.1: Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by designing, implementing, and evaluating a shape-changing control interface.



KnobSlider: Design of Shape-Change for Heterogeneous Controls

5.1 Introduction

In the two previous chapters, we proposed (1) the design requirements for control interfaces and (2) design tools for shape-changing interfaces. In this chapter, we focus on the intersection of the control interfaces and shape-changing interfaces (Figure 5.1 on page 96). In the intersection, we conduct a case study to evaluate the strength of the design requirements and the design tools. We are particularly interested in using them for shape-changing controls that have heterogeneous control types, e.g., having both a dial (rotational control) and a slider (linear control) in one device. There have been research papers combining heterogeneous controls through shape-changes. They embedded both rotational and linear controls through different pin-based interfaces [51, 148], Rubik’s Magic [142], and electromagnet-actuated deformable surface [188].

However, but they rarely fulfill all the design requirements for control interfaces, especially retro-compatibility. E.g., for rotational interactions, users have to make a ring shape and roll the shape with their two hands [142] or use a ball on the surface[51]. For linear interactions, users have to slide their fingers on the interfaces [142, 51, 148]. We see a design challenge here: designing shape-changing controls that combine heterogeneous controls and fulfill all the design requirements is difficult. We are thus motivated to investigate this area.

It might be because the previous work on shape-changing controls do not take exploratory design process: their interactions are often based on the form factors of the interfaces. We wonder if we can take the other approach: suggesting form factors based on the interactions. Rasmussen et al. [146] have shown that a shape-changing interface taxonomy can generate various form factors of shape-changing radios and phones, for interactions such changing the radio volume. We are therefore motivated to apply Morphees+ to suggest designs of shape-changing controls for combining rotational and linear control interactions. It would also allow us to evaluate the taxonomy's design idea generation power. Additionally, we use the collection of everyday reconfigurable objects gathered in Chapter 4.

There have been design exercises for shape-changing interfaces by using SCI taxonomies. The examples generated in the exercises contributed to design interactions [146, 168, 46] and applications [168] of shape-changing interfaces. However, the ideas are hardly evaluated by users' perspectives: we do not know if the interactions and applications are useful for users. This motivates us to evaluate the generated shape-changing control ideas in three steps: (1) evaluating low-fidelity prototypes by using the design requirements from Chapter 3, (2) evaluating a working prototype with professional users, (3) evaluating the prototype's shape-change speed properties in a controlled study.

In this chapter, we explore design ideas of shape-changing interfaces that can provide flexibility between a dial and slider. We report the best design and use it in a qualitative and controlled study. Our approach consists of the following five steps:

1. We generate ten design ideas for having shape-change between a dial and a slider. We use Morphees+ and the collection of everyday reconfigurable objects as idea generation tools.
2. We evaluate the design ideas based on the design requirements for control interfaces, derived in Chapter 3. This allows us to evaluate the ideas from users perspectives and choose the best design.
3. Based on the best design, we implement KnobSlider, a shape-changing control that shift between a dial and a slider.
4. We conduct a qualitative study with professional users by using KnobSlider as a probe. The results reveal that they appreciate the flexibility in the interface, and suggest applications for shape changing control interfaces.

5. Lastly, we conduct a controlled study on the perceptual feelings on Knob-Slider's shape-change speed. The analysis shows that users prefer a moderate speed for the shape-change rather than the fastest or slowest. Also, users prefer slightly faster shape-changes when they see the device on a screen than when they see the device for real.

5.2 KnobSlider Design

Our formative study in Chapter 3 shows that the users’ needs for physicality and flexibility are hardly addressed in current systems. To address this problem, we propose to design a device that is a self-transformable input device that can be changed to provide an interface on-demand from a knob to a slider and vice versa. This section presents our initial exploration for the design of such shape-changing device. In particular, our approach to find the best design candidate and to implement it consists in three steps described below.

1. We explore design space of existing control interfaces in terms of space- and time-multiplexing. We then specify where we target in the design space.
2. We create low-fidelity prototypes by using ideas inspired from Morphees+ taxonomy and the collection of everyday reconfigurable objects. We then analyze them using the design requirements from the formative study.
3. We implement a working prototype KnobSlider, based on the analysis of the low-fidelity prototypes.

5.2.1 Target Design Space

In Chapter 2, we presented the design space of current control interfaces regarding their flexibility, particularity time-multiplexing and space-multiplexing. Table 5.1 summarizes the design space, focusing on physical dials and sliders (rotational/linear interaction), which have some *R6. retro-compatibility*.

Here we discuss how the current work in the design space would or would not fulfill the design requirements¹. It turns out that the current solutions largely cover the design space but lack some of the requirements:

The current solutions largely cover the design space but lack some of the requirements:

- (A) A single dial [119, 170, 193] would hinder the fast and eyes-free operation of a parameter (R2, R4). A small single slider would either hinder precision (R3) and a large single slider would take too much space (R5) on a surface [32, 193].
- (B) A dial or slider sequentially morphing out of a surface [51, 148, 188] currently lacks continuity (R1) or physical cursors (R4). Manually placing a dial or a slider on a surface [124, 142] is time-consuming (R2).
- (C) Adjacent dial and slider [15, 25] are space-consuming (R5). A dial on top of a slider (and vice-versa) [40] would cause unwanted movement thus lack precision (R3).

¹R1. Interaction with a large number of parameters, R2. Fast interaction, R3. Precise interaction, R4. Eyes-free interaction, R5. Mobile interaction, R6. Retro-compatibility

Table 5.1: Design space of control interfaces, in the perspectives of time- and space-multiplexing.

	No time-multiplexing: Device(s) available all the time	Time-multiplexing: De- vices available in sequence
No space- multi- plexing: One de- vice available at the workspace	(A) A dial or a slider [32, 119, 170, 193]	(B) A dial and a slider in sequence [51, 124, 142, 148, 188]
Space- multiplexing: Multi-devices avail- able at the workspace	(C) Adjacent dials and slid- ers, and stacked dials and sliders [15, 25, 40] and cur- rent systems	(D) Dials and sliders any- where, anytime: [51, 88, 148, 188, 201] and current systems

(D) Physical dials and sliders anywhere, anytime are not fully supported yet. As in B, manually placing dials and sliders on a surface [124, 142, 88, 201] is time-consuming (R2) and dials and sliders morphing out [51, 148, 188] lacks continuity (R1) or physical cursors (R4). Current commercial systems partially support time-multiplexing through banks of sliders only.

We aim a novel solution improving the trade-off between users' requirements: a device that takes the shape of either a dial or a slider in sequence, improving time-multiplexed solutions (B). Several of such devices combined will improve time- and space-multiplexed solutions (D).

5.2.2 Low-Fidelity Prototype Exploration and Their Analysis

We extensively generated low-fidelity prototypes that combine a dial and a slider in one device through shape-change. To systematically generate the prototype ideas, we used Morphees+ features and the collection of everyday objects. We additionally used origami books e.g., [87] and fabrication websites² to accelerate the prototyping process. We present each prototype in the following three aspects.

1. Principle: describes the low-fidelity prototype and how it can make a linear shape to be used as a slider and make a round shape to be used as a dial. We also describe the key mechanical or materialistic features that would affect the shape-change implementation and user interaction.
2. Design: illustrates the envisioned implementations that suits the low-fidelity prototypes. To choose the implementation method, we first consider three actuation method that are widely used for shape-changing interfaces—rotational motor [123],

²e.g. <https://www.thingiverse.com>

Table 5.2: Summary of the low-fidelity prototype analysis based on the design requirements from the formative study in Chapter 3.

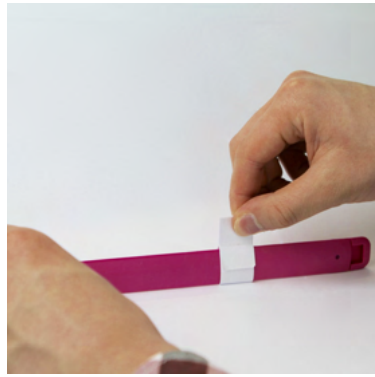
Design requirements	Low-fidelity prototype ideas									
	1	2	3	4	5	6	7	8	9	10
R1. Interaction with a large number of parameters	•	•	•	•	•	•	•	•	•	•
R2. Fast interaction	•	•	•	•	•		•	•		•
R3. Precise interaction	•			•		•	•	•	•	
R4. Eyes-free interaction	•	•	•	•		•		•	•	•
R5. Mobile interaction		•	•	•	•				•	•
R6. Retro-compatibility	•	•	•	•	•	•	•	•	•	•
Total score	5	5	5	6	4	4	4	5	5	5

pneumatic actuation [52, 204], and shape-memory alloy [149]—and then choose the best actuation method for each design.

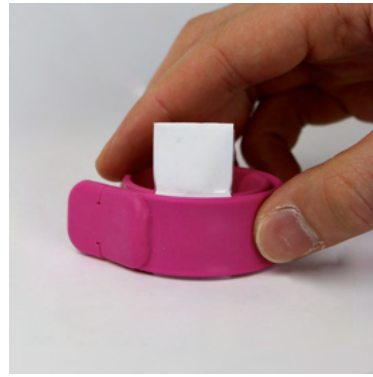
3. Analysis: reports how the low-fidelity prototypes satisfy or do not satisfy the design requirements based on their current designs and the envisioned implementations. For *R1. Interaction with a large number of parameters*, we count how many parameters the prototype can support without banks. For *R2. Fast interaction*, we consider how fast the shape-change between the dial and slider states would be. It is dependent on the actuation methods. For *R3. Precise interaction*, we consider the both dial and slider states of the device. First, it is desired to have multi-turn dial to allow low CD gain. We evaluate if the designs can allow multi-turn of the dial. Second, it is desired to have a long slider. We evaluate the ratio between the slider length and the dial circumference. We decide the minimum desired ratio as 1:1 and the bigger the ratio the better the system can support precise interaction. When evaluating if the prototype can support *R4. Eyes-free interaction*, we look at the slider cursors. By having a physical slider cursor, users can continue controlling the slider without looking at it once they grab it. *R5. Mobile interaction* refers to the fact if the device can be used in mobile context, e.g., while users are moving around a stage. Lastly for *R6. Retro-compatibility*, we see if users can interact with the prototypes in the same way they interact with currently available commercial interfaces. The summary of the analysis is provided in Table 5.2.

5.2.3 Idea 1. Slap Bracelet

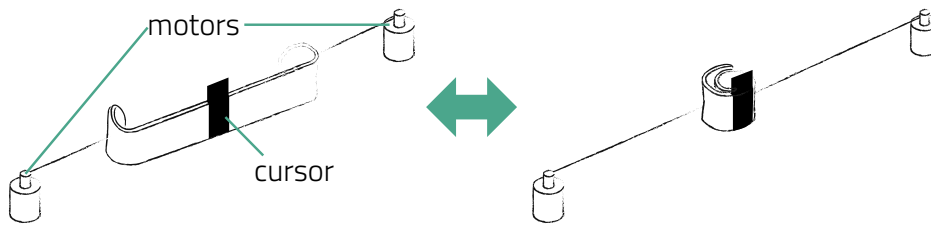
1. Principle (Figure 5.2A, 5.2B): An everyday object, slap bracelet inspired this design. The idea is to use a bi-stable strip, such as slap bracelets, bicycle ankle bands, or tape measurers. Such objects consist in a bi-stable material that can be



(A) Slider state



(B) Dial state



(C) The envisioned implementation

Figure 5.2: Idea 1. Slap Bracelet

in two stable shapes: rolled or straight. When straight, it can be used as a slider, and when rolled, it can be used as a dial.

2. Design (Figure 5.2C): The prototype could be actuated using two rotational motors. The motors are fixed on a surface and connected to each extremity of the strip via strings. When the motors rotate outward, they pull the strings and turn the strip into a slider, except at its extremities. The slightly rolled extremities stabilize the slider on the surface. We can place a slider cursor around the bracelet.

When the motors rotate inward, the strip rolls back to the dial state by its bi-stable property [140]. By letting the strings loose enough, it would be possible for users to perform rotational movements with the dial. In a dial state, the slider cursor would not be moved anymore.

3. Analysis: (R1) The design supports users to control two parameters with the dial and slider states. (R2) When the device changes its shape from slider to dial, the shape-change would be fast as the slap bracelet has the property of rolling fairly fast when it is bent a bit. The change from the slider to the dial would be fast as well, as the motors can actuate it fast. (R3) The slap bracelet can have the slider with variable length, including the length longer than the dial circumference. (R4) The device has the cursor and hence allow eyes-free interaction during the slider status. (R5) The actuation motors are fixed on a surface, and it would be hard to make the interface mobile. (R6) The design allows the same interaction of rotating the dial and sliding the slider cursor from current practice.

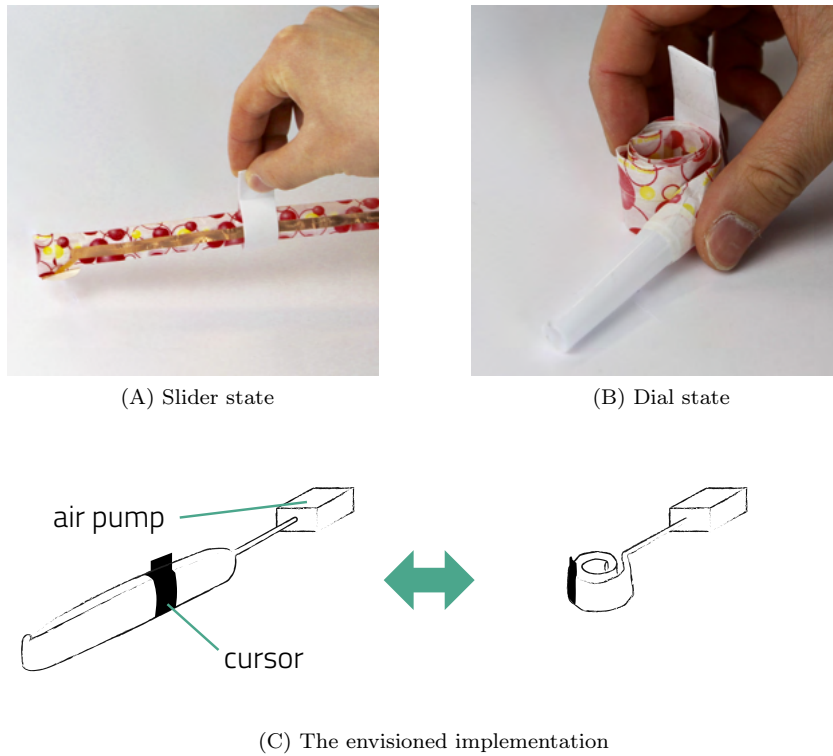


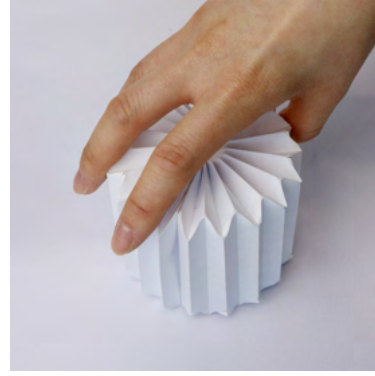
Figure 5.3: Idea 2. Party Whistle

5.2.4 Idea 2. Party Whistle

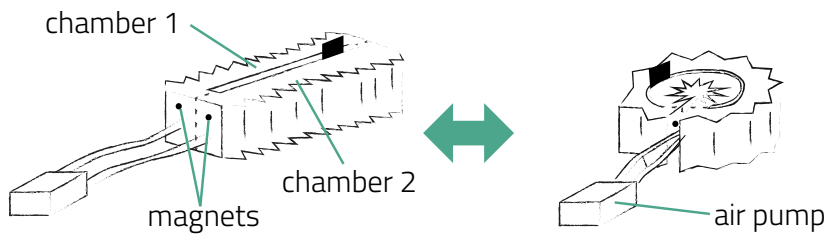
1. Principle (Figure 5.3A, 5.3B): The design is inspired by a party whistle, an everyday reconfigurable object. The prototype is initially rolled (dial state), and becomes linear when inflated (slider state).
2. Design (Figure 5.3C): The prototype could be actuated using pneumatic, i.e., using an air pump connected to the whistle in order to switch it between the slider state (inflated) to dial state (deflated). A slider cursor can be placed on a ring surrounding the prototype. The ringed part should be deformable enough in order for the cursor to fit to the changing prototype diameter.
3. Analysis: (R1) The design allows controlling two parameters through the two control widget states. (R2) The pneumatic actuation allows fast shape-changes. (R3) The input range of the rotational interaction would be limited by the air tube, as its length would be limited and the tension of the air tube would rotate the dial unintentionally. The ratio between the slider length and dial circumference can be more than 1 and allow precise control. (R4) The slider cursor would allow eyes-free control. (R5) The compact design and the pneumatic actuation would allow the device used in mobile scenarios [52], but the noise from the air pump can limit the usages (e.g., our contextual interviews showed that noise during movie shootings are not allowed). (R6) The rotational and linear interactions with the device is same to the ones with the current control interfaces.



(A) Slider state



(B) Dial state



(C) The envisioned implementation

Figure 5.4: Idea 3. Accordion

5.2.5 Idea 3. Accordion

1. Principle (Figure 5.4A, 5.4B): The design was inspired by *Closure* feature of Morphees+ and an accordion. The prototype consists of a rectangular prism whose structure use accordion origami folding. This structure allows the shape to be elongated straight to create a slider or "closed" to create a dial.
2. Design (Figure 5.4C): We can embed two inflatable chambers along the slider axis and use pneumatic actuation. By inflating both chambers, we can create a linear shape for the slider state, and the amount of air can possibly change the length of the slider. The groove along the slider axis can have a slider cursor inside. By inflating one chamber while deflating the other, the device can transform into a circular shape. Magnets at each end of chambers can then completely close the device and create a round shape form for the dial.
3. Analysis: (R1) The design allows controlling two parameters with the slider and dial states. (R2) The pneumatic actuation would allow fast shape-change. (R3) Similarly to the party whistle design, it would have air tubes around the dial circumference, and it would be hard to implement a multi-turn dial. However, the axis of the slider can have the same length with the dial circumference and allow relatively precise interaction at the slider status. (R4) The cursor on the slider would allow eyes-free interaction. (R5) Air pump can be small enough to support mobile interaction [52]. (R6) The interactions with the design stay linear

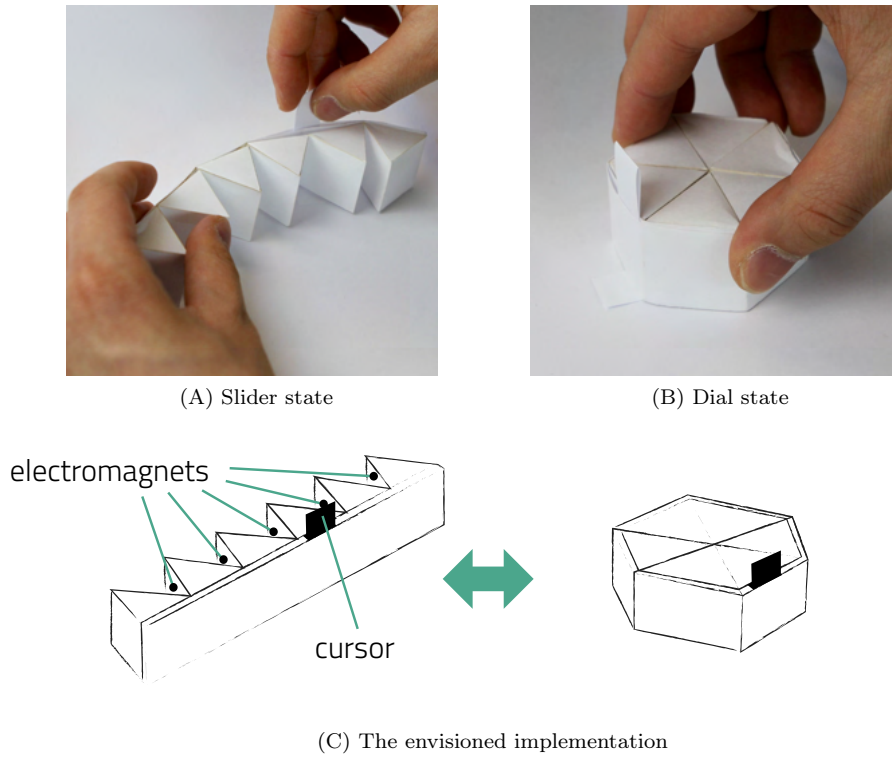


Figure 5.5: Idea 4. Roly-Poly

and rotational, which is same with the control interfaces in practice.

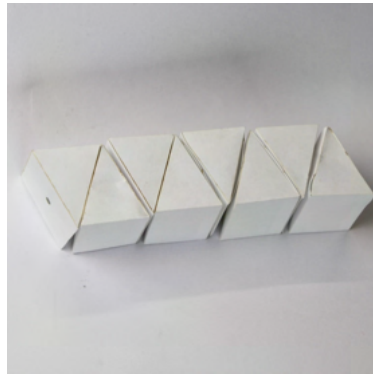
5.2.6 Idea 4. Roly-Poly

1. Principle (Figure 5.5A, 5.5B): The *Closure* feature of Morphees+ and the Sensitive Rolypoly [55] inspired the design. The idea is to use six trigonal prisms connected to each other. When unfolded, the prisms are aligned and create a surface for the slider cursor to slider. An additional wall on the surface can create a groove to hold the cursor. When folded, the prisms form a hexagonal prism (dial).

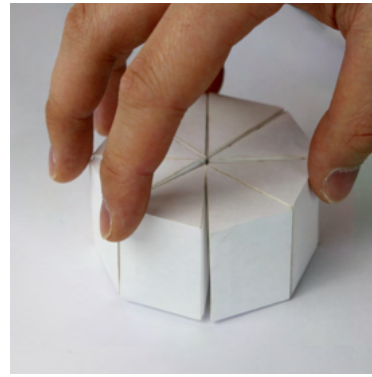
2. Design (Figure 5.5C): We see two possible ways to implement this idea. The first one is using motors, the second one is using electromagnets. In the motor implementation, a motor could be placed inside each prism (except one) to control the folding and unfolding of the hinge between two prisms.

In the electromagnet implementation, electromagnets could be placed on the two faces of each prism, where the faces touch other prisms when folded. By changing the polar direction of the electromagnets, the device can change its shape between the slider and dial states. The external wall should have a certain amount of tension to keep the straight shape when the magnets repulse the prisms. We analyze the design based on the electromagnet implementation.

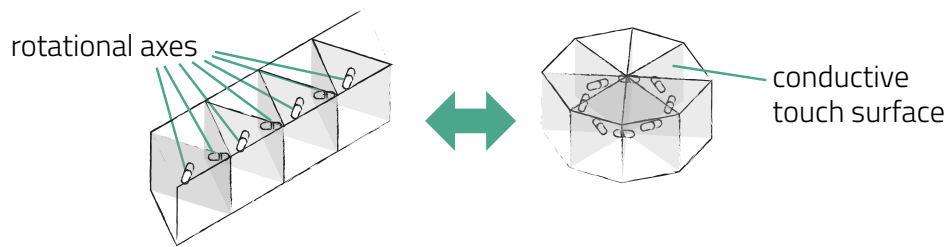
3. Analysis: (R1) Each dial and slider state can control one parameter. (R2) The



(A) Slider state



(B) Dial state



(C) The envisioned implementation

Figure 5.6: Idea 5. Twisty Toy

electromagnets in the device would allow fast shape-change between the two states. (R3) There is no air tube around the dial circumference, which allows boundless rotation. The length of the slider axis is similar to the knob circumference, which allow precise control on the slider. (R4) The design also has a physical cursor. Once they grab it, users can continuously manipulate the slider without visual attention. (R5) The electromagnets are only attached to the device and not on the surface. It would allow users to take the device on-the-go and use it on any surfaces including their palm. (R6) Similarly to other designs, it allows rotational and linear controls.

5.2.7 Idea 5. Twisty Toy

1. Principle (Figure 5.6A, 5.6B): The idea is to use a similar mechanism used in toys such as the ShengShou (or Rubik's) Magic Snake³. The device is made of eight trigonal prisms that are connected to each other through rotary joints. Unlike *Idea 4. Roly-Poly*, the prisms are connected by their faces, and there are no space between the prisms in the slider state. When the prisms are aligned in a zigzag manner, they make a linear shape (slider). When they align to place the unconnected faces on the one side, they create a hexagonal prism (dial).

³https://en.wikipedia.org/wiki/Rubik%27s_Snake

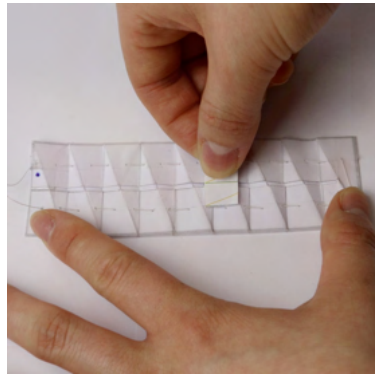
2. Design (Figure 5.6C): One motor can be placed at each rotational axis and would change how two prisms are aligned. It would be complex to add a groove to place a physical slider cursor, and capacitive sensors covering the prisms would be most feasible. Then the touch surface can be used in both slider and dial states.
3. Analysis: It has similar properties than the *Idea 4. Roly-Poly*: (R1, R2) It can support controlling two parameters; (R5) the motors in the device would enable fast shape-changes and mobile interaction; and (R6) the rotational and linear interaction would be retro-compatible. (R3) The device would not have air tubes around it, so that users can have a multi-turn dial. However, the length of the slider would be the half of the dial circumference and do not support precise control in the slider state. (R4) Also, it cannot have a physical cursor as the faces of each element will change the directions during shape-changes.

5.2.8 Idea 6. Origami

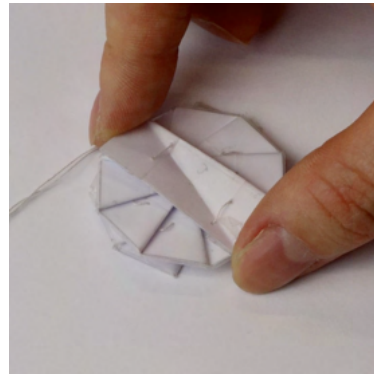
1. Principle (Figure 5.7B, 5.7A): The idea is inspired by *Amplitude* and *Zero-Crossing* features of Morphees+. In the slider state, the control points (the center points of the hinges) are on a flat surface. When device changes to the dial state, the amplitude of the control points change—while one control point stay on the surface, the rest control points move up. Also, the shape-change requires the control points to make a zero-crossing shape. The slider shape is a flat rectangle and the dial is a folded polygon. In order to approach the shape of a circle for the dial, many folds are needed. We referred an origami book [87] to create the precise folding pattern.
2. Design (Figure 5.7C): Instead of using a piece of paper it would be more robust to laser cut plastic or wood to create a series of triangle shapes. To create a groove for the slider cursor, we can then glue two pieces of the triangles and sandwich a trapezoid (the sharpest corner of the triangle is cut) between the two triangle pieces. Then the slider cursor can be fixed between the triangle pieces. The cursor should be able to be flattened before the shape-change to the dial state, in order to allow smooth folding of the triangles.

To actuate the shape-change, strings should be stitched between the sandwiched triangles and work as tendons. When the two motors attached to the strings pull the strings, the device is straightened and can be used as a slider. When only one of the motors pull the strings, the device is folded into the round shape and can be used as a dial. We did not consider SMAs as an implementation method: it is difficult to educate SMAs to fold at 180 degrees without industrial machineries. SMAs will be too weak and fragile to actuate the device.

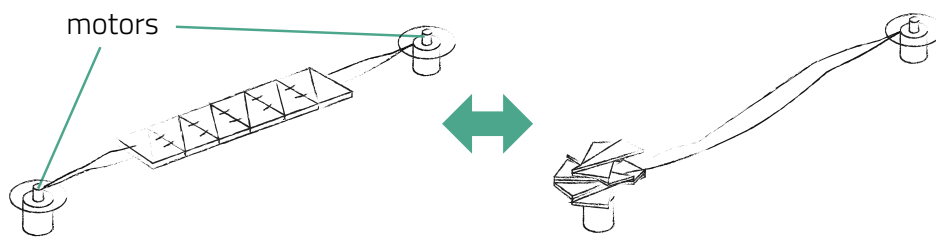
3. Analysis: (R1, R6) The linear and round shapes support controlling two parameters and retro-compatibility. (R2) The motors attached on the surface would allow fast shape-changes, but (R5) it would be hard to support mobile interaction. (R3) There would be strings around the dial, but they can be elastic. If they are long and thin enough, users can have a multi-turn dial. The minimum ratio between the slider length and the dial circumference is 0.5:1 to create the round shape, and



(A) Slider state



(B) Dial state



(C) The envisioned implementation

Figure 5.7: Idea 6. Origami

the slider length can be easily increased by adding the triangle pieces. (R4) We can embed a physical cursor on the slider, and it would allow eyes-free interaction.

5.2.9 Idea 7. Stackable Disks

1. Principle (Figure 5.8A, 5.8B): The design consists of a series of stackable disks. Morphees+'s *Amplitude* and *Area* features inspired the design. When the disks are stacked up to form a dial, the other control points move up while one control point stays on a surface, and they thus change the overall amplitude. Also, the surface area increase when the disks slide out form the slider.
2. Design (Figure 5.8C): In the slider state, all the upper disks are slided out, and the touch surfaces can be used for slider interaction. The lowest disk is fixed to a rotational axis.

Except the top most disk, each the disk has a rail for the upper disk to slide. This mechanism stabilizes the stacking/unstacking of the disks. To form the slider, the motor on the right side pulls the string connected to the top most disk. It would make all the disks slide out. To form the dial, the motor on the left side pull the disk to the other direction, and it would slide all the disks above the bottom disk. There should be some space in the rail to allow the disks tilted during the slider state.

5. KnobSlider: Design of Shape-Change for Heterogeneous Controls

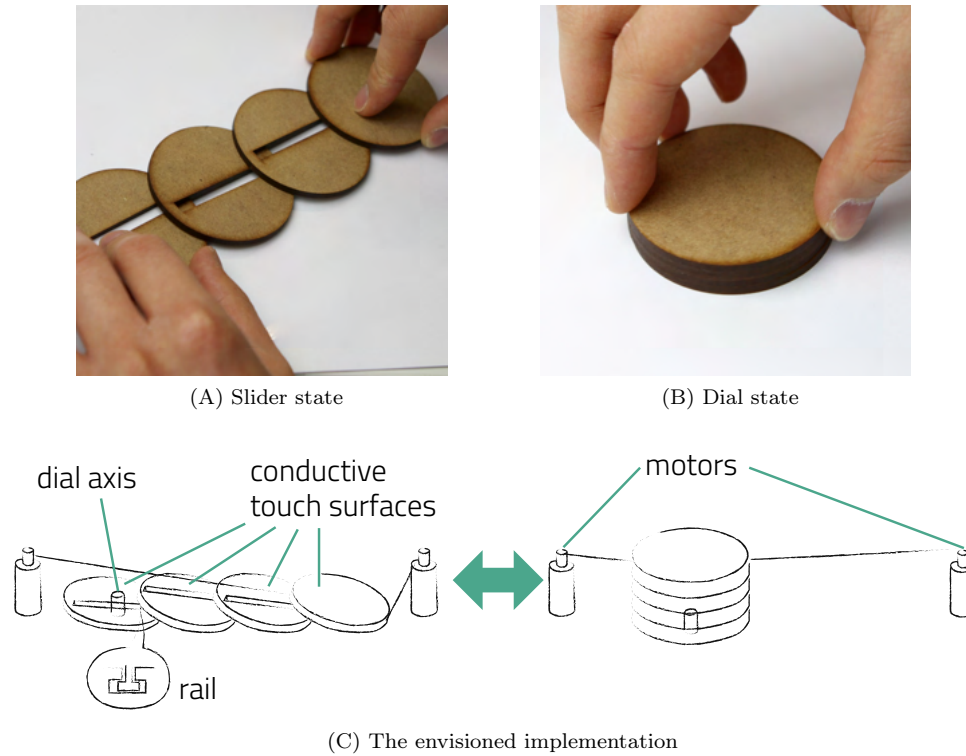


Figure 5.8: Idea 7. Stackable Disks

3. Analysis: (R1, R6) The stacked disks can support rotational control, and the unstacked disks can support linear control. Similar to *Idea 6. Origami*, (R2, R5) the motors on the surface would support fast shape-changes but not mobile interaction. (R3) It would be also possible to have a multi-turn dial thanks to the elastic strings. Also, the design can have the ratio of more than one, as it is easy to add more disks. (R4) However, it is not clear how to make the physical cursor to travel between the separate disks. Hence we envision touch sensing on the disk surfaces, although it would not allow eyes-free control.

5.2.10 Idea 8. Zip-Line

1. Principle (Figure 5.9A, 5.9B): The *Modularity* feature inspired the design. When the three pieces are separated, the middle piece can be used as a slider cursor thanks to the strings attached to the three pieces. When the pieces are combined, they create a round shape and can be used as a dial.
2. Design (Figure 5.9C): The motor on the right side can pull the right most piece and create a slider. The left most piece is anchored to a rotational axis, and the strings between the end pieces create an axis of the slider cursor (the middle piece). The motor on the left side can pull the right most piece to the left, and it would combine all the three pieces and create the round shape. The tension on the strings should be strong enough to create straight slider axis.

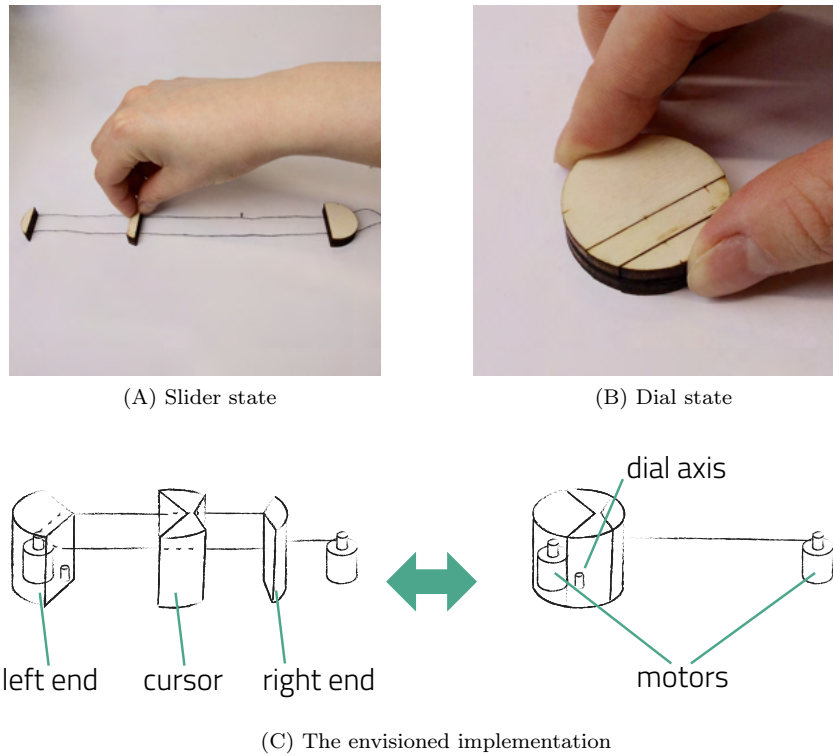


Figure 5.9: Idea 8. Zip-Line

3. Analysis: (R1, R6) The separated pieces would work as a slider, and the combined pieces would work as a dial. (R2, R5) The device has two motors on the surface and can have quick shape-changes. However, the motors fixed on the surface would not allow the device used in a mobile context, same to *Idea 7. Stackable disks*. (R3) It can have a multi-turn dial if the right motor keeps the string loose during the dial state. It can also have a long slider axis as much as the surface allows. (R4) The middle piece acts as a slider cursor and provides eyes-free interaction.

5.2.11 Idea 9. Fish Bone

1. Principle (Figure 5.10A, 5.10B): The design is inspired by the *Closure* feature. We used a fish bone model from a fabrication website⁴ to quickly produce the prototype. Each bone is connected to the next one such as in the chain of a bike. The resulting structure is highly flexible, and could be used as a physical version SketchSliders [187], which provides non-linear virtual sliders to mark values of interest. When the bones are aligned straight, they create a linear shape for slider. When they are closed and the two end bones are met, they create a round shape for dial.
2. Design (Figure 5.10C): Two SMAs could actuate the design. One on the inner circle surface can close the structure and form the dial state. Another SMA on

⁴<https://www.thingiverse.com/thing:1276095>

5. KnobSlider: Design of Shape-Change for Heterogeneous Controls

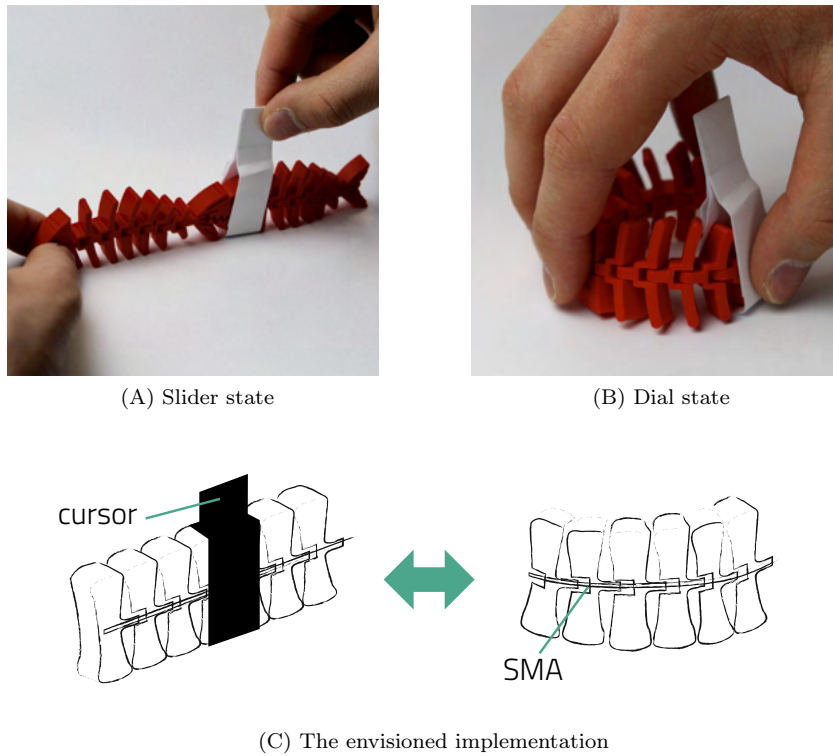


Figure 5.10: Idea 9. Fish Bone

the outer circle surface can open the structure and form the slider state. It would require educating the SMA's to bend to a certain shape. As with *Idea 2. Party Whistle*, the slider cursor can be wrapped around the structure and could move along it.

3. Analysis: (R1, R6) The straight open shape supports linear manipulations, and the closed shape supports rotational manipulations. (R2) The actuation of the SMAs would be slower than the motor or pneumatic actuations, and thus does not allow fast interactions. (R5) However, the compactness of the SMAs would allow mobile interactions. (R3) There would be no air tube around the dial shape, and users would be able to turn the dial multiple times and have precise interactions. The ratio between the slider and the dial is one, but it can be larger when the dial makes a spiral. (R4) The device can have a physical slider cursor and hence support eye-free interaction.

5.2.12 Idea 10. Dukta pattern

1. Principle (Figure 5.11A, 5.11B): We used the *Closure*, *Stretchability* and *Porosity* features of Morphees+ for the design. Dukta or kerfing cut patterns⁵ allowed us to create flexible prototype from a rigid wood material. Through the fine-tuning of the pattern parameters, we could control the bending direction and degree. When

⁵E.g., <https://dukta.com/>

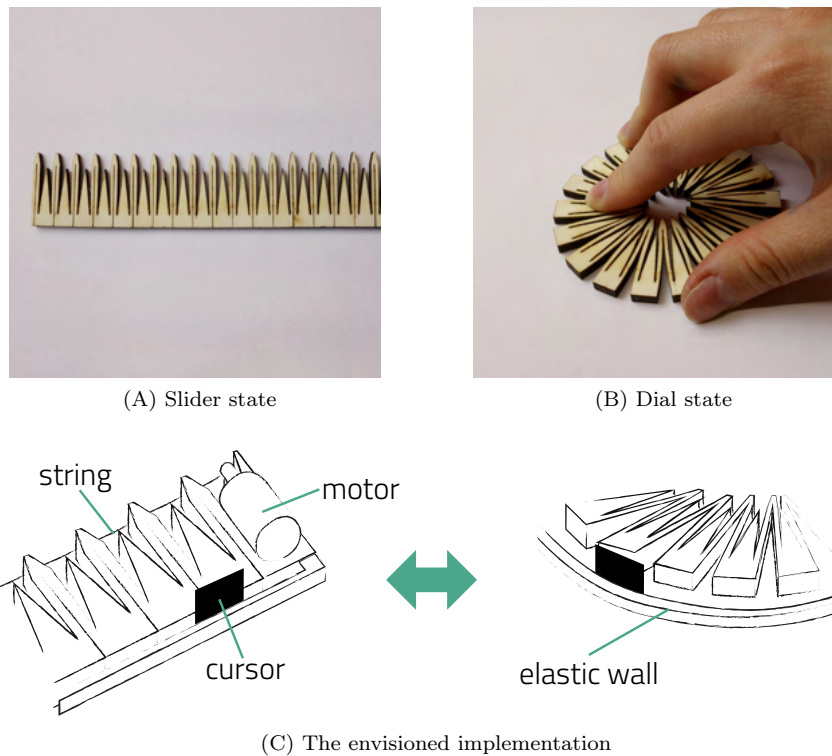


Figure 5.11: Idea 10. Dukta pattern

idle, it makes a rectangle shape (slider). It can also make a circular shape (dial) by bending and make holes within on its surface.

2. Design (Figure 5.11C): A string could be stitched along one side of the slider (at the center of the dial). One end of the string is attached a motor on an edge of the pattern, and the other end is attached to the other edge of the pattern. When the motor pulls the string, the string works as a tendon: it pulls the other edge and bend the pattern. It would change the the slider to the dial. A physical cursor and an elastic wall can be placed on one side of the slider, which becomes the circumference of the dial.
3. Analysis: (R1, R6) The device enables users to have linear and rotational interactions. (R2, R5) The motor would allow fast shape-changes and mobile interactions. (R3) Ideally, there should be nothing around the pattern when it has a battery on it. It would allow multi-turn of the dial status. However, the dial would have longer circumference than the slider axis, as the outer edge of the pattern would expand when it is bended to a dial. (R4) The device can have a physical cursor for eyes-free control.

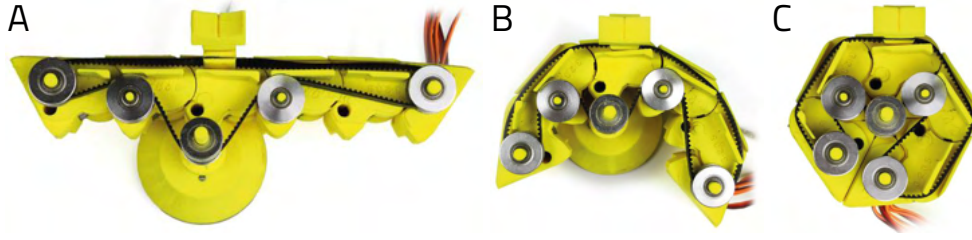


Figure 5.12: (A-C) KnobSlider working prototype without the top cover to expose the slider’s timing belt and the slider mechanism. (A) In slider shape, the movement of timing belt is conveyed through the gears, (B) during transformation, the edges of blocks start to lock the bottom central gear, (C) the edges completely lock the bottom central gear, the rotation of the knob does not affect the timing belt.

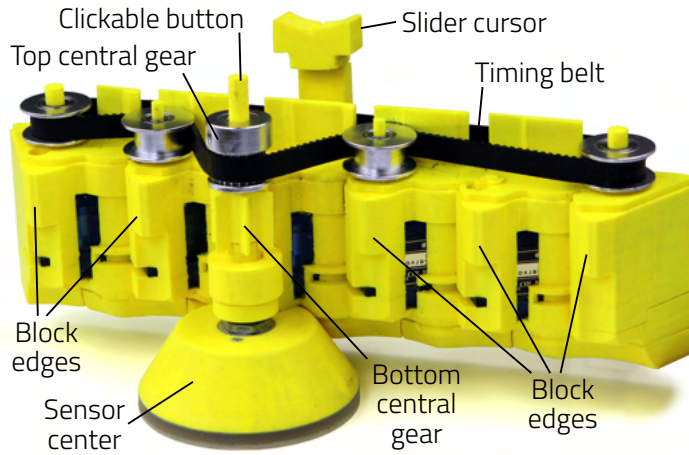


Figure 5.13: Elements of KnobSlider, here without the top cover to expose the slider’s timing belt.

5.3 Implementing the Working Prototype

Through the evaluation of the low-fidelity prototypes, we converged on a particular design that better supports the requirements. The design has six triangular prism blocks connected to each other (Figure 5.12 A-C). When folded (C), the prisms form a hexagonal prism (dial). When unfolded (A), the prisms are aligned, thus create a connected surface. A cursor can move along the surface. The final design looks similar to the InGen [7] when folded.

The shortest diameter of the knob status (hexagon) is around 71.6 mm. The longest diameter of the knob status is 78.6 mm. The length of the slider status is 181 mm. The width of the slider status is 60.5 mm including the sensor axis, and 30.2 mm excluding the axis. The height of device is 73.4 mm.

Figure 5.14 shows the elements of KnobSlider. The device consists of forty pieces of the 3D printed case (yellow), five pulleys, a timing belt, a rotational sensor, five servo motors (blue, SG90). Figure 5.15 shows how the motors and pieces are connected to create a hinge. Each motor opens and closes each hinge of the device by 60°. When

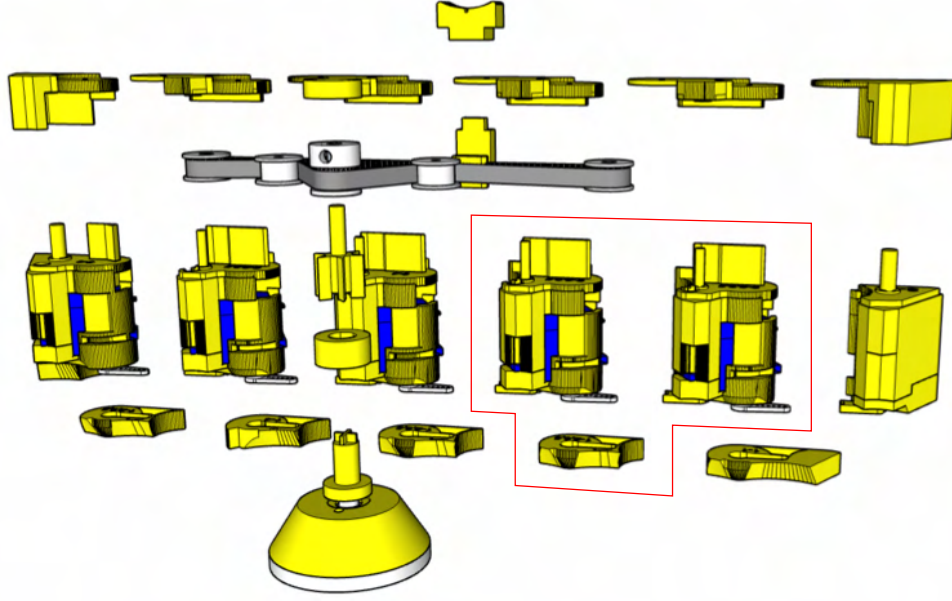


Figure 5.14: The assembly view of KnobSlider. The device consists of forty pieces of the printed case (yellow), five pulleys, a timing belt, a rotational sensor, five servo motors (blue). The method we used to connect the three pieces in the red line is illustrated in Figure 5.15.

all motors open and close, the device makes the straight shape for the slider state (Figure 5.12 A) and the round shape for the dial status (Figure 5.12 C). Each motor is individually controlled by an Arduino (Figure 5.16).

For sensing the dial or the slider value, we place a manufactured clickable dial⁶ at the base of the sensor center (Figure 5.13). The sensor is connected to the bottom and top central gear, and used for both dial and slider states of KnobSlider. When the hinges are closed, the block edges interlock with the bottom central gear making a dial state. User's rotation of the dial then translates to the sensor axis, and the device works as a dial. When the joints are open, the device makes a slider state. The central block is supported on the bottom central gear, but the rotation of the block does not affect the gear. Instead, the movement of the slider cursor is conveyed to the top central gear through the timing belt.

Table 5.3 summarizes how our prototype supports the requirements. The device can support two continuous parameters, and several can be used in parallel. The peak motor speed is 60° per 0.1s, enabling the shape-change in ~ 0.1 s. KnobSlider can reach similar precision than a dial and slider; in our prototype, dial has 100 control positions per rotation, and slider has ~ 237 control positions per 112 mm (cursor traveling length). The dial diameter is ~ 75 mm. The outer length of the slider is around 182 mm, and the cursor's traveling distance is 112 mm due to the gears at the corners of slider. When it is a slider, the footprint is about 68.2 cm^2 . When it is a dial, the footprint becomes around 43.6 cm^2 . Additionally, the silicon base ensures

⁶<http://griffintechology.com/us/powermate>

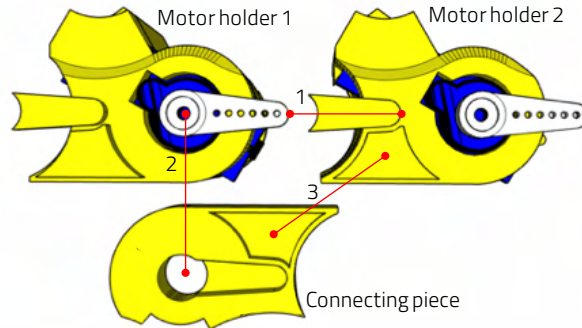


Figure 5.15: A closer look at the piece in the red box in Figure 5.14, to show how two motor holders are connected through the connecting piece. They are showing the bottoms of the motor holders and top of the connecting piece. The connecting piece is showing the top to show the grooves for connection. The dots on the red lines indicate which part should meet which part when assembled. (1) The prominent part of the motor holder 2 goes under the servo motor arm on the motor holder 1. (2) The groove on the connecting piece looking like the servo motor arm locks the prominent part and the servo motor arm. (3) The second groove on the connecting piece additionally holds the motor holder 2.

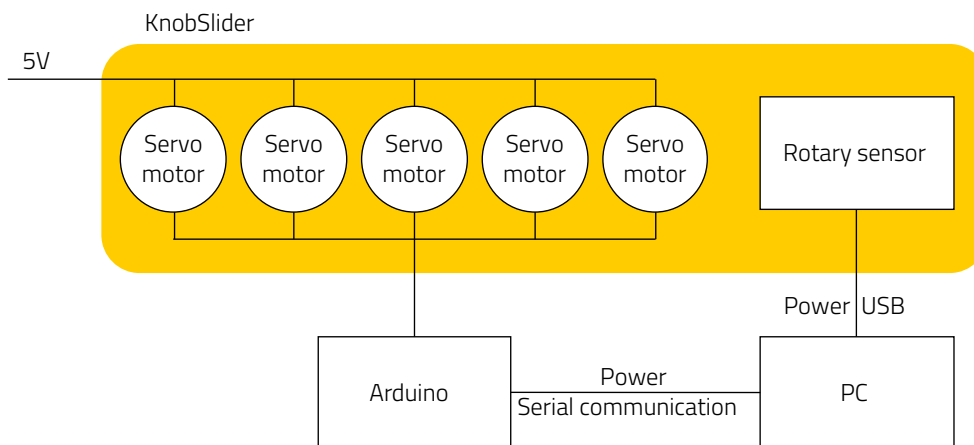


Figure 5.16: The system diagram of KnobSlider. Five servo motors are powered by an external source (5V). They are controlled by an Arduino, and the Arduino communicates with a PC. The rotary sensor in KnobSlider communicates with the PC separately.

Table 5.3: Summary of how KnobSlider fulfills the design requirements. The text in bold highlights what features KnobSlider support the requirements.

Design Requirements	Assessment
R1. Interaction with a large number of parameters	One KnobSlider accommodates two continuous parameters in sequence . Several KnobSliders can be used simultaneously.
R2. Fast interaction	Knob and slider interactions are as fast as standard ones. The shape change takes 0.1s .
R3. Precise interaction	Knob: 100 control positions /rotation, diameter is around 75 mm . Slider: ~ 237 control positions/112 mm. Silicon base sticks on the surface for stability.
R4. Eyes-free interaction	KnobSlider offers physical dial, button and slider.
R5. Mobile interaction	KnobSlider is small enough so that several are available on a mobile surface.
R6. Retro-compatibility	KnobSlider provides a button, dial and slider .

stability. KnobSlider has physical cursors for both dial and slider, but the slider friction varies because of the gaps between the blocks. Future engineering effort includes miniaturization, haptic feedback, cursor automation and cable removal to ensure better mobility and multi-turn dial. Even though the prototype is low fidelity, it is suitable to collect early feedback from users.

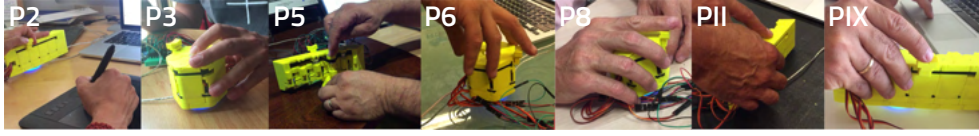


Figure 5.17: Seven out of the ten participants interacting with the probe. P2, PII and PIX are using the slider status. P3 and P5 are about the change the shape by clicking on the central button. P6 and P8 are using the dial status.

5.4 Qualitative Study with Professional Users

In this section, we evaluate KnobSlider and gather feedback from professional users in ecological setups. We are interested in evaluating the final KnobSlider design in users' perspectives. We also plan to gather possible applications and future developments of KnobSlider. For this, we use technological probing [82].

5.4.1 Participants

We recruited ten participants (2 females): six were the first study (P2,3,5,6,7,8), and four new via our extended social network or calling/emailing local professionals: PI and PII (light engineers), PIII (graphic designer), PIX (photographer using Photoshop like P2 and PIII). They were between 32 and 63 years old. All participants were voluntary and consented to photo and video recording.

5.4.2 Procedure

Each participant was interviewed while interacting with the probe for around an hour at their workplace when possible (e.g., P3 at a cafe and P7, P8 in their office). We demonstrated how the prototype worked. The participants were asked to perform given tasks in thinking-aloud protocol. We then conducted semi-structured interviews to assess our requirements. At the end, we asked them to explain a recent situation where KnobSlider might, or not, be useful.

5.4.3 Apparatus

Most systems used by our participants had very diverse and/or proprietary communication protocols. Instead of investing a lot of resources for interfacing a low-fidelity KnobSlider with them, we wanted to gather early feedback and prototyped custom applications tailored for each profession. This enabled close-to-real world tasks while providing simplicity and flexibility as required by technology probes [82]. One exception was Photoshop, used by three participants (graphic designers P2, PIII, PIX), which allowed us to easily interface KnobSlider directly through mouse and keyboard events.

Table 5.4: Tasks performed in the qualitative study.

Participant(s)	The slider status allows:	The dial status allows:
P2,III,IX Graphic designers	Switching between tools	Adjusting a tool's size
P3 Light artist	Adjusting the size of a rotating laser	Adjusting the speed of the laser dot's movement
PI,II Light engineers	Controlling the intensity of a projector	Controlling the rotation of the projector
P5,6 Sound engineers	Controlling the sound volume	
P7,8 Pilots	Controlling the flaps angle	

All participants manipulated the same hardware prototype (described in the previous section). The prototype was linked via USB connection and an Arduino to a MacBook Pro running the task applications.

5.4.4 Tasks

To ensure each participant uses KnobSlider in situations similar to their actual work, we implemented different tasks representing what each professional were frequently observed doing in our formative study (Table 5.4). We proposed a mapping between these tasks and KnobSlider's inputs and shapes (Figure 5.17) in order to support the user requirements.

For graphic designers (P2, PII, PIX), we implemented a script to control Photoshop functions through KnobSlider. With the slider shape, users switched among tools in Tools Palette. With knob shape, users changed tool size, such as Brush and Burn tools. For the rest of participants, we implemented stand-alone Processing applications because their interfaces were not compatible with our device. The light artist's (P3) task was changing the size of a moving laser light with the slider, and changing its movement speed with the knob. The light engineers (PI, PII) were asked to control the intensity (brightness) of a projector with the slider and angle of the projector with the knob. Sound engineers (P5, P6) could control volume of a song with both slider and knob. Pilots (P7, P8) controlled two different flap angles with the slider and knob.

5.4.5 Data collection and analysis

We collected 313 words of written notes, 1 photo and 7h14m33s of audio and video recording of particular sequences of the interview and use of KnobSlider. We transcribed the audio of the recordings. As in the first study, we used thematic analysis to analyze our results.

5.4.6 Results: Meeting the design requirements

For each requirement, we first present the ways KnobSlider supported them and then report on areas for improvement.

Interaction with a large number of parameters

Participants immediately confirmed that KnobSlider allows them to interact with a large number of parameters. First, its ability for time-multiplexing was praised. As P6 explained: "I have a volume slider, and when I adjust the pan, I have a knob. I gain space. Instead of having both a slider and a knob, I have two in one". PII even further wanted to have the central button dedicated to the control of a third parameter. Second, they saw its ability for space-multiplexing. Several participants, mostly sound and light engineers, mentioned that they would like to have several KnobSliders next to each other.

Fast interaction

Fast access to parameters: Most participants said the change of shape was fast. Expecting a slow change of shape, we observed two participants (P3, P5) first holding down the button, instead of a short click on the button (Figure 5.17). We noticed that for some of them, the change of shape was scary at first: "it seems that it is going to explode" (PIII), "it scares me [...] because it moves" (P5). However, after a few trials they liked it and appreciated its speed: "it needs to be fast" (PIII), "it is not disturbing" (PIII), "it is fun, like an animal" (PII). We observed participants clearly playing with the shape-change capability and getting used to its speed. P7 even said that it might take too much time to change the shape: "There is a time between both [shapes], so it has to be two different steps of my work. [...] It is for two distinct tasks, two ways to work on the same data". This suggests that the change of shape can be even faster for an expert user.

In particular, participants liked the way to trigger the change of shape (button). PIII said it allowed her to use her thumb for this, leaving other fingers in place, ready for adjustment of the parameter. Improving stability would ensure even faster access to parameters: P5 complained that the prototype sometimes fell when deformed.

Fast manipulation of parameters: All participants liked the smoothness of the knob. Seven participants mentioned or agreed that KnobSlider in slider shape (Figure 5.17, P2 and PIX) helps quickly reach the vicinity of a value. Even faster manipulation of parameters can be achieved through lower friction. Five out of ten participants complained that the slider had too much friction. For instance, PII said that "it needs to be smooth", like "velvet".

Fast observation of parameters: While the lack of smoothness of the slider was critical for sound and light engineers, P7 and PIII said that the detents of the slider

are useful. P7 (pilot) said that army pilots use detents for feedback, as they focus on external elements for survival. PIII (graphic designer) suggested using them as haptic feedback for switching between Photoshop tools with the slider. Further observation of parameters can be achieved through motorization: after the adjustment of a parameter with the knob, P6 (sound engineer) wanted the cursor of the slider to be updated.

Precise interaction

Seven participants mentioned or agreed to use KnobSlider in dial shape (Figure 5.17, P6) for precisely reach a parameter's value. For instance, P7 said "[in a cockpit], rotary means precision" and P6 "and then I need precision and shazam! It transforms to a dial". P6 cited example of parameters that can be controlled on mixing consoles with either dials or sliders, e.g., pan (whether the sound comes from left or right) or volume, depending on the required precision. In addition to multiturn with a low CD gain, the stability of the dial shape further helped fine adjustments: "I can rest my hand on it" (P7), "I feel I play with something solid" (PIX). Its shape further helped precision by preventing fingers from slipping: PII liked that the dial was not round, but provided edges for a secure grip.

More precise interaction can be achieved through longer slider shape. Light and sound engineers mentioned that they like sliders to be as long as possible. Stable slider would also help precise interaction. Eight participants said that the slider was not stable. In Figure 5.17, PII is holding it with his left hand. The rotation axis needs to be locked and supported on the surface when in slider state. Lastly, lower dial would increase precision in interaction. Sitting participants (PIII, PIX) found that the hand operating the prototype lacked support because the prototype is too high.

Eyes-free interaction

Probably because KnobSlider leverages standard physical interaction and its eyes-free capabilities [88], this requirement was less discussed. For example, three participants mentioned that the slider's shape allows for adjustment and haptic feel of bounded parameters. When in dial shape, the slider's cursor protrudes from the dial. P3 found it "efficient" to use it as a handle to rotate the dial.

Mobile interaction

Most participants saw KnobSlider as a solution to bring a few physical devices on a mobile surface: "I take it, I go there and I do my balance for real" (P5), "If you need it to be transportable, then this is a solution" (P6). They saw its abilities for deciding on the go which device they want. Either for (1) a different parameter: "I have a volume slider, and when I adjust the pan, I have a dial. I gain space. Instead

of having both a slider and a dial, I have two in one" (P6); or (2) for the same parameter, but with a different footprint: P5 wanted to have eight KnobSliders, and take them out of his mixing table to put them on a tablet-like surface and go on stage with the musicians or in the public with only the necessary channels to adjust. If eight do not fit on his surface, then he would change a few to dials. Even more mobile interaction can be achieved through removing cables (as half of the participant suggested), and miniaturizing the prototype. Five participants complained about the size of the prototype. Light and sound engineers (PI, PII, P3, P5, P6) were comparing the prototype to the sliders and knobs they daily use, and mentioned that they like knobs as small as possible.

Retro-compatibility

They understood it was either a knob or a slider and all participants manipulated the device without difficulty. They were particularly happy it could support their preference: P6 cited examples of parameters that can be controlled on mixing consoles with either knobs or sliders, e.g. pan or volume, depending on preference. He preferred "[...] a volume slider, and a knob to adjust the pan." Not hindering retro-compatibility, the novelty of shape-change had a positive impact on participants, e.g. one reacted saying "Wow!", "I want to play with it!"

The participants further suggested device features to improve retro-compatibility: (1) Actuating the slider's orientation to vertical after a shape change: it was a concern for two participants (PII and P6, used to vertically arrange banks of sliders). Similarly, most participants wanted to use the slider vertically, i.e. with flexion/extension movement of the finger, even when the virtual parameter was displayed horizontally (e.g., in Photoshop). (2) The slider's cursor should disappear on knob. It currently protrudes from the knob and P7 says it "interferes". (3) Further improvement of the knob's edges: because the knob has an even number of edges, the base cannot be centered when in slider's state, which confused P8. Also, PIII would like round edges for a circular knob. (4) Further studying its integration with other devices. At a table, P2,PIII,PIX already use a tablet/mouse and a keyboard with Photoshop. These participants wondered how to further combine KnobSlider with other devices, e.g., having a mouse sensor in KnobSlider. (5) Extreme solidity: Pilots might not accept a change of shape during the flight: "A system that deploys during the flight is not in the culture" (P7).

5.4.7 Results: envisioned interactions and applications

Envisioned interactions

Novel manipulation of the same prototype: Eight participants suggested novel interactions. E.g. P3 was holding the knob shape in one hand while turning with the other, and deforming the flexible slider. The additional rotational axis of the slider gave P8 (pilot) the idea to explore the surroundings' visualization with polar

coordinates, by orienting the slider (angle) and sliding the cursor (distance or scale). Two participants asked the interviewer if it was possible to use the slider’s cursor when in knob shape.

Beyond knobs and sliders: P3 suggested adding accelerometers, gyroscopes and compass for KnobSlider tracked when moved in hand. P3 suggested bending KnobSlider as a way to interact. P6 mentioned that the slider could be bent to mark values of interest.

Beyond mixing tables: P1 and P3 also thought about using KnobSlider on a flat table and tracking its displacement on the table (P1 mentioned the [93]). P3 also mention holding KnobSlider in its knob shape in a hand, without any support.

Envisioned applications

Participants gave feedback on the applications we prototyped and proposed new ones. Graphic designers agreed that the prototype allowed them to balance their need for a tidy desk with few devices and dedicated devices, either for fast navigation in Photoshop’s tools or precise adjustment of a parameter like the size. They expected to gain time by avoiding mouse movements and clicks [11]. They further envisioned easier access to parameters through a physical shape analog to the GUI widget: e.g., slider shape for red levels, displayed as sliders on the screen, and knob shape for rotating the canvas.

Sound and light engineers agreed that the prototype allowed gaining space when parameter adjustment happens in sequence: e.g., the slider to control the gain, and the knob the frequency, or the slider for the volume of an effect, (e.g., a reverb), and then the knob to send this effect to the master channel. They also agreed that the device allowed adapting to users’ preferences: some prefer to control volume or pan with a fader, while others prefer to do it with a knob. They further envisioned the flexible footprint of the device. If physical sliders do not fit any more on P5’s mobile surface, he would switch to physical knobs rather than graphical sliders or constantly switch between banks of sliders.

Pilots agreed that the prototype allowed adaption to the preferred control because they control flaps only twice (takeoff/landing). However, changing the shape of other controls might lead to errors, as the logic of each aircraft is different. Pilots further proposed to leverage the different precision of both shapes: When taking off, P7 wanted to coarsely slide from 0 to maximum power, and while cruising, he wanted the knob to precisely adjust the power. P7 proposed to have KnobSlider in flight simulators so that trainees can train on different controls while reducing costs. Pilots imagined prototype improvements to perform tasks that are currently not supported, like seeing backwards before performing a U-turn.

Our participants also proposed new application domains based on their experience. For example, P6 proposed to use the change of shape in the manufacturing industry. It could indicate that a security requirement is met after a first adjustment—e.g. the

5. *KnobSlider: Design of Shape-Change for Heterogeneous Controls*

pressure is low enough after rotating the knob—and that the worker can proceed to adjust the porosity with the slider if its shape is unlocked.

5.5 Controlled Experiment: Pairwise Comparison of Speed Properties

In the qualitative study, we learned that the participants had diverged opinion on the change of the shape. Some people did not mind the change of the shape, and some were surprised and felt they could get hurt by the device. Following this work our goal is now to investigate these effects through a controlled experiment. We are particularly interested in exploring user preferences on different speed conditions, and the preference difference according to the physicality of the device—if the device is in the real world or it is on a video. We conduct one controlled study where we compared two conditions: in the first we used KnobSlider to show different speed properties to the participants; in the second condition, the participants only saw videos of shape-changing KnobSlider on a screen, with the same speed properties from the first condition.

5.5.1 Rationale for the Experiment Design

The goal of our study is subjective in nature, and we choose to conduct a paired comparison experiment [35]. It is a typical method used to gather Quality of Experience (QoE) feedback in HCI, marketing, environmental sciences, and health economics [28, 1, 160, 91, 91, 202]. The study is conducted by asking participants to choose between two conditions, mostly to choose the most preferable condition out of two. The experiment is designed to show all possible combinations of two conditions to the participants. Performing pairwise comparison ratings has been proven to produce more realistic results than asking for individual rankings (e.g., using a Likert scale) [19].

5.5.2 Research Questions

In this study, we try to answer to the following questions.

Q1. Is the preference with the physical device equivalent to the videos on a screen?

In this study, the observation of the shape-changes is limited to visual feedback and does not include interaction with the prototype, or other types of feedback. Hence, we believe that the preference of the physical prototype is transferable to screen medium. However, there can be an offset between the most preferred speed between the physical and the screen medium. For instance, users may prefer a little faster speed on the screen, because they know that the device cannot harm them.

Q2. Do users prefer certain range of speed?

We expect that users would prefer a certain range of speed, not randomly any sort of speed. The preference will have a pattern such as a normal distribution.

Table 5.5: The variable and conditions of the controlled study. For the *physicality* variable, we use between-subjects design to remove the learning effect. For the *max speed* and *speed profile* variables, we use within-subjects design to eliminate individual differences by participants on the variables.

Variables	Conditions	Experiment design
<i>Physicality</i>	<i>device (physical), video (virtual)</i>	between-subjects
<i>Max speed</i>	<i>50, 200, 400°/s</i>	within-subjects
<i>Speed profile</i>	<i>square, mountain</i>	within-subjects

Q3. Which speed profile users prefer?

With the same maximum or average speed, people may prefer gradual speed change. We expect that users would prefer a speed profile that gradual changes the speed than one that instantly change the speed. I.e., they would prefer the device to gradually increase its speed from 0 to to a certain amount, then gradually decrease the speed to 0, than the device to instantly change its speed from 0°/s to a certain amount, then stop. We assume so because gradual speed profile gives time to users to prepare themselves for the shape-changes.

5.5.3 Experimental Design

The study had three independent variables: *physicality*, *max speed*, and *speed profile* (see Table 5.5). *Physicality* refers to the fact that the shape-changes occur on the physical KnobSlider device or on a video. We choose to have *physicality*, because studies of shape-changing interfaces choose to use either videos or physical devices [167, 182], and we do not know if they are equivalent and mutually substitutable. *Max speed* variable correspond to the maximum speed the shape-change of KnobSlider. We want to figure out between max aped and *speed profile*, which variable has more impact on preferences. We use three conditions—50°/s, 200°/s, 200°/s (Figure 5.18 left). They were distinguishable by users in a pilot study. The third variable *speed profile* was the dynamic of the shape-change: *square* and *mountain* (Figure 5.18 right). With the *square* profile, the motors changed their speed from 0°/s, to a *maximum speed*, and 0°/s over the shape-change. With the *mountain* profile, the motors linearly accelerated until reaching the *maximum speed* and then linearly decelerated until reaching 0°/s, resulting the speed making the mountain-like shape on the graph. This variable was to know if there is distinguishable preference on *speed profile* when the *maximum speed* is the same.

Physicality was a between-subject variable, i.e. participants were randomly assigned to either the condition with physical KnobSlider *device* or *video* if the device but did not do both. We chose this variable to be between-subject to eliminate potential learning effect. The other variables were within-subject variables. With the *Max speed* and the *Speed profile* variables, there were 6 permutation of 2 (${}_6P_2$) so a total of 30 pairs to compare. The order of the displayed pairs were randomized with Latin Square design.

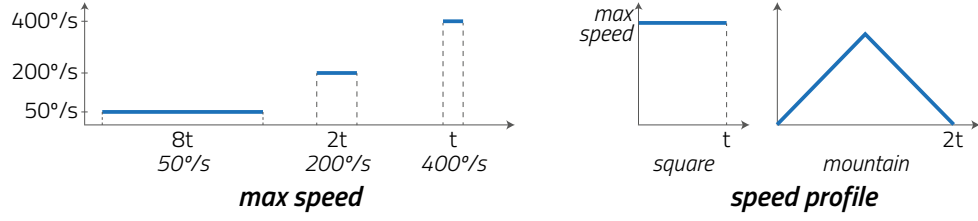


Figure 5.18: The speed variables explored in the experiment. *Max speed* is the maximum speed that the motors will have over shape-changes. We use three amounts of *max speed*: 50, 200, and 400°/s. *Speed profile* is the changes in the speed during shape-changes. *Square*: the speed of shape-change is constant over time. *Mountain*: the speed increases with a constant amount of acceleration until it reaches the maximum speed and then decreases with the same absolute amount of the acceleration.

5.5.4 Participants

We recruited 18 participants among PhD students and researchers in our institute (ages 14-59, avg. 29, SD 9.4, 5 females). We separated them into two groups for the *physicality* variable: nine people watched the physical device, and the rest nine people watched the videos on a screen. We surveyed the participants about the amount of experience with KnobSlider, technology adoption, and proficiency in using dials and sliders. None of the participants have interacted with the device, and only three people have seen KnobSlider moving on video or for real. Around the half of the participants (11/18) answered that they are early majority in the technology adoption life cycle [9], the rest people answered as an innovator (1/18), early adopters (4/18), and late majority (2/18). The majority of the participants (14/18) had used dials and sliders for simple interaction such as setting temperature with an oven dial. The rest of the participants responded having advanced experiences such as controlling sound parameters on a mixing board.

The participation for both studies was voluntary, and no compensation was offered. We followed a standard user study procedure in HCI where instructors show different types of interfaces and ask feedback from participants (e.g., [107, 182]). We explained the experiment procedure to the participants beforehand and acquired consent forms. They could withdraw their participation and their collected data at any point of the experiment or after it. There was no possibility of harming the participants, and the data was anonymized so that the person analyzing the data could not identify the participants. We gained ethics approval from our university ethics committee.

The this study, we chose to use non-professional users. For the qualitative study, we picked professional users because we wanted to understand the current interaction, usages, and applications. This is a common practice used in the user-centered design process, which is a typical modus operandi from designers and HCI researchers. However for the controlled pairwise comparison study, our goal was to investigate perception of the movement and this could be studied with non-professional users, as both professional and non-professional users have not experienced shape-changing controls before and perception of the shape-changes should be the same for them.

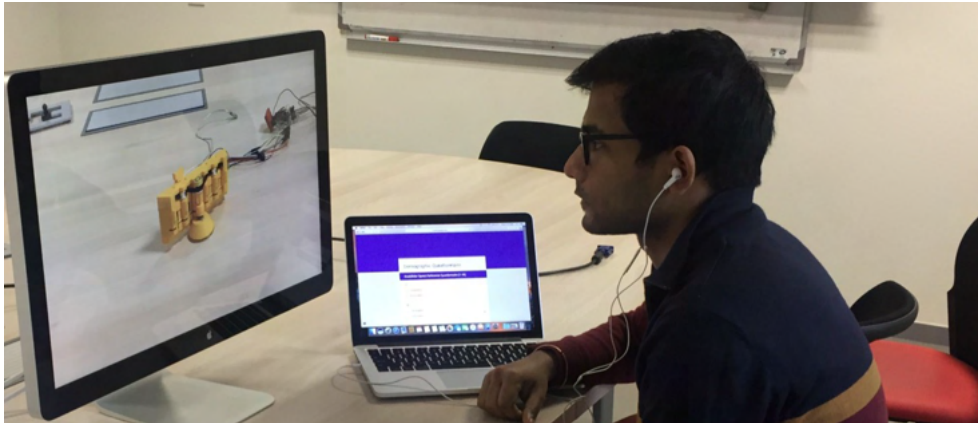


Figure 5.19: A participant in the *video* condition. He is looking at a video of KnobSlider changing its shape on a screen. The size of the device on the screen is controlled to have the same size in the *device* condition.

Having non-professional users also allowed us to have a broader range of participants and to increase the sample size for further statistical tests.

5.5.5 Tasks

After an introduction of the experiment and obtaining informed consent, participants filled a short demographic questionnaire and started seeing the pairs of two conditions. They could take a break anytime between seeing pairs.

The participants were asked to sit in front of a table on which there was either KnobSlider device ($\sim 30\text{cm}$ distance from the end of the table) or videos on a screen (Figure 5.19). They could freely position themselves before the experiment. They were asked to fix their eyes on it and not to move on the chair once the experiments started. The physical device or the device on a video changed its shape from a slider to dial and back to slider. After watching each pair of shape-changes with two different speed properties (*max speed* and *speed profile*), the participants answered their preferences on a separate computer. The size of the device on the screen was similar to the actual device size ($\sim 12\text{cm}$), so that the size would not affect user preferences.

After seeing all the pairs, the instructor demonstrated how to use KnobSlider with an example application (light control on a stage). The participants then answered to qualitative questionnaire about the study. Each session lasted around 20 minutes.

5.5.6 Results

We analyzed our results based on a literature that suggested a three-step analysis for pair-comparison studies [28]. We show the analysis in the following sections.

Initial responses

Among the eighteen participants, five participants reported that they could not see a difference between some pairs, and one participant reported that s/he does not have a preference over a pair. This happened for nine pairs among 540 pairs (30 pairs \times 18 participants), which was 1.6% of the responses. We assume that for some participants it was hard to see too fast movement. It occurred when the *max speed* of both conditions was equally high ($400^\circ/\text{s}$) or when the average speed of both conditions was equally medium ($200^\circ/\text{s}$), i.e., condition 1: *200°/s max speed and rectangle speed profile* (avg. speed of $200^\circ/\text{s}$), condition 2: *400°/s max speed and mountain speed profile* (avg. speed of $200^\circ/\text{s}$). We changed the responses to random as those participants would respond randomly when we force them to choose one of the conditions. We used discrete uniform distribution for the altered responses.

Individual consistency

As the first analysis, we evaluated each participant's consistency on the responses by using Transitivity Satisfaction Rate (TSR). It quantifies how much the participants' preferences were transferred when answering different pairs. For example, a participant responded that speed condition A is more preferable than condition B and condition B is more preferable than condition C. If participant responds that s/he prefers A over C, we can say that the responses to the condition A, B, C are consistent. We used a program used in a previous literature [1] to measure the individual consistency.

In the device condition, five participants showed the TSR of 1, which is the perfect consistency. Three participants had TSR between 0.71 and 0.75, meaning some disagreement. One participant showed TSR of 0.33. In the video condition, five participants had TSR above 0.8 (range from 0.82 to 1.0, avg. 0.92). The rest four participants' TSR ranged from 0.33 to 0.67. Our hypothesis about the inconsistency is that participants get used to faster speed of shape-changes more easily in the video condition, and they change their preferences.

Overall consistency

We then evaluated the overall consistency of responses among the participants in each *physicality* condition. We used Kendall's tau coefficient to calculate the overall consistency. We computed the ranking of preferred speed conditions for each participant, and then used calculated Kendall's tau coefficient, which shows how similar the rankings are. The participants in the device condition had Kendall's tau coefficient of 62%, and the participants in the video condition had Kendall's tau coefficient of 75.3%. It shows that there is positive correlation in the participants' preferences, not negative correlation, i.e., the participants liked the speed properties in a similar order, not an opposite order.

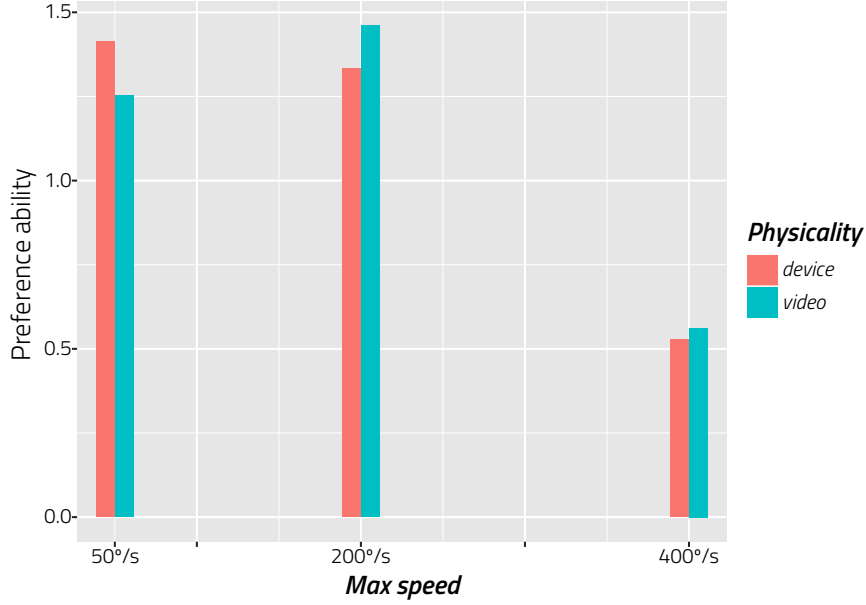


Figure 5.20: The Bradley-Terry-Luce model output of different max speed and tangibility variables. The red bars show the preference ability of physical *device* (*physical*) condition with different conditions of max speed, and the green bars show the preference ability of *video* (*virtual*) condition of the same device with different conditions of max speed.

Answers to the research questions

In this section, we answer to the research questions by analyzing the results. We used Bradley-Terry-Luce model [19] to compute the "ability" of the conditions that have been compared in the study. Figure 5.20 shows the ability of *max speed* conditions and Figure 5.21 shows the ability of *speed profile* conditions.

Q1. Is the preference with the physical device equivalent to the videos on a screen?

The participants preferred different *max speed* depending on the *physicality* variable (Figure 5.20). With the device, the participants most preferred the lowest speed ($50^\circ/s$), and with the videos, the participants most preferred the medium speed ($200^\circ/s$). It means that using videos for perceptual study on shape-changing interfaces [139, 182] can result different conclusion than using physical devices.

Q2. Do users prefer certain range of speed?

Users preferred a certain range of speed, instead of preferring all range of speed. The result is illustrated in Figure 5.20. We observed very the least preference on the highest speed ($400^\circ/s$). It reassures the result from our qualitative study [54] that some users got surprised by the shape-changes of KnobSlider. Users do not like surprising feelings caused by the fast movements of the device.

Q3. Which *speed profile* do users prefer?

5.5. Controlled Experiment: Pairwise Comparison of Speed Properties

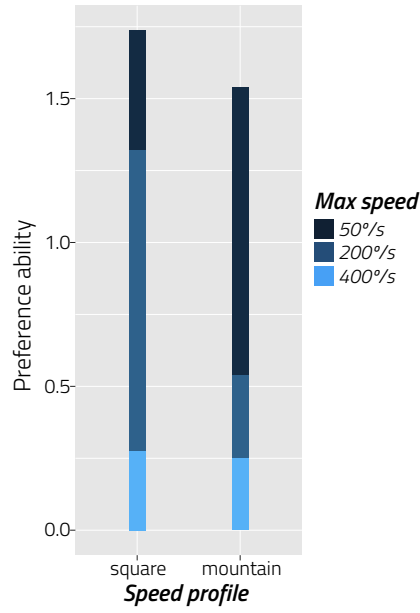


Figure 5.21: The Bradley-Terry-Luce model output of *speed profile* variable. The participants preferred the *square* profile over the *mountain* profile, when the *max speed* conditions were accumulated.

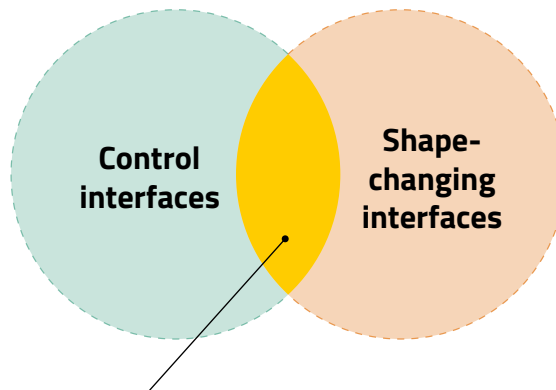
Figure 5.21 shows the users preferences on the *speed profile* conditions, square and mountain. Surprisingly, they preferred the mountain profile over the square profile, regardless of the *max speed*. It was not consistent with the fact that the mountain profile reduced the average speed of shape-changes with the highest *max speed* (e.g., $400^\circ/\text{s}$) to the half ($200^\circ/\text{s}$), and that the participants preferred the medium *max speed* ($200^\circ/\text{s}$) than the highest *max speed* ($400^\circ/\text{s}$). It might be related to that some participants mentioned too slow shape-changes were "boring." They explained that they could know the device would change its shape once it started moving. In the same sense, we can hypothesize that the first acceleration part of the mountain profile made the participants prepared for shape-changes with any maximum speed, and they felt bored over shape-changes with the mountain profile. It would be interesting to investigate if it is more acceptable to have gradual speed change only at the beginning of shape-changes.

5.6 Conclusion

In this chapter, we utilized design tools (Morpheus+ and the collection of everyday reconfigurable objects) to explore ten design ideas of a shape-changing control for rotational and linear controls. We then used the six design requirements to evaluate the ideas and implemented the best idea, KnobSlider. KnobSlider combines the benefits of a physical dial and a physical slider through on-demand shape-change. We evaluated the KnobSlider with professional users. The results showed that KnobSlider supports the design requirements for control interfaces. They also showed implications for shape-changing interfaces, especially for the speed of shape-changes. It motivated the pairwise comparison study regarding shape-change speed. It revealed that users prefer medium speed (not too fast or too slow) and the preference can change depending on the physicality (i.e., whether the device is shown in the real world or on a video).

The design process shows that the design tools enable ideation of various shape-changing interactions, and assures that the six design requirements can be used as a design evaluation tool for control interfaces. The controlled study on speed preference opened a new research direction of shape-changing interfaces: perceptual study on dynamic parameters. Future studies should systemically consider different dynamic parameters as well as the features of Morpheus+ in the study. Also, the effect of physicality variable should be confirmed by having statistically significant sample size.

In the next chapter, we conduct the second case study by using other features of Morpheus+. We used six features and various everyday reconfigurable objects, and we go one step further by utilizing unused features in the KnobSlider design process. Also, we plan to strengthen human aspects in the design of the next case study. E.g., we did not optimize the size of KnobSlider to users' grasps. The size was decided by the motors embedded in KnobSlider. Also, we learned that users' grasp had to change between the dial and slider states of KnobSlider. In the second study, we aim to design a shape-changing control that conforms to users' current grasp on control interfaces by using the unused features.



Chapter 6. ExpanDial: Designing a Shape-Changing Dial Based on a Grasp Study



Figure 6.1: Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by looking at the design space of shape-changing dials. We look into grasps of dials and future applications and gestures for shape-changing dials.

ExpanDial: Design of a Shape-Changing Dial Based on a Grasp Study

6.1 Introduction

In the previous chapter, we designed KnobSlider, which provides flexibility between two types of controls through change of Morphees+ Curvature feature. In this chapter, we go one step further in the shape-changing control interface area by focusing on flexibility of one type of control (Figure 6.1 on page 134). We use a shape-change feature that was not used in the previous chapter and increase the number of parameters that can be controlled at the same time. Additionally, we consider human factors in the process. Human factors are rarely considered when designing shape-changing interfaces and we want to learn how they can inform the design space. We are especially interested in grasps as physical control interfaces require grasps for interaction. Also, literature shows that users have different grasps depending on the shape of objects [43, 127], meaning that they would have different grasps on interfaces when they change their shape.

To explore an unused shape-change feature in the previous chapter and provide human factor guidelines in a focused area, we choose to use one type of control: a dial. A dial, also called round knob or rotary control [43], is a control device for "analogue (infinitely variable) adjustment of a one-dimensional variable" [8]. It is controlled through its rotation around the axis that is perpendicular to its support surface. Dials allow precise and rapid control that is not achievable with other tangible devices [8]. Design handbooks and previous research explore different ranges of width and height: e.g., between 10 and 30 mm (height and width) [8], 25 and 75 mm (width) [43], or 10 mm and 8.25 mm (width) [18]. Despite being widespread, there have been few researches on opportunities and challenges of dials that can change their size

automatically and how users would grasp them.

Early grasping studies (e.g., [43, 127]) showed how users grasp objects. They also investigated how users grasp tangible controls, like dials (e.g., [62]). However, they did not explore grasps on dials with different sizes. More recent work explored how users grasp tangible tokens on a surface [122]. While the authors explore different shapes and sizes (3, 4 and 5 cm), they do not vary the height of the tangible tokens. In this chapter, we wish to extend the grasp study to all common and usable dial widths and heights [18, 43].

Within the HCI community, there have been height-changing dials [170] or width-changing dials [133] but none doing both at the same time. These papers also focus on certain applications, i.e., music or temperature control, and only the system activates the shape-changes. This raises the question of broad applications for future shape-changing dials and control and/or display modalities in different applicative contexts. To investigate the applications, we decide to take a similar approach with Sturdee et al. and Everitt et al. [168, 46]. They provided working shape-changing interfaces to end users as probes and facilitated the idea generation process. We provide a shape-changing dial in a design session.

In addition, there has been little exploration on how to trigger shape-changes of shape-changing controls. Many of the shape-changes are triggered by the system [170, 133], require users to press buttons [101, 134], or allow limited direct deformations by users [170]. They provide a limited design space of user gestures to trigger shape-changes, and we do not know what kind of gestures would be suitable for shape-changing dials. This chapter also explores the possible gestures to trigger shape-changes through user-elicitation, as the method was used for other shape-changing interfaces such as elastic screens [185], for bendable surfaces [110] and for deformable displays [111].

Our approach in this chapter consists in the following steps:

1. We first start with a controlled study where we explore how users grasp the dials of different heights and widths in order to inform the form factor of shape-changing dials. We collect data on users' hand postures when they rotate static 3D printed dials with different sizes (two heights and four width). It helps us draw design guidelines for shape-changing dials.
2. We then implement ExpanDial, a shape-changing dial that allows height and width changes (Figure 6.11).
3. We then use the prototype as a probe during design sessions with participants to explore what applications can benefit from such device and what interaction and manipulation could be harnessed from this device to enrich the input bandwidth. Using the participants' feedback, we draw a space of potential application and interaction for shape-changing dials. We also gather feedback on our prototype and conclude by discussing design implications for future shape-changing dials.

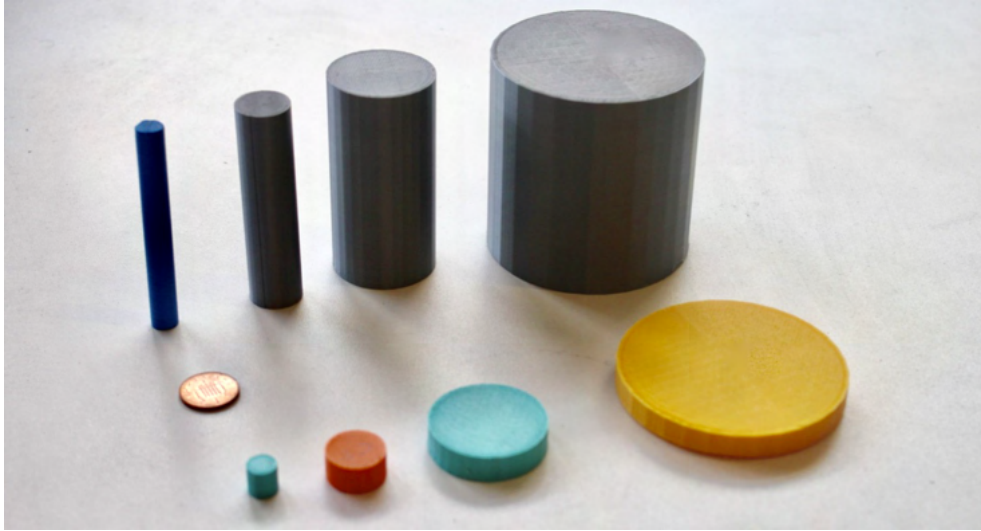


Figure 6.2: The dials used in the study: four widths (1, 2, 4, 8 cm from left to right) and two heights (1, 8 cm, from bottom to top).

6.2 Grasp Study

In this section, we conduct a grasp study on dial of different sizes. The goal of this study is to better understand how users grasp dials of different shapes when asked to perform different tasks (turning a dial with different angle). The answer to these insights would inform on how to place handles for user-initiated deformation of the dial, as well as independent handle for turning the dial and deforming it. It would also help envision how the hand would relocate as the dial deforms during manipulation.

6.2.1 Participants

10 participants (5 females) from various university institutions participated in the study, ranging from 19-40 years. 3 participants were left-handed. They all used their dominant hands to do the study (for clarity in the results we mirrored the left-handed videos).

6.2.2 Task

Participants were presented 8 cylinders of different heights and widths (Figure 6.2). They were asked to grasp the dials in order to perform three different tasks: turn the dial by 10° , 90° and 360° clockwise. They did not have to turn the dial but rather to grasp the dial and hold it in position while the data was recorded. They thus had to first think about how to hold it to perform the rotation. They had to keep the position for 10 seconds to leave a thermal print on the dial for the thermal camera.

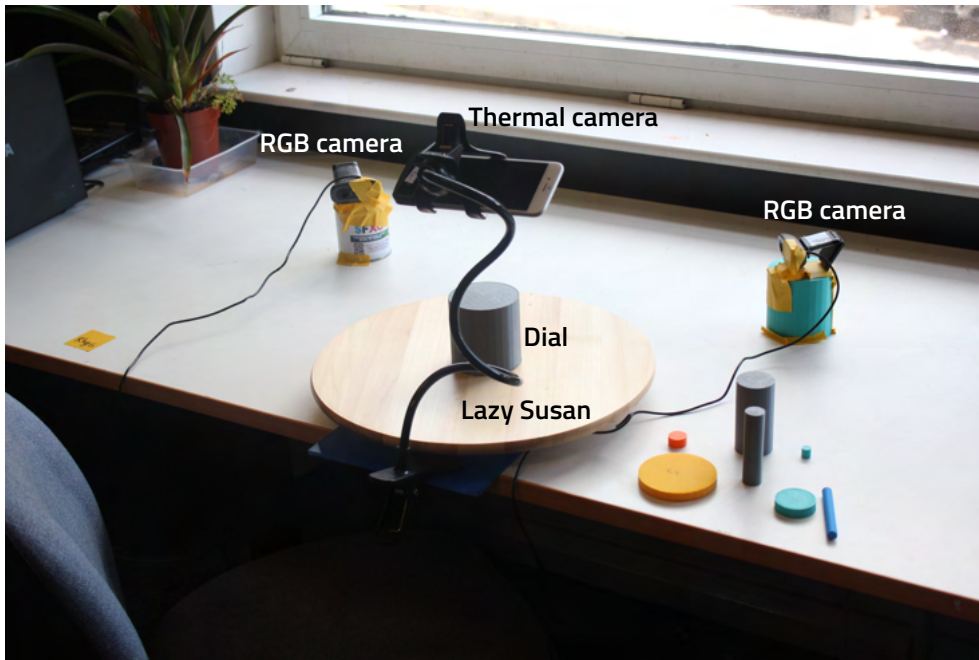


Figure 6.3: The study setup with two RGB cameras and one thermal camera above the dial placed on a Lazy Susan. Participants were sitting in front of the setup and were asked to stay seated.

6.2.3 Apparatus

We used three cameras placed at different angles to gather videos of the grasp positions. Two were RGB cameras placed as illustrated in Figure 6.3. We used a simple program to record the input of the two cameras simultaneously. The third camera was a thermal camera placed as illustrated in Figure 6.3. The dials were placed on a Lazy Susan that we manually rotated once the participants finished assuming their grasp position after holding the grasps for ten seconds. A visual marker on the Lazy Susan (unobservable in Figure 6.3) helped measuring its rotation. This allowed the thermal camera to record the finger traces all around the dial. We used the eight 3D printed dials shown on Figure 6.2. We chose widths ranging from 1 cm to 8 cm based on previous studies of optimal dial widths [18] and current commercial dials that reach down to 1 cm¹. For the heights we used a range from 10-80 mm which goes above recommendations for dials height (e.g. 10-30 mm [8]) but we wanted to cover a large range of heights to identify differences in grasping.

6.2.4 Experimental Design

We used a within subject design. The variables were the *Width* of the dial (1, 2, 4 and 8 cm in diameter), its *Height* (1, 8 cm) and the *Angle* of rotation (10°, 90° and 360°) of the task. The conditions were counterbalanced among participants to

¹E.g., <https://www.adafruit.com/product/2057>

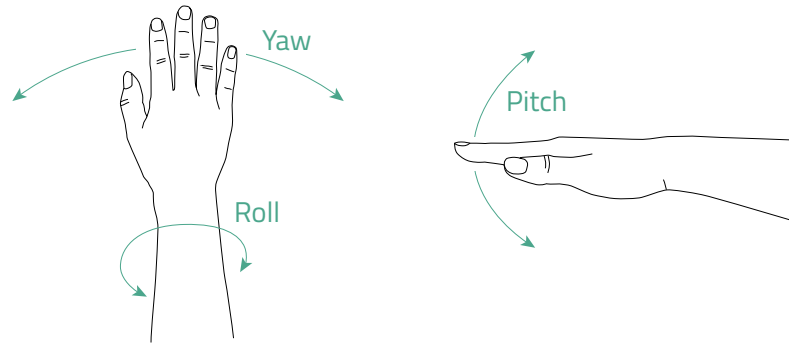


Figure 6.4: Hand yaw, roll, and pitch.

avoid learning or order effects. Sometimes the thermal camera would freeze so we asked the participant to assume the same grasp again and recorded a new video. The experiment lasted around 12-16 minutes per participant.

6.2.5 Hypothesis and Research Questions

We had hypothesis and questions we wanted to evaluate.

- Q1. Overall posture:** We first wanted to list the different types of grasps observed. We assumed some patterns would emerge to reflect the theory of the grasping hand by Napier [127], i.e., the position of the fingers would follow a classical pattern where the thumb opposed the other fingers.
- Q2. Hand roll:** Additionally, we wondered what hand roll (Figure 6.4) the users would prefer, i.e., approaching the dial from its side or its top. We did not have any assumptions on this question although our assumption was that they would approach it mainly by the side because they were sited in front of the setup and not standing.
- Q3. Hand yaw:** We wanted to observe the hand yaw (Figure 6.4), i.e., the angle made by the hand at the start of the movement relatively to the user. We assume that when users were asked to perform a larger Angle of rotation of the dial, the hand yaw would be larger too, as the users need to prepare their hand to achieve a larger motion without clutching.
- Q4. Number of fingers:** We wanted to observe how many fingers were used. We assumed that the larger the dial, the more fingers would be used. We also hypothesize that the smaller the Angle of rotation of the dial, the less fingers would be used. This would corroborate with Napier's theory of hand grasping, suggesting that precision grasps involve using the index and the thumb [127]. It would also corroborate with observations that users make as most contact as possible with the fingers on TUI, probably to reach better performance [189].
- Q5. Placement of finger:** We wanted to observe where the fingers were placed on the length of dials (not its circumference). With taller dials, we assumed that

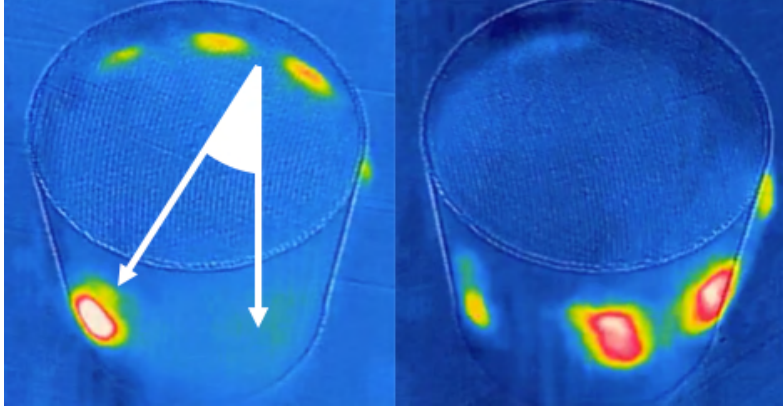


Figure 6.5: Thermal camera images from the beginning (left) to the end (right) of the Lazy Suzan rotation. The angle shows the hand yaw computed from the thumb to the centroid of the other fingers relatively to the user’s position.

users would place their finger either on the top (if the hand comes from the top) or on the middle of it. The reason is that those positions ensure that the dial is more stable.

6.2.6 Data Generation

We manually annotated all the videos to retrieve the position of fingers (placement on the circumferences of the dials and on the length) as well as the orientation of the hand (roll and yaw) and the type of grasp. To measure the yaw of the hand we measured the angle made from the thumb to the centroid of the other fingers relatively to the user position (Figure 6.5 left). As we will see later, we choose this measurement because participants had consistent posture where the thumb always opposed the other fingers. Figure 6.5 and Figure 6.6 illustrate the type of images we captured as well as specify the hand roll and yaw metric we used.

6.2.7 Results

We performed Shapiro-Wilk tests on our different metrics that did not follow a normal distribution ($p < 0.05$). We thus used non-parametric tests when necessary.

Q1. Overall posture: As we hypothesized, there was a finite number of postures assumed by the participants, in total eight corresponding to the number of fingers used (2, 3, 4 or 5) and two hand rolls (coming from the top or the side). Those postures are illustrated on Figure 6.7. We observed very little variations on the positions of the fingers on the circumferences of the cylinder, i.e. the positions always matched the typical patterns of the thumb being diametrically opposed to the other fingers, which corroborated previous work [127].

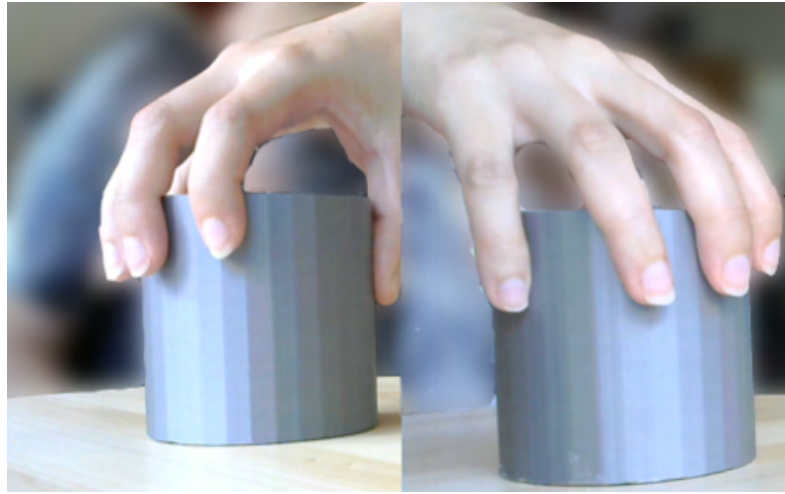
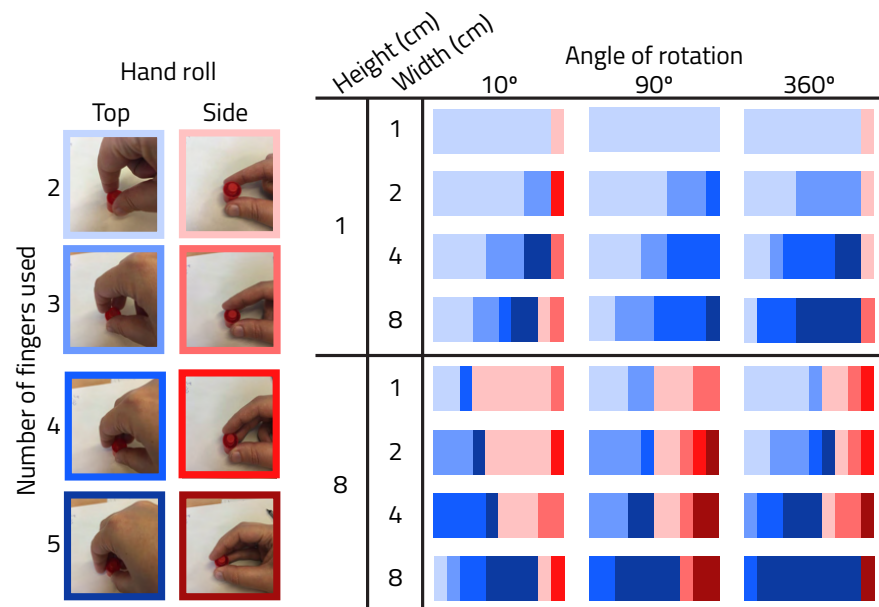


Figure 6.6: Images from the RGB camera. Here the hand comes from the top (hand roll).



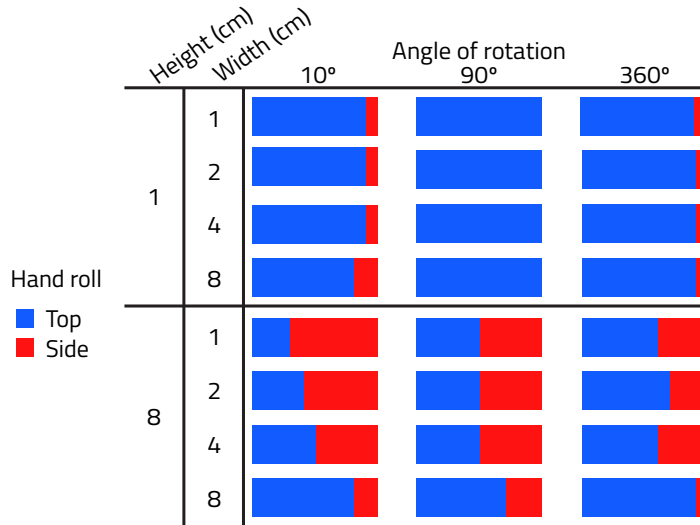


Figure 6.8: Hand rolls per dial Height, Width and Angle of rotation.

Q2. Hand roll: Figure 6.8 shows the distribution of hand roll across the different dials and Angles of rotation. The data revealed very few variations in term of hand roll angle, thus why we coded this metric in two categories only: coming from the top or the side. We observe a difference between the 1cm height (often grasped from the top) and the 8cm height dials. This difference was confirmed to be significant through a McNemar Test ($p < 0.05$). We thought the 8cm dials would be grasped from the side because there is more space to place the fingers, but we observed a mix of behaviors.

Q3. Hand yaw: The data revealed a lot of variation in term of hand yaw angle, thus why we used the continuous value of the angle measured. Figure 6.9 left shows the distribution of hand yaw angles across the different dials and Angles of rotation. We can observe that the size of the hand yaw angle seems to correlate with the size of the Angle of rotation but there is a lot of variability across dials size. A Friedman's analysis of variance confirmed a significant difference on the yaw angle between 10° and 360° Angle of rotation, i.e. the angle is bigger with 360°, suggesting that our hypothesis is true (the participants prepared their rotation movement by assuming a larger hand yaw at the beginning of the movement). We did not find any significant differences for the other comparisons (dial Width and Height).

Q4. Number of fingers: Figure 6.9 right shows the mean number of fingers used across the different sizes of dials. A Friedman's analysis of variance showed no significant difference between dial Height and Angle of rotation but showed an effect on dial Width. All pairwise comparisons showed a significant difference for the dial Width ($p < 0.05$). Smaller cylinders thus correlate with less number of fingers, which make sense as they have less surface for the users to use.

Q5. Placement of finger: Figure 6.10 shows the distribution of vertical placement of fingers across the different dials' Width and Angles of rotation. We only looked

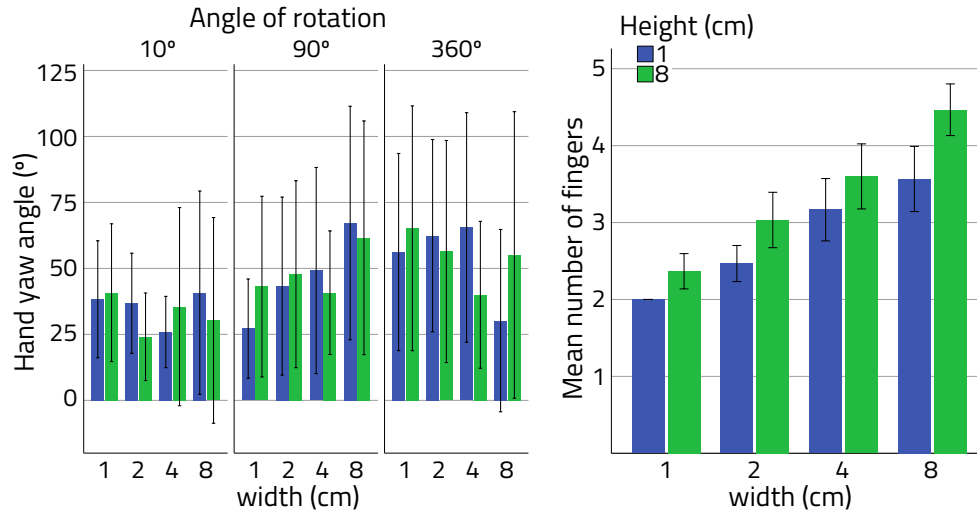


Figure 6.9: (Left) Hand yaws per Width and Height of the dials and Angle of rotation. (Right) Number of fingers per Width and Height of the dials.

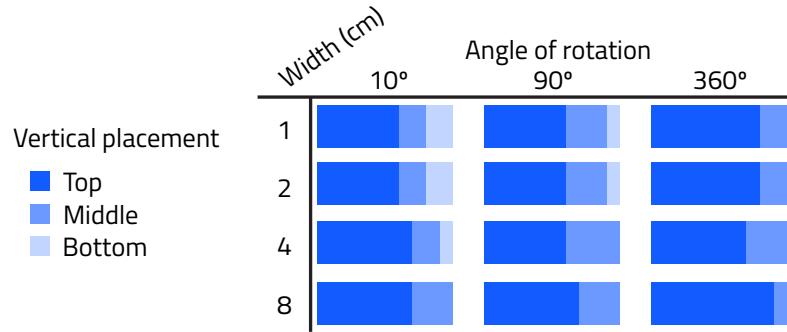


Figure 6.10: Placement of the fingers on the length of the 8cm dials per Width and Angle of rotation.

at the 8cm dials that actually offer different alternatives for vertical placement. The data revealed very few variations in term of hand roll angle, thus why we coded this metric in three categories only: placed at the top, middle, or bottom. Overall, the top of the dials was clearly more used. The grasps at the bottom seem to have correlation with Angle of rotation ($\leq 90^\circ$) and Width ($\leq 4\text{cm}$).

6.2.8 Lessons Learned

From the observations gathered in the study we learned some insights for the design of shape-changing dials. We know that users will use only postures in which fingers and thumb oppose. But we also observed large variation in the hand yaw angle. This leads us to think that the circumference of the dial should allow the user to assume any type of finger configuration (many possible hand yaws). It can be supported by

smooth side surface of shape-changing dials.

We also know that users will largely use the top of the dial rather than the bottom or middle. This corroborates the fact that they use the hand from top more often as well. Increasing/decreasing the height of the dial should not result in uncommon, possibly uncomfortable, grasps. It shows that the side of shape-changing dials can have less design requirements, i.e., when the dial is high, the side surface does not have to have a seamless surface near the bottom or middle.

Users can prefer to grasp dials from the side when the height is high, the width is smaller than the height, and the angle of rotation is small ($\leq 90^\circ$). This means that users may either (1) continuously change the hand roll when the dial goes up/down and the width gets larger/smaller, or (2) keep their hand grasping from the top. Users will also very probably increase/decrease their number of fingers as the dial increases/decreases in width.

Users will use a different number of fingers depending on the size of the dial width (the smaller the fewer fingers). A shape-changing dial with flexible width would better support any number of fingers.

Lastly, based on the eight postures of Figure 6.7, we need to figure out if it is ok for users to deform the dial from the very same postures, or if they would prefer to deform the dial from a different, explicit posture/gesture so that deformation does not happen when turning the dial. We explore gestures to activate shape changes of shape-changing dials in a following section.

6.3 ExpanDial Prototype Implementation

Following the first study, we implemented ExpanDial, a dial that is able to change its width and height (Figure 6.11, 6.12, 6.13). We first explain how we built the prototype and then show how the prototype brings off the lessons we learned from the grasp study.

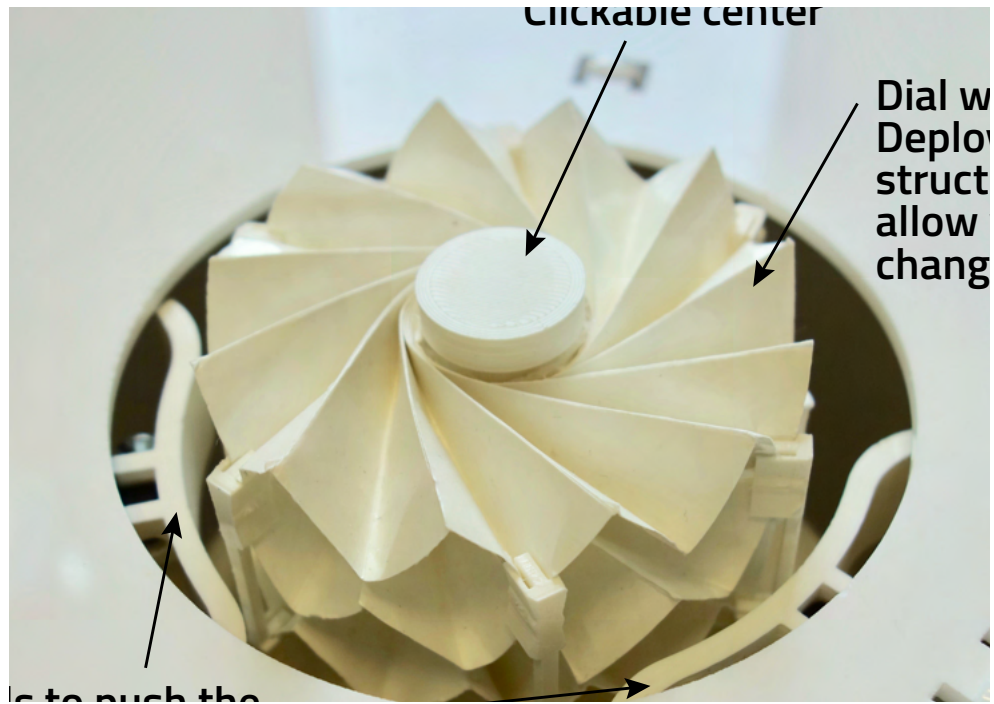


Figure 6.11: The ExpanDial, a shape-changing dial prototype using expandable origami.

6.3.1 Design

We used NASA’s Star Shade pattern [133, 153] (Figure 6.12 left) for the resizing mechanism of a round paper piece. The pattern allows the folded piece of paper to change width while keeping the round circumference. The ratio between the minimum and the maximum width varies depending on the design and the paper material [129]. We tried various patterns and chose the one working well with simple paper.

6. *ExpanDial: Design of a Shape-Changing Dial Based on a Grasp Study*

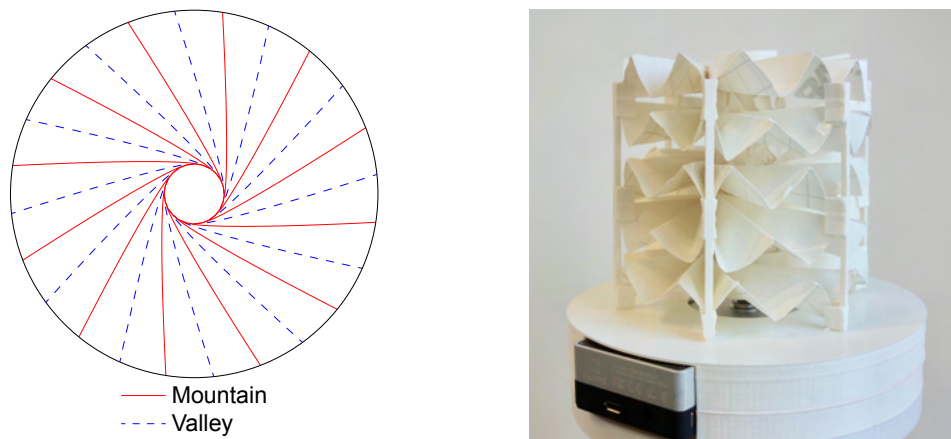


Figure 6.12: Left) The folding pattern of a paper piece layer of ExpanDial. Right) The paper pieces folded along the pattern, stacked, and connected through 3D printed connectors.

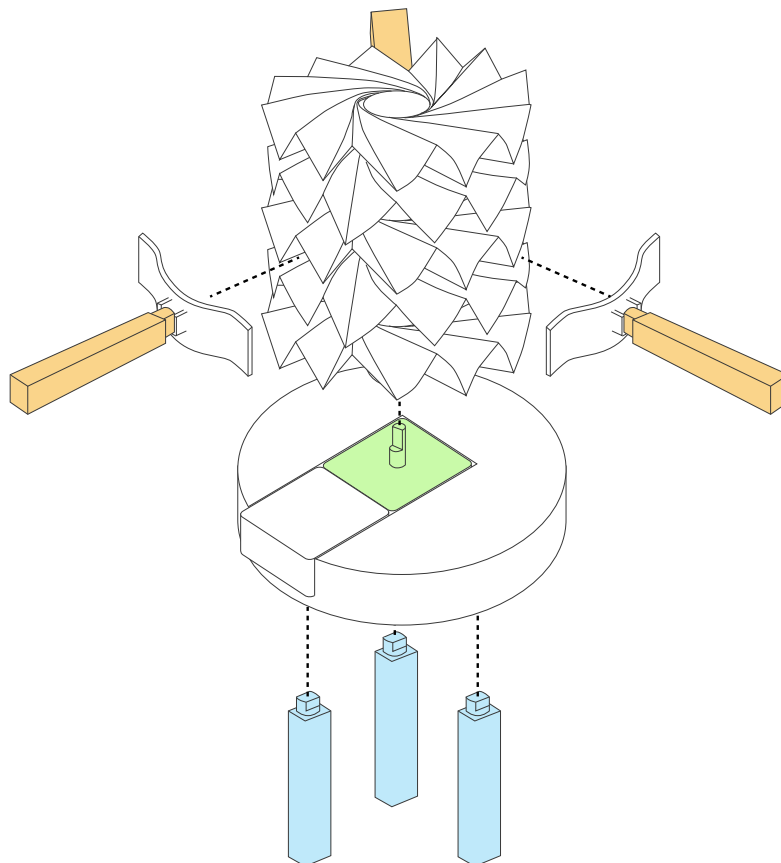


Figure 6.13: The schematic of ExpanDial showing the shape-change mechanism. Three motors control the width (orange) and three motors control the height (blue). A rotational sensor (green) captures the rotation and click of the dial.

We grooved the pattern on paper by using a vinyl cutter. We then stacked five pieces of the folded paper to make a cylinder and connected the edges of the sheets using 3D printed connectors (Figure 6.12-Right). As the height of the folded paper changed along the change of the width, we connected only one side of the creases (mountains or valleys) to the connectors. We then fixed the stack on a Palette sensor that senses rotational movement and click.

Below the sensor, we placed three linear actuators that enable height changes (Firgelli L12-50-100-6-R, Figure 6.13). To change the width, we placed the three identical linear actuators around the circumference, with walls at their extremities. They could evenly push and release the circumference. When the walls push the stack, its width is reduced. When released, the stack goes back to its maximum width thanks to the paper tension.

The size of the case below the dial was around $W360 \times L305 \times H230$ mm. For clarity, we call the stack of folded sheets of paper the dial, and the box that accommodates the shape-changing mechanism the case in the rest of the paper. The current version of prototype can change its width from 3.6cm to 9cm and its height from 2.3cm to 6.3cm. Users can use 2-5 fingers when rotating it, and they will be more likely to use 3-5 fingers (Figure 6.9).

6.3.2 Design Rationale

We tried to make a good trade-off between finding a viable technical solution for height and width change and also addressing the lessons found in our initial study.

First of all, the circumference of ExpanDial allows the user to assume almost any types of finger configuration. The exception is the very top of the dial (around 1.8cm from the top), due to the empty space on the valley crease. It forces users to grasp the mountain crease when they grasp from the top.

ExpanDial consists of multiple layers of folded round paper pieces, and the circumference of each piece has closely placed creases. It allows users to grasp the dial even from the side, although it was less popular in the grasp study.

Finally, users can also freely increase/decrease the number of fingers when changing the dial width. The paper pieces offer a shape close to a cylinder. Users can place additional fingers anywhere around the circumferences.

6.4 Design of Applications and Gestures

We collected opinions on dials that change height and width through design sessions with end users. We provided ExpanDial (Figure 6.11) as a probe. We aimed to gather feedback and suggestions on (1) our ExpanDial prototype, (2) applications, and (3) gestures to change the height and width. We conducted two group interviews. Each interview consisted of five people and lasted about 80 minutes. During the interviews, we took pictures and recorded audio with participants' consent.

6.4.1 Participants

We recruited 10 participants (2 females) from our university. Their age ranged between 25 and 43 years old. They were Ph.D. students or post-docs in computer science, HCI, machine learning, geomatics, compilers, etc.

6.4.2 Procedure

We had a short introduction, followed by an ice-breaking activity. We then asked all participants to try the prototype (Figure 6.11) such as rotating, clicking, and squeezing. They were asked to write down their answers to the following questions on sticky notes: (1) What do you like/don't like about the dial? (2) What would be the dial's applications? (3) Let's say you know that you can change the dial's width and height, but you don't know how. What kind of actions or gestures would you perform? They were asked to consider only the dial and not the case. They were asked to think that the device works perfectly and sense the width and height change by users. After each question, the participants shared their ideas with others while putting the notes on a board.

For the second question, we asked the participants to think in the frame of application areas (work, home, entertainment, others) and modalities (control and/or display), where ExpanDial may be able to support current applications and replace existing current interfaces. It was also to guide the participants to focus on shape-changing dials as interfaces rather than as new devices (e.g., a shape-changing road in a public ideation [168]). By doing this, we expected the participants to generate application ideas that can reveal potential advantages and challenges of shape-changing dials.

For the third question, we asked participants to think about at least one gesture for each of the following control methods of the dial: increasing width, decreasing width, increasing height, and decreasing height.

6.5 Results

The interviews suggested design improvement for our ExpanDial prototype, future applications of shape-changing dials as well as gestures to change the shape of the dials.

6.5.1 Q1. ExpanDial Improvement

Here we report the opinions about ExpanDial that were repeated over once or not repeated but interesting for us.

Six participants liked the haptic feedback of the prototype. They said that squeezing the device is fun and relaxing, as well as soft but sturdy enough to interact with. One of them liked that it can give haptic feedback even when he is not looking at the device. Five people liked the visual aspect of the device, mentioning that it was aesthetically pleasing, and the origami pattern well showed how the width can be changed.

Four people liked that the dial could control multiple parameters, removing the need for many devices. Two people talked about ergonomic aspects of the device; one liked that it could fit in different hand sizes, and the other liked that it could fit in his one hand. Two people mentioned that they liked the new interaction of having both control and display on a device and also moving an arm up/down, as they did not perform much of such interaction at work. One person mentioned that the size is good enough to find it on a desk without looking (like a mug).

On the other hand, six participants were concerned that the prototype looked fragile, especially the paper layers and the connectors for them. Three people complained about the finishing state of the prototype: sharp edges, too stiff connectors and unfinished look. Similarly, two people were concerned about the maintenance of the prototype: the device had too many parts and it might not be easy to fix it when a part breaks; and the creases seemed hard to clean when they get dusty.

Three people said that the dial was too easily squeezable so that it could cause unwanted squeezing while grasping or rotating. Also, two said that the possible range of widths and the value the width was indicating were not clear. Another two complained that they could not "squeeze" the device vertically. One person mentioned that it might be difficult to control multiple parameters with the device because it would be hard to remember all the parameters.

6.5.2 Q2. Envisioned Applications of ExpanDial

The participants suggested 44 application ideas (avg. 4.4 ideas per participant), and 41 of them were relevant to height or width changing dials. We used the 41 ideas in the analysis. We revisited all the ideas to categorize them into the application areas and

control/display modalities (see Figure 6.14). We allowed multiple categories for the application areas (Figure 6.14 left). E.g., a participant categorized a 3D interaction idea to the work category, but it could also belong to the entertainment, for VR games. In this case, we allocated the idea to both categories. We did not allow multi-selection in the control/display modality categorization as it was mutually exclusive (Figure 6.14 right).

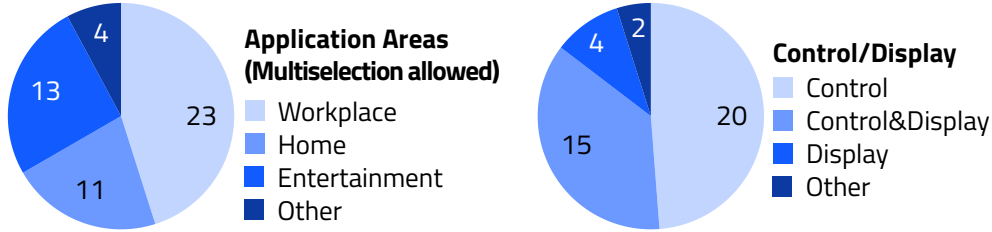


Figure 6.14: The application areas and control/display modality of envisioned application ideas.

After the categorization, we added context or detailed interaction when applicable. In the below sections, we describe the ideas based on the application areas and modalities. We introduce the ideas a single time either through its application area or modality, unless both are interesting.

Ideas based on application areas

In total, 23 ideas were categorized into work, eleven were categorized into home, thirteen belonged to entertainment, and four belonged to the others (Figure 6.14 left).

Around half (11/23) of the work ideas were using ExpanDial to interact with desktop computers. It was not surprising as participants were from Computer Science. Seven of them were using ExpanDial for 3D interaction or graphical tools, e.g., changing camera-view in a 3D modeling software and changing airbrush size in Photoshop by rotating or squeezing the device. The rest of the desktop computer interaction ideas were OS level interactions, e.g., users squeezing the dial to minimize all windows, or the dial changing its width to notify new emails.

Only three of the work ideas were not related to desktop computers: using the dial as a controller of a surgery robot or a construction machine. E.g., the width would change when patients' heart rate dropped around a limit.

Many of the home ideas (7/11) were about controlling remote home appliances and displaying information about them, as in smart home scenarios. Three other ideas were changing the width and rotating the dial to set the temperature or the timer of an oven. The system changed the dial height and/or width to show remaining time (Figure 6.15a). The last idea was using the dial as a morning alarm clock. E.g., users set the time by rotating the dial, and the dial would become larger and larger until

that users cannot ignore it anymore. The participant said that the dial would have light inside, and it would get brighter as the set time comes as well (Figure 6.15b).

Among the 13 ideas in the entertainment category, five were related to gaming. The system gives feedback on the game status (e.g., the character in a danger) with shape-changes, or users squeeze the dial to activate certain functions. Two ideas were using the dial to control multiple audio parameters (e.g., volume, distortion, tone) at the same time. Another two were to use the dial as stress release by squeezing it.

Ideas in others category were general interaction methods and could be applied to any applications or systems. Two of them were using the particular design of ExpanDial (i.e. origami), e.g. using each paper layer for discrete control or display. For instance, each layer could set or display the temperature of each room in a house. Another idea was to change the dial size for better ergonomics, e.g., smaller sizes for small children or bigger sizes for elderlies who lack fine motor skills [168]. The last idea was to give force feedback when the system cannot perform a desired function. E.g., users try to squeeze the dial to reduce a Photoshop brush size while the size is minimum. The dial gets stiffer and prevents any further squeezing.

Ideas based on the control and/or display modality

Twenty ideas categorized into control, fifteen into both control & display, four into display, and the last two into others (Figure 6.14 right). For these categories, we did not allow multi-selection as they were mutually exclusive.

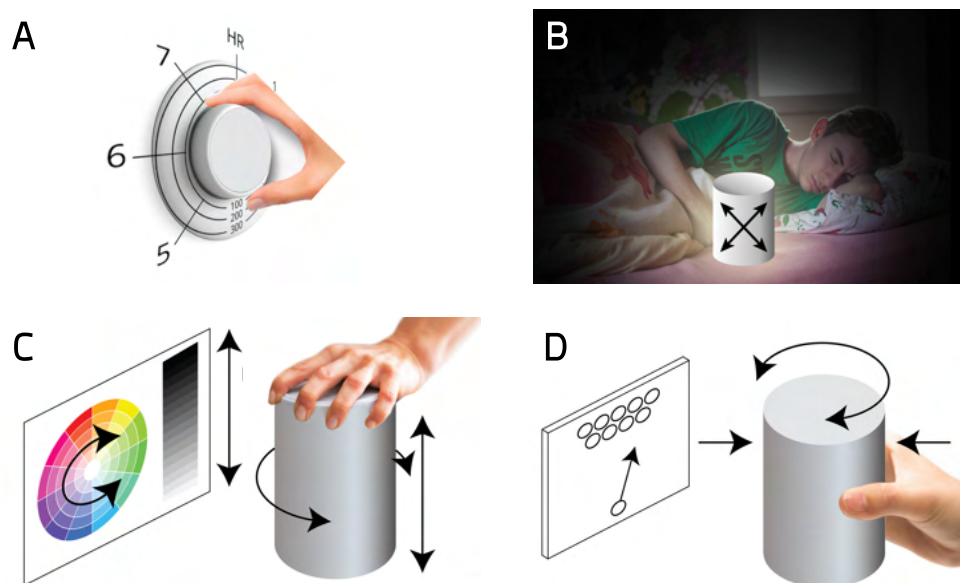


Figure 6.15: Examples of envisioned applications of ExpanDial. (A) timer and temperature setting for an oven. (B) An alarm clock that gets bigger and brighter as the set time comes. (C) Using the dial to explore a color space. (D) A rehabilitation game.

Half of the control ideas (10/20) were controlling multiple parameters by using the shape-changing ability of ExpanDial. For example, users can explore a color space (Figure 6.15c), or change transparency and size of a brush by rotating, squeezing, and change height of the device simultaneously. There was no idea of controlling different parameters by changing the force or speed of interaction, which was suggested in Dynamic Knobs [76]. Two control ideas were combining the dial to existing devices, such as a joystick or Wii[®] remote.

Fifteen ideas were in the control & display category. Among them, ten were to give haptic or force feedback with the width/height change of ExpanDial. They included to force users to use different forearm muscles (e.g., rehabilitation game, Figure 6.15d), to give immersive experience (e.g., force feedback for an airbrush interaction in VR), and to notify users when they are holding the dial (e.g., expanding the width when there is an urgent task while scrolling through a to-do list with rotation). A control & display idea was using the dial combined with a mouse, to scroll by rotating or to notify users of desktop events by expanding the width, similarly to the Inflatable Mouse [103].

One display idea was to use the device as a shape-changing ambient or peripheral display as in previous work [77, 206]. The participant said that ExpanDial would animate air quality in a room with a breathing rhythm (i.e., slow breathing when the air quality is good and fast breathing in the other case). The other two ideas were changing the width or height to notify a new email or that a cooking timer has finished.

6.5.3 Q3. Gestures for Shape-Changing Dials

We collected 48 gesture ideas to increase or decrease the circumference width or height of ExpanDial (see Figure 6.16). After merging duplicated ideas, we got on average six types of gestures per interaction: increasing width, decreasing width, increasing height, and decreasing height. We describe the overall findings and discuss them in the below section.

Changing the width

Nine ideas were to rotate the dial to increase or decrease the circumference width. Two participants explained that the interaction is the same with rotating screws, while one participant said it was using centrifugal force. To distinguish the rotation for width-change from the one for rotational input, the participants suggested three ideas:

- Using different speed (e.g., quicker rotation for width change).
- Rotating while pulling up the dial for width change.


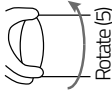


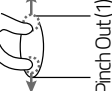
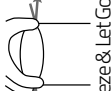
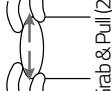
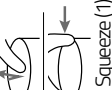


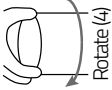


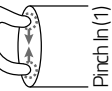
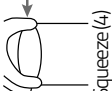

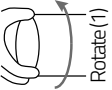


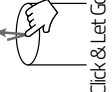
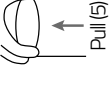





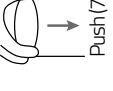
Interactions	Rotate	Slide	Tap	Pinch	Decr. Width/Height & Let Go	Direct Deformation	Click & Action	Use All Fingers	Use Segments
Increasing Width 	 Rotate (5)	 Slide Outward (1)	 Tap (1)	 Pinch Out (1)	 Squeeze & Let Go (1)	 Grab & Pull (2)	 Click & Squeeze (1)	 Stretch Out (1)	
Decreasing Width 	 Rotate (4)	 Slide Inward (1)	 Double Tap (1)	 Pinch In (1)	 Squeeze (4)				
Increasing Height 	 Rotate (1)	 Slider Up (1)	 Double Tap (2)/Tap (1)	 Click & Let Go (2)	 Pull (5)	 Click & Push (1)			Add Segments (1)
Decreasing Height 	 Rotate (1)	 Slide Down (1)	 Tap (2)/Double Tap (1)	 Push (7)					

Figure 6.16: Suggested gestures to increase/decrease circumference and height of dials. The numbers in the parenthesis show how many participants suggested the gesture. Left column: targeted shape-changes of the dial. Right columns: suggested gestures and how frequently they were suggested (in parenthesis). They are vertically aligned by their similarity with other shape-change gestures (e.g., Squeeze & Let Go for width increase and Squeeze for width decrease were suggested together).

- Having two rotational modes of the dial such as a mouse scroll wheel that has friction and non-friction modes (e.g., on Logitech MX Master 2S).

Six ideas were inspired by touchscreen gestures. I.e., sliding outward or inward on the top of the dial, tapping or double-tapping side of the dial, and pinch-out or pinch-in on the dial. One participant said that she prefers touch gestures as they were simple, and she would feel lazy to do other gestures (e.g., rotating).

Four ideas to decrease the width were squeezing the circumference, and the gestures to increase the width varied (Figure 6.16, four gestures on the top row right). They varied as four types of gestures:

- Squeezing the circumference quickly, to activate its expansion, and grasping it again, to stop the expansion at the desired width.
- Grasping and pulling the circumference outward.
- Clicking the top of the dial to reset it to the biggest width and then reduce the circumference.
- Putting all five fingers on the dial and stretching out the fingers.

Changing the height

Only two of the height-changing gestures were rotating the dial. Although two participants said that the rationale of rotating ideas for height change was from rotating screws, surprisingly fewer rotating ideas were suggested for height change than for width change.

Similar to the width-changing gestures, touch gestures (slide and tap) were also suggested for height change. The gestures stayed the same from the width change gestures, but the locations of the gestures changed: sliding on the side of the dial and tapping on the top of the dial. The directions of the finger movements were parallel to the direction of the height changes, not perpendicular.

Five ideas revolved around pulling up or pushing down the dial, although two participants mentioned that they would feel lazy to move their arm upward. An idea was clicking the dial to make it go back to the maximum height then decrease the height by any other gestures. The last idea was manually adding more layers of segments (e.g., layers of folded paper), which was probably inspired by the unique design of ExpanDial based on origami folding.

Table 6.1: Comparison of KnobSlider and ExpanDial based on the design requirements from Chapter 3. Understanding interactions with control interfaces.

Design Requirements	KnobSlider	ExpanDial
R1. Interaction with a large number of parameters	+ Two parameters	++ Three parameters
R2. Fast interaction	+ Sequential control of the parameters. The shape-change takes 0.1s.	++ Simultaneous control of the parameters
R3. Precise interaction	+ Same precision as standard dials and sliders	? Unknown for width and height change
R4. Eyes-free interaction	+ Eyes-free interaction during dial or slider state	++ Eyes-free interaction at any state
R5. Mobile interaction	+ Small enough for a mobile surface	- No mobile interaction due to the case
R6. Retro-compatibility	+ Provides a button, dial and slider	+ Provides a dial

6.6 Comparison with KnobSlider

We focused on enhancing flexibility in control interfaces by allowing simultaneous input of multiple parameters on one device. The increased flexibility contributed to fulfillment of the design requirements from Chapter 3 (see Table 6.1). First, ExpanDial can control three parameters while KnobSlider could control two parameters (R1. Interaction with a large number of parameters). Second, the simultaneous manipulation of multiple parameters through rotation, height and width changes remove the need of switching between different modes and increase the speed of interaction (R2. Fast interaction). Lastly, users do not need to look at the device when they change the shape, while they had to look at KnobSlider during shape-changes (R4. Eyes-free interaction). However, it is unknown how precise users can change the width and height (R3. Precise interaction). A future study should explore it. Also, the current actuation method of ExpanDial (motors under and around the foldable structure) increased the device size and did not allow users to bring the device on the go (R5. Mobile interaction). Alternative actuation methods such as SMAs or mini motors should be considered to improve it. R6. Retro-compatibility of ExpanDial stays the same to KnobSlider as it takes the shape of traditional dials.

6.7 Conclusion

In this chapter, we systematically explored how users grasp dials with different heights and widths and provide lessons for designing shape-changing dials. Based on the lessons, we designed ExpanDial, a shape-changing dial that can not only accept users' rotation and deformation to enable multi-parameter control on a single device, but also change its height and width to display information. The design session with ExpanDial revealed challenges on designing applications and gestures for shape-changing dials. Our work provides foundational knowledge on users' dial grasp and show how the knowledge can be applied in designing shape-changing dials.

When designing ExpanDial, we took a different approach than KnobSlider. I.e., we used the grasp study results and not the design tools. It allowed us to take human factors into account in the design process and opened up future research questions such as how users would change grasps during shape-changes. To accelerate users' acceptance of shape-changing interfaces, future research should inform the shape-changing interface community with more human factor and ergonomic understanding on shape-changing interfaces. Such studies would help the community strengthen the benefit of shape-changing interfaces in addition to design tools and implementation explorations.

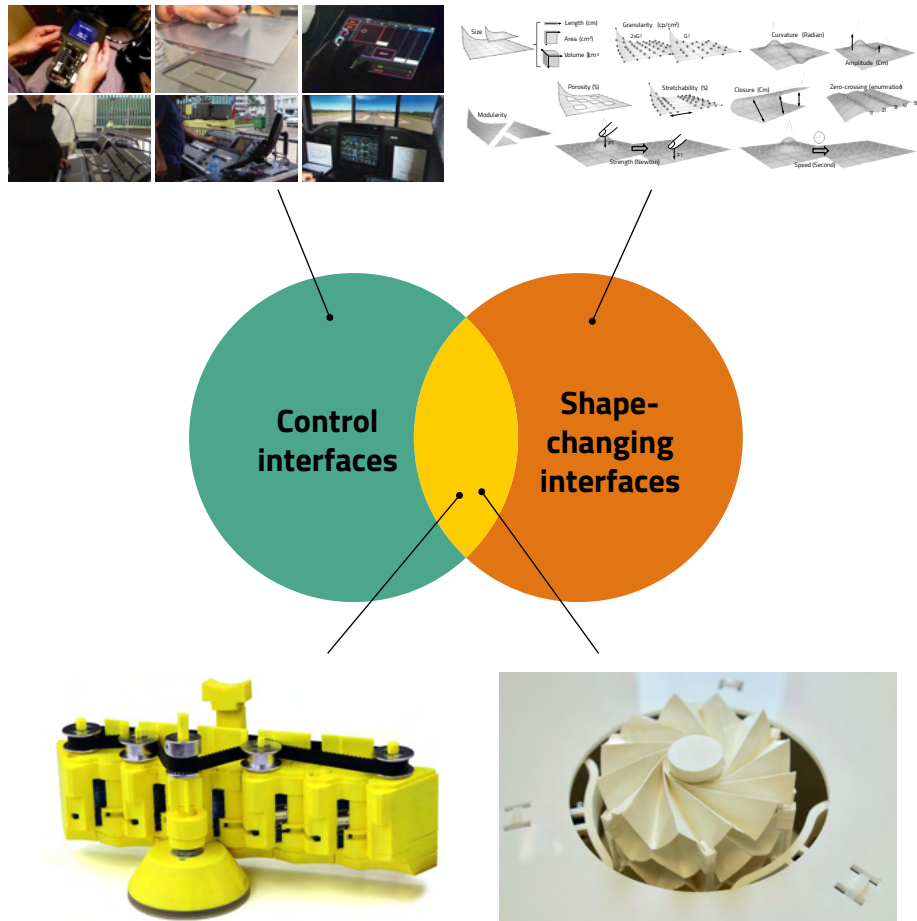


Figure 7.1: Contribution of this chapter: we contribute to the intersection of control interfaces and shape-changing interfaces by looking at the design space of shape-changing dials. We look into grasps of dials and future applications and gestures for shape-changing dials.

Conclusion

7.1 Thesis Contributions

In this thesis, we investigated two areas in HCI (see Figure 7.1 on page 158): (1) control interfaces and (2) shape-changing interfaces. We provided design guidelines for control interfaces and design tools for shape-changing interfaces. By using them, we further investigated the intersection of the two areas, (3) shape-changing controls. We provided two case studies in the area. As a result, we tackled three types of challenges in shape-changing interfaces: user behavior, design, and technological challenges [4]. In this section, we summarize our contributions in the areas in HCI and the three types of challenges.

In the control interface area, there was lack of general design guidelines for future control interfaces, regardless of types of control widgets or particular. Some literature [21, 61, 8] suggested design guidelines for existing control interfaces, but focused on measurements of the interfaces and mechanical designs, e.g., force for actuation. Such guidelines take the interfaces for granted and do not support the design of new types of control interfaces. Other literature [137, 134, 133, 174, 32] suggested design guidelines based on user studies, but they focused on specific devices or target users. In this thesis, we provided design guidelines focusing on users' current interactions with control interfaces. For the interviews, we recruited eight professional users from five professions. Hence the guidelines are applicable to a larger range of professional users. The guidelines are focusing on interactions regardless of types of control widgets, such as mobile interaction and controlling a large number of parameters. Hence, they are not limited to specific types of designs of control interfaces.

In the shape-changing interface area, there were many taxonomies suggested and used as a design tool to design new shape-changing interfaces. However, they were hardly analyzed, improved, and merged, hence their descriptive power remained unevaluated. In this thesis, we evaluated their descriptive power by using everyday reconfigurable objects. We merged missing features into Morpheus, the shape-resolution taxonomy.

7. Conclusion

We also clarified vague definitions of the features of the taxonomy. The merged and improved taxonomy is called *Morphees+* [97]. Researchers can use the taxonomy to describe and inspire new shape-changing interfaces. We also shared the collection of the everyday reconfigurable objects on a public website¹. Designers and researchers can use them when they want another inspirational tool and need a quick implementation of low-fidelity shape-changing interfaces. In addition, they can contribute to the collection by adding more objects.

Lastly, we contributed to the shape-changing control area, by investigating two case studies, *KnobSlider* and *ExpanDial*. Both case studies show that the taxonomies and the everyday reconfigurable objects can be used to generate new forms of shape-changing controls. Also, the design requirements from the contextual interviews were used to evaluate the designs. With *KnobSlider* [99, 101, 100], we also conducted qualitative study with professional users, to show how *KnobSlider* fulfills or does not fulfill the design requirements. The study motivated the subsequent perceptual study on speed of shape-change. The results show that users prefer a certain range of speed, and the preference can be different if the device is shown in the real world or on videos.

To further investigate suggest shape-changing controls that better fulfills the design requirements, we suggested *ExpanDial* [102]. *ExpanDial* is a shape-changing dial that allows simultaneous control of three parameters. Unlike *KnobSlider*, *ExpanDial* does not have separate states and users can control the rotation, width, and height of a dial at the same time. To design *ExpanDial*, we explored used the *Morphees+* features that were not used in *KnobSlider* (Length and Area). Before implementing the device, we conducted a grasp study to provide design guidelines for shape-changing dials. We concluded the case study by demonstrating some of the applications and gestures to initiate the device's deformation through a focus group study.

¹<http://phyflex.imag.fr/EverydayObjects.html>

7.2 Limitations and Short-term Future Work

Our studies have limitations and raised further questions for future studies. Here we discuss the limitations and future work of this thesis.

7.2.1 Design Requirements for Control Interfaces

The contextual interviews provided design requirements for users with diverse professions that use linear and rotary controls, in contrast to previous work that has often targeted single professions (e.g., musicians [184] or cooks [200]) or the general public [66]. Future studies can include a wider range of professions, such as engineers in factories or power plants. It would also allow categorizing user groups depending on their task risk, complexity, etc. For example, pilots and engineers in power plants can have higher stake for making mistakes. The categorization and in-depth analysis on their tasks would help providing tailored design guidelines for each group of users.

Moreover, the retro-compatibility requirements should be further studied to quantify shape-changing interfaces' retro-compatibility and help their adoption by professionals. KnobSlider could provide better retro-compatibility than touchscreen interfaces thanks to the physicality. However, the users in the qualitative said that the sliding of the slider cursor should be smooth, and the size of the device should be reduced. It shows that retro-compatibility can include many factors, and they should be listed, categorized, and prioritized for efficient exploration of new control interfaces.

The professional users in the qualitative study were excited by the reconfigurable aspect, suggesting they are open to adopting flexibility through shape-change. The current approach in the industry for embedding flexibility is to provide touchscreen interfaces², while a recent accident³ suggests that such interfaces increase mental load and physical controls are better. Shape-changing controls can be a next step to provide both flexibility and physicality. To design broadly deployable shape-changing interfaces, future studies can continue comparing the mental load, accuracy, and efficiency of GUIs, PUIs, and shape-changing interfaces, as in [148, 137].

Lastly, a long-term field study should be conducted to study how professionals adapt shape-changing interfaces into their daily workflows. The interviewed users needed dynamic interaction in timely manner and mistakes could be critical. The study can investigate how to design shape-changing interfaces to support various context including stressful and risky situations such as in a cockpit. It can also study how to promote users' transition to expert functions, as shape-changing interfaces will get more sophisticated. It can refer research in GUI, e.g., [158].

²E.g., THALES Avionics 2020 or Slate Media Technology RAVEN MTi2

³https://www.theverge.com/2019/8/11/20800111/us-navy-uss-john-s-mccain-crash-ntsb-report-touchscreen-mechanical-controls?fbclid=IwAR2uD4hqD6nT2urQfZXmPyFMQN6FL3pck2KwoT58UgC_IrhK30EHkFHW1IQ

7.2.2 Design Tools for Shape-Changing Interfaces

A limitation of Morphees+ is the lack of exhaustive coverage of everyday objects. To improve this, the collection of everyday reconfigurable objects is now open for contribution [98]. Another limitation of the work is the classification’s subjectivity. To address this problem, the general public could be engaged in the future in the classification through gamification [181].

Another limitation is that we do not know if some features are underused because of technical limitations, or because end users do not perceive them well. Future research should reveal the relationship between an actual change in shape and its perception by users [89].

Most objects we collected are manually reconfigurable and thus only inform us on shapes at a state, and not how they transit between states. Features like Morphees’s Speed [149] thus seems orthogonal to the others. Rasmussen’s taxonomy [145] treats this feature separately, alongside other kinetic parameters. Further investigation is needed to investigate these kinetic features.

Future work should collect reconfigurations inspired by nature⁴. Example of these are armadillos who roll up into a ball when threatened by a predator and Venus flytraps that snap shut when insect crawl on their leaves. Studying their mechanisms can reveal new, miniaturized, and sustainable shape change mechanisms.

An important next step is to evaluate Morphees+, to ensure that the improvements presented here also benefit research. As a form of evaluation, we plan to verify that the refined taxonomy can describe existing interfaces and inspire new ones.

Once Morphees+ is evaluated, we can apply it to literature that used Morphees as an inspirational tool. For example, a large-scale user study of shape-changing mobile phones [139] used Morphees features for the design of the phones. We can conduct the same study but with the added features and learn what kinds of affection and functionality they provide.

Lastly, we wonder if we can also apply Morphees+ in other research fields, which involves physical reconfiguration. Metamaterial is a good example. A previous work [10.1145/3173574.3173910] investigated a wide range of reconfigurable vocabulary for texture-changing material. We wonder if Morphees+ can widen the vocabulary.

7.2.3 Users’ Acceptance of Shape-Changing Interfaces

Due to technical limitations, the implementation of KnobSlider became larger than we expected and the height of the dial status forced the users not to rest their arms or palms when rotating it. Also, the width of the dial status forced them to grasp it from the top and rotate with their entire hands, while in the formative study they mostly approached the small dials from the side and used two fingers only. A future study

⁴E.g., <https://asknature.org/>

should implement the device with dimensions similar to existing dials and sliders, so that users can keep their micro-gestures on the devices. Lastly, the length of the slider is fixed and do not provide flexibility to users to balance between precision and performance time [32]. Considering that many participants preferred large sliders, future studies can investigate the spiral-based low-fidelity prototypes (Idea 1. Slap Bracelet and Idea 2. Party Whistle).

In the controlled study, we learned that users do not like too fast shape-change. Physicality also affects the preference on speed: users preferred slower shape-changes with the physical device and faster shape-changes on videos. It means that studies using videos for perceptual studies, e.g., [84, 143], should consider the confounding factor of the *physicality* (i.e., whether the device is in the video or in the real world). To enable researchers to freely use videos instead of physical devices when they have limited resources, future studies can find a mathematical model of speed preferences on physicality. For example, the participants in our study preferred the shape-changes on videos four times faster than the shape-changes on the device. Future work can further verify how much faster speed is preferred on videos than physical devices and provide a formula such as:

$$PreferredSpeed_{Video} \approx C \times PreferredSpeed_{Device}, \text{ where } 0 < Speed < \infty$$

It would be interesting to investigate whether the necessity of touching shape-changing interfaces would affect the speed preferences or not. Also, the distance between users and the device might have affected the result—the device was at a reachable distance. If the device was meant for information display and far from the users, the result could have been different. The volume of shape-change can affect the preference as well. Additionally, if users know beforehand that the device would change the shape, they may prefer faster shape-changes. A future study can investigate the effect of users' interaction and the user-device distance on speed preference. In summary, the preference can be initially formulated as:

$$PreferredSpeed_{Device} \approx \frac{T \times \log Distance \times PreferredSpeed_{Device} \times Vol}{K},$$

where $T_{NeedToTouch} < T_{NoNeedToTouch}$,
 $K_{KnowingShape-Change} < K_{NotKnowingShape-Change}$,
 $Vol = VolumeOfPartMoving \times MovingDistance$

Once the formula is validated, future studies can use the estimated preference to adjust the amount of surprising feelings from shape-changing interfaces. For instance, control interfaces would be not need surprising feelings to maximize their efficiency. However, artistic shape-changing interfaces can trigger surprising feelings on purpose, e.g., [66].

Lastly, the folding design raised ergonomic issues. For example, users cannot rest their hands on the device during shape-changes, because the folding and unfolding of the device can pinch their hands. A future study should consider ergonomic aspects of shape-changes such as where users' hand should rest during shape-changes, in addition to the design requirements from the formative study. Such studies have not been done because shape-changing interfaces are relatively new, and most studies have been

7. Conclusion

focusing on fabrication methods of the interfaces. It would be interesting to explore dynamic ergonomics, how the kinetic parameters of shape-changing interfaces—e.g., speed, path, direction, and space [145]—would affect ergonomics. From the observations in our study, we suggest future designs of shape-changing interfaces not to disturb the grasp on the device during shape-change.

7.2.4 Considering Ergonomics in Shape-Changing Interfaces

A limitation of the grasp study in Chapter 6 is that the study was based on static dials. Future work should first investigate if users keep the initial grasps while rotating a dial. The study should consider additional factors, such as rotational friction and the friction between the dial and fingers. Users would probably use more fingers when there are high rotational friction and low friction between the dial and fingers.

Future work should investigate how users dynamically change their grasps according to the size of a dial changed by the system. Users may have different strategies depending on whether they know the final size of the dial. For instance, when users know which size the dial would have at the end of the shape-change, their grasp would be prepared for the final size. When users cannot predict the final size, they may wait until the shape-change ends, rather than continuing a task. To measure their dynamic grasp, future work can design a study where users need to continuously rotate the dial. The task should be balanced to give enough time for grasp change.

When users can activate the shape-changes, the dynamic grasp study should consider more factors, such as the force resistance for squeezing gesture. When the force resistance is high, for example, users may feel more comfortable to grasp the dial from the side, as it would allow more contact area with the hand and possibly more squeezing force.

The participants were concerned about their own capability to control the width and height of ExpanDial. This raises the question of the human resolution [11, 12] for these deformation gestures. A future study should measure the precision of the gestures and prices for the precision such as muscle tension.

The participants were also concerned about their ability to properly perceive a change in width and height. A study of Jansen et al. [89] showed that different heights of bars can be recognized, which can be applied to the height of the dial. However, the question remained unanswered for the width. More importantly, we do not know if users can perceive the change in height and width while they are conducting a task with the dial. A future study should investigate it. If it is not easy for users to perceive it, another study should investigate how to design shape-changes perceivable.

The participants were concerned about the undesired width change when grasping or rotating the prototype. Future work should study how much pressure users may apply to rest their hands, to rotate the device, and to change the width or height of the device.

The participants proposed applications in work and entertainment domains. This suggests that performance, emotional and hedonic user experience [145] of shape-changing dials should be studied. Some of the work ideas were less error-tolerant and needed more concentration on the tasks (e.g., surgery robot interface) than others (e.g., desktop interaction). This raises the following questions: can the force/haptic feedback provided by the ExpanDial provide distinguishable warnings and notifications? How can such a shape-changing device balance between notifications and users' focus on their tasks?

Interestingly, many of the suggested gestures were from touchscreen interactions. On the one hand, one of the aims of shape-changing interfaces is to fully use human's dexterity [86], and thus mapping touchscreen-based gestures to them might not fully exploit their capabilities. On the other hand, it could improve users' learnability and transition from touch interfaces to shape-changing ones. The challenge lies in finding a trade-off between gestures that are general and easy to be applied to all kinds of interfaces and gestures that leverage the input capabilities for each particular interface.

Many of the non-rotating gestures (e.g., slide, pinch, click & action) were using the top of the dial. It may be related to our grasp study where we found that users grasp dials mostly from the top. Squeezing, pushing and pulling also require grasping the device, but they are new interaction with dials and users may have different grasps from rotating. Future work can study users' grasp change for those interactions.

7.3 Perspectives for Future Shape-Changing Interfaces

In this section, we explore questions for future shape-changing interfaces and try to guess what likely to happen based on the trend of the society and technology.

7.3.1 Pushing the Boundary of Materials and Implementation Methods

Current implementation of shape-changing interfaces is largely rely on mechanical actuations (motors) [51, 206], SMAs [149, 136], and pneumatic actuation [72, 204]. To push the boundary of shape-changing interfaces, future studies should explore novel materials from other fields, such as material science [4, 140]. Such exploration has already started, e.g., using self-healing materials [128, 199]. Novel materials have been investigated in many fields, but how to use them for user interfaces is little explored. HCI should actively explore them (1) to overcome the limitations of current implementation methods (e.g., the self-healing materials would not have the problem of the gap on a surface due to mechanic actuation [137]) and (2) suggest applications that can leverage the limitations of novel materials (e.g., slow healing time).

The exploration of novel materials should consider environmental impact as well. The implementation of shape-changing interfaces require many parts such as actuators and plastic case. It makes the maintenance of the devices more difficult [4]. One promising way is using bio materials such as bacteria [203]. There are many kinds of bacteria and they have different characteristics. For example, they can generate electricity from light [155] and heal cracked cement [199]. We imagine bioengineering bacteria for shape-changing interfaces would reduce environmental impact. One thing to note about bacteria is that they are sensitive to environment such as temperature, humidity, and food sources [203]. Then users may need to take care of the bacteria-based shape-changing interfaces instead of just using them. If so, how would it change the relationship between users and the interfaces? As long as the interfaces do not require great care, users may feel more attached to the interfaces and consider them as partners [179].

7.3.2 Shape-Changing Objects Everywhere

Currently, shape-changing interfaces stay in the area of research. Very few of them are commercialized and they focus on special purposes such as marketing⁵. To benefit end-users in daily life, future studies should investigate a standard platform allowing physical prototyping of shape-changing interfaces. While 3D printers and other fabrication tools are wide spreading, building reconfigurable objects still require substantial modeling skills and design iterations. 3D printing and combining actuation electronics take many hours and significantly slow down the design process. Future study should extend a research direction of physical toolkits for reconfigurable objects

⁵<https://www.youtube.com/watch?v=geMEB8zJLiU>

[71, 112, 141]. Such physical toolkits should enable physical exploration of full lexica of shape-changes, such as Morphees+ [97]. It should provide end-users with broad design vocabularies and great usability with simple physical mechanics such as Lego. We believe that physical toolkits will be more important for the future generations, as they would probably have different design requirements from the participants in the contextual study (Chapter 3, aged between 25 and 63). For instance, the participants in the design session for ExpanDial (Chapter 6) were younger (mostly between 24 and 30) and suggested gestures from touchscreens. Even younger generations would be more familiar with touchscreens and may need less retro-compatibility with control interfaces. As we do not know design requirements for them, they should be able to design interfaces through the toolkits.

Some research started investigating large scale shape-changing interfaces. Shape-changing furniture [65, 125], a VR haptic platform that users can sit [178], and room-sized shape-changing objects [105] are examples. Scaling up shape-changing interfaces go further by implementing shape-changing walls in research [206, 173] and commercial buildings⁶⁷⁸. Such exploration would benefit users to use their living and working space more economically and customize their spaces. Such ideas are being prototyped⁹¹⁰. However, the flexibility of current approaches is quite limited: users can change the shapes of furniture and space in the way the designers designed. We believe the flexibility of large-scaled shape-changing interfaces would expend by allowing users to design new designs and reconfiguring modular shape-changing interfaces. Such shape-changing furniture and space would not be necessarily interfaces. Shape-changing interfaces can benefit this area by applying existing shape-change mechanisms in this area.

7.3.3 Shape-Changing Interfaces as a Part of Human Bodies

We believe that humans naturally want to be "better." With the such instinct, bio-hackers hack their bodies to make their bodies and brains function better¹¹. Futurologists also say that humans will try to be "superhumans" [70]. Research has been pushed in this direction by the superhuman visions¹² and medical purposes [26].

With shape-changing interfaces going small scale, they will be on and in human bodies following the trend of Unlike wearable-oriented approaches. Small-scaled shape-changes are already shown, e.g., by using SMAs [69], pneumatic actuation [164], and magnetic fields [121], and they would be different from wearable-oriented approaches [81, 204, 203, 13] or robot-oriented approaches [113]. Small-scaled shape-changing

⁶https://www.architectmagazine.com/technology/detail/detail-mayseptember-installation-at-eskenazi-hospital-parking-garage_o

⁷<https://www.dezeen.com/2017/06/09/foster-heatherwick-complete-shanghai-arts-centre-curtain-like-facade-fosun-foundation-theatre-architecture/>

⁸https://www.boredpanda.com/geometric-sun-shades-al-bahar-towers-abu-dhabi/?utm_source=google&utm_medium=organic&utm_campaign=organic

⁹<https://www.youtube.com/watch?v=bmIrRRFVHrA>

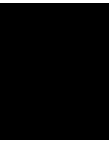
¹⁰<https://www.youtube.com/watch?v=dAa6bOWB8qY>

¹¹<https://www.youtube.com/watch?v=NWvUs8el8-A>

¹²E.g., <https://www.wired.com/story/heres-how-elon-musk-plans-to-stitch-a-computer-into-your-brain/>

7. Conclusion

interfaces can provide subtle change in human bodies, e.g., creating small bumps on skins. We can think of several ways the interfaces can be used: (1) advancing or intervening human senses e.g., a shape-changing structure on ears can help hearing sound from far focused area or blocking sound, and (2) enhancing self awareness and consciousness through gentle haptic feedback, e.g., slightly squeezing or stroking arms when users are stressed. Future studies should further investigate applications of on-body or in-body shape-changing interfaces. In a long-term, they should also investigate the interfaces' impact on humans' mind and body.

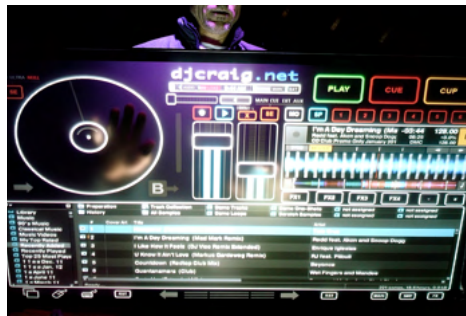


Résumé en français

Cette thèse contribue au domaine de l'Interaction Humain-Machine, un domaine de l'informatique axé sur la conception et les technologies de l'interaction entre les utilisateurs et les ordinateurs. L'objectif principal de la thèse est d'améliorer la flexibilité du contrôle des interfaces physiques, en particulier via le changement de forme physique. La flexibilité, ou souplesse, est la capacité d'une interface à fournir de multiples moyens aux utilisateurs et au système d'échanger de l'information [39]. Cette flexibilité se trouve souvent dans les interfaces utilisateur graphiques (GUI). Par exemple, les utilisateurs peuvent personnaliser la palette d'outils dans Photoshop®, et le système peut ajuster les fenêtres pour les adapter à l'écran. D'une part, la souplesse des interfaces est important pour l'utilisation souvent changeante des systèmes numérique. D'autre part, la physicalité des interfaces utilisateur physiques (PUI) fournit un retour d'information haptique passif riche grâce à leurs formes physiques. En cela, elles permettent un contrôle de l'ordinateur sans regarder [161]. Les PUIs exploitent la mémoire spatiale [29], permettent l'interaction directe [10, 161], et exploitent la dextérité humaine [40]. Cependant, les PUIs manquent souvent de flexibilité. Par exemple, les phicons—icônes physiques, représentants physiques de l'information numérique qui peuvent remplacer les icônes graphiques [85]—sont souvent statiques, et les utilisateurs doivent utiliser d'autres phicons quand ils changent de tâches ou de paramètres à contrôler [161]. Cela se produit en particulier avec les interfaces de commande telles que les boutons rotatifs et les boutons linéaires, qui sont très répandus : ils conservent leur forme tout au long des interactions. Ils ne s'adaptent pas aux paramètres que les utilisateurs contrôlent à chaque instant, à l'environnement de travail des utilisateurs ou aux utilisateurs eux-mêmes. Dans cette thèse, nous abordons le problème du manque de flexibilité des interfaces de contrôle physique à travers les interfaces à changement de forme. Les interfaces à forme physique variable permettent une grande flexibilité. Pour intégrer la flexibilité dans les interfaces de contrôle, nous suivons une approche en trois étapes : (1) nous étudions les avantages et les limites des interfaces de contrôle actuelles au moyen d'une étude empirique ; (2) nous proposons un outil de conception pour les interfaces à forme variable ; et (3) nous démontrons et évaluons deux études de cas basées sur les leçons de l'étude empirique et les outils de

8. *Résumé en français*

conception.



(A) Console de mixage audio à écran tactile



(B) Console de mixage audio physique

Figure 8.1: Mélangeurs audio (A) virtuel et (B) physique. (A) *Matrix DJ Touchscreen System*, un mélangeur audio à écran tactile, fournit de la flexibilité à ses utilisateurs. Il permet à l'utilisateur de prérégler plusieurs “fenêtres” avec des éléments d’interface, et de passer d’une fenêtre à l’autre pendant la lecture audio. Image utilisée ici avec l’aimable autorisation de Cal Blanco. (B) un mélangeur audio physique : les utilisateurs peuvent contrôler plusieurs paramètres simultanément grâce à retour haptique passif des éléments de contrôle.

8.1 Contexte

8.1.1 Interfaces de contrôle

Les interfaces de contrôle font référence aux widgets de contrôle de paramètres tels que les boutons poussoirs, rotatifs ou linéaires [88]. Ils sont également nommés “contrôles” ou “éléments de contrôle” [8]. Ils se divisent en trois types d’interaction : binaire (p. ex., boutons poussoirs), rotationnelle (boutons rotatifs) et linéaire (p. ex., boutons linéaires). Les interfaces de contrôle sont largement utilisées dans les tâches professionnelles telles que le mixage du son¹ et le contrôle de la lumière². Ils existaient déjà avant la numérisation des données analogiques telles que les tables de mixage³, donc les utilisateurs sont habitués à ces interfaces. Chaque widget peut être associé à un ou plusieurs paramètres d’une tâche, et les associations sont supposées rester les mêmes pendant la tâche. Elles se distinguent des autres interfaces conçues pour modifier l’association entre le dispositif physique et l’objet de la tâche numérique, tels que la souris, le clavier ou l’interaction gestuelle.

Les interfaces de contrôle peuvent être graphiques (GUI) ou physiques (PUI) (voir Figure 8.1). D’une part, les interfaces graphiques de contrôle offrent une grande flexibilité, par exemple en changeant l’interface en cours d’utilisation. Par exemple, une console de mixage tactile ne peut afficher que quelques boutons linéaires virtuels lorsque les besoins de contrôle sont simples. Le même écran tactile peut ensuite afficher beaucoup plus de widgets lorsque c’est nécessaire (Figure 8.1A). D’autre part, la physicalité permet une interaction plus riche que les interfaces graphiques, qu’elles

¹<https://www.bax-shop.co.uk/digital-mixing-desk/behringer-x32-digital-mixer-and-usb-midi-controller>

²<https://www.bax-shop.co.uk/dmx-lighting-controllers/eurolite-color-chief-dmx-controller>

³https://en.wikipedia.org/wiki/Mixing_console

soient tactiles ou avec une souris. Par exemple, les utilisateurs peuvent saisir les widgets avec leur main, ce qui leur fournit un retour haptique sur la façon dont ils contrôlent les widgets (Figure 8.1B).

Les interfaces de contrôle forcent aujourd’hui les utilisateurs à choisir entre la flexibilité des interfaces graphiques ou la physicalité dans les interfaces physiques. Ils doivent donc renoncer aux avantages de la flexibilité ou à ceux de la physicalité. Pourtant, de récentes recherches proposent à la fois la flexibilité et la physicalité pour les interfaces de contrôle [133, 134, 32, 148]. C’est aussi l’objectif de cette thèse, pour laquelle nous adoptons une approche centrée utilisateur. Nous voulons d’abord connaître les avantages de la flexibilité et de la physicalité, et explorer comment les combiner dans de nouvelles interfaces de contrôle.

8.1.2 Les avantages de la flexibilité dans les interfaces utilisateur

La flexibilité des interfaces décrit la capacité d’une interface à changer de forme pour s’adapter aux diverses tâches, aux besoins et aux préférences des utilisateurs [156]. La flexibilité est un avantage typique des interfaces utilisateur graphiques (GUI). Un unique système, s’il est flexible, peut être utilisé pour de nombreuses applications différentes. Par exemple un utilisateur moyen utilise 40 applications mobiles chaque mois [180]. La flexibilité permet aussi la personnalisation. Les interfaces graphiques offrent souvent de nombreuses options de personnalisation. Par exemple, pour un bouton rotatif simple, une console de mixage du son tactile permet aux utilisateurs de choisir parmi différentes plages d’entrée et visualisations qui conviennent à leurs tâches [45]. L’interface peut également fournir de nombreux widgets tels que des boutons linéaires, des boutons rotatifs, qui peuvent être déplacés sur un écran à volonté.

Contrairement aux interfaces graphiques, les interfaces utilisateur physiques (PUI) sont des objets du monde réel (c’est-à-dire physiques) qui permettent aux utilisateurs d’interagir avec le monde numérique [36]. Les PUI, bien que permettant une certaine flexibilité, sont beaucoup moins flexibles que les GUI. Un des quelques exemples de flexibilité dans les interfaces physiques est l’interface modulaire telle que Palette[®]⁴. Les utilisateurs peuvent arranger les boutons poussoirs, rotatifs et linéaires, et l’écran, pour créer une interface personnalisée qui convient à leur tâche. Les interfaces physiques peuvent également permettre une certaine souplesse grâce à des correspondances flexibles entre les paramètres. Les tables de mixage audio peuvent avoir plusieurs “banks”: les ingénieurs du son assignent plusieurs paramètres sur un seul bouton linéaire, et passent de l’un à l’autre en appuyant sur des boutons situés à côté des boutons linéaires. Les interfaces physiques sont recommandées pour être spécifiques à une tâche [47]. Cependant, la spécificité de la forme des interfaces physiques limitent actuellement leur flexibilité : les boutons rotatifs restent des boutons rotatifs et les boutons linéaires restent des boutons linéaires. En raison de cette limitation physique intrinsèque, une interface physique se concentre généralement sur un ensemble limité de tâches [161]. Par exemple, une interface physique pour la planification

⁴<https://palettegear.com/>

urbaine remplit des fonctions limitées telles que la simulation des ombres et du vent [192]. Lorsque les utilisateurs changent de tâches, ils doivent également changer leurs interfaces physiques. Ce problème augmente l'encombrement de l'espace physique [190], le volume [41], et le risque de perdre les interfaces physiques [104].

8.1.3 Les avantages de la physicalité dans les interfaces utilisateur

La physicalité est la capacité d'une interface à fournir des caractéristiques physiques (forme, dureté, etc.) qui aident les utilisateurs à accomplir leur tâche, telles que parcourir des images IRM [60] ou zoomer sur une carte [85]. La physicalité est un avantage typique des PUI et apporte de nombreux avantages pour l'interaction :

- La physicalité permet un contrôle sans regarder. Par exemple, même lorsque l'objet de la tâche est loin, les utilisateurs peuvent les contrôler sans regarder l'interface physique. La physicalité d'une interface peut indiquer aux utilisateurs si leurs mains sont bien placées sur le dispositif souhaité. La physicalité permet aux utilisateurs de réduire le temps moyen de réacquisition d'une interface, ainsi que le taux d'erreur pour les tâches de poursuite [88, 148].
- La physicalité tire parti de la dextérité humaine et encourage les utilisateurs à utiliser divers gestes et parties du corps en plus du bout des doigts [161]. Dans Bricks [49], les utilisateurs utilisaient toutes leurs mains et tous leurs bras pour effectuer une tâche de tri de briques de Lego[®], sans avoir reçu aucune instruction. Tuddenham et al. ont approfondi ces résultats en comparant les interfaces physiques et un écran tactile : les utilisateurs utilisaient plus de doigts, plus de positions des mains sur les objets, et plus de mouvements avec les interfaces physiques, alors qu'ils utilisaient surtout le bout de deux doigts sur l'écran tactile [189]. La physicalité des interfaces contribue à la flexibilité dans la mesure où elle permet ces divers moyens d'utilisation.
- La physicalité des interfaces encourage le multiplexage (ou combinaison) dans l'espace plutôt que le temps : un widget physique contrôle souvent une seule fonction. Il permet de faire une correspondance persistante entre les widgets de contrôle et les fonctions [161]. Le multiplexage spatial exploite ainsi notre mémoire spatiale (ou mémoire musculaire). [47]. Il réduit le temps d'acquisition d'un widget [161] et permet aux utilisateurs d'être plus performants qu'avec des interfaces multiplexées dans le temps, telle que la souris [47].

La flexibilité et la physicalité se retrouvent souvent exclusivement dans les GUI ou les PUI : Les PUI manquent de flexibilité (par exemple, le multiplexage temporel) et les GUI manquent de physicalité (par exemple, de retour cutané et kinesthésique). Cela nous amène à la catégorie suivante d'interfaces, les interfaces à changement de forme, pouvant offrir les deux.

8.1.4 Interfaces physiques changeant de forme, permettant à la fois la flexibilité et la physicalité de l'interface

Les interfaces à changement de forme sont des “dispositifs d’interaction destinés à se transformer en toute forme ou matérialité pertinente au contexte d’utilisation” [4]. Ils combinent flexibilité et physicalité au sein d’une même interface et présentent ainsi de nombreux avantages :

- Les interfaces à changement de forme fournissent des widgets d’interaction à la demande. Par exemple, lorsque les utilisateurs ont besoin de peindre un modèle 3D, le modèle peut être rendu physiquement [51]. Lorsque les utilisateurs ont besoin de mettre à l’échelle le modèle 3D, un curseur apparaît sur la surface et permet aux utilisateurs de mettre à l’échelle physiquement le modèle. Un autre exemple est celui des dispositifs mobiles flexibles dont la forme est actionnée par le système, qui peuvent fournir des formes appropriées pour différentes applications: par exemple une forme plate et large pour une carte, une forme de console pour un jeu, etc. [149, 151].
- Les interfaces à changement de forme fournissent des affordances dynamiques, c.-à-d., que les interfaces peuvent changer leurs caractéristiques physiques telles que la forme, la taille et l’emplacement [51] pour adapter la forme à la fonction que le dispositif fournit. Par exemple, une tablette plate se transforme en une forme incurvée pour indiquer son utilisation comme téléphone, puis se transforme en un cercle suggérant son utilisation comme bracelet [204]. Les interfaces à forme variable permettent également aux utilisateurs eux-mêmes de transformer l’affordance du dispositif. Par exemple, les interfaces “Jamming”, c’est-à-dire contenant des particules et dont la pression interne permet soit de modeler les interfaces, soit de les figer en les durcissant, permettent aux utilisateurs de déformer l’interface d’un téléphone, d’une télécommande, d’une montre et d’un contrôleur de jeu pour modifier les fonctionnalités perçues de l’interface [52].
- La personnalisation des interfaces physiques est plus facile si celles-ci sont flexibles et/ou peuvent changer de forme. Bien qu’il ne soit pas encore entièrement étudié comment la personnalisation des interfaces à changement de forme doit être conçue, certaines publications montrent la possibilité de personnalisation des interfaces à changement de forme. Par exemple, un thermostat à effet de vague [133] a été proposé : Le bouton rotatif peut modifier sa taille et son retour de force pour les adapter à la volonté de consommation énergétique des utilisateurs. Un autre exemple, bien que ses auteurs n’aient pas suggéré la personnalisation, est Inflatable Mouse [103] : la souris pourrait changer sa taille pour s’adapter à celle de la main de l’utilisateur.
- Les interfaces à changement de forme permettent également un contrôle sans regarder, tout comme les interfaces physiques. Les “Emergeables” [148] montrent que les interfaces à changement de forme nécessitent moins d’attention visuelle

de la part des utilisateurs que l'écran tactile pour une tâche de poursuite de cible. Des gouttes tangibles [152] montrent que même les matériaux liquides peuvent permettre un contrôle sans regarder via le déplacement ou la vibration au bout des doigts des utilisateurs.

- Les interfaces à changement de forme héritent des PUI la possibilité d'utiliser la dextérité humaine et les gestes dont les utilisateurs sont capables. Dans "LineFORM" [123], un utilisateur enroule le dispositif autour de son bras et apprend ainsi la boxe par le mouvement et le retour de force du dispositif autour de son bras. "Materiable" [125] montre que certains utilisateurs utilisent leurs bras et le haut du corps au lieu des mains pour appuyer sur l'interface et sentir le retour de force.

8.2 Énoncé du problème

Comme nous l'avons montré précédemment, les interfaces à changement de forme ont le potentiel de proposer à la fois de la flexibilité et de la physicalité. Nous pensons que cette double caractéristique est particulièrement pertinente pour le contrôle du système. Cependant, il existe peu de travaux sur les interfaces à changement de forme pour le contrôle. Pourtant, les utilisateurs pourraient en retirer beaucoup d'avantages. Nous pensons que cela est dû à deux défis principaux qui doivent être relevés : (1) du côté de l'interface de contrôle, nous devons mieux comprendre les besoins de l'utilisateur final pour concevoir de telles interfaces ; (2) du côté des interfaces qui changent de forme, il y a un manque d'outils pour aider leur conception. Par exemple, l'espace de conception des interfaces à changement de forme est vaste : les interfaces peuvent avoir une des dix caractéristiques de forme [149], ou bien plusieurs, ou bien même la totalité de ces caractéristiques. Chaque caractéristique peut prendre un nombre infini de valeurs. Ces interfaces peuvent donc amener les concepteurs à effectuer beaucoup d'itérations lors de leur conception. L'objectif de cette thèse est donc d'aborder ces deux défis pour permettre la (3) création de nouvelles interfaces de contrôle à forme variable.

Problème I : absence d'aide à la conception pour les interfaces de contrôle

Actuellement, la façon de concevoir les interfaces de contrôles qui changent de forme n'est pas claire. Une aide à la conception, comme une taxonomie par exemple, permet d'explorer efficacement différentes idées. Par exemple, les concepteurs utilisent des règles pour la conception de sites Web⁵, la conception de jeux⁶ et la conception d'études utilisateurs⁷. Il existe quelques conseils de conception pour les interfaces de contrôles à forme variable fournissant un retour d'information kinesthésique [133], pour les interfaces fournissant différents niveaux d'accès à un système [170], et pour un outil permettant aux personnes malvoyantes de naviguer dans un fichier audio [174]. Cependant, ces approches (1) sont axées sur des utilisateurs et des applications particulières, et (2) visent des interfaces particulières. Nous avons besoin d'aide à la conception basée sur un ensemble plus large d'applications et d'interfaces de contrôle afin d'apporter des connaissances communes, fondées sur ce que les utilisateurs attendent des contrôles à forme variables. De ce point de vue, nous voyons deux objectifs de recherche à atteindre :

Objectif 1 : Comprendre les besoins réels d'un large éventail d'utilisateurs finaux.

Objectif 2 : Synthétiser leurs besoins pour la conception des interfaces de contrôle à forme variable.

⁵<https://html5forwebdesigners.com/design/>

⁶<https://www.giantbomb.com/profile/therpgfanatic/blog/10-simple-rules-for-good-game-design/61994/>

⁷<https://uxplanet.org/ultimate-guide-to-user-research-bed4a57d260>

Problème II : Absence d’outils de conception pour les interfaces à forme variable

Il existe des outils pour les interfaces à forme variable qui peuvent décrire et inspirer différents types de changement de forme [149, 145]. Cependant, ces outils sont construits à partir d’interfaces à forme variable existantes. Leur puissance descriptive n’est pas souvent testée dans des cas réels. Nous ne connaissons pas non plus leur capacité à générer de nouvelles interfaces. Nous voulons évaluer leur pouvoir descriptif.

Objectif 3 : Évaluer et affiner les outils actuels de conception d’interfaces qui changent de forme.

De plus, nous constatons un manque de variété dans le type d’outils de conception qui existent actuellement. Les approches actuelles de conception d’interfaces à forme variable utilisent soit des taxonomies [130, 146], s’inspirent des utilisateurs [168], de la nature [195] ou des matériaux [184]. Nous voulons ajouter un nouveau type d’inspiration qui peut être systématiquement utilisée pour concevoir des interfaces à forme variable. Nous voyons un autre objectif à atteindre :

Objectif 4 : Générer un nouvel outil de conception pour les interfaces qui changent de forme.

Problème III : Absence d’interfaces de contrôle changeant de forme

À la croisée de ces deux domaines (interfaces de contrôle et interfaces à forme variable), la communauté scientifique manque d’exemples d’interfaces de contrôle à forme variable. Par exemple, les interfaces actuelles de changement de forme se concentrent sur les surfaces à picots actionnés [51, 148], sur le changement de hauteur des boutons [170], sur le changement de largeur des boutons [133], sur la modification de la forme extérieure d’un bouton rotatif [134], sur la longueur d’un curseur linéaire [32], ou sur l’actionnement des curseurs linéaires par le système [174, 56]. L’espace de conception des interfaces à forme variable est vaste, et nous avons besoin de plus d’exemples pour comprendre les caractéristiques des interfaces de contrôle à forme variable, et pour suggérer des règles de conception dédiées. L’objectif final de cette thèse est donc de :

Objectif 5 : Concevoir et évaluer de nouvelles formes d’interfaces de contrôle à forme variable.

8.3 Méthodologie

La figure 8.2 illustre les deux domaines de recherche sur lesquels nous nous concentrons dans cette thèse : les interfaces de contrôle et les interfaces à forme variable. Avant de passer à l'axe de recherche principal de la thèse, à savoir les interfaces de contrôle à forme variable, à leur intersection, nous prenons un peu de recul et examinons les deux domaines de recherche les plus connexes.

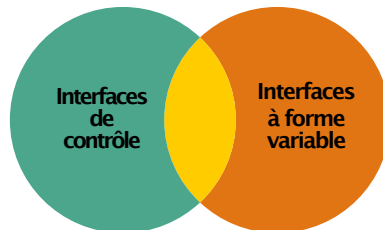


Figure 8.2: Les deux domaines de recherche que nous étudions dans la thèse : les interfaces de contrôle et les interfaces à forme variable. L'intersection est le changement de forme des interface de contrôle, notre principal centre d'intérêt dans la thèse.

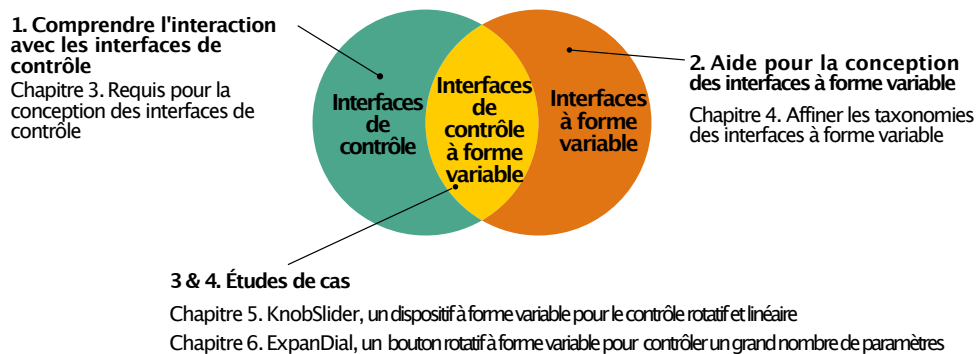


Figure 8.3: La vue détaillée de nos recherches montre l'approche en quatre étapes : (1) Nous étudions d'abord les besoins sous-jacents des utilisateurs et les exigences de conception des interfaces de contrôle. (2) Nous fournissons ensuite des outils de conception d'interfaces changeant de forme en affinant une taxonomie existante et en fournissant une collection d'objets reconfigurables du quotidien. (3, 4) Enfin, nous menons deux études de cas qui explorent la conception d'interfaces de commande à forme variable. Ces deux études s'appuient sur la compréhension des interfaces de commande et les outils de conception d'interfaces de changement de forme.

La figure 8.3 montre les quatre étapes que nous avons suivies tout au long de cette thèse. Dans un premier temps, nous étudions les techniques d'interaction actuelles des utilisateurs finaux afin d'explicitier les requis de conception pour les futures interfaces de contrôle à forme variable. Dans un deuxième temps, nous étudions des outils de conception d'interfaces à forme variable pour nous permettre de concevoir les interfaces de contrôle à forme variable de manière systématique. Pour les troisième

et quatrième étapes, nous utilisons les leçons tirées des techniques d'interaction et des outils de conception actuels pour concevoir et implémenter deux interfaces de contrôle à forme variable : KnobSlider et ExpanDial. Nous détaillons ci-dessous ces quatre étapes.

1. Requis pour la conception des interfaces de contrôle

La première étape de notre approche consiste à examiner le domaine des interfaces de contrôle : nous étudions comment les utilisateurs professionnels interagissent avec les interfaces de contrôle. Comme les contrôles à forme variable sont un nouveau type d'interfaces de contrôle, nous devons adopter une approche centrée sur l'utilisateur pour accroître leur acceptation par les utilisateurs finaux. Cependant, il n'existe pas de règles de conception pour les interfaces de contrôle, en particulier en ce qui concerne la flexibilité et la physicalité. Nous étudions donc l'interaction des utilisateurs avec les interfaces de contrôle actuelles, afin de fournir des requis pour leur conception. Dans une première étape, nous réalisons des entretiens contextuels avec des professionnels qui utilisent des interfaces de contrôle pour leur travail. Nous nous concentrons sur les interfaces de commande rotatives et linéaires car ce sont des interfaces de commande typiques. Nous voulons également savoir si la question de la flexibilité et de la physicalité se retrouve dans toutes les professions. C'est pourquoi nous incluons cinq professions qui nécessitent l'utilisation intensive d'interfaces de contrôle. Cela nous fournit des requis pour guider la conception des interfaces de commande à forme variable, en y incorporant à la fois la flexibilité et la physicalité.

2. Outils de conception pour les interfaces changeant de forme

La deuxième étape consiste à étudier les interfaces changeant de forme. Avant de concevoir des interfaces de contrôle à forme variable, basées sur les requis de conception de la première étape, nous réexaminons les outils de conception existants pour les interfaces à forme variable. Pour explorer systématiquement l'espace de conception des interfaces changeant de forme, les chercheurs utilisent des taxonomies. Les taxonomies sont des outils qui décrivent les caractéristiques des interfaces. Elles sont été utilisées comme cadre de conception pour l'exploration systématique de ces caractéristiques. Cependant, les taxonomies existantes pour les interfaces à forme variable ont été proposées indépendamment: il n'y a pas encore eu d'approche globale pour unifier et mettre à l'épreuve leur pouvoir descriptif. Par conséquent, avant d'utiliser ces taxonomies pour proposer de nouvelles interfaces de contrôle à forme variable, nous les évaluons et nous les améliorons. Pour évaluer les taxonomies, nous proposons d'utiliser des objets du quotidien reconfigurables pour mettre à l'épreuve le pouvoir de description des taxonomies existantes. Cela nous permet de fournir deux outils de conception. Le premier outil est Morphees+, une taxonomie dédiée aux interfaces changeant de forme, qui affine les précédentes. Le deuxième outil est une collection d'objets du quotidien reconfigurables, pour aider à générer de nouvelles idées d'interfaces à forme variable.

3 & 4. Études de cas

Les troisième et quatrième étapes combinent les domaines des interfaces de commande et des interfaces changeant de forme: nous étudions les interfaces de commande changeant de forme. Nous avons mené deux études de cas : (1) KnobSlider, une interface de contrôle changeant de forme qui peut prendre la forme d'un bouton rotatif ou d'un bouton linéaire, et (2) ExpanDial, un bouton rotatif qui peut changer de hauteur et de diamètre.

3. Étude de cas I : KnobSlider, conception et implémentation d'une interface dont la forme varie entre deux types de widgets

Dans la troisième étape, nous utilisons les requis de conception d'interfaces de commande et les outils de conception d'interfaces changeant de forme, pour concevoir une interface de contrôle à forme variable. Nous vous proposons KnobSlider, une interface qui peut basculer entre un bouton rotatif et un bouton linéaire. Afin de ne pas biaiser la conception et d'explorer en profondeur l'espace de conception, nous utilisons d'abord les outils de conception pour générer des idées de conception, puis nous utilisons les requis des utilisateurs finaux pour les évaluer. Cette approche nous permet d'identifier une solution comme meilleure: KnobSlider. Pour évaluer KnobSlider, nous le protétypons pour le faire utiliser par les utilisateurs finaux lors d'une étude qualitative. L'étude qualitative confirme les requis de conception de l'étude exploratoire, mais montre aussi que KnobSlider peut provoquer des réactions négatives, comme la peur, chez les utilisateurs. Cette observation nous motive à mener la deuxième étude, qui explore les préférences des utilisateurs quant à la vitesse du changement de forme. L'analyse montre que les utilisateurs préfèrent une certaine plage de vitesse et que leurs préférences dépendent de la physicalité de l'interface.

4. Etude de cas II : ExpanDial, conception d'un cadran à forme variable à partir d'une étude de préhension

Dans la dernière étape, nous présentons une étude de cas qui fait suite à un inconvénient de KnobSlider. Bien que KnobSlider permette aux utilisateurs de choisir leur interface de contrôle préférée et de contrôler au moins deux paramètres sur un seul dispositif, KnobSlider manque d'une certaine flexibilité : les utilisateurs ne peuvent pas utiliser KnobSlider simultanément sous la forme d'un bouton rotatif et linéaire. Cela nous motive à mener la deuxième étude de cas sur ExpanDial. ExpanDial est un bouton rotatif qui permet aux utilisateurs de contrôler plusieurs paramètres en même temps grâce à la rotation du bouton, mais aussi grâce au changement de son diamètre et de sa hauteur. Dans cette étude de cas, nous introduisons la flexibilité dans un type d'interface de contrôle au lieu de combiner deux interfaces de contrôle dans un seul dispositif. Nous menons d'abord une étude sur la préhension des boutons rotatifs, pour étudier comment les utilisateurs positionnent leur main et leurs doigts sur les boutons rotatifs actuels. Ceci nous permet de prendre en compte l'ergonomie dans la conception d'ExpanDial. Nous utilisons ensuite ExpanDial dans le cadre d'une

étude pour explorer les applications et les gestes pour activer le changement de forme d'ExpanDial.

8.4 Contributions de la thèse

Cette thèse propose les quatre contributions suivantes au domaine de l'Interaction Humain-Machine :

1. Des requis pour la conception des interfaces de contrôle rotative et linéaire, issus des utilisateurs finaux⁸ (Chapitre 3).
 - a) Grâce à des entretiens contextuels, nous comprenons les besoins des utilisateurs professionnels en matière de contrôle de paramètres. Les résultats montrent les avantages et les limites des contrôleurs physiques et tactiles actuels.
 - b) Sur la base de cette étude exploratoire, nous déduisons les requis pour la conception d'une interface physique flexible : les utilisateurs ont besoin d'interagir rapidement, avec précision et sans regarder avec un grand nombre de paramètres, et ils ont besoin de mobilité. Ils ont également besoin de rétrocompatibilité avec les techniques d'interaction actuelles.
2. Des outils de conception d'interfaces à forme variable⁹ (Chapitre 4).
 - a) Nous fournissons une collection de 82 objets reconfigurables du quotidien [98]. Cette collection est réutilisable et extensible par d'autres chercheurs. La collection comprend une image et une description de chaque objet, et vise à inspirer de nouvelles interfaces à forme variable.
 - b) Nous étudions les relations entre les deux taxonomies les plus utilisées [145, 149] pour les interfaces à forme variable, et identifions les éléments à améliorer dans ces deux taxonomies.
 - c) Nous ajoutons les caractéristiques de taille et de modularité à la taxonomie « Shape resolution » [149] qui s'est avérée être la taxonomie la plus complète et référencée pour décrire les formes et la quantité de changement de forme.
 - d) Nous montrons comment la reconfigurabilité est implémentée dans les objets du quotidien. Ces idées d'implémentation peut informer l'implémentation des caractéristiques de Morphees+, et aider au prototypage rapide de certaines caractéristiques en s'inspirant ou en utilisant les objets du quotidien correspondants.
3. La conception et l'implémentation d'une interface de contrôle à forme variable (KnobSlider) permettant de passer d'un contrôle rotatif à un contrôle linéaire, et inversement, est publiée à CHI 2018 [101] et IHM 2016 [99]. La conception de KnobSlider se base sur les requis des utilisateurs finaux. La version étendue de ce travail, avec l'expérience en laboratoire, est publiée dans la revue *Frontiers in*

⁸Les résultats et les requis de conception des entretiens contextuels sont publiés au sein des articles sur KnobSlider. Voir ¹¹

⁹Ces travaux sont publiés dans les actes de la conférences ACM CHI 2018 [97] et ont reçu le prix « Honorable mention » (c'est-à-dire que l'article fait parti des 5% meilleurs, parmi plus de 2500 soumissions à la conférence)

Robotics and AI [100]. Le dispositif a également fait l'objet d'une démonstration à la conférence en robotique IROS 2018. (Chapitre 5)

- a) Nous générons dix prototypes basse fidélité qui permettent tous un contrôle alternativement linéaire et rotatif. La conception de ces prototypes se base sur l'exploration systématique des caractéristiques de Morphees+. Nous évaluons ensuite les prototypes en fonction des requis des utilisateurs finaux issus des entretiens contextuels, pour identifier le meilleur prototype pour KnobSlider.
 - b) Nous implémentons un prototype de plus haute fidélité de KnobSlider, c'est-à-dire un dispositif d'interaction qui peut changer entre un bouton linéaire et rotatif.
 - c) L'étude qualitative de l'utilisation de KnobSlider, réalisée auprès d'utilisateurs professionnels de boutons rotatifs et linéaires, confirme les requis de conception de l'étude exploratoire. Elle révèle également les défis que posent les interfaces à forme variable, comme les réactions de surprise ou de peur que suscitent le changement de forme.
 - d) L'étude sur la vitesse de changement de forme de KnobSlider montre que les utilisateurs préfèrent une certaine plage de vitesse et que leurs préférences de vitesse changent selon que le dispositif est présenté dans sa forme tangible ou sur une vidéo.
4. L'augmentation du nombre de paramètres contrôlés par un bouton rotatif¹⁰ (Chapitre 6).
- a) Nous menons une étude sur la préhension des boutons rotatifs de différentes hauteurs et diamètres, et nous en présentons les conséquences pour la conception des boutons rotatifs à forme variable.
 - b) En nous basant sur les requis de conception des entretiens contextuels et sur les résultats de l'étude de préhension, nous concevons et prototypons ExpanDial. ExpanDial est un bouton rotatif qui peut modifier sa hauteur et son diamètre, permettant ainsi de contrôler trois paramètres en même temps. ExpanDial varie sa caractéristique de taille de Morphees+, ce qui n'était pas le cas de KnobSlider.
 - c) L'étude d'ExpanDial par un groupe focalisé suggère des applications pour ce type de boutons rotatifs, ainsi que de gestes pour déclencher et contrôler le changement de forme.

¹⁰ExpanDial est publié sur DIS 2019 [102].

Bibliography

- [1] Ahmed Al Maimani and Anne Roudaut. “Frozen Suit: Designing a Changeable Stiffness Suit and Its Application to Haptic Games”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: ACM, 2017, pp. 2440–2448. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025655. URL: <http://doi.acm.org/10.1145/3025453.3025655>.
- [2] Jason Alexander, John Hardy, and Stephen Wattam. “Characterising the Physicality of Everyday Buttons”. In: *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces*. ITS ’14. Dresden, Germany: ACM, 2014, pp. 205–208. ISBN: 978-1-4503-2587-5. DOI: 10.1145/2669485.2669519. URL: <http://doi.acm.org/10.1145/2669485.2669519>.
- [3] Jason Alexander, Andrés Lucero, and Sriram Subramanian. “Tilt Displays: Designing Display Surfaces with Multi-axis Tilting and Actuation”. In: *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services*. MobileHCI ’12. San Francisco, California, USA: ACM, 2012, pp. 161–170. ISBN: 978-1-4503-1105-2. DOI: 10.1145/2371574.2371600. URL: <http://doi.acm.org/10.1145/2371574.2371600>.
- [4] Jason Alexander et al. “Grand Challenges in Shape-Changing Interface Research”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: ACM, 2018, 299:1–299:14. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173873. URL: <http://doi.acm.org/10.1145/3173574.3173873>.
- [5] T. H. Andersen et al. “Feel the beat: direct manipulation of sound during playback”. In: *First IEEE International Workshop on Horizontal Interactive Human-Computer Systems (TABLETOP ’06)*. Jan. 2006, 2 pp.–. DOI: 10.1109/TABLETOP.2006.14.
- [6] Art+com. *Kinetic Sculpture — The Shapes of Things to Come, BMW Museum, Munich*. 2008. URL: <https://artcom.de/en/project/kinetic-sculpture/> (visited on 05/23/2019).

- [7] Akash Badshah et al. “Interactive Generator: A Self-powered Haptic Feedback Device”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: ACM, 2011, pp. 2051–2054. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979240. URL: <http://doi.acm.org/10.1145/1978942.1979240>.
- [8] Konrad Baumann and Bruce Thomas. *User interface design of electronic appliances*. CRC Press, 2001.
- [9] George M Beal and Joe M Bohlen. *The diffusion process*. Tech. rep. 1956.
- [10] Michel Beaudouin-Lafon. “Instrumental Interaction: An Interaction Model for Designing post-WIMP User Interfaces”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’00. The Hague, The Netherlands: ACM, 2000, pp. 446–453. ISBN: 1-58113-216-6. DOI: 10.1145/332040.332473. URL: <http://doi.acm.org/10.1145/332040.332473>.
- [11] François Bérard and Amélie Rochet-Capellan. “Measuring the Linear and Rotational User Precision in Touch Pointing”. In: *Proceedings of the 2012 ACM International Conference on Interactive Tabletops and Surfaces*. ITS ’12. Cambridge, Massachusetts, USA: ACM, 2012, pp. 183–192. ISBN: 978-1-4503-1209-7. DOI: 10.1145/2396636.2396664. URL: <http://doi.acm.org/10.1145/2396636.2396664>.
- [12] François Bérard, Guangyu Wang, and Jeremy R. Cooperstock. “On the Limits of the Human Motor Control Precision: The Search for a Device’s Human Resolution”. In: *Human-Computer Interaction – INTERACT 2011*. Ed. by Pedro Campos et al. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 107–122. ISBN: 978-3-642-23771-3.
- [13] Joanna Berzowska and Di Mainstone. “SKORPIONS: kinetic electronic garments”. In: *ACM SIGGRAPH 2008 talks*. ACM. 2008, p. 46.
- [14] Durrell Bishop. “Marble answering machine”. In: *Royal College of Art, Interaction Design* (1992).
- [15] Alan F. Blackwell and Darren Edge. “Articulating Tangible Interfaces”. In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. TEI ’09. Cambridge, United Kingdom: ACM, 2009, pp. 113–118. ISBN: 978-1-60558-493-5. DOI: 10.1145/1517664.1517693. URL: <http://doi.acm.org/10.1145/1517664.1517693>.
- [16] Cal Blanco. *Matrix Touch Screen in action*. CC BY-SA 3.0. URL: https://commons.wikimedia.org/wiki/File:Matrix_Touch_Screen_by_DJCraig.jpg (visited on 04/14/2020).
- [17] Alberto Boem and Giovanni Maria Troiano. “Non-Rigid HCI: A Review of Deformable Interfaces and Input”. In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS ’19. San Diego, CA, USA: ACM, 2019, pp. 885–906. ISBN: 978-1-4503-5850-7. DOI: 10.1145/3322276.3322347. URL: <http://doi.acm.org/10.1145/3322276.3322347>.
- [18] James V Bradley. “Optimum knob diameter”. In: *Human Factors* 11.4 (1969), pp. 353–360.

- [19] Ralph Allan Bradley and Milton E. Terry. “Rank Analysis of Incomplete Block Designs: I. The Method of Paired Comparisons”. In: *Biometrika* 39.3/4 (1952), pp. 324–345. ISSN: 00063444. URL: <http://www.jstor.org/stable/2334029>.
- [20] Virginia Braun and Victoria Clarke. “Using thematic analysis in psychology”. In: *Qualitative research in psychology* 3.2 (2006), pp. 77–101.
- [21] Ulrich Burandt. *Ergonomie für Design und Entwicklung*. O. Schmidt, 1978.
- [22] Jesse Burstyn, Amartya Banerjee, and Roel Vertegaal. “FlexView: An Evaluation of Depth Navigation on Deformable Mobile Devices”. In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’13. Barcelona, Spain: ACM, 2013, pp. 193–200. ISBN: 978-1-4503-1898-3. DOI: 10.1145/2460625.2460655. URL: <http://doi.acm.org/10.1145/2460625.2460655>.
- [23] Gaelle Calvary et al. “Plasticity of User Interfaces: A Revisited Reference Framework”. In: *In Task Models and Diagrams for User Interface Design*. Publishing House, 2002, pp. 127–134.
- [24] Juan Angel Lorenzo del Castillo and Nadine Couture. “The Aircraft of the Future: Towards the Tangible Cockpit”. In: *Proceedings of the International Conference on Human-Computer Interaction in Aerospace*. HCI-Aero ’16. Paris, France: ACM, 2016, 11:1–11:8. ISBN: 978-1-4503-4406-7. DOI: 10.1145/2950112.2964582. URL: <http://doi.acm.org/10.1145/2950112.2964582>.
- [25] Liwei Chan et al. “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*. CHI ’12. Austin, Texas, USA: ACM, 2012, pp. 2189–2192. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2208371. URL: <http://doi.acm.org/10.1145/2207676.2208371>.
- [26] Chun-Hung Chang, Hsien-Yuan Lane, and Chieh-Hsin Lin. “Brain Stimulation in Alzheimer’s Disease”. In: *Frontiers in psychiatry* 9 (May 22, 2018). 29910746[pmid], pp. 201–201. ISSN: 1664-0640. DOI: 10.3389/fpsy.2018.00201. URL: <https://www.ncbi.nlm.nih.gov/pubmed/29910746>.
- [27] Olivier Chapuis and Pierre Dragicevic. “Effects of Motor Scale, Visual Scale, and Quantization on Small Target Acquisition Difficulty”. In: *ACM Trans. Comput.-Hum. Interact.* 18.3 (Aug. 2011), 13:1–13:32. ISSN: 1073-0516. DOI: 10.1145/1993060.1993063. URL: <http://doi.acm.org/10.1145/1993060.1993063>.
- [28] Kuan-Ta Chen et al. “A Crowdsorceable QoE Evaluation Framework for Multimedia Content”. In: *Proceedings of the 17th ACM International Conference on Multimedia*. MM ’09. Beijing, China: ACM, 2009, pp. 491–500. ISBN: 978-1-60558-608-3. DOI: 10.1145/1631272.1631339. URL: <http://doi.acm.org/10.1145/1631272.1631339>.
- [29] Andy Cockburn and Bruce McKenzie. “Evaluating the Effectiveness of Spatial Memory in 2D and 3D Physical and Virtual Environments”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’02. Minneapolis, Minnesota, USA: ACM, 2002, pp. 203–210. ISBN: 1-58113-453-3. DOI: 10.1145/503376.503413. URL: <http://doi.acm.org/10.1145/503376.503413>.

- [30] Marcelo Coelho and Pattie Maes. “Shutters: A Permeable Surface for Environmental Control and Communication”. In: *Proceedings of the 3rd International Conference on Tangible and Embedded Interaction*. TEI '09. Cambridge, United Kingdom: ACM, 2009, pp. 13–18. ISBN: 978-1-60558-493-5. DOI: 10.1145/1517664.1517671. URL: <http://doi.acm.org/10.1145/1517664.1517671>.
- [31] Marcelo Coelho and Jamie Zigelbaum. “Shape-changing Interfaces”. In: *Personal Ubiquitous Comput.* 15.2 (Feb. 2011), pp. 161–173. ISSN: 1617-4909. DOI: 10.1007/s00779-010-0311-y. URL: <http://dx.doi.org/10.1007/s00779-010-0311-y>.
- [32] Céline Coutrix and Cédric Masclet. “Shape-Change for Zoomable TUIs: Opportunities and Limits of a Resizable Slider”. In: *Human-Computer Interaction – INTERACT 2015*. Ed. by Julio Abascal et al. Cham: Springer International Publishing, 2015, pp. 349–366. ISBN: 978-3-319-22701-6.
- [33] DJ Craig. *Matrix DJ Touchscreen System*. URL: <https://djcraig.net/> (visited on 04/14/2020).
- [34] Dhairya Dand and Robert Hemsley. “Obake: Interactions on a 2.5D Elastic Display”. In: *Proceedings of the Adjunct Publication of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13 Adjunct. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 109–110. ISBN: 978-1-4503-2406-9. DOI: 10.1145/2508468.2514734. URL: <http://doi.acm.org/10.1145/2508468.2514734>.
- [35] Herbert Aron David. *The method of paired comparisons*. Vol. 12. London, 1963.
- [36] Oleg Davidyuk, Valérie Issarny, and Jukka Riekki. “MEDUSA: Middleware for end-user composition of ubiquitous applications”. In: *Handbook of research on ambient intelligence and smart environments: trends and perspectives*. IGI Global, 2011, pp. 197–219.
- [37] Jessica Q. Dawson et al. “It’s Alive!: Exploring the Design Space of a Gesturing Phone”. In: *Proceedings of Graphics Interface 2013*. GI '13. Regina, Saskatchewan, Canada: Canadian Information Processing Society, 2013, pp. 205–212. ISBN: 978-1-4822-1680-6. URL: <http://dl.acm.org/citation.cfm?id=2532129.2532164>.
- [38] Nicholas A. Diakopoulos and David A. Shamma. “Characterizing Debate Performance via Aggregated Twitter Sentiment”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, 2010, pp. 1195–1198. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753504. URL: <http://doi.acm.org/10.1145/1753326.1753504>.
- [39] Alan Dix et al. *Human-computer Interaction*. Upper Saddle River, NJ, USA: Prentice-Hall, Inc., 1997. ISBN: 0-13-437211-5.
- [40] Tom Djaajadiningrat, Ben Matthews, and Marcelle Stienstra. “Easy doesn’t do it: skill and expression in tangible aesthetics”. In: *Personal and Ubiquitous Computing* 11.8 (Dec. 1, 2007), pp. 657–676. ISSN: 1617-4917. DOI: 10.1007/s00779-006-0137-9. URL: <https://doi.org/10.1007/s00779-006-0137-9>.

- [41] Darren Edge and Alan Blackwell. “Correlates of the cognitive dimensions for tangible user interface”. In: *Journal of Visual Languages & Computing* 17.4 (2006). Ten Years of Cognitive Dimensions, pp. 366–394. ISSN: 1045-926X. DOI: <https://doi.org/10.1016/j.jvlc.2006.04.005>. URL: <http://www.sciencedirect.com/science/article/pii/S1045926X06000292>.
- [42] Benj Edwards. “The computer mouse turns 40”. In: *Macworld*. December (2008).
- [43] Katrin Kroemer Elbert, Henrike B Kroemer, and Anne D Kroemer Hoffman. *Ergonomics: how to design for ease and efficiency*. Academic Press, 2018.
- [44] W. K. English, D. C. Engelbart, and M. L. Berman. “Display-Selection Techniques for Text Manipulation”. In: *IEEE Transactions on Human Factors in Electronics* HFE-8.1 (Mar. 1967), pp. 5–15. ISSN: 0096-249X. DOI: 10.1109/THFE.1967.232994.
- [45] DJ Esco. *DJ Esco Presents: Smithson Martin Emulator Elite Demo by Cody Myer at Hermes Houston*. Oct. 2014. URL: <https://youtu.be/WukYuNs8WZc?t=68>.
- [46] Aluna Everitt, Faisal Taher, and Jason Alexander. “ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: ACM, 2016, pp. 2778–2782. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858316. URL: <http://doi.acm.org/10.1145/2858036.2858316>.
- [47] George W. Fitzmaurice. “Graspable User Interfaces”. PhD thesis. Toronto, Ont., Canada, Canada, 1996. ISBN: 0-612-18871-X.
- [48] George W. Fitzmaurice and William Buxton. “An Empirical Evaluation of Graspable User Interfaces: Towards Specialized, Space-multiplexed Input”. In: *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*. CHI ’97. Atlanta, Georgia, USA: ACM, 1997, pp. 43–50. ISBN: 0-89791-802-9. DOI: 10.1145/258549.258578. URL: <http://doi.acm.org/10.1145/258549.258578>.
- [49] 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. Denver, Colorado, USA: ACM Press/Addison-Wesley Publishing Co., 1995, pp. 442–449. ISBN: 0-201-84705-1. DOI: 10.1145/223904.223964. URL: <http://dx.doi.org/10.1145/223904.223964>.
- [50] Joseph L Fleiss. “Measuring nominal scale agreement among many raters.” In: *Psychological bulletin* 76.5 (1971), p. 378.
- [51] Sean Follmer et al. “inFORM: Dynamic Physical Affordances and Constraints Through Shape and Object Actuation”. In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST ’13. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 417–426. ISBN: 978-1-4503-2268-3. DOI: 10.1145/2501988.2502032. URL: <http://doi.acm.org/10.1145/2501988.2502032>.

- [52] Sean Follmer et al. “Jamming User Interfaces: Programmable Particle Stiffness and Sensing for Malleable and Shape-changing Devices”. In: *Proceedings of the 25th Annual ACM Symposium on User Interface Software and Technology*. UIST ’12. Cambridge, Massachusetts, USA: ACM, 2012, pp. 519–528. ISBN: 978-1-4503-1580-7. DOI: 10.1145/2380116.2380181. URL: <http://doi.acm.org/10.1145/2380116.2380181>.
- [53] Kenneth Friedman. *Alan Kay: Doing with Images Makes Symbols (Full Version)*. URL: https://www.youtube.com/watch?v=p2LZLYcu_JY (visited on 04/22/2020).
- [54] Alexandra Fuchs, Miriam Sturdee, and Johannes Schöning. “Foldwatch: Using Origami-inspired Paper Prototypes to Explore the Extension of Output Space in Smartwatches”. In: *Proceedings of the 10th Nordic Conference on Human-Computer Interaction*. NordiCHI ’18. Oslo, Norway: ACM, 2018, pp. 47–59. ISBN: 978-1-4503-6437-9. DOI: 10.1145/3240167.3240173. URL: <http://doi.acm.org/10.1145/3240167.3240173>.
- [55] Johanna Fulda et al. “Raising User Impulse Awareness: The Sensitive Roly-poly”. In: *Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’14. Munich, Germany: ACM, 2013, pp. 347–348. ISBN: 978-1-4503-2635-3. DOI: 10.1145/2540930.2555205. URL: <http://doi.acm.org/10.1145/2540930.2555205>.
- [56] Romain Gabriel et al. “BounceSlider: Actuated Sliders for Music Performance and Composition”. In: *Proceedings of the 2Nd International Conference on Tangible and Embedded Interaction*. TEI ’08. Bonn, Germany: ACM, 2008, pp. 127–130. ISBN: 978-1-60558-004-3. DOI: 10.1145/1347390.1347418. URL: <http://doi.acm.org/10.1145/1347390.1347418>.
- [57] Steven Gelineck and Stefania Serafin. “A Quantitative Evaluation of the Differences Between Knobs and Sliders”. In: *In Proc. NIME 2009, Pittsburgh*. 2009, pp. 13–18.
- [58] James J Gibson. “The theory of affordances”. In: *Hilldale, USA* 1.2 (1977).
- [59] MA Lighting International GmbH. *Company History*. <https://www.malighting.com/company/history/> and <https://www.malighting.com/>. (Visited on 04/24/2020).
- [60] J. C. Goble et al. “Two-handed spatial interface tools for neurosurgical planning”. In: *Computer* 28.7 (July 1995), pp. 20–26. DOI: 10.1109/2.391037.
- [61] Etienne Grandjean. *Physiological Work Design: Guide to Ergonomics; static and dynamic work, bodywork as design, gravity and dexterity, work facilitation, man-machine systems, fatigue, and monotony Stress, working time, shift work, break and meals, lighting and coloring, the screen workstation, work and lifestyles, the indoor climate at work*. Ott, 1991.
- [62] Etienne Grandjean and Harold Oldroyd. *Fitting the task to the man: an ergonomic approach*. Vol. 387. Taylor & Francis London, 1980.

- [63] Miriam Greis et al. “SplitSlider: A Tangible Interface to Input Uncertainty”. In: *Human-Computer Interaction – INTERACT 2019*. Ed. by David Lamas et al. Cham: Springer International Publishing, 2019, pp. 493–510. ISBN: 978-3-030-29390-1.
- [64] Mick Grierson and Chris Kiefer. “NoiseBear: A wireless malleable instrument designed in participation with disabled children”. In: (2013).
- [65] Jens Emil Grønbaek et al. “Proxemic Transitions: Designing Shape-Changing Furniture for Informal Meetings”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: ACM, 2017, pp. 7029–7041. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025487. URL: <http://doi.acm.org/10.1145/3025453.3025487>.
- [66] Erik Grönvall et al. “Causing Commotion with a Shape-changing Bench: Experiencing Shape-changing Interfaces in Use”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: ACM, 2014, pp. 2559–2568. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557360. URL: <http://doi.acm.org/10.1145/2556288.2557360>.
- [67] Shad Gross, Jeffrey Bardzell, and Shaowen Bardzell. “Structures, forms, and stuff: the materiality and medium of interaction”. In: *Personal and Ubiquitous Computing* 18.3 (2014), pp. 637–649.
- [68] Yves Guiard. “Asymmetric Division of Labor in Human Skilled Bimanual Action”. In: *Journal of Motor Behavior* 19.4 (1987). PMID: 15136274, pp. 486–517. DOI: 10.1080/00222895.1987.10735426. eprint: <https://doi.org/10.1080/00222895.1987.10735426>. URL: <https://doi.org/10.1080/00222895.1987.10735426>.
- [69] Nur Al-huda Hamdan et al. “Springlets: Expressive, Flexible and Silent On-Skin Tactile Interfaces”. In: *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*. ACM. 2019, p. 488.
- [70] Yuval Noah Harari. *21 Lessons for the 21st Century*. Random House, 2018.
- [71] John Hardy et al. “ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 19–28. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702599. URL: <http://doi.acm.org/10.1145/2702123.2702599>.
- [72] Chris Harrison and Scott E. Hudson. “Providing Dynamically Changeable Physical Buttons on a Visual Display”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’09. Boston, MA, USA: ACM, 2009, pp. 299–308. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518749. URL: <http://doi.acm.org/10.1145/1518701.1518749>.
- [73] Richard Hartenberg and Jacques Danavit. *Kinematic synthesis of linkages*. New York: McGraw-Hill, 1964.
- [74] Rex Hartson. “Cognitive, physical, sensory, and functional affordances in interaction design”. In: *Behaviour & Information Technology* 22.5 (2003), pp. 315–338.

- [75] Fabian Hemmert et al. “Animate Mobiles: Proxemically Reactive Posture Actuation As a Means of Relational Interaction with Mobile Phones”. In: *Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction*. TEI '13. Barcelona, Spain: ACM, 2013, pp. 267–270. ISBN: 978-1-4503-1898-3. DOI: 10.1145/2460625.2460669. URL: <http://doi.acm.org/10.1145/2460625.2460669>.
- [76] Fabian Hemmert et al. “Dynamic Knobs: Shape Change As a Means of Interaction on a Mobile Phone”. In: *CHI '08 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '08. Florence, Italy: ACM, 2008, pp. 2309–2314. ISBN: 978-1-60558-012-8. DOI: 10.1145/1358628.1358675. URL: <http://doi.acm.org/10.1145/1358628.1358675>.
- [77] Fabian Hemmert et al. “Shape-changing Mobiles: Tapering in One-dimensional Deformational Displays in Mobile Phones”. In: *Proceedings of the Fourth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '10. Cambridge, Massachusetts, USA: ACM, 2010, pp. 249–252. ISBN: 978-1-60558-841-4. DOI: 10.1145/1709886.1709936. URL: <http://doi.acm.org/10.1145/1709886.1709936>.
- [78] David Holman and Roel Vertegaal. “Organic User Interfaces: Designing Computers in Any Way, Shape, or Form”. In: *Communications of the ACM* 51.6 (June 2008), pp. 48–55. ISSN: 0001-0782. DOI: 10.1145/1349026.1349037. URL: <http://doi.acm.org/10.1145/1349026.1349037>.
- [79] Karen Holtzblatt, Jessamyn Burns Wendell, and Shelley Wood. *Rapid contextual design: a how-to guide to key techniques for user-centered design*. Elsevier, 2004.
- [80] Oren Horev. “Talking to the hand—The interactive potential of shape-behavior in objects and tangible interfaces”. In: *Design and semantics of form and movement* 68 (2006).
- [81] Da-Yuan Huang et al. “RetroShape: Leveraging rear-surface shape displays for 2.5 D interaction on smartwatches”. In: *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. ACM. 2017, pp. 539–551.
- [82] Hilary Hutchinson et al. “Technology Probes: Inspiring Design for and with Families”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '03. Ft. Lauderdale, Florida, USA: ACM, 2003, pp. 17–24. ISBN: 1-58113-630-7. DOI: 10.1145/642611.642616. URL: <http://doi.acm.org/10.1145/642611.642616>.
- [83] Hiroshi Ishii, Ali Mazalek, and Jay Lee. “Bottles As a Minimal Interface to Access Digital Information”. In: *CHI '01 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '01. Seattle, Washington: ACM, 2001, pp. 187–188. ISBN: 1-58113-340-5. DOI: 10.1145/634067.634180. URL: <http://doi.acm.org/10.1145/634067.634180>.

- [84] Hiroshi Ishii, Sandia Ren, and Phil Frei. “Pinwheels: Visualizing Information Flow in an Architectural Space”. In: *CHI '01 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '01. Seattle, Washington: ACM, 2001, pp. 111–112. ISBN: 1-58113-340-5. DOI: 10.1145/634067.634135. URL: <http://doi.acm.org/10.1145/634067.634135>.
- [85] Hiroshi Ishii and Brygg Ullmer. “Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms”. In: *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems*. CHI '97. Atlanta, Georgia, USA: ACM, 1997, pp. 234–241. ISBN: 0-89791-802-9. DOI: 10.1145/258549.258715. URL: <http://doi.acm.org/10.1145/258549.258715>.
- [86] Hiroshi Ishii et al. “Radical Atoms: Beyond Tangible Bits, Toward Transformable Materials”. In: *interactions* 19.1 (Jan. 2012), pp. 38–51. ISSN: 1072-5520. DOI: 10.1145/2065327.2065337. URL: <http://doi.acm.org/10.1145/2065327.2065337>.
- [87] Paul Jackson. *Cut & Fold Techniques for Promotional Materials*. 2.2.2013. Laurence King Publishing, 2013.
- [88] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. “Tangible Remote Controllers for Wall-size Displays”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, 2012, pp. 2865–2874. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2208691. URL: <http://doi.acm.org/10.1145/2207676.2208691>.
- [89] Yvonne Jansen and Kasper Hornbæk. “A psychophysical investigation of size as a physical variable”. In: *IEEE transactions on visualization and computer graphics* 22.1 (2016), pp. 479–488.
- [90] Yvonne Jansen, Thorsten Karrer, and Jan Borchers. “MudPad: Tactile Feedback and Haptic Texture Overlay for Touch Surfaces”. In: *ACM International Conference on Interactive Tabletops and Surfaces*. ITS '10. Saarbrücken, Germany: ACM, 2010, pp. 11–14. ISBN: 978-1-4503-0399-6. DOI: 10.1145/1936652.1936655. URL: <http://doi.acm.org/10.1145/1936652.1936655>.
- [91] Robert E. Jensen. “COMPARISON OF CONSENSUS METHODS FOR PRIORITY RANKING PROBLEMS”. In: *Decision Sciences* 17.2 (1986), pp. 195–211. DOI: 10.1111/j.1540-5915.1986.tb00221.x. eprint: <https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1540-5915.1986.tb00221.x>. URL: <https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1540-5915.1986.tb00221.x>.
- [92] Gunnar Johansson. “Visual perception of biological motion and a model for its analysis”. In: *Perception & psychophysics* 14.2 (1973), pp. 201–211. DOI: <https://doi.org/10.3758/BF03212378>.
- [93] Sergi Jordà et al. “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. Baton Rouge, Louisiana: ACM, 2007, pp. 139–146. ISBN: 978-1-59593-619-6. DOI: 10.1145/1226969.1226998. URL: <http://doi.acm.org/10.1145/1226969.1226998>.

- [94] Mohammadreza Khalilbeigi et al. “FoldMe: Interacting with Double-sided Foldable Displays”. In: *Proceedings of the Sixth International Conference on Tangible, Embedded and Embodied Interaction*. TEI ’12. Kingston, Ontario, Canada: ACM, 2012, pp. 33–40. ISBN: 978-1-4503-1174-8. DOI: 10.1145/2148131.2148142. URL: <http://doi.acm.org/10.1145/2148131.2148142>.
- [95] Mohammadreza Khalilbeigi et al. “Xpaaand: Interaction Techniques for Rollable Displays”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’11. Vancouver, BC, Canada: ACM, 2011, pp. 2729–2732. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979344. URL: <http://doi.acm.org/10.1145/1978942.1979344>.
- [96] Johan Kildal and Graham Wilson. “Feeling It: The Roles of Stiffness, Deformation Range and Feedback in the Control of Deformable UI”. In: *Proceedings of the 14th ACM International Conference on Multimodal Interaction*. ICMI ’12. Santa Monica, California, USA: ACM, 2012, pp. 393–400. ISBN: 978-1-4503-1467-1. DOI: 10.1145/2388676.2388766. URL: <http://doi.acm.org/10.1145/2388676.2388766>.
- [97] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. “Morpheus+: Studying Everyday Reconfigurable Objects for the Design and Taxonomy of Reconfigurable UIs”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: ACM, 2018, 619:1–619:14. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3174193. URL: <http://doi.acm.org/10.1145/3173574.3174193>.
- [98] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. *Collection of Everyday Reconfigurable Objects*. 2018. URL: <http://phyflex.imag.fr/EverydayObjects.html> (visited on 05/23/2019).
- [99] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. “KnobSlider: Design of a Shape-changing Device Grounded in Users’ Needs”. In: *Actes De La 28IèMe Conference Francophone Sur L’Interaction Homme-Machine*. IHM ’16. Fribourg, Switzerland: ACM, 2016, pp. 91–102. ISBN: 978-1-4503-4243-8. DOI: 10.1145/3004107.3004125. URL: <http://doi.acm.org/10.1145/3004107.3004125>.
- [100] 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”. In: *Frontiers in Robotics and AI* 6 (2019), p. 79. ISSN: 2296-9144. DOI: 10.3389/frobt.2019.00079. URL: <https://www.frontiersin.org/article/10.3389/frobt.2019.00079>.
- [101] Hyunyoung Kim, Céline Coutrix, and Anne Roudaut. “KnobSlider: Design of a Shape-Changing UI for Parameter Control”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: ACM, 2018, 339:1–339:13. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173913. URL: <http://doi.acm.org/10.1145/3173574.3173913>.
- [102] Hyunyoung Kim et al. “ExpanDial: Designing a Shape-Changing Dial”. In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS ’19. San Diego, CA, USA: ACM, 2019, pp. 949–961. ISBN: 978-1-4503-5850-7. DOI: 10.1145/3322276.3322283. URL: <http://doi.acm.org/10.1145/3322276.3322283>.

- [103] Seoktae Kim et al. “Inflatable Mouse: Volume-adjustable Mouse with Air-pressure-sensitive Input and Haptic Feedback”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '08. Florence, Italy: ACM, 2008, pp. 211–224. ISBN: 978-1-60558-011-1. DOI: 10.1145/1357054.1357090. URL: <http://doi.acm.org/10.1145/1357054.1357090>.
- [104] David Kirk et al. “Putting the Physical into the Digital: Issues in Designing Hybrid Interactive Surfaces”. In: *Proceedings of the 23rd British HCI Group Annual Conference on People and Computers: Celebrating People and Technology*. BCS-HCI '09. Cambridge, United Kingdom: British Computer Society, 2009, pp. 35–44. URL: <http://dl.acm.org/citation.cfm?id=1671011.1671016>.
- [105] Robert Kovacs et al. “TrussFormer: 3D Printing Large Kinetic Structures”. In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST '18. Berlin, Germany: ACM, 2018, pp. 113–125. ISBN: 978-1-4503-5948-1. DOI: 10.1145/3242587.3242607. URL: <http://doi.acm.org/10.1145/3242587.3242607>.
- [106] Myron W. Krueger, Thomas Gionfriddo, and Katrin Hinrichsen. “VIDEO-PLACE—an Artificial Reality”. In: *SIGCHI Bull.* 16.4 (Apr. 1985), pp. 35–40. ISSN: 0736-6906. DOI: 10.1145/1165385.317463. URL: <https://doi.org/10.1145/1165385.317463>.
- [107] Matthijs Kwak et al. “The Design Space of Shape-changing Interfaces: A Repertory Grid Study”. In: *Proceedings of the 2014 Conference on Designing Interactive Systems*. DIS '14. Vancouver, BC, Canada: ACM, 2014, pp. 181–190. ISBN: 978-1-4503-2902-6. DOI: 10.1145/2598510.2598573. URL: <http://doi.acm.org/10.1145/2598510.2598573>.
- [108] Byron Lahey et al. “PaperPhone: Understanding the Use of Bend Gestures in Mobile Devices with Flexible Electronic Paper Displays”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 1303–1312. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979136. URL: <http://doi.acm.org/10.1145/1978942.1979136>.
- [109] Johnny C. Lee, Scott E. Hudson, and Edward Tse. “Foldable Interactive Displays”. In: *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology*. UIST '08. Monterey, CA, USA: ACM, 2008, pp. 287–290. ISBN: 978-1-59593-975-3. DOI: 10.1145/1449715.1449763. URL: <http://doi.acm.org/10.1145/1449715.1449763>.
- [110] Sang-su Lee, Youn-kyung Lim, and Kun-Pyo Lee. “Exploring the Effects of Size on Deformable User Interfaces”. In: *Proceedings of the 14th International Conference on Human-computer Interaction with Mobile Devices and Services Companion*. MobileHCI '12. San Francisco, California, USA: ACM, 2012, pp. 89–94. ISBN: 978-1-4503-1443-5. DOI: 10.1145/2371664.2371682. URL: <http://doi.acm.org/10.1145/2371664.2371682>.
- [111] Sang-Su Lee et al. “How Users Manipulate Deformable Displays As Input Devices”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '10. Atlanta, Georgia, USA: ACM, 2010, pp. 1647–

1656. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753572. URL: <http://doi.acm.org/10.1145/1753326.1753572>.
- [112] Danny Leen, Raf Ramakers, and Kris Luyten. “StrutModeling: A Low-Fidelity Construction Kit to Iteratively Model, Test, and Adapt 3D Objects”. In: *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*. UIST ’17. Québec City, QC, Canada: ACM, 2017, pp. 471–479. ISBN: 978-1-4503-4981-9. DOI: 10.1145/3126594.3126643. URL: <http://doi.acm.org/10.1145/3126594.3126643>.
- [113] Sang-won Leigh and Pattie Maes. “Body Integrated Programmable Joints Interface”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: ACM, 2016, pp. 6053–6057. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858538. URL: <http://doi.acm.org/10.1145/2858036.2858538>.
- [114] Daniel Leithinger et al. “Direct and Gestural Interaction with Relief: A 2.5D Shape Display”. In: *Proceedings of the 24th Annual ACM Symposium on User Interface Software and Technology*. UIST ’11. Santa Barbara, California, USA: ACM, 2011, pp. 541–548. ISBN: 978-1-4503-0716-1. DOI: 10.1145/2047196.2047268. URL: <http://doi.acm.org/10.1145/2047196.2047268>.
- [115] Daniel Leithinger et al. “Sublimate: State-changing Virtual and Physical Rendering to Augment Interaction with Shape Displays”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’13. Paris, France: ACM, 2013, pp. 1441–1450. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466191. URL: <http://doi.acm.org/10.1145/2470654.2466191>.
- [116] Catherine Letondal et al. “Being in the Sky: Framing Tangible and Embodied Interaction for Future Airliner Cockpits”. In: *Proceedings of the Twelfth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’18. Stockholm, Sweden: ACM, 2018, pp. 656–666. ISBN: 978-1-4503-5568-1. DOI: 10.1145/3173225.3173229. URL: <http://doi.acm.org/10.1145/3173225.3173229>.
- [117] Lars Lischke et al. “Using Variable Movement Resistance Sliders for Remote Discrete Input”. In: *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*. ISS ’17. Brighton, United Kingdom: ACM, 2017, pp. 116–125. ISBN: 978-1-4503-4691-7. DOI: 10.1145/3132272.3134135. URL: <http://doi.acm.org/10.1145/3132272.3134135>.
- [118] Luckybite. *Durrell Bishop Marble Answer Machine*. vimeo. 2011. URL: <https://vimeo.com/19930744> (visited on 04/23/2020).
- [119] G. Michelitsch et al. “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. Vienna, Austria: ACM, 2004, pp. 1305–1308. ISBN: 1-58113-703-6. DOI: 10.1145/985921.986050. URL: <http://doi.acm.org/10.1145/985921.986050>.
- [120] Matthias Milczynski et al. “A malleable device with applications to sonification-based data exploration”. In: Georgia Institute of Technology. 2006.

- [121] S. Miyashita et al. “An untethered miniature origami robot that self-folds, walks, swims, and degrades”. In: *2015 IEEE International Conference on Robotics and Automation (ICRA)*. May 2015, pp. 1490–1496. DOI: 10.1109/ICRA.2015.7139386.
- [122] Rafael Morales González et al. “TouchTokens: Guiding Touch Patterns with Passive Tokens”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 4189–4202. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858041. URL: <http://doi.acm.org/10.1145/2858036.2858041>.
- [123] Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. “LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint”. In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST '15. Charlotte, NC, USA: ACM, 2015, pp. 333–339. ISBN: 978-1-4503-3779-3. DOI: 10.1145/2807442.2807452. URL: <http://doi.acm.org/10.1145/2807442.2807452>.
- [124] Ken Nakagaki et al. “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. Tokyo, Japan: ACM, 2016, pp. 87–96. ISBN: 978-1-4503-4189-9. DOI: 10.1145/2984511.2984587. URL: <http://doi.acm.org/10.1145/2984511.2984587>.
- [125] Ken Nakagaki et al. “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. San Jose, California, USA: ACM, 2016, pp. 2764–2772. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858104. URL: <http://doi.acm.org/10.1145/2858036.2858104>.
- [126] Yusuke Nakagawa, Akiya Kamimura, and Yoichiro Kawaguchi. “MimicTile: A Variable Stiffness Deformable User Interface for Mobile Devices”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, 2012, pp. 745–748. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2207782. URL: <http://doi.acm.org/10.1145/2207676.2207782>.
- [127] John R Napier. “The prehensile movements of the human hand”. In: *The Journal of bone and joint surgery. British volume* 38.4 (1956), pp. 902–913.
- [128] Koya Narumi et al. “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. New Orleans, LA, USA: ACM, 2019, pp. 293–306. ISBN: 978-1-4503-6816-2. DOI: 10.1145/3332165.3347901. URL: <http://doi.acm.org/10.1145/3332165.3347901>.
- [129] Taketoshi Nojima et al. “Origami modeling of functional structures based on organic patterns”. In: *Master’s thesis, Graduate School of Kyoto University, Kyoto, Japan* (2002).

- [130] Mie Nørgaard et al. “Exploring the Design Space of Shape-changing Objects: Imagined Physics”. In: *Proceedings of the 6th International Conference on Designing Pleasurable Products and Interfaces*. DPPI ’13. Newcastle upon Tyne, United Kingdom: ACM, 2013, pp. 251–260. ISBN: 978-1-4503-2192-1. DOI: 10.1145/2513506.2513533. URL: <http://doi.acm.org/10.1145/2513506.2513533>.
- [131] Donald A Norman. *The psychology of everyday things*. Basic books, 1988.
- [132] Simon Olberding et al. “Foldio: Digital Fabrication of Interactive and Shape-Changing Objects With Foldable Printed Electronics”. In: *Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology*. UIST ’15. Charlotte, NC, USA: ACM, 2015, pp. 223–232. ISBN: 978-1-4503-3779-3. DOI: 10.1145/2807442.2807494. URL: <http://doi.acm.org/10.1145/2807442.2807494>.
- [133] Anke van Oosterhout, Miguel Bruns Alonso, and Satu Jumisko-Pyykkö. “Ripple Thermostat: Affecting the Emotional Experience Through Interactive Force Feedback and Shape Change”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI ’18. Montreal QC, Canada: ACM, 2018, 655:1–655:12. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3174229. URL: <http://doi.acm.org/10.1145/3173574.3174229>.
- [134] Anke van Oosterhout et al. “DynaKnob: Combining Haptic Force Feedback and Shape Change”. In: *Proceedings of the 2019 on Designing Interactive Systems Conference*. DIS ’19. San Diego, CA, USA: ACM, 2019, pp. 963–974. ISBN: 978-1-4503-5850-7. DOI: 10.1145/3322276.3322321. URL: <http://doi.acm.org/10.1145/3322276.3322321>.
- [135] Kas Oosterhuis and Nimish Biloria. “Interactions with Proactive Architectural Spaces: The Muscle Projects”. In: *Commun. ACM* 51.6 (June 2008), pp. 70–78. ISSN: 0001-0782. DOI: 10.1145/1349026.1349041. URL: <http://doi.acm.org/10.1145/1349026.1349041>.
- [136] Young-Woo Park, Joohee Park, and Tek-Jin Nam. “The Trial of Bendi in a Coffeehouse: Use of a Shape-Changing Device for a Tactile-Visual Phone Conversation”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 2181–2190. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702326. URL: <http://doi.acm.org/10.1145/2702123.2702326>.
- [137] Sylvain Pauchet et al. “GazeForm: Dynamic Gaze-adaptive Touch Surface for Eyes-free Interaction in Airliner Cockpits”. In: *Proceedings of the 2018 Designing Interactive Systems Conference*. DIS ’18. Hong Kong, China: ACM, 2018, pp. 1193–1205. ISBN: 978-1-4503-5198-0. DOI: 10.1145/3196709.3196712. URL: <http://doi.acm.org/10.1145/3196709.3196712>.
- [138] Sylvain Pauchet et al. “Multi-plié: 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. Glasgow, Scotland Uk: ACM, 2019, 154:1–154:13. ISBN: 978-1-4503-5970-2. DOI: 10.1145/3290605.3300384. URL: <http://doi.acm.org/10.1145/3290605.3300384>.

- [139] Esben W. Pedersen, Sriram Subramanian, and Kasper Hornbæk. “Is My Phone Alive?: A Large-scale Study of Shape Change in Handheld Devices Using Videos”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '14. Toronto, Ontario, Canada: ACM, 2014, pp. 2579–2588. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557018. URL: <http://doi.acm.org/10.1145/2556288.2557018>.
- [140] Isabel P. S. Qamar et al. “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. Montreal QC, Canada: ACM, 2018, 374:1–374:23. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173948. URL: <http://doi.acm.org/10.1145/3173574.3173948>.
- [141] Hayes Solos Raffle, Amanda J. Parkes, and Hiroshi Ishii. “Topobo: A Constructive Assembly System with Kinetic Memory”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '04. Vienna, Austria: ACM, 2004, pp. 647–654. ISBN: 1-58113-702-8. DOI: 10.1145/985692.985774. URL: <http://doi.acm.org/10.1145/985692.985774>.
- [142] 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*. CHI '14. Toronto, Ontario, Canada: ACM, 2014, pp. 2569–2578. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557340. URL: <http://doi.acm.org/10.1145/2556288.2557340>.
- [143] M Ramsgard Thomsen. “Textile Logics in a Moving Architecture”. In: *Transitive Materials Workshop, CHI Computer Human Interface*. 2009.
- [144] Majken Kirkegård Rasmussen et al. “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. Eindhoven, Netherlands: ACM, 2016, pp. 202–210. ISBN: 978-1-4503-3582-9. DOI: 10.1145/2839462.2839499. URL: <http://doi.acm.org/10.1145/2839462.2839499>.
- [145] Majken K. Rasmussen et al. “Shape-changing Interfaces: A Review of the Design Space and Open Research Questions”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '12. Austin, Texas, USA: ACM, 2012, pp. 735–744. ISBN: 978-1-4503-1015-4. DOI: 10.1145/2207676.2207781. URL: <http://doi.acm.org/10.1145/2207676.2207781>.
- [146] Majken K. Rasmussen et al. “Sketching Shape-changing Interfaces: Exploring Vocabulary, Metaphors Use, and Affordances”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 2740–2751. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858183. URL: <http://doi.acm.org/10.1145/2858036.2858183>.
- [147] Franz Reuleaux. *The kinematics of machinery: outlines of a theory of machines*. Courier Corporation, 2013.

- [148] Simon Robinson et al. “Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI '16. San Jose, California, USA: ACM, 2016, pp. 3793–3805. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858097. URL: <http://doi.acm.org/10.1145/2858036.2858097>.
- [149] Anne Roudaut et al. “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. Paris, France: ACM, 2013, pp. 593–602. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2470738. URL: <http://doi.acm.org/10.1145/2470654.2470738>.
- [150] Anne Roudaut et al. “Rubikon: A Highly Reconfigurable Device for Advanced Interaction”. In: *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. CHI EA '14. Toronto, Ontario, Canada: ACM, 2014, pp. 1327–1332. ISBN: 978-1-4503-2474-8. DOI: 10.1145/2559206.2581275. URL: <http://doi.acm.org/10.1145/2559206.2581275>.
- [151] A. Roudaut et al. “Cubimorph: Designing modular interactive devices”. In: *2016 IEEE International Conference on Robotics and Automation (ICRA)*. May 2016, pp. 3339–3345. DOI: 10.1109/ICRA.2016.7487508.
- [152] Deepak Ranjan Sahoo et al. “Tangible Drops: A Visio-Tactile Display Using Actuated Liquid-Metal Droplets”. In: *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*. CHI '18. Montreal QC, Canada: ACM, 2018, 177:1–177:14. ISBN: 978-1-4503-5620-6. DOI: 10.1145/3173574.3173751. URL: <http://doi.acm.org/10.1145/3173574.3173751>.
- [153] Robert Salazar. *Starshade: An Origami Odyssey*. June 16, 2015. URL: <http://www.salazarigami.com/starshade/> (visited on 09/17/2018).
- [154] Angela Sasse et al. *Plasticity of User Interfaces: Framework and Research Agenda*. 1999.
- [155] Marin Sawa et al. “Electricity generation from digitally printed cyanobacteria”. In: *Nature communications* 8.1 (2017), p. 1327.
- [156] Dominique L Scapin and JM Christian Bastien. “Ergonomic criteria for evaluating the ergonomic quality of interactive systems”. In: *Behaviour & information technology* 16.4-5 (1997), pp. 220–231.
- [157] Joey Scarr, Andy Cockburn, and Carl Gutwin. “Supporting and Exploiting Spatial Memory in User Interfaces”. In: *Foundations and Trends in Human-Computer Interaction* 6.1 (2013), pp. 1–84. ISSN: 1551-3955. DOI: 10.1561/11000000046. URL: <http://dx.doi.org/10.1561/11000000046>.
- [158] Joey Scarr et al. “Dips and Ceilings: Understanding and Supporting Transitions to Expertise in User Interfaces”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '11. Vancouver, BC, Canada: ACM, 2011, pp. 2741–2750. ISBN: 978-1-4503-0228-9. DOI: 10.1145/1978942.1979348. URL: <http://doi.acm.org/10.1145/1978942.1979348>.

- [159] Carsten Schwesig, Ivan Poupyrev, and Eijiro Mori. “Gummi: A Bendable Computer”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’04. Vienna, Austria: ACM, 2004, pp. 263–270. ISBN: 1-58113-702-8. DOI: 10.1145/985692.985726. URL: <http://doi.acm.org/10.1145/985692.985726>.
- [160] Marcos Serrano, Anne Roudaut, and Pourang Irani. “Visual Composition of Graphical Elements on Non-Rectangular Displays”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI ’17. Denver, Colorado, USA: ACM, 2017, pp. 4405–4416. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3025677. URL: <http://doi.acm.org/10.1145/3025453.3025677>.
- [161] Orit Shaer and Eva Hornecker. “Tangible User Interfaces: Past, Present, and Future Directions”. In: *Foundations and Trends in Human-Computer Interaction* 3.1-2 (2010), pp. 4–137. ISSN: 1551-3955. DOI: 10.1561/1100000026. URL: <http://dx.doi.org/10.1561/1100000026>.
- [162] Ali Shahrokni et al. “One-dimensional Force Feedback Slider: Going from an Analogue to a Digital Platform”. In: *Proceedings of the 4th Nordic Conference on Human-computer Interaction: Changing Roles*. NordiCHI ’06. Oslo, Norway: ACM, 2006, pp. 453–456. ISBN: 1-59593-325-5. DOI: 10.1145/1182475.1182535. URL: <http://doi.acm.org/10.1145/1182475.1182535>.
- [163] Earl D Sharp. *Maximum torque exertable on knobs of various sizes and rim surfaces*. Tech. rep. AIR FORCE AEROSPACE MEDICAL RESEARCH LAB WRIGHT-PATTERSON AFB OH, 1962.
- [164] Emmanuel Siéfert et al. “Bio-inspired pneumatic shape-morphing elastomers”. In: *Nature materials* 18.1 (2019), p. 24.
- [165] David Canfield Smith et al. “Human-computer Interaction”. In: ed. by Jenny Preece. Upper Saddle River, NJ, USA: Prentice Hall Press, 1990. Chap. Designing the Star User Interface, pp. 237–259. ISBN: 0-13-444910-X. URL: <http://dl.acm.org/citation.cfm?id=87725.87741>.
- [166] Jürgen Steimle, Andreas Jordt, and Pattie Maes. “Flexpad: Highly Flexible Bending Interactions for Projected Handheld Displays”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’13. Paris, France: ACM, 2013, pp. 237–246. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2470688. URL: <http://doi.acm.org/10.1145/2470654.2470688>.
- [167] Paul Strohmeier et al. “An Evaluation of Shape Changes for Conveying Emotions”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: ACM, 2016, pp. 3781–3792. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858537. URL: <http://doi.acm.org/10.1145/2858036.2858537>.
- [168] Miriam Sturdee et al. “A Public Ideation of Shape-Changing Applications”. In: *Proceedings of the 2015 International Conference on Interactive Tabletops & Surfaces*. ITS ’15. Madeira, Portugal: ACM, 2015, pp. 219–228. ISBN: 978-1-4503-3899-8. DOI: 10.1145/2817721.2817734. URL: <http://doi.acm.org/10.1145/2817721.2817734>.

- [169] Miriam Sturdee et al. “Visual Methods for the Design of Shape-Changing Interfaces”. In: *Human-Computer Interaction – INTERACT 2019*. Ed. by David Lamas et al. Cham: Springer International Publishing, 2019, pp. 337–358. ISBN: 978-3-030-29387-1.
- [170] Jihoon Suh, Wooshik Kim, and Andrea Bianchi. “Button+: Supporting User and Context Aware Interaction Through Shape-Changing Interfaces”. In: *Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction*. TEI ’17. Yokohama, Japan: ACM, 2017, pp. 261–268. ISBN: 978-1-4503-4676-4. DOI: 10.1145/3024969.3024980. URL: <http://doi.acm.org/10.1145/3024969.3024980>.
- [171] Ivan E Sutherland. “Sketchpad a man-machine graphical communication system”. In: *Simulation* 2.5 (1964), R-3.
- [172] Faisal Taher et al. “Exploring Interactions with Physically Dynamic Bar Charts”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 3237–3246. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702604. URL: <http://doi.acm.org/10.1145/2702123.2702604>.
- [173] Kazuki Takashima et al. “Study and Design of a Shape-Shifting Wall Display”. In: *Proceedings of the 2016 ACM Conference on Designing Interactive Systems*. DIS ’16. Brisbane, QLD, Australia: ACM, 2016, pp. 796–806. ISBN: 978-1-4503-4031-1. DOI: 10.1145/2901790.2901892. URL: <http://doi.acm.org/10.1145/2901790.2901892>.
- [174] Atau Tanaka and Adam Parkinson. “Haptic Wave: A Cross-Modal Interface for Visually Impaired Audio Producers”. In: *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*. CHI ’16. San Jose, California, USA: ACM, 2016, pp. 2150–2161. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858304. URL: <http://doi.acm.org/10.1145/2858036.2858304>.
- [175] Tangible Media Group, MIT Media Lab. *ICC 2000 Tangible Bits Exhibition*. URL: <https://tangible.media.mit.edu/project/icc-2000-tangible-bits-exhibition/> (visited on 04/22/2020).
- [176] Stuart Taylor et al. “Type-hover-swipe in 96 Bytes: A Motion Sensing Mechanical Keyboard”. In: *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’14. Toronto, Ontario, Canada: ACM, 2014, pp. 1695–1704. ISBN: 978-1-4503-2473-1. DOI: 10.1145/2556288.2557030. URL: <http://doi.acm.org/10.1145/2556288.2557030>.
- [177] tdjgordon. *Mixer Sound Studio Edit Free Photo*. URL: <https://www.needpix.com/photo/284582/mixer-sound-studio-edit-music-board-hands-melody-electronic-entertainment> (visited on 04/14/2020).
- [178] Shan-Yuan Teng et al. “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. New Orleans, LA, USA: ACM, 2019, pp. 639–649. ISBN: 978-1-4503-6816-2. DOI: 10.1145/3332165.3347958. URL: <http://doi.acm.org/10.1145/3332165.3347958>.

- [179] Marc Teyssier et al. “MobiLimb: Augmenting Mobile Devices with a Robotic Limb”. In: *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*. UIST ’18. Berlin, Germany: ACM, 2018, pp. 53–63. ISBN: 978-1-4503-5948-1. DOI: 10.1145/3242587.3242626. URL: <http://doi.acm.org/10.1145/3242587.3242626>.
- [180] *The Average Smartphone User Accessed Close to 40 Apps per Month in 2017*. URL: <https://www.appannie.com/en/insights/market-data/apps-used-2017/>.
- [181] Sarah-Kristin Thiel and Peter Fröhlich. “Gamification as Motivation to Engage in Location-Based Public Participation?” In: *Progress in Location-Based Services 2016*. Ed. by Georg Gartner and Haosheng Huang. Cham: Springer International Publishing, 2017, pp. 399–421. ISBN: 978-3-319-47289-8.
- [182] 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. San Jose, California, USA: ACM, 2016, pp. 2752–2763. ISBN: 978-1-4503-3362-7. DOI: 10.1145/2858036.2858350. URL: <http://doi.acm.org/10.1145/2858036.2858350>.
- [183] 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. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 91–100. ISBN: 978-1-4503-2271-3. DOI: 10.1145/2512349.2512812. URL: <http://doi.acm.org/10.1145/2512349.2512812>.
- [184] Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. “Deformable Interfaces for Performing Music”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 377–386. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702492. URL: <http://doi.acm.org/10.1145/2702123.2702492>.
- [185] Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. “User-defined Gestures for Elastic, Deformable Displays”. In: *Proceedings of the 2014 International Working Conference on Advanced Visual Interfaces*. AVI ’14. Como, Italy: ACM, 2014, pp. 1–8. ISBN: 978-1-4503-2775-6. DOI: 10.1145/2598153.2598184. URL: <http://doi.acm.org/10.1145/2598153.2598184>.
- [186] Giovanni Maria Troiano, John Tiab, and Youn-Kyung Lim. “SCI-FI: Shape-Changing Interfaces, Future Interactions”. In: *Proceedings of the 9th Nordic Conference on Human-Computer Interaction*. NordiCHI ’16. Gothenburg, Sweden: ACM, 2016, 45:1–45:10. ISBN: 978-1-4503-4763-1. DOI: 10.1145/2971485.2971489. URL: <http://doi.acm.org/10.1145/2971485.2971489>.
- [187] Theophanis Tsandilas, Anastasia Bezerianos, and Thibaut Jacob. “SketchSliders: Sketching Widgets for Visual Exploration on Wall Displays”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 3255–3264. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702129. URL: <http://doi.acm.org/10.1145/2702123.2702129>.

- [188] Jessica Tsimeris et al. “ForceForm: A Dynamically Deformable Interactive Surface”. In: *Proceedings of the 2013 ACM International Conference on Interactive Tabletops and Surfaces*. ITS ’13. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 175–178. ISBN: 978-1-4503-2271-3. DOI: 10.1145/2512349.2512807. URL: <http://doi.acm.org/10.1145/2512349.2512807>.
- [189] 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. Atlanta, Georgia, USA: ACM, 2010, pp. 2223–2232. ISBN: 978-1-60558-929-9. DOI: 10.1145/1753326.1753662. URL: <http://doi.acm.org/10.1145/1753326.1753662>.
- [190] B. Ullmer and H. Ishii. “Emerging Frameworks for Tangible User Interfaces”. In: *IBM Syst. J.* 39.3-4 (July 2000), pp. 915–931. ISSN: 0018-8670. DOI: 10.1147/sj.393.0915. URL: <http://dx.doi.org/10.1147/sj.393.0915>.
- [191] Brygg Ullmer and Hiroshi Ishii. “The metaDESK: Models and Prototypes for Tangible User Interfaces”. In: *Proceedings of the 10th Annual ACM Symposium on User Interface Software and Technology*. UIST ’97. Banff, Alberta, Canada: ACM, 1997, pp. 223–232. ISBN: 0-89791-881-9. DOI: 10.1145/263407.263551. URL: <http://doi.acm.org/10.1145/263407.263551>.
- [192] John Underkoffler and Hiroshi Ishii. “Urp: A Luminous-tangible Workbench for Urban Planning and Design”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’99. Pittsburgh, Pennsylvania, USA: ACM, 1999, pp. 386–393. ISBN: 0-201-48559-1. DOI: 10.1145/302979.303114. URL: <http://doi.acm.org/10.1145/302979.303114>.
- [193] Marynel Vázquez et al. “3D Printing Pneumatic Device Controls with Variable Activation Force Capabilities”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI ’15. Seoul, Republic of Korea: ACM, 2015, pp. 1295–1304. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702569. URL: <http://doi.acm.org/10.1145/2702123.2702569>.
- [194] Jo Vermeulen et al. “Crossing the Bridge over Norman’s Gulf of Execution: Revealing Feedforward’s True Identity”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI ’13. Paris, France: ACM, 2013, pp. 1931–1940. ISBN: 978-1-4503-1899-0. DOI: 10.1145/2470654.2466255. URL: <http://doi.acm.org/10.1145/2470654.2466255>.
- [195] Roel Vertegaal and Ivan Poupyrev. “Organic user interfaces”. In: *Communications of the ACM* 51.6 (2008), pp. 26–30.
- [196] Nicolas Villar et al. “Mouse 2.0: Multi-touch Meets the Mouse”. In: *Proceedings of the 22Nd Annual ACM Symposium on User Interface Software and Technology*. UIST ’09. Victoria, BC, Canada: ACM, 2009, pp. 33–42. ISBN: 978-1-60558-745-5. DOI: 10.1145/1622176.1622184. URL: <http://doi.acm.org/10.1145/1622176.1622184>.

- [197] Jean-Luc Vinot et al. “Could Tangibility Improve the Safety of Touch-based Interaction?: Exploring a New Physical Design Space for Pilot-system Interfaces”. In: *Proceedings of the International Conference on Human-Computer Interaction in Aerospace*. HCI-Aero '16. Paris, France: ACM, 2016, 8:1–8:8. ISBN: 978-1-4503-4406-7. DOI: 10.1145/2950112.2964581. URL: <http://doi.acm.org/10.1145/2950112.2964581>.
- [198] VintageCG. *Videoplace (1985)*. URL: https://www.youtube.com/watch?time_continue=2&v=d4DUieXSEpk&feature=emb_logo (visited on 04/22/2020).
- [199] J.Y. Wang et al. “Self-healing concrete by use of microencapsulated bacterial spores”. In: *Cement and Concrete Research* 56 (2014), pp. 139–152. ISSN: 0008-8846. DOI: <https://doi.org/10.1016/j.cemconres.2013.11.009>. URL: <http://www.sciencedirect.com/science/article/pii/S0008884613002482>.
- [200] Wen Wang et al. “Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction Through Cooking”. In: *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. CHI '17. Denver, Colorado, USA: ACM, 2017, pp. 6123–6132. ISBN: 978-1-4503-4655-9. DOI: 10.1145/3025453.3026019. URL: <http://doi.acm.org/10.1145/3025453.3026019>.
- [201] Malte Weiss et al. “SLAP Widgets: Bridging the Gap Between Virtual and Physical Controls on Tabletops”. In: *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. CHI '09. Boston, MA, USA: ACM, 2009, pp. 481–490. ISBN: 978-1-60558-246-7. DOI: 10.1145/1518701.1518779. URL: <http://doi.acm.org/10.1145/1518701.1518779>.
- [202] Langdon Winner. “Do Artifacts Have Politics?” In: *Daedalus* 109.1 (1980), pp. 121–136. ISSN: 00115266. URL: <http://www.jstor.org/stable/20024652>.
- [203] Lining Yao et al. “bioLogic: Natto Cells As Nanoactuators for Shape Changing Interfaces”. In: *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. CHI '15. Seoul, Republic of Korea: ACM, 2015, pp. 1–10. ISBN: 978-1-4503-3145-6. DOI: 10.1145/2702123.2702611. URL: <http://doi.acm.org/10.1145/2702123.2702611>.
- [204] Lining Yao et al. “PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces”. In: *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*. UIST '13. St. Andrews, Scotland, United Kingdom: ACM, 2013, pp. 13–22. ISBN: 978-1-4503-2268-3. DOI: 10.1145/2501988.2502037. URL: <http://doi.acm.org/10.1145/2501988.2502037>.
- [205] Thomas Young. *A Course of Lectures on Natural Philosophy and the Mechanical Arts: I [-II]*. Vol. 1. Taylor and Walton, 1845.
- [206] Bin Yu et al. “LivingSurface: Biofeedback Through Shape-changing Display”. In: *Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction*. TEI '16. Eindhoven, Netherlands: ACM, 2016, pp. 168–175. ISBN: 978-1-4503-3582-9. DOI: 10.1145/2839462.2839469. URL: <http://doi.acm.org/10.1145/2839462.2839469>.