Anthropomorphic devices for affective touch communication

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ANTHROPOMORPHIC DEVICES
FOR AFFECTIVE TOUCH COMMUNICATION

DEVICES THAT TOUCH TO CONVEY EMOTIONS AND FEEL THAT CONTACT

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Abstract

Communicating emotions is important for human attachment and bonding as well as for physical and psychological well-being. We communicate emotions through voice, but also through body language such as facial expressions, posture or touch. Among all these nonverbal cues, the tactile modality plays a particular role. Touch happens in co-located situations and involves physical contact between two individuals. A touch contact can convey emotions such as comforting someone by gently stroking her arm. Current technologies and devices used for mediated communication are not designed to support affective touch communication. There is a need to have new interfaces to mediate touch, both to detect touch (to replace the receiver's skin) and to convey touch (to replace the emitter's hand).

My approach takes inspiration from the human body to inform the design of new interfaces. I promote the use of *anthropomorphic affordances* to design interfaces that benefit from our knowledge of physical interaction with other humans. *Anthropomorphic affordances* project human functioning and behaviour to the attributes of an object to suggest ways of using it. However, anthropomorphism has received little attention so far in the field of Human-Computer Interaction; its design space is still largely unexplored. In this thesis, I explore this design space and focus on augmenting mobile and robotic devices with tactile capabilities to enhance the conveying of emotions to enrich social communication. This raises two main research problems addressed in this thesis.

A first problem is to define the type of device needed to perform touch. Current actuated devices do not produce humanlike touch. In the first part of this thesis, I focus on the design and implementation of interfaces capable of **producing** humanlike touch *output*. I highlight human touch factors that can be reproduced by an actuated device. I then experimentally evaluate the impact of humanlike device-initiated touch on the perception of emotions. Finally, I built on top of these findings to propose MobiLimb, a small-scale robotic arm that can be connected onto mobile devices and can touch the user.

A second problem is to develop interfaces capable of **detecting** touch *input*. My approach is to integrate humanlike artificial skin onto existing devices. I propose requirements to replicate the human skin, and a fabrication method for reproducing its visual, tactile and kinaesthetic properties. I then propose an implementation of artificial skin that can be integrated onto existing devices and can sense expressive touch gestures. This interface is then used to explore possible scenarios and applications for mediated touch input.

In summary, this thesis contributes to the design and understanding of anthropomorphic devices for affective touch communication. I propose to use anthropomorphic affordances to design interfaces. To address the research questions of this thesis, I built upon human biological characteristics and digital fabrication tools and methods. The devices presented in this thesis propose new technical and empirical contributions around touch detection and touch generation.

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I would like to thank all the people that supported me during the past three years and who accompanied me during the writing of this Thesis.

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Articles in Peer-reviewed Conference Proceedings

– Marc Teyssier, Gilles Bailly, Catherine Pelachaud, and Eric Lecolinet, Andrew Conn, Anne Roudaut.“ Skin-On Interfaces: A Bio-Driven Approach for Artificial Skin Design to Cover Interactive Devices.” In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology (UIST '19).*

– Marc Teyssier, Gilles Bailly, Catherine Pelachaud, and Eric Lecolinet. “MobiLimb: Augmenting Mobile Devices with a Robotic Limb.” In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology (UIST '18).* ACM, New York, NY, USA, 53-63. DOI: https://doi.org/10.1145/3242587.3242626

– Marc Teyssier, Gilles Bailly, Eric Lecolinet and Catherine Pelachaud. “Revue et Perspectives du Toucher Social en IHM (Survey and Perspectives of Social Touch in HCI) .” In *29ème conférence francophone sur l'Interaction Homme-Machine.* Sous la dir. d'AFIHM, AFIHM. Poitiers, France: ACM, oct 2017

Journal Articles

– M. Teyssier, G. Bailly, E. Lecolinet and C. Pelachaud, “Conveying Emotions Through Device-Initiated Touch ”, *Submitted to: IEEE Transactions on Affective Computing*.

Articles in Workshop

– M. Teyssier, G. Bailly, E. Lecolinet and C. Pelachaud, “Investigating Social Touch with a Robotic Arm ”, in *CHI 2018 Workshop : Reshaping Touch Communication: An Interdisciplinary Research Agenda*, Apr. 2018.

Patent

– M. Teyssier, G. Bailly, E. Lecolinet and C. Pelachaud, “Robotic finger for mobile devices” (FR: Doigt robotisé pour dispositif portable), *patent pending FR 1858553, 09-20-2018*

Contents

1

Introduction

Communication is crucial for Humans, as individuals rely on communication to build complex society and advanced knowledge. Communication is the transmission of messages or information between an emitter and a receiver with signs or signals.It allows people to share useful information as well as to convey thoughts and emotions. The tone of voice, body language such as facial expressions, posture or touch are social signals that are understood and interpreted by others, and all these modalities play an important role in the quality of the communication:

Nonverbal communication is defined as a wordless transmission of information through visual, auditory, tactile, or kinesthetic (physical) channels [Mehrabian, 2017]. Nonverbal communication cues are used to share information about our intentions, state of mind or personality and constitute an additional channel of communication [McDaniel and Andersen, 1998]. During a conversation, these nonverbal cues can reinforce or contradict what has already been said, complement the verbal message or even replace words.

Among all the nonverbal cues that are used for communication, the

tactile modality plays a particular role. Touch involves physical contact between two individuals and has several functions. During real-life communication, we use touch in a co-located situation to convey a wide range of intentions and emotions [Hertenstein et al., 2006b]. For instance, a gentle stroke on the arm is performed to comfort someone. The communication of emotions is crucial for human attachment and bonding as well as physical and psychological well-being [Morrison and Olausson, 2010]. Skin affords touch contact, and the human hands and fingers are the perfect interfaces to perform touch.

With digital technologies, the means of communication have quickly evolved. People far apart can communicate remotely, and socially interact with others, friends and family. The communication is performed using devices such as smartphones, which are now the main device for mediated communication [Oksman and Turtiainen, 2004]. These devices are principally used for voice communication and instant text messaging [Do et al., 2011]. The signs of non-verbal communication cues that usually accompany conversations are generally absent in these applications, which can lead to a number of ambiguities [Tossell et al., 2012] and deteriorate the quality of communication.

Affective touch communication cues are important in real-life, yet are generally absent in digital communication. Smartphones are not built to interpret and convey affective touch. Their shape is static, and, unlike the human skin, their touch input interface is flat and stiff. The question I address in this thesis is: **How natural touch affordances can be conveyed through an interface that has similar touch capabilities as humans?** To answer this question, I focus on the augmentation of mobile devices with the tactile modality to facilitate the expression of feelings and emotions to enrich social communication. My approach is to use *anthropomorphic affordances* for the design of new artifacts. Anthropomorphism is defined as "*the tendency to attribute human characteristics to inanimate objects, animals and others with a view to helping us rationalise their actions*" [Duffy, 2003]. Based on this definition, Anthropomorphic affordances project human functioning and behaviour to the attributes of an object to suggest the way of using it. Novel technologies and new digital fabrication tools facilitate the fabrication of anthropomorphic interfaces. They offer an opportunity for Human-Computer Interaction (HCI) researchers and designers to leverage touch communication in mediated communication by using anthropomorphic design.

In this introductory chapter, we first position the thesis within the research domains. Then we define the problem statement in section 1.1, and present our approach in section 1.3 and our methods in section 1.4. We follow by stating the contribution of our work and present a brief description of the thesis chapters.

1.1 *Problem Statement*

When communicating, we use touch in a co-located situation to convey a wide range of intentions and emotions [Hertenstein et al., 2006a]. For instance, a stroke on the arm convey comfort. Affective touch involves two individuals that perform a direct tactile contact: the hand of the emitter typically touches the skin of the receiver. A simplified co-located interpersonal touch interaction, illustrated in Figure 1.1, can be schematized as follows:

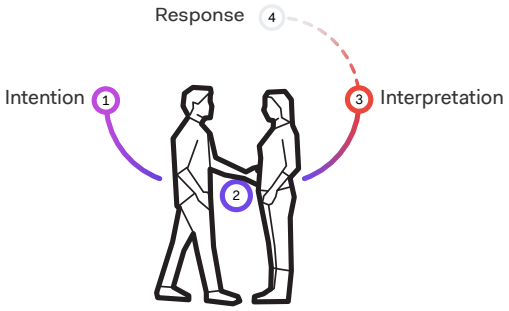


Figure 1.1: **Co-located touch**. The process of touch to communicate emotion in a co-located context. *(1)* The individual on the left has and emotion he wants to convey through touch. *(2)* He performs a touch contact on the other. *(3)* This touch is interpreted and eventually the other respond *(4)*

1 **Intention**. The *emitter* (left) forms an emotion that he wants to convey through touch.
2 **Touch**. The touch is performed, from the *emitter* to the *receiver*.
3 **Interpretation**. The *receiver* then interprets the touch stimulus and can eventually formulate a **response** (4) though either verbal communication or non-verbal communication cues such as facial expressions or affective touch.

In the context of remote mediated touch communication, this direct touch contact cannot be performed. There is a need to have new interfaces to mediate touch. This challenges the creation of two interfaces (summarized in Figure 1.2): One to detect touch (to replace the receiver skin) and another one to convey touch (to replace the emitter hand).

In the literature, existing approaches to convey emotions through touch

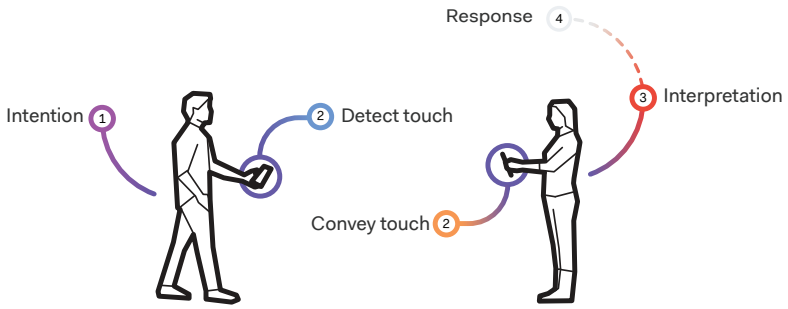


Figure 1.2: **Mediated remote touch** communication requires two different devices to perform a complete touch communication loop. One device should be detected to detect touch, one other to convey touch.

during mediated communication usually rely on haptic devices. The most common existing technologies are vibration motors [Seifi and Maclean, 2013, Ahmed et al., 2016, Wilson and Brewster, 2017] or force feedback devices (Knob [Smith and MacLean, 2007], Phantom [Bailenson et al., 2007]). They require dedicated hardware which are not adapted to common personal devices such as smartphones or the mobility context in which we commonly perform mediated communication. Moreover, these technologies simplify human touch to simple patterns or touch vocabularies, and do not replicate the complexity of human touch.

During mediated communication, we usually interact with the flat screen of the mobile devices. Touching a flat screen does not convey the same affordances as the human skin, which might impact the naturalness and spontaneity of interaction.

In this thesis, the question I address is: *How devices for mediated touch communication can be more humanlike and integrated with our daily used devices.* I am interested both in touch input (performed by the user) and touch output (provided to the user). My approach is to draw inspiration from the human and anthropomorphism to design new interfaces, which led to two research problems:

PROBLEM 1 *Can actuated devices produce humanlike touch?*
This problem can be addressed by studying in the literature how emotional touch is performed , and by exploring how it can be transposed to Human-Computer Interaction. This implies several sub challenges: First, PROBLEM 1.1, What are the characteristics of human touch and how can we transpose them into a device. Second, PROBLEM 1.2, is it possible to perform humanlike device-initiated touch that conveys emotions? Finally, PROBLEM 1.3, how can we design a portable device or artifact that can touch the user?

PROBLEM 2 *Can humanlike artificial skin be embedded into existing devices?*
PROBLEM 1 consider interfaces capable of producing humanlike touch *output*. We are also interested in exploring how users can transmit information through every day devices. We explore interfaces that can detect touch *input* with similar properties as human skin. This implies two sub challenges: First, PROBLEM 2.1, what are the requirements to replicate realistic human skin? Second, PROBLEM 2.2, how to integrate artificial skin into existing devices?

1.2 *Research domains*

The research topic of this thesis lies in the domain of mediated interpersonal communication that uses touch to convey emotions (also called Social Touch [Van Erp and Toet, 2015] in the literature). This research topic is a multidisciplinary field at the crossroads of experimental physiology, social interaction, human-computer interaction, affective computing and haptics (Figure 1.3).

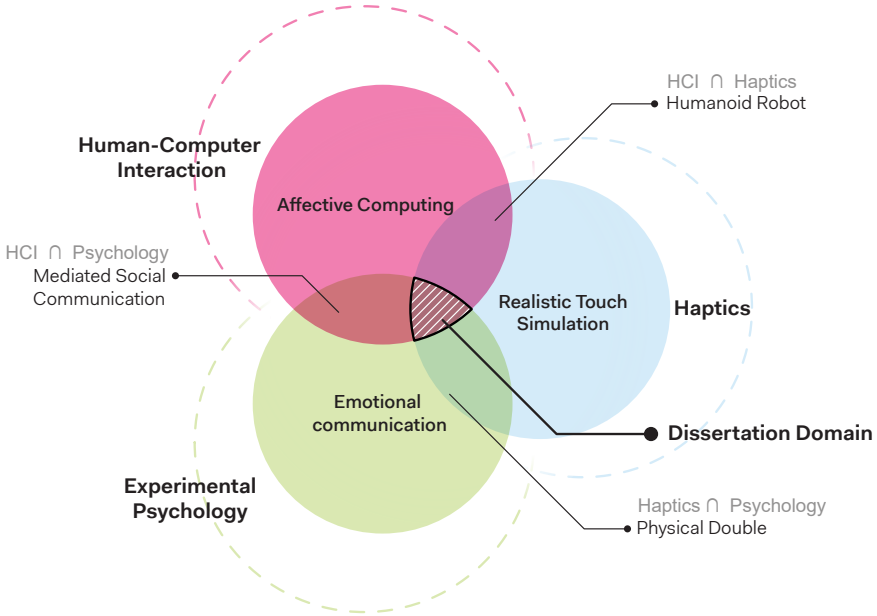


Figure 1.3: Research scope of this thesis, between Experimental Psychology, Human-Computer Interaction and Haptics

The field of experimental psychology examines the relationship between human behavior and cognition, and researchers in psychology base some of their reflections through observation and user experiments. Efforts

for understanding affective touch for emotional communication are fairly recent: Hertenstein et al. [2006a, 2009] conducted the first thorough studies. Although some touch-related phenomenon, such as Midas Touch [Crusco and Wetzel, 1984], were already known, Hertenstein et. al. systematically explored the link between touch movement and emotions perception. This work serves as a foundation for affective touch communication in other research fields, such as Human-Computer Interaction.

In the field of Human-Computer Interaction, the tactile modality for affective communication is receiving a growing attention [Van Erp and Toet, 2015, Huisman, 2017]. A variety of works have been performed, ranging from the creation of new dedicated devices [Huisman et al., 2013b, Cha et al., 2009, Lemmens et al., 2009, Van Erp and Van Veen, 2003] to the augmentation of existing devices with touch capabilities.

Affective Computing is also exploring affective touch communication. Researchers create computing interfaces capable of recognizing, expressing, synthesizing and modeling human emotions [Picard, 1997]. They mainly use touch to detect the user intent [Yohanan and MacLean, 2012] or foster engagement [Huisman et al., 2014b]. Two main categories of systems are frequently developed for affective touch: zoomorphic stuffed animals [Yohanan et al., 2005, Yohanan and MacLean, 2008] and Embodied Conversational Agents (ECAs) [Serenko et al., 2007, Huisman et al., 2014b].

The field of Haptics propose technologies dedicated to simulate touch. Traditionally, haptic technologies are used to create and experience touch, to feel virtual forces or objects in a 3D world. However, some haptic devices have been designed to reproduce a realistic human touch. These devices mostly use technologies such as vibration motors [Ahmed et al., 2016], high-bandwidth vibrotactile transducer (e.g. Haptuators [Yao and Hayward, 2010]), air jet systems [Tsalamlal et al., 2013] or Force-feedback systems [Bailenson et al., 2007]. These devices can be controlled precisely in order to apply a specific force for the user or to create haptic illusions.

The studies in this dissertation are presented through a Human-Computer Interaction perspective, taking inspiration from the research fields mentionned above. I focus on the design and development of artifacts that aim to perform realistic touch, and detect affective touch, that helps better understand the affective touch phenomenon.

1.3 *Research Approach*

Humans have a perfect interface to perform touch communication: their body. In this thesis, my approach is to develop humanlike interfaces that can reproduce a realistic human touch and provide an interface similar to human skin.

In a first step, I was interested in kinesthetic replication of touch and in its perception (PROBLEM 1.1). This requires to understand how complex and rich touch gestures can be reproduced through interactive systems and devices. To this aim, I explored the design space of touch for conveying emotions with an interactive system. I used a robotic arm with a hand as end-effector that touches people's forearm to produce humanlike touch stimuli (PROBLEM 1.2). I used this device to run studies investigating the impact of different touch factors in a context-free setup as well as in a setup with context cues such as some facial expressions of a virtual character. I further explored the creation of devices capable of conveying humanlike tactile feedback, but focusing on mobile devices (PROBLEM 1.3). This motivated the development of MobiLimb, a finger-like shape-changing component with a compact form factor that can be deployed on mobile devices. In the spirit of human augmentation, which aims at overcoming human body limitations by using robotic devices, this approach aims at overcoming mobile device limitations, not only by providing haptic feedback but also enabling tangible input control and motion control. The goal of this step is to inform the design of an interface that convey affecive touch with similar movements as humans (PROBLEM 1).

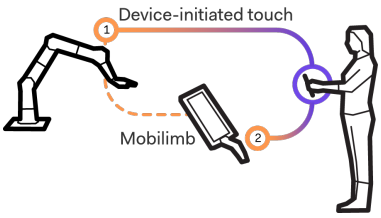


Figure 1.4: Two devices explored that can convey affective touch.

As a second step, I explored how devices could provide a humanlike input interface that resembles human skin properties. I first tried to understand and replicate appearance of human skin (PROBLEM 2.1). For this, I followed a bio-driven approach: from a sensory point of view, I studied how to reproduce the look and feel of the three different layers of the human skin through three user studies. From a gestural point of view, I studied what kind of gesture users perform on skin. From a technical point of view, I explored and discuss different ways of fabricating interfaces that mimic human skin sensitivity and can afford natural touch gestures. With these findings, I proposed a paradigm called Skin-On interfaces, in which

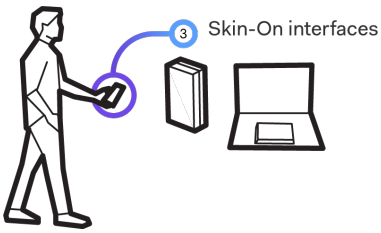


Figure 1.5: Interface that can detect touch.

interactive devices have their own artificial skin, thus enabling new forms of input gestures for end users such as twisting and pinching (PROBLEM 2.2). The goal of this part is to propose an interface where users could interact with it like they would do on a normal skin PROBLEM 2.

1.4 *Research Methods*

My research process was formed as a cyclic interaction around the following steps: Generating new and radical ideas, Designing a working artifact/prototype, Developing interaction techniques based on literature, Gathering feedback (informal or formal studies) to further refine the artifact or understand a phenomenon. The different methods I used during this thesis for designing artifacts and for observing phenomena are listed below. Each of them provides different benefits as well as limitations.

Interaction Design. According to [Jones et al., 2006] and [Saffer, 2010], interaction design in general is concerned with the design of function, behavior and appearance of systems. This method focuses on the user needs in terms of required functionality, how this functionality is to be assessed and controlled, and the way a system is integrated with other systems in the user's context. I used this method to explore the application space (Chapter 5) and to identify desired features and to design and develop interactions for the different prototypes (Chapter 6 and 8).

Digital Fabrication. To build working prototypes I used digital fabrication method and tools. Digital fabrication consists in building devices and prototypes with the help of digital tools, from designing a computer generated object in generative software to building the prototype with tools available in a fab-lab [Gershenfeld, 2012]. I used this method to develop working prototypes. I used a combination of digital software to generate the design of the 3D-printed prototype (Chapter 6) and generative software to create laser cutted stencils (Chapter 8).

Critical Design According to [Jakobsone, 2017, Dunne, 2008], the Critical Design process is part of the common creative design methods. This process aims to seek different viewpoints and to identify

alternative explanations over a well-defined problem [Newton and Pak, 2015]. The objective of this method is to provide new insights on tool or technology, with a creative approach and to propose a critic of existing technologies. I used this method to motivate the general approach of this thesis, by endowing existing devices (such as smartphones in Chapter 6 or a laptop in Chapter 8) with anthropomorphic qualities.

Qualitative Study. This method consists in gathering qualitative data to perform analysis [Creswell and Poth, 2017]. The feedback can be collected from online surveys, informal meetings or during small focus groups with novices, designers or HCI researchers. I used the qualitative study method to quickly gather feedback in order to better understand the perception of the experience (Chapter 5), relevance of interactive scenarios (Chapter 6) or to inform the design of an artifact (Chapter 8).

Laboratory Experiments. This method is inherited from Experimental Psychology. It consists in conducting studies under controlled conditions using a standardized procedure [Skinner, 1947]. To better understand the effects of a tactile contact with emotional perception, I performed controlled touch gestures in a controlled context, in order to study the variation of perception in arousal and valence.

1.5 *Contribution of the Research*

This research makes several major contributions, that are presented in two distinct parts in this thesis. The first research contribution (Part II) is focused around **Output devices**: 1) Understanding how affective touch can convey meaning through anthropomorphic devices capable of touching the user, and 2) designing a small scale handheld prototype. The second research contribution (Part III) is focused on **Input interfaces**, 1) that replicate skin capabilities and 2) that are capable of sensing complex gestures. The contributions can be framed around both technological and human-behavioural aspects [Wobbrock and Kientz, 2016]. The contributions made in this thesis are related to engineering, design, or the social sciences, and

are Empirical, Artefact, Methodological and Opinion contributions.

- Empirical contributions
  - I defined a set of touch factors compatible with a device that applies touch movements on users in order to convey emotions. I proposed to consider dynamic touch movements as a composition of Velocity, Amplitude, Speed and Type (or repetition). To validate the relevance of these touch factors, I conducted a study that demonstrated that their combination have an impact on the emotional perception. This contribution addresses PROBLEM 1.1 and is discussed in Chapter 5.
  - I conducted perceptual studies in order to understand the impact of device-initiated touch on the arousal valence perception. I used the touch factors above mentioned performed with a device on the user forearm. The results of these studies suggest that emotions can be interpreted through device contact, and that the context modifies slightly the perception of touch. This contribution addresses the PROBLEM 1.2 and is presented in the Chapter 5
- Artifact contributions
  - I created a finger-like robotic device that can be plugged to a mobile device to perform touch on the user's wrist. This contribution demonstrates the feasibility of a small scale actuator that can be combined with an existing device already used for mediated communication. I define the Input and Output capabilities of this device and present application examples to use it as a tool or as a virtual partner. This contribution addresses the problem PROBLEM 1.2 and PROBLEM 1.3 and is discussed in the Chapter 6.
  - I developed a novel hardware interface for multi-touch detection that can be attached to existing devices. This engineering contribution reproduce the dermis sensing capabilities of the skin. I based the hardware on the mutual capacitive technique and developed a low-cost open-source and open-hardware platform that enables simple multi-touch detection and advanced computer vision treatment. This contribution is presented in Chapter 8 and is one response to the PROBLEM 2.1.

- Methodological contributions
  - I proposed a bio-driven approach that follows bio-mechanical aspect and properties in order to inform the design of artifacts. This approach conciliates an holistic approach and an iterative design process, drawing inspiration from the analysis of the different layers of the human skin. It helped selecting materials with adequate mechanical properties in order to reproduce the dermis, epidermis and hypodermis as well as visual and kinesthetic qualities. This contribution is an answer to the PROBLEM 2.1 and can inspire other research in HCI.
  - I proposed a new fabrication method for multi-touch sensing on malleable surfaces that enable research practitioners to create easily a realistic artificial skin. For this extent, I encapsulated stretchable insulated conductive wires to create electrodes within a silicone substrate. This contribution addresses the PROBLEM 2.2.
- Opinion contributions
  - I promote the design of devices with *anthropomorphic affordances*. I illustrate this by designing a device that look like humans hands and fingers and that touch in a similar fashion is order to convey emotions. I also illustrated this approach with an interface that augments existing devices with artificial skin. This input surface transposes the tactile and haptic qualities to replace existing input methods or add new ones, more natural and closer from human-human interaction. I used three working prototypes to further explore this contribution (Chapter 8).

1.6 *Overview of the Thesis*

This dissertation is divided into three parts. In Part I, I present the background and related works, in Part II I present interfaces for touch output and in the last part, Interfaces for touch input.

Part I *Background*
In this Part, I present the Human sense of Touch, covering the related works in HCI and related to anthropomorphism, the inspiration for the design approach. I use this part as a foundation for my research.

Chapter 2 *The Human Sense of Touch*
In this chapter, I present what is human touch, starting by the biological aspect of the sense of touch and the evidence of social touch for humans. This understanding is necessary to later introduce the functions and the role of touch for affective communication.

Chapter 3 *Devices for affective touch*
In this chapter, I present the state-of-the-art related to HCI interfaces that use affective touch and that inspire my work. I introduce technologies and communication systems that are developed for mediated touch communication, following three axes, technologies and systems that enable touch output, touch input, and systems that close the interaction loop.

Chapter 4 : *Anthropomorphism*
In this chapter, I introduce the anthropomorphism in HCI, concept that drives my research and creative process. First, I present what is anthropomorphism, and how art and science-fiction inspired this vision. I then present devices and interfaces that use anthropomorphic cues and I discuss the challenges of anthropomorphism for HCI.

Part II : *Output*
The second part of this dissertation investigates the use of generated mediated affective touch, from an empirical point of view, by exploring touch factors that impact emotions, and from an artifact point of view by proposing interface that enables affective touch in a mobility context.

Chapter 5 : *Device Initiated Touch*
In this chapter I explore the communication of emotions through device-initiated touch in view of adding touch a modality in human-machine interaction. To reproduce touch stimuli I use a robotic arm reproducing human touch characteristics based on Chapter 2. I then report three user studies that examine how artificial touch can convey emotions, in a setup without context and with some context (facial cue) presented to the user.

Chapter 6 : *Mobile Device with a Robotic Limb*
In this chapter I present Mobilimb. Building on the findings of Chapter 5, I develop a robotic finger that can be connected to a

mobile device. This prototype demonstrates the feasibility of a portable device that can be used as a medium and can provide rich haptic feedback such as strokes or pat on the hand or the wrist. I illustrate how this device can be used as a partner or as a tool through different scenarios.

Part III : *Input*

The first part of the dissertation was dedicated to anthropomorphic output devices capable of touching users. This part of this thesis presents my approach to endow new lifelike Input capabilities to existing devices, by first demonstrating how to reproduce human-like skin then how this input method can be used with existing devices.

Chapter 7 : *Replicating Human Skin*

In this chapter, I present a bio-driven approach to develop an artificial skin design that covers existing interactive device. To this extent, I first present how to reproduce the look, feel and texture of human skin from a sensory perspective, drawing inspiration for human skin presented in Chapter 2. I then explore how gestures naturally performed on the skin can be transposed to artificial skins.

Chapter 8 : *Skin-On Interfaces*

In this chapter, I introduce a new paradigm for input interfaces called Skin-On interfaces. I propose an easy to do and DIY fabrication method that mimics human skin sensitivity and that can recognize a variety of skin-specific gestures. I also present how this artificial skin can be embedded into existing devices and propose various applications.

Chapter 9 : *Conclusion*

This chapter concludes the dissertation and summarizes my findings and the contributions. I also discuss the short, medium and long term perspectives and opportunities that this thesis opens.

Part I

Background

2

Touch for Emotional Communication

Figure 2.1: A touch contact performed between two individuals. The skin serve as a social organ to detect affection through touch.

Our human body perceive sensory information about the external world thanks to the five senses as defined by Aristotle: Sight, Sound, Smell, Taste, and Touch. The combination of all these senses allows us to feel our surrounding environment, but only the sense of touch allows us to interact with it. Touch, also called tactile perception, is a proximal sense that allows dexterity when we manipulate an object and provides information about the surrounding texture or the temperature. The sense of touch is also essential for the maintenance and development of social interactions [Burgoon et al.,

1992].

Touch can have several meanings [Morrison and Olausson, 2010]. It allows humans to infer other's mental states and behavior such as beliefs, desires and intentions. During a conversation, it can serve to enhance interpersonal speech communication, for instance by reinforcing verbal information by holding the forearm of someone, or to manage turn taking during a conversation by touching someone to inform you want to speak. Touch is also used to draw attention, like touching the shoulder to make someone turn around. More generally, touch plays an important role during conversations.

To develop anthropomorphic interactive devices that detect or convey touch, it is important to understand what are the different components involved in the sense of touch and their respective effects. This chapter is at the intersection of biology and psychology. The goal of this chapter is to present what is touch, from a physiological perspective and from a social and affective perspective. For that purpose, I start by describing the human sense of touch, I then cover the physiological aspects of affective touch and its role and effects.

2.1 *The Human Sense of Touch*

First, I present what is unique about the skin, the organ that senses touch. I then explain, from a neurological point of view what are the mechanisms we use to interpret it, and how different types of nerve cells contribute to our tactile sense.

2.1.1 *The Human Skin: A Remarkable Organ*

The skin is the largest human organ, weights around 3.6kg in the average adult, covers almost 2 square meters. In total, the skin accounts for about 5.5% of body mass. This organ is present in all mammals [Insel, 2000] and it is the first one that develops in the womb. It plays a key role in health and well-being, and acts as different interfaces between the self and the external world that serves as a protective interface, a regulation interface, an exploration interface and a social interface [Rawlings and Harding, 2004].

– *Protective interface.* Skin protects our internal organs against external conditions. This waterproof layer blocks sunlight and chemicals, and acts as an anatomical barrier against damages from pathogens such as microbes and viruses. Through this layer, humans can sense external sensations like heat, which is important as it enables us to act safely and adapt to our environment.

– *Regulation interface.* Skin serves for heat regulation (thermic insulator), and allows precise control of energy loss by radiation, convection and conduction. Skin also enables the synthesis of vitamin D, and other vital chemical transformations. Finally, skin serves to store lipids and water, thus helping regulating the body.

– *Exploration interface.* Due to its fine sensory capabilities, the skin is one of our organs dedicated to sense our environment. Various receptors (nerves) allow exploring the world by touching. For instance, the finger tip enables us to discover textures or the warmth of natural elements or objects. Overall, the skin contributes to a better comprehension of our environment.

– *Social interface.* Skin is a visible organ that serves as a social interface. Skin appearance (due to pigmentation or texture) conveys information about health condition or ethnicity. More importantly, others can interact with it, and touch it.

Skin is the only sensing organ that is distributed all over the body, contrary to the eyes or the nose, which have a restricted range of actions. The different layers that compose skin embed a huge network of nerves cells. This structure, which allows us to feel, is the biological foundation of the sense of touch.

2.1.2 *Neurophysiology of Touch Perception*

The sense of touch is part of the system of nerve cells (or sensory receptors) that responds to changes at the surface of the body or inside it, the *somatosensory* system. Tactile perception relies on two types of systems, which are characterized by their underlying neural input [Klatzky and Lederman, 2003]: The *kinesthetic system* and the *cutaneous system* [Loomis and Lederman, 1986].

The *kinesthetic system* provides information about the relative position

of limbs and is dedicated to the perception of touch and its interpretation (spatial location, size and weight of objects). It allows to perceive the shape of objects (contours, roughness, etc.) and to detect the intensity of touch. The kinesthetic receptors are mainly located in muscles, tendons, and joints.

The *cutaneous system* determines tactile sensory acuity (or resolution). It provides information about fine stimulation on the skin surface, such as the texture of objects or the location and duration of a contact. The tactile receptors are located mainly on the inner surface of the skin. They include three types of receptor cells, which have different roles: The *thermoreceptors* detect changes in skin temperature, the *mechanoreceptors* have the ability to feel pressure, vibration and friction; the *nociceptors* are dedicated to pain detection.

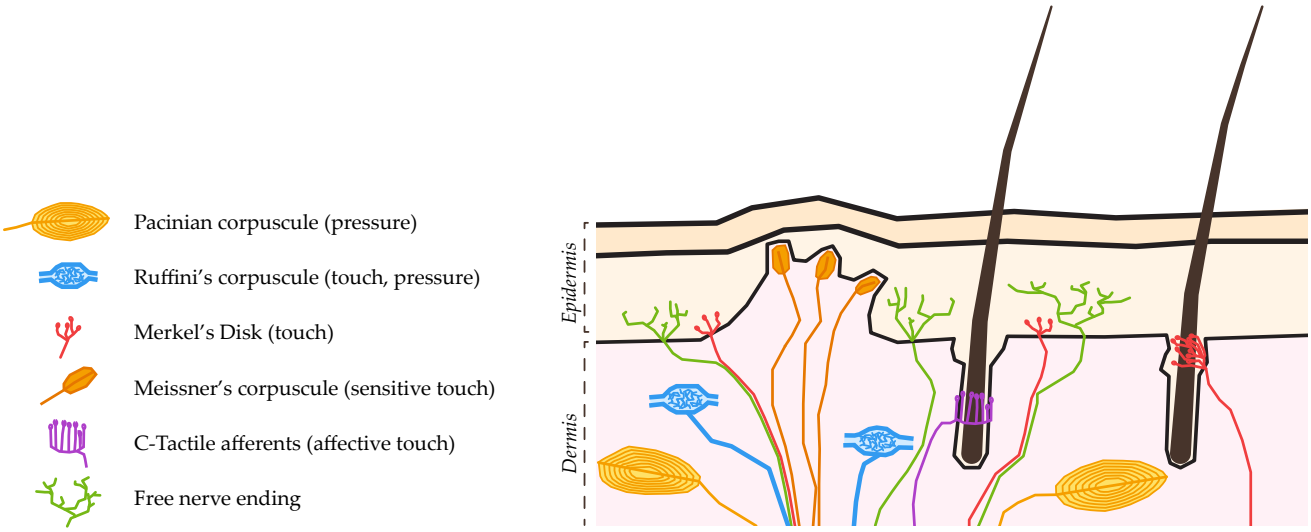


Figure 2.2: Representation of a skin cross-section, with the nerve cells that detect touch. Each circle correspond to a basic emotion.

Figure 2.2 is an abstract representation of a cross-section of the skin. The different nerves are located in the first millimeters of the dermis or at the edge of the dermis. Four types of mechanoreceptors inside the skin bring information from the body's periphery toward the brain, and have distinct functions. The Pacininan corpuscles are sensitive to vibration and pressure and respond to sudden disturbances. The Ruffini's corpuscles are sensitive to skin stretch and respond to sustained pressure. The Merkel's corpuscles detect light touch and are especially well distributed in a zone like fingertips. The Meissner's corpuscles also detect light touch, but with a higher sensitivity and they can detect vibrations between 10 and

50 Hertz. These mechanoreceptors are mainly located in the glaborous part of the skin [Gallace and Spence, 2014] (i.e. skin without hair such as palms and the soles of the feet). Other receptors play a crucial role in cutaneous perception. Free nerve endings are unspecialized. They function as cutaneous nociceptors and are essentially used to detect pain. Finally, the C-Tactile (CT) afferents are mechanoreceptors that respond particularly strongly to slow stroking of the skin. Contrary to mecanoreceptors, these nerve endings are located mainly on hairy skin, next to the bulb of the hairs [Nagi et al., 2011]. They are present in locations such as the forearm and thigh, and are not found at the non-hairy (glabrous) part of the skin.

The case of pleasant touch

The sense of touch is principally treated by the *somatosensory* cortex, however, recent studies [Olausson et al., 2010] suggest that the sense of touch is also interpreted in the *insular* cortex, a part of the brain that mainly interprets pleasant touch and motivational relevance [Morrison and Olausson, 2010]. This recent finding is based on the discovery of the specific **C-Tactile** (or CT) fibers.

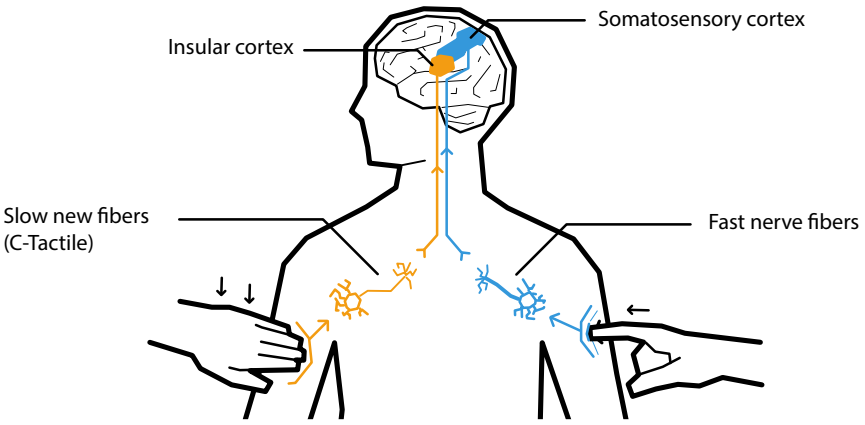


Figure 2.3: Social touch hypothesis, from a biological point of view. Some nerve cells, the C-Tactile cells are connected to the insular cortex of the brain, that is dedicated to treat and assess emotions.

During a touch contact, the other nerve cells convey messages quickly through their myelinated nerves fibers (i.e. nerve fibers with a sheath). This signal is then processed by the *somatosensory* cortex, the region of the brain which makes sense of proprioceptive information: it supports spatial localization and intensity encoding of a stimulus and supports tactile information such as texture, forms, and information from other modalities

such as temperature. However, the CT fibers are unmyelinated (i.e. nerve fibers with a sheath) and their signals is sent by a direct and specific neural connection [McGlone et al., 2014] to the *insular* cortex. This part of the brain is associated plays a role in mapping emotional experience. Unlike the other types of nerve cells, this specific tactile system is not very effective to treat the discriminative aspect of touch, but is suitable for detecting a slow and soft touch, or pleasant touch. In summary, some perceived touch contact are not only interpreted through conscious signs, but also transmitted at an unconscious physiological level. Touch for affective communication is considered as a specific and distinct domain of touch perception.

According to these findings, the role of CT fibers is to provide emotional and behavioral responses to skin contact with other individuals. This type of cells is more adapted (even dedicated) to the perception pleasant sensation, and it could explain, for example, that soft contacts can reduce stress level [Seiger Cronfalk, 2008] or the heart rate [Billhult and Määttä, 2009].

2.2 *Affective Touch: A Social Phenomenon*

During a co-located discussion, touch is used as a dedicated channel to convey emotions. In this section, I first present what is affective touch, why we use affective touch, in which context and its effects on humans. Finally, I present the type of actions and gestures that are performed to communicate emotions.

2.2.1 *What is the Affective Touch Phenomenon*

Touch is used as a communication channel between an *emmiter* and a *receiver* during interpersonal communication. The perception of an interpersonal touch contact varies depending on the context in which it occurs and the perceived intention of the emitter. In both cases of intentional or unintentional touch, the touch signal is interpreted by the receiver according to the information perceived on his skin (sensory judgment). A major study by Hertenstein et al. [Hertenstein et al., 2006a, 2009] identified the perceived emotions when a person is touched by someone else on the forearm or all over the body. The results suggest that humans can recognize several emotions through touch and that touch gestures related to pro-social

behaviour (love, gratitude, sympathy) are more easily conveyed through touch.

Recognizing emotions through touch is also called *Social Touch* [Van Erp and Toet, 2015]. Although social touch between individuals is generally less frequent than other forms of non-verbal social communication (e.g., a smile), it plays an important role in human-to-human interaction [Gallace and Spence, 2010, Field, 2010], especially for the communication of emotions. Social touch takes place between two or more people, with one person *emitter* of the touch and another *receiver*, who perceives and interprets the touch. Since touch is proximal and requires close or direct physical contact, social touch takes place in a co-located context [Heller and Schiff, 2013]. It is influenced by previous experiences, social conventions, context and the person performing the contact [Van Erp and Toet, 2015].

This behavioural phenomenon has also been observed in other mammals, including rats or chimpanzees. Young chimpanzees can prefer a soft tactile contact over food [Seay et al., 1964], highlighting the importance of a soft affective touch for the development. A similar study was reproduced more recently with rats [Zhang et al., 2006]. A population of rats with daily soft tactile stimulation showed fewer signs of stress than another population without tactile stimulation. For humans, one study showed that the way mothers carry a child on their knees changes the child's interaction with their environment and surrounding objects [Tronick, 1995].

Affective touch is a phenomenon that depends on the touch as a biological signal. To study social touch, researchers are using three distinct and complementary methods. The observational study method is used when the researchers go in the field and observe how people act after a touch contact. This method has the advantage of being non-obtrusive, but researchers have low control over the variables of interest as the subjects behave normally in a natural context. For instance, this method has been used to observe the effect of a touch contact by waiters in a bar [Hornik, 1992a]. Another method is self-report, where researchers ask participants to recall when they experienced a touch contact and how it affected them. This method might induce bias, as the observer is the people who also report the effect of the touch. Finally, laboratory experiments take place in a research laboratory with participants performing a specific task in a well-defined context. It allows to study a specific phenomenon of social touch, such as how the velocity of touch impact valence perception [Essick

et al., 1999].

These different methods allowed researchers to study affective touch in detail to understand the different effects it produces. In this thesis, we principally use the laboratory experiment method (See Chapter5), because a controlled environment is suited to test participants with a large device, and also because the context is the same for all participants, which allows us to isolate a precise phenomenon.

2.2.2 *The effects of Affective Touch*

The effects of a touch contact during human-to-human communication are more diverse and not only limited to the communication of emotions [Morrison and Olausson, 2010]: Four effects of social touch have been identified in the literature: attitude and behaviour change, physical and emotional well-being, attachment and bonding and finally communication of affect.

Attitude and behaviour change.

Touch can reinforce verbal impact during a discussion by affecting the behaviour of the touch receiver. The attitudes can be positively changed by a simple contact on the hand, forearm or shoulder [Burgoon et al., 1992, Fisher et al., 1976, Hornik, 1992b]. The receiver of the touch can change its perception of the context [Fisher et al., 1976, Hornik, 1992b] or it can change its affective state, for instance when the receiver is comforted by the touch [Fisher et al., 1976]. In the case of accidental contact touched individuals have more positive emotional evaluation of others (judgments of others) than in the absence of contact [Fisher et al., 1976].

Interpersonal contact also helps to influence the behaviour of others. The Midas touch effect [Haans and IJsselsteijn, 2009] is probably the most studied effect of social touch. It describes the positive effects and influence of a touch contact on pro-social behaviour. On his study, Kornik et al. showed that bar customers were more likely to give a tip when they were hit by servers [Hornik, 1992a]. It was later replicated by [Haans and IJsselsteijn, 2009, Guéguen and Jacob, 2005], and it was demonstrated that this effect was impacting the behaviour in other experimental settings: the Midas touch effect was increasing the willingness to return money [Kleinke, 1977], and influenced purchase decisions [Hornik, 1992b] (for instance customers

were following the suggestions on a menu item restaurant after being touched by a waiter [Gueguen et al., 2007]). Other studies demonstrated this effect in a health care setting to adhere medication [Willis and Hamm, 1980] or eat more [Eaton et al., 1986]. The result is always the same: touch has a positive impact on pro-social behaviour by giving more confidence, in others or in self. It can be noted that touch can also have a negative impact on pro-social behaviour, although the examples in the literature are rare. For instance, in a competitive rather than a supportive context [Camps et al., 2013], touch on the shoulder will reduce helping behaviour.

Some results suggest that individual differences impact social touch perception: Physically or attractive people have a stronger positive effect on pro-social behaviour [Burgoon et al., 1992, Hornik, 1992b]. Moreover, preliminary results suggest that there is a difference in the impact on the touch emitter on the pro-social behaviour. A touch performed by a female has a stronger positive impact than a touch performed by a male [Paulsell and Goldman, 1984].

The interpretation mechanisms of the Midas touch effect are still not clear, as this effect happened whether the touch receiver is aware of being touched or not [Guéguen, 2002]. Some hypothesis suggests that the touch conveys a pro-social behaviour because it is interpreted as a sign of likeness and trust from the emitter to the receiver, which positively influences the receiver perception of the emitter [Gallace and Spence, 2010]. Another hypothesis suggest that the touch recipient is more compliant because touch signals conveys a power status difference. [Camps et al., 2013]. Midas touch might also be influenced by other non-verbal social cues that impact behaviour, such as gaze [Kleinke, 1977], which might also have an impact on the results of these studies.

Physical and Emotional Well-being.

Touch can provide physical and emotional well-being mainly by conveying trust and compassion as well as facilitating the formation and maintenance of social bonds and attachment. This is especially the case during the early development of children, where affective touch has been shown to be necessary. A total lack of physical contact during the first months of developments can severely impair children [Duhn, 2010] and impact, later in life, their cognitive, social and emotional development [Nelson, 2007].

On the opposite, repeated physical contact between a mother and her child may improve the development of the infant, including neurological and visual motor skills [Sohr-Preston and Scaramella, 2006]. This maternal touch often involves stroking touches [Fairhurst et al., 2014] and might relate to positive feelings and sensations, such as a feeling of security while being held in the mother's arms [Hertenstein, 2002]. Overall, maternal touch has positive effects on children stress level and also reduces physical discomfort and pain [Feldman et al., 2010].

The effects of affective touch on well-being are not only limited to infant development but also plays an important role in our adult's life. When we hold our partner's hand, it feels good. An affective contact from another individual reduces the stress level [Ditzen et al., 2007], especially with touch contacts such as holding hand or hugging. This phenomenon is present whether the individuals holding hands do not know each other, but it is much more significant when the two individuals are engaged in a romantic relationship [Coan et al., 2006].

Whereas maintaining a physical contact with a partner has a positive impact on affect and psychological well-being [Debrot et al., 2013], affective touch provided by a stranger is frequent in the context of health care. Nurses performing therapeuthic affective touch can reduce the patient's stress level [Henricson et al., 2008, Seiger Cronfalk, 2008], lower their heart rate [Drescher et al., 1980, Billhult and Määttä, 2009] and influence their overall affective state [Whitcher and Fisher, 1979]. It is not yet clear what creates this sensation of well-being, but recent studies suggest that the effect might be related to the social bonding effect.

Attachment and bonding.

Interpersonal touch is also linked to affiliation and attachment, as it promotes collaboration, a desire of attachment and sexual behaviour [Löken et al., 2009]. It helps inferring mental states of others, such as beliefs, desires, intention, but also thoughts, and provides trust and security. Physiologically, a physical contact results in the release the oxytocin hormone [Feldman, 2012] (called "the bonding hormone") which is found inside every mammals [Insel, 2000]. The oxytocin helps reducing the blood pressure level, and contributes to physical well-being [Light et al., 2005].

Touch plays an important role for couples bonding and attachment.

Frequent partner hugs might help forming romantic bonds [Gulledge et al., 2007], and demonstrating physical affection through frequent touch contact and hugs is highly correlated to overall relationship and partners satisfaction [Gulledge et al., 2003].

A touch contact is a also a sign of safety [Main et al., 1985]. During a stressful event, the children will try to get in physical contact with his/her mother [Anisfeld et al., 1990]. The repetition of this action and the response of the mother help shaping the particular attachment relationship between the children and the mother [Main et al., 1985]. Children with fewer touch contact during the early moments of their lives are often more stressed and less secure in the remaining of their lives. The lack of social touch can also indicate a difficulty to deal with social communication [Torii et al., 2012], someone generally less secure will tend to hate hugs and cuddles [Chopik et al., 2014].

Communication of Affect

A touch contact can be performed in addition to other non-verbal social cues to reinforce emotional display, such as facial expressions [Russell, 1994]. A touch contact can influence the perception of arousal and valence and can elicit positive or negative responses in the receiver [Hertenstein et al., 2006a]. [Hertenstein et al., 2009] demonstrated that specific touch contacts communicate distinct emotions: By only touching the forearm of another person, it is possible to convey emotions such as love, with a stroke or a pat, anger, by hitting the other. The emotions conveyed by the emitter were recognized by the receiver with rates similar to those found in emotion recognition research from facial expressions. To communicate intimate emotions such as love, people prefer using the tactile communication channel over the facial expression [App et al., 2011], which suggests that affective touch is particularly relevant to communicate emotions with a partner. The specific touch gestures for affective communication are further discussed in the following section.

Affective touch is important for human, at an individual level and at a social level. The meaning and interpretation of touch depend not only the location of touch on the body, but also strongly on the nature of the relationships between individuals, the identity of the person who touches, its gender [Dibiase and Gunnoe, 2004, Hertenstein and Keltner, 2011] and

how we perceive their personality and the intentions we attribute to them. The interpretation of touch also depends on external factors such as the context [Maclean and Road, 2000] and the culture [McDaniel and Andersen, 1998].

2.2.3 *Actions and Gestures that Communicate Affect*

Morrison and Olausson [Morrison and Olausson, 2010] propose three main types of nonsexual forms of social touch.

- *Simple* touch involves brief and intentional touches relatively restricted to certain body locations, such as the arm or hand. An example of simple touch is tapping someone on the shoulder to get his/her attention, or when a waitress briefly touches the forearm of a customer, this resulting in a tip increase from the customer [Crusco and Wetzel, 1984].
- *Protracted* touch involves longer and often mutual skin-to-skin contact where some pressure is applied, such as when holding a loved one's hand, which reduces stress and anxiety [Gallace and Spence, 2010].
- *Dynamic* touch involves continuous, often repetitive movement over the skin, as for example in stroking or patting to comfort someone.

People can communicate emotions by using simple, protracted or dynamic touch only by interacting on the forearm [Hertenstein et al., 2006a]. Indeed, touching the forearm is considered more pleasant and socially acceptable than touching other parts of the body or hairless skin (such as the palm of the hand). Different types of gestures are used to transmit distinct emotions. In the context of this thesis, I define a touch gesture as *an act of physical manipulation carried out voluntarily on another individual, most often with the help of the hand*. By combining the results of the studies of [Hertenstein et al., 2006a] and [Huisman and Darriba Frederiks, 2013], eight pro-social emotions are more clearly interpreted by touch: anger, fear, disgust, sadness for the negative emotions and happiness, love, gratitude and sympathy for the positive ones. These emotions are communicated through a variety of touch gestures, including hitting, tapping, stroking, rubbing [Huisman and Darriba Frederiks, 2013, Hertenstein et al., 2009]

The touch gestures conveying emotions can be categorized in two clusters. First, the emotion-specific touches, such as simple touch like hit to convey Anger, are gestures that are used most often for this purpose and are not ambiguous. Second, participants also use a variation of the

same touches gesture such as stroking and rubbing to convey positive emotions. These gestures have variable speed and duration which impacts the meaning of touch.
The work of Guest [2009] and Essick et. al. [2010] explores the dynamics of touch. They consider every affective touch contact as a combination of several dimensions: the location on the body, the pressure on the skin surface, the contact zone, the duration of the touch as well as the repetition and rhythm of the touch gesture. For Hertenstein et. al. [2009], the duration and intensity of the gestures characterize different emotions. For instance, according to this study, sadness is mainly characterized by a touch of moderate duration and a light intensity. Touches with a strong intensity and a short duration communicate negative emotions such as anger or fear, while positive emotions such as love or gratitude correspond to gestures made with a lower intensity (soft touch) and a longer duration. These studies suggest that it is the variation and combination of these parameters that modulates the perception of the emotions. So, several parameters compose a meaningful touch signal and allow the receiver to interpret the meaning of the interpersonal touch. These factors are further described in Chapter 5, but can be summarized as follows:

The *location* of the touch, the *contact surface* and the *duration* determine if the touch is intentional or not. For instance, a sustained intentional contact can emphasize the importance of the speech. We observe a direct link between the feeling of pleasure and the *speed* of touch as well as the *force of contact* [Willemse et al., 2016].The *temperature* and the *texture* are factors that influence the perception of touch, but are more difficult for the emitter to control. They allow us to form a judgment on the type of touch contact being performed. For instance, feeling very cold or warm temperature indicates if the touch is performed or not by a human being.

2.3 *Affective Touch in Interaction*

Affective touch is a complex process that is used during interaction between two or more individuals. In this section I First clarify the limits of affective touch by presenting the external factors that impacts affective touch perception. Then, I present the case of Mediated Communication and finally how the communication of emotion is assessed.

2.3.1 *The Role of External factors on Touch Perception*

It is important to acknowledge the role and the impact of external factors on touch perception. Various studies in psychologies explore the individual impact of these factors.

Background and Culture The interpretation of touch is modulated by the background and culture of individuals. For instance, in Japan, a proper greeting consists of a bow without tactile contact, while in western countries a handshake is the social norm and kisses on the cheeks is very frequent [Finnegan, 2005]. More generally, there is a high disparity of frequency of touches in different countries, for instance, countries in Asia touch each other far less than in European countries such as France or Italy [Jourard, 1966, Dibiase and Gunnoe, 2004]

Age Using affective touch evolves with age. For instance, touch contact is more frequent with children than adults [Williams and Willis, 1978]. Moreover, children tend to more frequently perform touch in same-gender pairs while in cross-gender pairs: this evolves with adulthood, where the opposite is observed [Williams and Willis, 1978].

Gender Studies of the effect of gender on touch perception suggests that there is a gender difference in the frequency of touch. Females tend to initiate touch more than males. There is a tendency for same-gender dyads to touch more than opposite-gender dyads. Moreover, female same-gender touch is more often observed than male same-gender touch [Stier and Hall, 1984, Nguyen et al., 1975]. There is also a gender disparities in the ways of communicating a specific emotion from a touch stimuli. For instance, Sympathy was communicated by woman more frequently through tactile contact on the arm [Hertenstein and Keltner, 2011]

Relationship The social relationship of two people must be congruent. The study by Heslin et.al. [1983] suggests that our response to touch is influenced by our relationship with the person touching. Participants agree that touch from a close friend of the opposite sex is pleasant, while touch from a same-sex person is more unpleasant. However, touch from an opposite-sex stranger, is considered to be unpleasant by women but quite pleasant by men. This can be explained by a recent study that demonstrate that attractiveness impacts perception of touch [Gazzola

et al., 2012]. There is also an impact of the family relationship. Male and females have on average three times more touch contact with their closest opposite-sex friends than they do with their parents [Jourard and Rubin, 1968]. Overall, we tend to touch more frequently our partner than our colleague [Gallace and Spence, 2010].

Setting

The context where the interaction takes place is also important. For instance, in a collaborative setting, interpersonal touch increases willingness to comply to a request and altruistic behaviour [Willis and Hamm, 1980]. However, in a competitive setting, touch reduces the helping behaviour [Camps et al., 2013]. Other examples include the location. In airports, people perform more frequently touch contact than in coffee shops [Burgoon et al., 1989]. In a playground, children initiate contact more often outside than inside [Williams and Willis, 1978].

Other factors might impact the perception of touch. Touch is a complex phenomenon, and it is difficult to take into account all these factors when designing a study in a laboratory setup and raises methodological concerns [Stier and Hall, 1984]. This thesis is mainly centred around the creation of devices that detect and convey touch. Such questions are important to consider for this specific application area but beyond the scope of this thesis.

2.3.2 *The case of Mediated Communication*

Mediated affective touch in the context of HCI is defined by Van Erp et. al. [2015] as the ability of one individual to touch another one over a distance by using kinesthetic or haptic feedback technology. Currently, the use of this modality is generally absent or very limited in mediated communication interfaces. However, the addition of a tactile or haptic channel to communication devices enhances mediated communication [Insel, 2000], and several benefits of mediated affective touch are mentioned in the literature [Haans and IJsselsteijn, 2006].

1. Communication is improved as the touch channel increases the amount of information exchanged.
2. The touch channel can compensate when the other nonverbal cues are not conveyed with the current communication device. For instance, touch can be used during instant messaging [Rovers and van Essen,

2004b] to convey "haptic icons" [Chan et al., 2005].

3. It can be used as a substitute of the other senses in situations where other interpersonal interactions cannot be performed. For instance, very personal information can be exchanged in public without others noticing it [Chang et al., 2002b].
4. The touch channel can be used when users faces a cognitive overload or when interacting while performing other tasks.

Touch for mediated communication can not only enhance *Human-to-Human* communication, but also *Human-to-Agent* communication, for instance when a user interacts with virtual entities (ECAs) in a video game. Such audiovisual virtual environments, which are becoming more immerse thanks to new technologies such as Virtual Reality, would then benefit from a multi-sensory experience [Srinivasan and Basdogan, 1997]. In this context, affective touch through haptic feedback can increase the user's sense of presence and his feeling of being immersed in the virtual space [IJsselsteijn, 2004] and of sharing this space with a virtual entity [Guadagno et al., 2007].

2.3.3 The Communication of Emotions

To understand touch in a social context, it is necessary to consider the role of emotions for communication between individuals. An emotion is defined as a psychological reaction to a change in the state of mind, that happened following the evaluation of external or internal stimuli [Damasio, 2003], which helps the decision process. The modification of the emotional state leads to physiological and motor reactions such as changes in facial expression, gaze, prosody, posture and tactile contact. These reactions can then be perceived by other individuals. *Non-verbal emotional communication* is the visible production of these emotional-related physiological and motor changes. More generally, non-verbal communication is essential for human-to-human interactions and has an impact on the quality of the communication. It allows the transmission of interpersonal attitudes such as dominance or friendliness, helps presenting the personality to others, can accompany a discussion or speeches and helps coordinate with a partner [Argyle, 2013]. Most importantly, non-verbal communication serves for the communication and expression of emotions.

Several types of classifications describing human emotions have been proposed over the years in experimental psychology. However, two classifi-

cation models are mainly been used to assess emotional touch:

One classification follows Ekman's theory, [Ekman, 1994] and considers that each emotion perceived can be characterized as a combination of six basic emotions: sadness, joy, anger, fear, disgust and surprise (Figure 2.4.) These six emotions correspond to fundamentally different behaviours and are considered innate emotions.

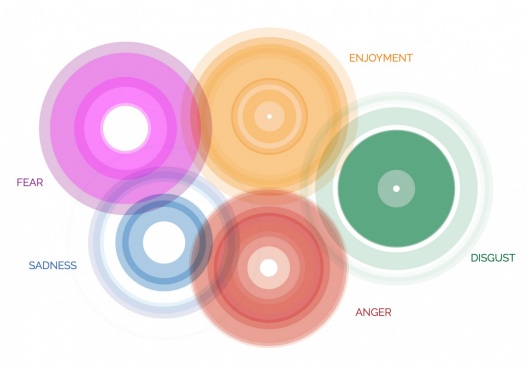


Figure 2.4: Ekman's Atlas of Emotions, a visualization of the six basic emotions.

The second classification describes emotions according to a dimensional space. Different dimensional models have been developed. Schlosberg [1954] created a three dimensional model of emotion, consisting of the axis "pleasantness–unpleasantness", "attention–rejection" and "level of activation". The PANA (Positive Activation – Negative Activation) dimensional model [Watson and Tellegen, 1985] or "consensual" model of emotion, suggests that positive affect and negative affect are two separate systems. Russell's circumplex model [Russell, 1980] considers an emotion as being a point on a diagram of two axes: the valence (unpleasantness/pleasure of the emotion), often presented as the x axis, and the arousal (softness/intensity of the emotion), presented as the y axis. The center represent the neutral emotions (Figure 2.5).

When running an experiment, assessing emotions with the circumplex model of emotions have some advantages over Ekman's model of emotions. Ekman's model considers emotions as discrete items or categories, while Russel's model provides a linear scale. When using Ekman's model, the emotional labels are picked to cover all the range of emotions. This model is appropriate when the stimuli are very different. However, if a phenomenon is only affecting positive emotions, a single label is not sufficient to disambiguate subtle nuances of perception. On the opposite, with Russell's model, the emotions are related to each other on the scale

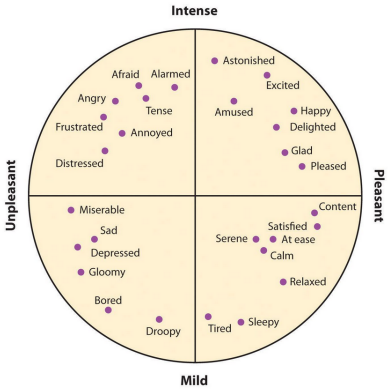


Figure 2.5: Russell's circumplex model of emotions. Emotions are dispatched among the four quadrants.

and are defined by their spatial position. One advantage is that this allows highlighting nuances of perception and which criteria (arousal or valence) is more affected by the studied phenomenon.

> The circumplex model has been used most commonly to study the perception of emotional facial expressions, or touch-related emotional perception. For all this reasons, we use this model in the chapter 5.

2.4 *Conclusion*

Understanding the effect of social touch as well as the type of touches used to convey emotion can help us to better comprehend humans complex social interactions. Affective touch can benefit several research domains such as health and well-being or Human-Computer and Human-Machine Interaction, especially in a mediated communication context.

The main goal of this chapter was to ground our research on the biological and psychological aspects of touch and affective touch. The sense of touch is perceived though our skin, and is a crucial and vital organ for human beings. What allows us to feel touch contact is a series of complex nerves cells directly connected to our brain, mostly to the somatosensory system. Although we would expect all the tactile and haptic information being treated with this neural pathway, I presented here the specific case of affective touch. Affective Touch is not only a psychological phenomenon, but also a physiological one: the C-Tactile nerve fibers are linked directly to the part of our brain that deals with emotions. It enables us to treat touch as a social signal, in particular to communicate emotions. I draw

inspiration from the composition of the human skin to design artificial skin in Chapter 8.

The use of touch to convey emotions is a newly explored field in the psychology literature. Researchers demonstrated that specific gestures are used to communicate distinct emotions, and also that the variation of individual factors, for instance the contact force, has an impact on arousal and valence perception. In this thesis, I used the factors presented in this chapter to generate device-initiated touch (Chapter 5). Using controlled affective touch in contexts such as mediated communication can greatly improve the interaction between two individuals. The effects of social touch helped us design various applications of the prototypes built during this thesis (Chapters 6 & 8).

WHAT YOU MUST REMEMBER

Positioning:

- Affective touch is a physiological and psychological phenomenon, important at an individual and social level.
- Specific touch gestures communicates distinct emotions
- In psychology and HCI literature, Russell's circumplex model is used to assess emotional perception.

3

Devices for Affective Touch

Figure 3.1: A device that is being touch by a user

In the previous chapter, we highlighted the importance of affective touch between individuals. However, using this phenomenon in a remote communication context means that devices should this mediate this form of tactile communication.

In this Chapter[1], I present devices that uses touch communication from a Human-Computer and Human-Machine Interaction perspective. That is, I offer a global vision of devices (smartphones, worn computers, etc.) that can detect or generate touch in order to convey emotions between

[1] Portions of this chapter were previously published in [Teyssier et al., 2018a] with Gilles Bailly, Catherine Pelachaud and Eric Lecolinet

individuals or between individuals and machines.
In the literature, these interfaces are referred with different names. They are called Touch illusion interfaces [De Vignemont et al., 2005], Emotional Touch interfaces [Stiehl et al., 2005], Haptic stimulation interfaces, [Burdea, 1996], Social Touch Technologies [Huisman, 2017] or even touch communication interface [Chang et al., 2002a]. I used these keywords to browse several research fields, and focus in particular to recent devices and emerging technologies presented in conferences in Human-Computer Interaction, such as *CHI* [2] or *UIST* [3], and in Robotic and Haptics, such as *World Haptics* or ICRA[4]. This chapter does not aim to provide an exhaustive list of all the existing devices. The purpose of this literature review is to bring together and organize projects and touch technologies explored in various research communities. Another goal is to provide an overview of existing devices and inform the design of the touch interfaces presented in the following chapters.

[2] ACM CHI Conference on Human Factors in Computing Systems

[3] ACM Symposium on User Interface Software and Technology

[4] IEEE International Conference in Robotics and Automation

This part is structured according to the challenges proposed by Van Erp et al. [2015].

3.1 Devices and systems for touch Generation (i.e., from a device to a receiver)
3.2 Devices and systems for touch Input (i.e., from the sender to an input interface)
3.3 Devices and systems that close the interaction loop (i.e., interfaces capable to sense, interpret and respond to touch)

3.1 *Touch Generation*

Since a long time, the Haptics and HCI communities have explored technologies that provide kinesthetic feedback. However, research on technologies dedicated to affective touch for mediated communication is quite recent. In this section, we first present technologies and techniques for generating touch, then different systems that use these technologies. We do not only focus on technologies for mediated communication but also present other touch generation technologies. Many different characteristics makes up a realistic touch contact (See Chapter 2). For the systems presented in this section, I discuss their principal properties, how they generate touch, and present their advantages and drawbacks, both in terms of tactile qualities and technological accessibility (cost, size, etc.)

3.1.1 *Technologies*

An interface capable to generate touch must be able to emulate aspects of the human touch, such as applying a soft or strong force of contact or a tap, and should stimulate mechanoreceptors, cutaneous tactile receptors as well as C-Tactile fibers of the user. While available technology is not yet capable of delivering the same haptic qualities as human touch, various types of actuators have been proposed in an attempt to reach this goal. The term actuator here refers to a mechanical component that produces movement and transfers it to another mechanism or system.

Vibrotactile devices

Vibrotactile devices are rotary motors or solenoids capable of generating motion. In contact with the skin, they can act on the skin's mechanoreceptors [Lemmens et al., 2009, Huisman et al., 2013b, Rovers and van Essen, 2004a, ur Réhman and Liu, 2010]. The technology most frequently used in HCI rely on the small eccentric rotating mass vibration motors (ERM) [Cha et al., 2009, Lemmens et al., 2009, Van Erp and Van Veen, 2003], which use a small unbalanced mass to create vibrations (Figure 3.2). A single motor usually vibrates at only one specific frequency (usually between 50 Hz to 200Hz), making this technology not adapted to produce rich and complex feedback. However, this type of motor is relevant to stimulate motion (like stroking), as their low cost makes them appropriate to create an array of actuators. A large contact surface with the skin mates it possible to creates patterns against the skin. Recent motor design based on "Tactor" design [Yao and Hayward, 2010] (Figure 3.3) can produce vibrations over a wide frequency bandwidth while being dynamically controlled. When in contact with the user skin, these motors allow creating haptic illusions, for instance to simulate texture [Romano and Kuchenbecker, 2011], which are perceived by the user through touch cutaneous perception when the index finger is in contact with the surface [Delhaye et al.]. And advantage of vibrotactile devices is their low cost and they have been largely be used in HCI research.

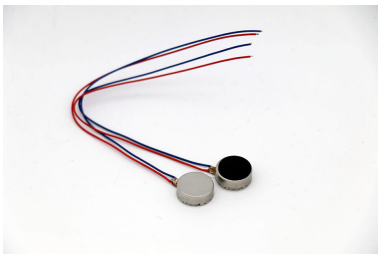


Figure 3.2: Vibration motors present in most smartphones.

Figure 3.3: Haptuators vibration motors, capable to perform a wide range of vibration frequencies.

(a) (b)

Figure 3.4: Force-feedback devices. a) Phantom device, desktop force-feedback device commercially available. b) Haption large-scale system

Force-Feedback Devices

Force-feedback devices consist of an articulated mechanical part, often an arm, combined with position sensors to achieve precise spatial positioning. They have mainly used for interacting with objects in virtual environments to increase the realism of interaction in navigation tasks [Burdea, 1996], for texture simulation (through fine movements) or for simulating collision with virtual objects [Dipietro et al., 2008].

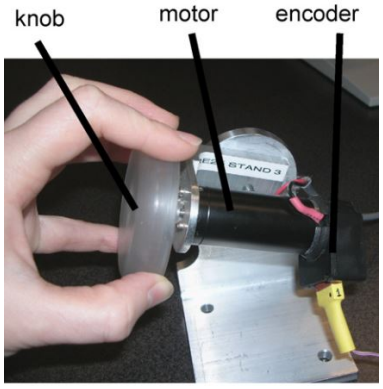


Figure 3.5: Haptic feedback through actuated Knob interface for mediated communication by [Smith and MacLean, 2007]

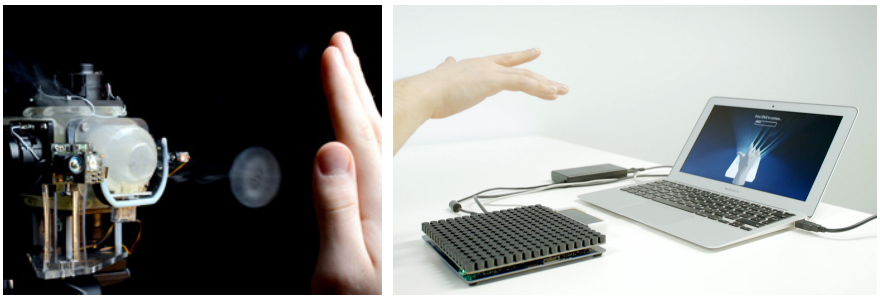
Small-scale force-feedback devices with one dimensional axis can move the user hand. For instance, a knob interface [Smith and MacLean, 2007] (Figure 3.5) have been used to communicate touch interaction metaphors. Commercially available devices with higher definition such as the Phantom (Figure 3.4-a), have been used to express and recognize emotions through movement [Bailenson et al., 2007]. In projects involving large-scale force-feedback, the user must actively hold the dedicated interface (such as with the Haption device, Figure 3.4-b).

Force-feedback actuators have also been used to autonomously with the user. humanlike hands have been developed to perform a realistic hands shake between a human and a device [Wang et al., 2011, Ammi et al., 2015]. Although hand shaking is a specific form of interaction, this shows that research around robotic devices and force-feedback actuation is interested in reproducing human touch capabilities to perform a transparent interaction.

> I draw inspiration from large-scale force-feedback actuators to develop the experiment described in chapter 5 of this thesis, and I designed a small-scale actuator in chapter 6.

Air Displacement Devices

Air Displacement devices propel air locally on the skin. The simplest technique consists in expulsing air through a nozzle. The nozzle makes it possible to vary the speed of airflow expulsion, the width of the air jet and the temperature [Tsalamlal et al., 2013]. Another technique, used in AirReal [Sodhi et al., 2013] (Figure-a), relies on producing a micro vortex that is shot against the user. This allows a very localized and discontinuous haptic sensation on the user skin. Finally, it is possible to create a local air pressure difference by focusing several ultrasonic transmitters at a specific 3D point in space. This technique is used in UltraHaptics [Carter et al., 2013] (Fig. 3.6-b) to allow a user to feel shapes his palm.



(a) (b)

Figure 3.6: a)AirReal [Sodhi et al., 2013] creates a small air vortex that hit users' body. b) UltraHaptics [Carter et al., 2013] is mid-air interface that produces feedback on the users hands

These technologies are mainly used for producing notifications or for haptic feedback during mid-air interactions. However, Tsalamlal et.al. [2013] also used air jets for conveying emotions. The results of this study suggests that the intensity, movement and velocity of the air jet impact the perception of emotions. A low flow rate stimulus was judged more pleasant, while and high flow rate had an impact in the perception of arousal and dominance. Finally, Hashimoto et al. [Hashimoto et al., 2009] proposed to link two people in real time, imitating a situation where they hold hands, using an air-compressing devices (Figure 3.8). This interface is limited to the transmission of touch pressure and does not use other touch modalities.

Pneumatic Actuators

Pneumatic Actuators, which rely on using air chambers and variable air pressure to inflate or deflate surfaces, have been recently explored in HCI to design Shape-Changing Interfaces [Holman and Vertegaal, 2008]. Pneu-

matic interfaces can have various form factors. They have for instance been used to create aesthetic and dynamic furniture, such as an inflatable mattress or chairs Some projects also propose body-worn pneumatic interfaces, such as inflatable bracelet [Yao et al., 2013], which can bend around the wrist of the user. A haptic jacket [Vaucelle et al., 2009] (Figure 3.7) made of pneumatic chambers around the shoulders, chest and back [Delazio et al., 2018] can stimulate a large zone of the body. Another device by Hashimoto et al. [2009] uses two air chambers, held by different users. The air chambers inflate and deflate creating a sensation against the palm of the users (Figure 3.8).

Figure 3.7: Pneumatic jack, capable to reproduce a physical "Hug" [Vaucelle et al., 2009]

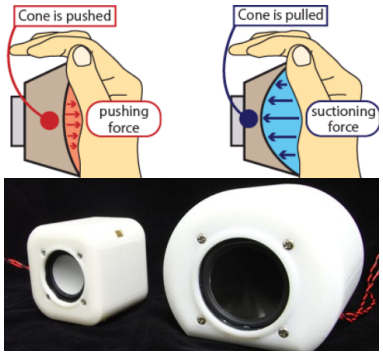


Figure 3.8: *Sense of Being Alive* A device for contraction and expansion of air that simulates our partner holding our hand at a distance

A drawback of pneumatic devices is that actuation is quite slow and that the control of the contact force against the skin is not as precise as with motorized force-feedback devices . However the materials that compose them (soft silicone) make it appropriate for a comfortable contact against the skin.

Pin Array Display

Also called variable shape interfaces, Pin Array Displays are surfaces that can change their shape. Typically made up of small solenoids or pneumatic actuators, the scale of these interfaces can greatly vary: from large surfaces such as a walls [Yu et al., 2016], tables [Follmer et al., 2013b], to small surfaces such as mobile devices [Jang et al., 2016] or the fingertip [Benko et al.] (Figure 3.9).

Figure 3.9: *NormalTouch* stimulates fingertip with small-size distributed touchscreen capable to create textures.

Actuation of small surfaces provides sensations that are distributed spatially directly on the surface of the skin (usually the fingertip). This technique has been used for creating reading aids (in particular small braille cells) and arrays for displaying virtual shapes, images or textures [Vidal-Verdú and Hafez, 2007] (Figure 3.10). Different form factors are explored, for instance on the side of the phone to enrich smartphone output capabilities though lateral tangible display [Jang et al., 2016]. This technique has also been used in to haptically represent virtual objects [Benko et al.] in virtual reality environments. Contrarily to vibration motors, they don't perform a stimulus on the surface of the skin but interact with the *normal* surface of the skin, i.e apply touch with a certain force perpendicular against the user skin. This not only stimulates fine cutaneous nerve receptors, but the mechanoreceptors, which provides a more realistic perception

on the surface of the skin.

Figure 3.10: Braille cells capable to display figures and graphical elements [Vidal-Verdú and Hafez, 2007]

The technologies presented here have different advantages and drawbacks. They stimulate different types of haptic receptors. While large haptic-feedback systems are more adapted to stimulate proprioception and the mechanoreceptors, small vibration motors can stimulate fine cutaneous tactile sensations. Distributed touchscreens need an active exploration of the user, who has to use his fingers to feel surface changes. Usually, vibration motors are in direct contact with the user's skin to perform haptic feedback. On the opposite, air-displacement devices can perform a tactile stimulus without direct contact with a device against the user's skin. The scale and bulkiness of these technologies is very variable. While vibration motors can be invisible, integrated and embedded into textiles (sleeves) worn by users, force-feedback systems are usually large, and they require a complex instrumentation.

(a) (b) (c)

Figure 3.11: Systems using generated touch for communication. a) HapticEdge Display, providing tactile information on the side of the smartphone. b) *TaSST*, an interactive cuff capable to touch the forearm with vibrations. c) Haptic Jacket , jacket augmented with vibration motors that produce localized haptic illusions.

3.1.2 *Systems*

Technologies for touch generation are versatile and can be embedded into systems for affective touch communication. Due to the large surface of the skin, it is difficult to build an interface that can stimulate the whole body. Existing devices are designed to operate in predefined and relatively small areas, depending on the context of interaction. In a mobility context, small and handheld systems will be preferred, while in a gaming context, users can wear more bulky hardware such as haptic clothing. In this section, I mainly focus on three classes of devices. First, mobile devices that have been augmented to support touch communication, second, dedicated

devices that are worn on the forearm, and finally, other types of haptic clothing.

Augmented Mobile Devices

Smartphones are the main tool used for mediated communication. It is therefore quite natural that they are considered as a relevant support for tactile communication. Moreover, smartphones already have a simple haptic interface: most of them embed a vibration motor, which mainly serves to notify users. Rovers and van Essen [2004a] proposed to enrich an instant messaging application with emotional tactile feedback. To do this, they developed a system that combines text messages with haptic effects (hapticons) consisting of vibration patterns, that convey emotions. This inspired various studies that use simple vibration motors to convey effects [ur Réhman and Liu, 2010, Yoo et al., 2015]. Positioned in array under the phone, they can render complex patterns [Yoo et al., 2015], combined with other modalities they can communicate a wide range of emotions [Wilson and Brewster, 2017] (Figure 3.1.2).

Figure 3.12: Multi-Moji uses multimodal cues (including tactile) to convey a wide range of emotions from a smartphone. [Wilson and Brewster, 2017]

While these projects use text messaging as a support to send emotional feedback, CheekTouch [Park et al., 2010] (Figure 3.1.2) transmits emotions through touch during vocal conversations. When one of the callers touches the screen of the phone, the other feel vibrations against his cheek. These vibrations are transmitted through a vibrating matrix located at the front of the phone. This prototype shows that users can easily learn a tactile vocabulary from 12 vibrator patterns, even when the stimuli do not correspond to a real touch mapping. For instance, a *stroke* pattern will be represented by vibration motors triggering from top to bottom, while *pinching* consists in a successive trigger of patterns for the extremity to the center.

Figure 3.13: Smartphone augmented with pneumatic actuators, that inflate and deflate during conversation [Park et al., 2010]

Augmenting mobile devices is constrained by their form factor. The systems presented here can only stimulate areas in contact with the phone such as the hand or cheek, which involves limitations as this is not the only part of the body used for mediated touch communication.

> Because mobile devices are ubiquitous and are the main tools for mediated communication, we augment their input and output capabilities in the chapter 8 and 6 of this thesis.

Touching Bracelets

The arm is probably the best place for emotional contact in a public context because it has both sensitivity (see Chapter 2) and a large surface to interact with, and is also the most appropriated body segment over cultures. Huisman et al. developed TaSST [Huisman et al., 2013b, Huisman and Darriba Frederiks, 2013] (Figure 3.11-*b*), a device to be worn on the arm consisting of tactile sensors and a matrix of vibration motors. This device allows one to record and play back emotional tactile stimuli by triggering vibration motors in a sequential order. These vibrations are intended to mimic dynamic touch (gestures like stroking), as well as specific gestures such as hit. The perceived sensations approximate a real touch in terms of dynamism. In order to increase the realism of the touch, this device has been also linked with a virtual agent's hand in augmented reality [Huisman et al., 2014a]: the user see the hand of the virtual agent touch his forearm, and the vibration patterns are synchronized with the touch of the virtual agent. The perceived intention behind a touch contact is therefore reinforced by the visualization of this touch contact.

Other technologies have also been used to stimulate the forearm of the participants. Bracelets for therapeutic relief can inflate to cause compression, control pain or temperature changes on the forearm [Vaucelle et al., 2009] (Figure 3.1.2). These prototypes are fixed, against the human skin: the tactile richness of this type of device could be increased by including the lateral movement along the skin.

Figure 3.14: Interface that warp around the forearm, that uses pneumatic compression to compress the user.

The fingers and the fingertips possess a very high tactile acuity. Although the hand is less frequently used for social touch (except for the case of a handshake), vibration motors have been used in a glove to transmit "emoticons" [Krishna et al., 2010]. Playing with an array of vibration motors and different patterns allows creating a touch stimuli. However one constraint of this technique is that it only stimulates a localized part of the body.

Haptic Clothing

Systems have been used to stimulate a larger part of the users' body. Haptic jackets has been used for touch communication because of their specific properties (close to the body, can be quickly put on, etc.) Vibration

motors are then integrated into the back of the jacket to provide notifications [Chung et al., 2009] or guidance information while navigating in the streets or in 3D space [Van Erp and Van Veen, 2003] (Figure 3.11-c). Haptic jackets have also been used for leisure activities, for instance to enhance the user's cinematic experience [Lemmens et al., 2009] [Israr et al., 2014]. Haptic jackets demonstrated that they can enrich the narrative and strengthen the emotional connection between the story and the user. Their form factor makes them adapted to simulate the feeling of embracing and hugging in situations of prolonged mediated communication [Tsetserukou, 2010, Cha et al., 2009, Rahman and El Saddik, 2011, Hossain et al., 2011]. They can be used in teleconference applications where people interact together or for communicating with a virtual agent, so that the popularization of virtual worlds should leverage the use of such devices.

A full-body always-on interface may be too intrusive with current technologies. With haptic jacket, the haptic feedback is applied only when the user wears the device: the user can decide when he wants to be in an interaction setup [MacLean, 2000]. However, haptic clothing can hardly cover the entire tactile surface of the body, and is thus generally limited to certain zones. Another drawback is that such devices tend to be expensive.

3.1.3 Synthesis

In the past few years, technologies to generate affective touch tended to be more diverse and open-up to creative solutions. To convey emotions, many devices still use vibration motors, often positioned in arrays. This technology has the advantage of being inexpensive and easy to use, but lacks realism as it can only control the dynamics of patterns. Conveying affective touch with imperfect technology is in itself a challenge. Multimodal interfaces can help solving this problem, as shown by Wilson et. at. [2017] where several modalities are combined (including vibrations) to increase the spectrum of emotional signals.

Generating realistic touch requires controlling various characteristics in order not only to stimulate the cutaneous sense but also the haptic sense. The creation of such interfaces still remains a challenge. When designing an interface, the choice of technology to convey affective touch result of trade-off between a lot of factors. The designer or researcher have to consider what type of stimulation she wants to perform, the desired accuracy on

the skin surface or the target surface, the bulkiness, aestheticism, cost and ease of manufacturing. Force-feedback systems and robotic actuation seem relevant in our perspective as they can reproduce many characteristics, such as the location, dynamism and force of contact in a reproducible way.

3.2 *Detection of Touch*

Touching a device is now part of our daily interactions, through the presence of tactile screens on smartphones. However, touching objects or individuals in real-life is not limited to pointing on a surface with the finger. Touch movements are more complex and usually involve the whole hand, and manipulations that involve a variable force and velocity.

In chapter 2, I presented how the human skin senses touch. To correctly interpret affective touch, a sensing device must be able to determine where the touch has been applied and evaluate the type of tactile stimulation and the emotional quality of touch [Nguyen et al., 2007]. In this section, we first present the current state of the art of techniques for detecting touch on the skin or an object, we then present complex systems leveraging tactile input.

3.2.1 *Technologies*

In this section we focus on technologies that can detect touch input, and more specifically on technologies that are easily available and frequently used in HCI.

Electronic sensors

Various types of electronic sensors have been used to detect touch pressure or the position of the contact. *Capacitive* (or capacitance) sensors [Karrer et al., 2010, Lissermann et al., 2013] (Figure 3.15-a) are based on capacitive coupling (or transfer of energy) [Dietz and Leigh, 2001] and can detect contact with conductive objects. As our body is conductive, finger proximity and pressure can be detected by this type of sensor. A variation of this technology, mutual capacitance sensing [Ritter et al., 2015, Nittala et al., 2018], is now used in recent smartphones touch screens for precise location and multi-touch detection. *Resistive* sensors convert a mechanical change

(a) (b) (c)

Figure 3.15: Different types of touch sensing technologies; a) Capacitive touch sensor commercially available. b) *SkinPut* [Harrison et al., 2010] a touch detection device on the arm using depth sensing. c) *Skintrack*, sensor using waves propagation through the body to detect touch

between two layers into an electrical signal. This technology used to be the most used for touch screens, it now frequently serves for pressure sensing, for instance with FSRs (Figure 3.16). *Piezoelectric* sensors [Arai et al., 2003] use materials that can accumulate electric charge in response to mechanical stress. Other sensing techniques include *magnetic sensors* [Chan et al., 2013], that can be integrated into a thin surface bonded to the skin [Melzer et al., 2015], and temperature sensors [Stiehl et al., 2005]. Such sensors can serve to detect proximity but do not allow accurate position measurement.

Figure 3.16: Force Sensitive Resistor (FSR)

These different sensors are frequently combined together to improve the detection and simultaneously detect pressure, strain and touch location when positioned as a grid. They are usually fixed on a rigid surface (PCB), but can be made small enough (<1µm) to be integrated into curved surfaces, like the skin [Weigel et al., 2017] or placed within stretchable and deformable surfaces [Wessely et al., 2016].

Optical sensing

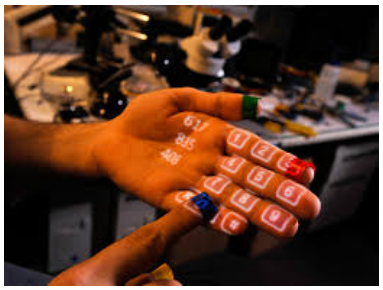


Figure 3.17: Sixth sense detects touch on skin with a 2D camera

This technique uses one or several cameras and computer vision to detect touch. With 2D color cameras, software can segment the hand of a user, and extrapolate its position relative to a surface [Mistry et al., 2009] (Figure 3.17). The detection of the fingers is used for precise touch interactions like pointing [Tamaki et al., 2010]. However, 2D cameras are subject to lighting conditions and are not robust to depth sensing. More recently, 3D depth cameras such as the Microsoft Kinect have been used to detect touch not only on a static flat surface[Wilson, 2010], but also on the forearm [Dezfuli et al., 2012, Harrison et al., 2011, Gannon et al., 2016] (Figure 3.15-b). Although promising for input, depth cameras requires lines of sight and are not capable of precisely detecting pressure on the skin surface. Their

use has not been yet explored for social and affective touch detection.

Body-Specific sensors

Some sensing techniques explore body-specific characteristics to detect touch on the skin surface. Bio-acoustic sensing [Harrison et al., 2010] works by using acoustic dissipation inside the body. The wave resulting from the contact is propagated by the body, detected and translated into coordinates by the system. These techniques tend to require a large electrical apparatus and a frank contact of the finger on the skin. These techniques are currently not suitable to detect a light touch such a stroke. SkinTrack [Zhang et al., 2016] (Figure 3.15-c) uses the conductive capacity of the human body and can track the finger location on the forearm. Other techniques include Electrical Field sensing [Zhou et al., 2016], Electro Impedance Tomography (EIT) [Zhang and Harrison, 2015] and multi-directional strain [Lee et al., 2017] of a 3D surface. These technologies require the surface to be fully filled or covered with conductive particles. They are mainly used to detect touch location of one finger, and cannot detect variable levels of pressure.

3.2.2 *Systems*

Usually, interactive systems detect touch on a flat surface for command input and rely on the screen to display information. Systems for sensing touch on other kinds of surfaces, such as fabric or the body, have also been developed. These technologies often rely on a Do It Yourself (DIY) fabrication process, which has the advantage of being inexpensive and easy to reproduce. In this section, I mainly focus on four types of systems that use touch input for something else than command selection or that detect touch on unusual surfaces. First I present Input for body-interaction, then touch on objects and textile sensing, and finally touch sensors for robots.

Body-related interfaces

As already explained, various technologies have been used to detect touch on the skin, in particular on the forearm or the hand [Wang et al., 2015] [Dezfuli et al., 2012, Harrison et al., 2010, Weigel and Steimle, 2017, Steimle et al., 2017]. They have been used for command selection [Lin et al., 2011,

(a) (b)

Figure 3.18: a) *iSkin* uses a semi-transparent layer over the skin. b) *DuoSkin* senses touch on the skin through a tatoo-like interface.

Harrison et al., 2010] and memorization [Gustafson et al., 2010]. Interaction zones and virtual buttons on the skin make advantage of natural physiological zones and landmarks such as beauty spots, tatoo, wrinkles [Weigel et al., 2017]. Skinput [Harrison et al., 2010], was one of the first working prototypes using skin as interaction medium. Finger touch location was combined with video projection to display the interface on the skin. On-skin electronics (or interactive "second skin") can be directly bound to the skin [Wessely et al., 2016, Weigel et al., 2015] (Figure 3.18-a). These devices consist of very thin epidermal electronics overlays (<50 µ) relying on capacitive sensing [Hammock et al., 2013, Kim et al., 2011]. Such systems are a promising direction because of their near invisibility, and can detect single [Kao et al., 2016] or multi-touch [Nittala et al., 2018] input. Piezoresistive thin film also [Arai et al., 2003] enables accurate pressure detection .

> On the opposite of electronic sensors, the On-Skin interfaces are flexible and are compliant to deformations such as stretching. They harvest interactive properties of the skin, which is one of our aim in the chapter 7 of this thesis.

Figure 3.19: Covering existing objects with conductive paint enable detecting touch though EIT sensing.

Touch on Objects

Inherited from Weiser's vision of Ubiquitous Computing [Weiser, 1993], one direction in HCI is to embed computers everywhere, in everyday objects. Considering every object as an input interface requires to endow objects with interaction capabilities.

Low-cost techniques such as capacitive paint can be used to make large objects conductive [Zhang and Harrison, 2018]. Electro-Impedence To-

mography (EIT) can serve to detect touch after spraying a conductive on top of existing objects [Zhang et al., 2017] (Figure 3.19). This allows performing interactions on unusual surfaces that have different shapes and textures [Groeger and Steimle, 2018]. This technique works particularly well with highly curved organic geometries and conserves their visuo-haptic surface properties. One its advantage is it's accessibility as the objects can be augmented with a DIY approach using cheap hardware.

Textile sensing

Another type of touch sensitive objects are clothes. Interactive textiles are explored by HCI researchers and in the DIY community [Stoppa and Chiolerio, 2014]. They have the advantage of not requiring the user to wear a particular device and allow a certain "invisibility" of the device. The combination of different conductive garments and threads allows creating touch-sensitive interfaces that can be worn while taking advantages of the properties of fabric such as strain and stretch. Commercially available clothes such as the Jacquard jacket [Poupyrev et al., 2016] (Figure 3.20) only use few conductive threads, which make them capable to detect simple gestures such as swipe and tap. Pressure sensing on clothes can be implemented by using layers of different textiles including piezoelectric materials [Donneaud et al., 2017] organized as a grid of sensors. This technique is particularly used for interactive sleeves to detect finger or hand touch and gestures such as strokes or pinch [Parzer et al., 2017] and can be used to detect different levels of pressure using piezo-resistive fabric materials [Rosenberg et al., 2009]. Sleeves are also combined with touch output technologies [Huisman et al., 2014a] to provide a two-way interaction device for emotional communication: for instance, a stroke performed on the device can be detected, interpreted and then reproduced on a remote user.

Figure 3.20: *Project Jacquard*, textile augmented with conductive yarn to detect capacitive touch.

Sensors for robots

In Robotics, the "*artificial sensitive skin*" concept [Lumelsky et al., 2001] has been explored, not only to imitate the sensing capabilities of human skin but also to foster collaboration [Cramer et al., 2009] and ensure safety [Duchaine et al., 2009] when a user is interacting with the device.

Endowing skin on such interfaces is not only used for humanoid robots, but more generally serves to sense user interaction and to favor collaboration. For instance, small robots like Nao [Andreasson et al., 2018] have pressure sensors positioned in specific locations on the robot: arms, legs and head. Other devices try to bend the sensors within the structure of the robot by for instance, endowing fur with tactile capabilities [Flagg and MacLean, 2013] (Figure 3.21). To sense the location of touch, the most common approach in robotics is to use an array of similar sensors [Lee and Nicholls, 1999, Argall and Billard, 2010, Tiwana et al., 2012, Dahiya et al., 2013].

Figure 3.21: Conductive fur, conductive yarns are mixed within the fur.

Robotic skin cells have also been developed to simulate human tactile sense to robots [Cannata et al., 2008, Florian Bergner and Cheng, 2016] (Figure 3.22). These cells cover a wide surface and can be spatially reconfigured. They integrate multimodal sensors (proximity, force, temperature and acceleration sensors), that can also be integrated into various surfaces, such as surfaces imitating a human hand [Wang et al., 2011]. The human fingertip is the location of the biggest tactile acuity [Vallbo et al., 1984]. In robotics, sensors on the fingertip allow robots to explore their environment, to manipulate and hold objects. The KRISS interface [Kim et al., 2013] is a touch detection module that reproduces a human finger (in size and shape) and detects the force and position of the contact on its surface. Overall, sensitive artificial skin is crucial for robotics and miniaturization. The accuracy of these sensors remains a major challenge to enable precision similar to human capabilities.

Figure 3.22: Spatially reconfigurable robotic cells that embed a variety of sensors: touch, temperature,..

3.2.3 *Synthesis*

The integration of sensing technology into affective touch mediated devices is a crucial step in achieving tactile communication between two individuals. The technologies are diverse, and often one sensor is dedicated to the detection of one touch feature, such as the location or the contact force. Using a single touch sensing technology is generally not sufficient to interpret a complex touch stimulus. For instance, an unique sensor cannot capture the dynamics of the touch (i.e. its direction, duration, etc.). A series of sensors must thus be used to analyze the various touch features (localization, force) over time in order to interpret an affective touch signal appropriately [Jung et al., 2014].

Input devices often have flat surfaces. Although their tactile spacial resolution is precise enough to match the acuity of human sensing, these interfaces do not have the same mechanical properties as the skin, such as strain, flexibility and texture. The use of On-Body and On-Skin interfaces suggests that skin is an interaction medium to consider. The DIY fabrication approach also allows researchers to endow touch detection capabilities to traditionally non-interactive surfaces, such as clothes [Poupyrev et al., 2016].

3.3 *Closing the interaction loop*

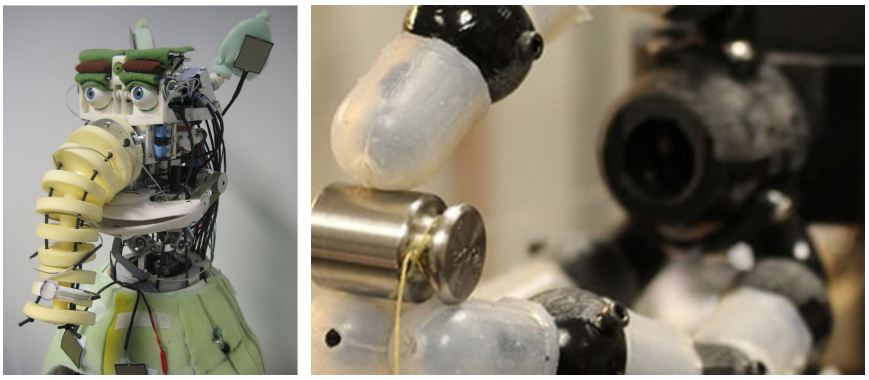
In the previous section, I presented technologies and devices to generate affective touch and to detect touch. One main challenge in the design of affective touch simulation and detection is the development of interfaces that can take into account the entire interaction loop, i.e., interfaces that can interpret touch and communicate a response using the same non-verbal communication channel. Closing the interaction loop typically involves a system capable of both "capturing", "interpreting" and "transmitting" affective touch [Van Erp and Toet, 2015]. To design such interface, Huisman et al. [Huisman et al., 2013a] specify three steps:

1. Detect affective touch (as well as other relevant social signals),
2. Understand this signal, interpret it and make the necessary decisions so that the virtual agent or robot can react appropriately,
3. Interact with the environment and transmit social signals (including affective touch).

Without these three steps, the interaction may be perceived as incomplete or bizarre. There are few research systems that both allow affective touch detection and generation and are combined with a cognitive model. Such systems are a step towards a realistic humanlike companion capable of conveying emotions through non-verbal affective signals. We found three main categories of systems or devices that can perform a closed loop touch interaction. In this section, I present these systems from a technological point of view. Their physical aspect is further discussed in the next chapter.

3.3.1 *Touching Robots*

There are expectations driven by science-fiction literature of what a robot should look like and how it should behave [Love, 2001].



(a) (b)

Figure 3.23: a) Social Robot Probot, capable of displaying and conveying emotions through actuation [Saldien et al., 2010]. b) Robotic hand with a finger capable to sense with a high spacial acuity [Yousef et al., 2011b]

As emotions are fundamental for human well-being and often assimilated as being alive, we expect robots to be able to understand and express them. During an interaction, the user may touch the robot to communicate an intention, with the hope that the device can understand it and react accordingly. The improvement of sensing technologies embedded into robotic devices enable them to detect signals about the affective state of the interaction partner. After a touch is detected, robots can communicate back to the user either using verbal response [Andreasson et al., 2018], facial expression [Saldien et al., 2010] or using actuation such as touching [Stiehl et al., 2005]. They can convey emotions through mechanical actuation [Saldien et al., 2010] (Figure 3.23-a) by performing movements such as raising eyebrows, smiling or moving a tail. These movements are usually not in physical contact with the user, and touching the user remain a challenge.

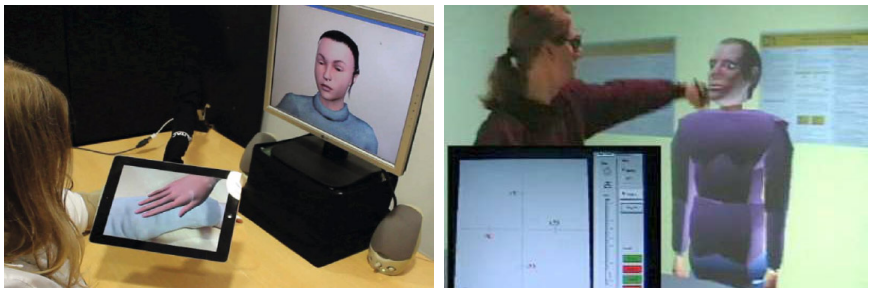
Figure 3.24: Robot touching in a nursing context [Chen et al., 2014]

According to some studies, a touch performed by a robot can be equivalent to human contact [Willemse et al., 2016], that is, the user's sensory and emotional reaction is similar to what he would have had if he had been touched by a human. Touch by robots can be assimilated to social touch as it produces similar effects (Chapter 2), such as influencing attitude and behavior to help performing a task [Shiomi et al., 2016], improving motivation [Nakagawa et al., 2011], health and well-being [Chen et al., 2014] (Figure 3.3.1), or reinforcing attachment, bonding and communicating affect [Yohanan and MacLean, 2012]. However, although robotic devices are now capable of precise actuation thanks to a variety of sensors [Tiwana

et al., 2012], especially sensors located on robots' hands (Figure 3.23-b), direct two-sided interaction is still fairly rare. Work thus remain to be done to provide robots with the ability to transmit a greater variety of emotions through physical contact in a safely way.

> The work presented in the chapter 5 of this thesis is a step towards this goal. It explores a similar problematic in a different context.

3.3.2 *Touching Virtual Agents*



(a) (b)

Figure 3.25: a) *TaSST*, a social touch transmission device that overlays an agent's hand in augmented reality. b) Perception of touch on a virtual agent

Embodied Conversational Agents (ECAs) are humanlike virtual characters that try to replicate a real human for the purpose of face-to-face communication [Cassell et al., 2000]. ECAs uses various channels for communication. The non-verbal visual and acoustic behavior of the agent enable ECAs to convey a wide range of emotional and social signals to its humans interlocutors [Lee and Marsella, 2006].. Touch is used as an additional channel of expression for the ECAs, and several systems have been developed for an agent to touch the user. In general, touch made by a virtual agent in response to a user's action is performed to express empathy [Bickmore et al., 2010]. Nguyen et al. [Nguyen et al., 2007] have developed a virtual agent technology with a human scale that is physically embodied within a CAVE immersive system. The agent reacts according to the location where the touch contact is made.

Figure 3.26: Photo realistic portrait of a realistic conversational agent, *Digital Vincent* made by GxLab.

Huisman et al. [Huisman et al., 2014b] explored how social contact simulated by a virtual agent could influence perceived trust in a cooperative or competitive augmented reality game. Participants wore a vibrating belt and an armband to perceive the contact of a virtual agent. The results revealed that a virtual agent touching participants were perceived as warmer than an agent not touching them. In [Huisman et al., 2013a], an augmented

reality screen and an affective touch sleeve allowed a virtual agent to visually and haptically touch a user (Figure 3.25-a). Virtual and Augmented Reality are used to create visuo-tactile illusions [Haans and IJsselsteijn, 2009] (Figure 3.25-b), and provide congruent stimulus that reinforces touch perception and makes it more believable and realistic. The development of immersive and video game technologies for the general public makes multimodal communication even more relevant, as the photorealism of facial expressions has now reached a lifelike quality (Figure 3.26).

3.3.3 *Toys as Mediated Communication Interfaces*

(a) (b)

Figure 3.27: Two commercial successes of zoomorphic robotic toys. a) Furby, b) Sony's Aibo dog.

Zoomorphic Toys are actuated artifacts halfway between animals and articulated robots. Furby (Figure 3.27-a) or Sony's Aibo (Figure 3.27-b) are commercially available toys designed to respond to physical interactions in order to create an emotional link between robots and humans.In the literature, Baby Seal and Cat [Shibata and Tanie, 2001] are precursors of this type of artificial emotional creatures, and have been developed to foster interactions between children and robots. These robots are capable to move their ears, tails, and imitate breath thanks to robotic actuation. They were programmed to react to user interaction thanks to embedded sensors such as touch and pet gestures. Their reactive behavior is multimodal, however we are interested in their capabilities to respond to touch.

Figure 3.28: *Hapticat*, a zoomorphic toy that reacts according to the emotions of users [Yohanan et al., 2005]

One other example of an advanced robotic zoomorphic device is the haptic creature developed by Yohanan and MacLean [Yohanan and MacLean, 2012, 2008, Yohanan et al., 2005] (Figure 3.28). This robot responds to human touch interactions and conveys its emotional state back with actuation of its ears or tails. The device is also able to change its temperature, imitate the humming or breathing. For this device, the interaction loop was closed

using the Wizard of Oz technique, a hidden external observer who triggered the robot's reactions according to the users' actions. A more in-depth exploration of the role of the materials used to cover zoomorphic robots was also carried out [Stiehl et al., 2005]. It can also be noted that fur can be used as a sensor or to mask more complex sensors [Chang et al., 2010]. The use of appearance as invisible touch sensing interface gives a real sense of the animal's incarnation. These creatures can detect and respond to human touch and are well adapted for emotional communication with individuals, but are not adapted to mediate an interaction between two distant individuals as they embody entities. They also have limited touch capabilities and are not able to perform affective touch.

3.3.4 Synthesis

A device that has the capability to *feel*, *understand* and *respond* to touch as effectively as humans will be able to interact more intuitively and meaningfully during a co-located communication. Today, artificial devices or entities (robots, ECAs, etc.) with tactile capabilities can independently produce or interpret touch, but rarely both at the same time. The limit does not come from the sensing capabilities but mainly from their capabilities to respond via touch and their reasoning process. The main challenge lies into the combination of the two technologies into a same interface and in the reasoning process (or cognitive model) of the entity, to interpret touch and decide how or when to respond. All these three components (detect, generate and interpret) are necessary to complete the interaction loop and enable a transparent bidirectional touch interaction. This is a crucial part of the development of a robotic "intelligence" capable of interacting autonomously and "naturally", as we expect from an interaction partner.

Another challenge lies in the awareness of the context. Future devices will have to approach the functions of human touch and linking this touch stimulus to other non-verbal communication cues while taking into account the context of interaction to propose a response adapted to the user. An unsynchronized handshake with a partner can, like any other unsatisfactory social touch, results in a sense of rejection due to uncanny valley or cultural differences [Cranny-Francis, 2011, Dibiase and Gunnoe, 2004]. Taking into consideration the culture and the internal cognitive scheme of the touch receiver requires more theoretical and experimental knowledge of affective touch communication and psychology.

> Although this thesis is not focused in the creation of a system that close the interaction loop, these dystems are inspiring. They often use and anthropomorphic stance, which is further described in the following chapter.

3.4 Conclusion

This chapter highlights different technologies for touch generation and touch detection. As this chapter illustrates, there is a great diversity of technologies and systems that are designed to detect or convey touch. Coming from various communities, these techniques have been historically used in HCI for the interaction with screen-based computing interfaces (manipulation of information and interfaces, notifications, etc.). However, more recent works use touch specifically for the purpose of mediated communication.

Existing technologies made for a specific task (e.g. vibration motors for notifications) were purposed to serve for mediated communication. Although these systems demonstrated their efficiency, they are not the more adapted specifically for this task. We argue that more general-purpose systems and technologies of force feedback would be better candidates, as their precision is remarkable and they can provide contact directly on the user's body. However, they have not been explored for this purpose, nor they have been miniaturized to be adapted for a daily and frequent use. In addition, the ECA serves as a platform for multi-modal emotional display, and is an opportunity for the development of new touch communication with congruent feedback. From this related work, we inferred properties properties that should be considered when designing a device. The quality of the tactile contact, the accessibility (price or easiness of replication). For instance, few technologies provide friction with a sustained contact on the skin, and the easily available technologies such as vibration motors do not reproduce a realistic touch contact. In the **Part II** of this thesis (Chapter 5 and Chapter 6), I draw inspiration from this factor to develop and probe devices for touch generation on a user for mediated communication purpose.

Devices for touch detection rely traditionally on an array of sensors. This type of system is very efficient to detect fingers and usually require a hard and flat surface combined with a complex instrumentation. Similarly

to devices for touch generation, detection is used principally for interface control and pointing. This devices are not capable to detect complex communication gestures, such as pinching. From the most recent related work and trend in HCI, we see that the sensing interface moves from dedicated surfaces to be embedded in the object itself. The input surfaces are being externalized (e.g eTextiles) to enable a rich and versatile input method. Moreover, there is tendency to provide DIY and easy to replicate technologies for HCI researchers. For robotic devices, precise and accurate sensing interfaces are used. They are often located on the finger and are dedicated to manipulation tasks, but are really expensive and complicated to fabricate. Some low-resolution sensors are located at different locations around the surface of the robot and serve to detect user's intentional touch. These interfaces aim at reproducing a skin for devices. The use of skin as interactive medium is particularly interesting: its softness makes it a really expressive medium. Although the sensing capabilities on the skin are limited as the sensor cannot be embedded inside it, we believe that this surface is adapted for input. We further explore this input surface in the **Part III** of this thesis, and build on this related work to propose technique that senses touch on a skin-like interface.

WHAT YOU MUST REMEMBER

Positioning:

- Force-Feedback systems are used to communicate emotions and can perform touch on the users
- Mobile Devices are augmented with Output and Input interfaces
- On-Skin interfaces uses the properties of human skin to control interfaces

4

Anthropomorphic Devices

Figure 4.1: Artificial skin that mimics real human skin.

The word "Anthropomorphism" comes from the Greek word *anthropos* (man) and *morphe* (form, structure). In Human-Computer Interaction, the concept of Anthropomorphism is defined by Duffy [2003] as "*the tendency to attribute human characteristics to inanimate objects, animals and others with a view to helping us rationalise their actions*". Anthropomorphism is related to our perception of reality, and it helps individuals to make sense of our environment, including the understanding of unfamiliar objects. Anthropomorphism arises from the expectation of individuals towards objects or

systems.

An anthropomorphic interface is an interface that borrows elements from humans and nature in its physical manifestation or that acts or has a behaviour that we can rationalize. Realistic robots and stuffed animals have features that replicate humans and animals affordances to improve and facilitate social communication and acceptance. These interfaces can look humanlike or even feel *alive*. This practice, frequent in the field of Human-Robot-Interaction, is not commonly used in HCI.

In this chapter, I provide some background information on anthropomorphism and focus on anthropomorphic interfaces and their affordances. I first introduce what are the roots of anthropomorphism, and why it is an important design consideration for devices. I then present different devices and systems that use some form of anthropomorphism, such as Product Design, Virtual Agents and and HCI. Finally, I conclude this chapter with a discussion on the challenges of designing anthropomorphic interfaces for affective touch communication.

4.1 Roots of Anthropomorphism

From a historical perspective, the origin of anthropomorphism lies well before the introduction of computing interfaces. Researchers observed that in the early development of civilization and religions, there was a tendency of people to picture the unknown and gods after themselves. The concept of Animism is also related, and was described by Piaget [1931] as the *"Attribution of life to the nonliving"*. The reason behind such an attribution may arise from the fact that when facing uncertainty and the unknown, people implicitly fall back to what they already know from their daily experiences and interactions and have the tendency to perceive the world from an egocentric perspective in terms of look and behavior.

Figure 4.2: A face in the clouds, observed in the Canadian town of Grand Falls, posted online on 1 August 2011 by Denis Laforge.

The attribution of life-like characteristics to inanimate objects is frequent in our daily lives. For instance Pareidolia refers to the fact that one can see human faces everywhere like in the clouds (Figure 4.2). This phenomenon has been well explored in the domain of child psychology [Mead, 1932], where children interact with their stuffed animals as if it was lifelike companions.

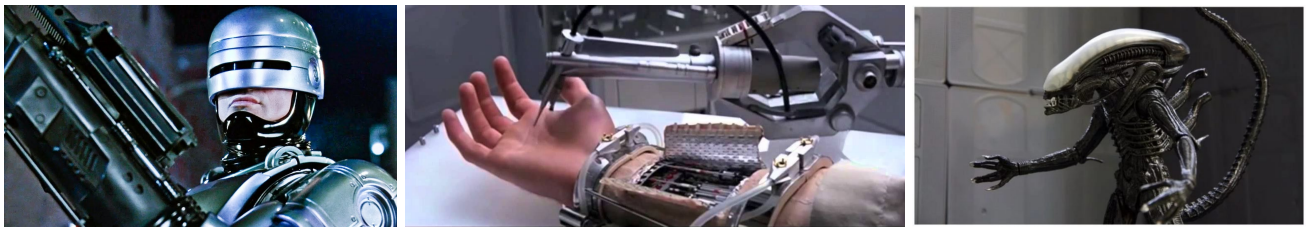
4.1.1 *Inspiration from Science-Fiction*

There is a long history of anthropomorphic design in Science-Fiction, and indeed, science-Fiction literature and cinema has inspired and influenced the field of Human-Machine Interaction and Robotics [Love, 2001].

(a) (b) (c)

Figure 4.3: Anthropomorphism in the literature. a) A Prague reproduction of the Golem, 16th century. b) Boris Karloff in the classic 1930s film version with the makeup artist Jack Pierce c) Tik-Tok in Wizard of Oz, 1907.

In *literature*, the horror genre plays an important role with the notion of incarnation and anthropomorphism. As a famous example we can cite *Doctor Frankenstein*'s monster, who appeared in Mary Shelley's 1818 novel. This monster is a reference to the Jewish myth of the *Golem* (Figure 4.3-a), an animated anthropomorphic being that is created from inanimate matter. But rather than being created through magic, Frankenstein's creature (Figure 4.3-b) is created with the help of *technology* and *science*. The first appearance of a robot in the literature is considered to date from 1907 with *Tik-Tok* (Figure 4.3-c), the robot of the Frank Baum's *the Wizard of Oz* movie. Tik-Tok is capable of movement and speech and displays typical human features such as face or limbs and even a cosmetic feature: a moustache. From this point in history, robots and cyborgs were recurrent characters of the children's literature and later in science-fiction. These fictional characters were most of the time pictured as humanlike, capable of speaking, moving, and more generally interacting with their environment. Later, the notion of anthropomorphic robots led to another tightly linked vision: the notion of bodily transformation through technology, which is the root of *transhumanism* and, later, *cyberpunk* in Science-Fiction literature. This topic has been widely explored in science fiction since the 70's [Bostrom, 2005]. It features the future of humans and machines as a mix between biological and mechanical entities, where the new devices or the new humans borrow parts from one each other.



(a) (b) (c)

Figure 4.4: Anthropomorphism in Cinema. a) Robocop b) Luke Skywalker's prosthetic hand. c) Alien

Cinema made it possible to visually represent anthropomorphic features. Film with robots reached a wide audience thanks to popular movies and TV series, such as Astro Boy (1952), Star Trek (1979), RoboCop (1987) (Figure 4.4-a), etc. The robots figures have different form factors and are popular example of anthropomorphic interfaces, by replicating everything that makes a human: the senses, the movement and notion of agency and physical incarnation. Prostheses can also be seen as anthropomorphic devices, attached to the human body, aiming at reproducing human body. Usually, prostheses are pictured as being capable of humanlike movement, and are even transparent. For instance in Star Wars *The Empire Strikes Back*, released in 1980, Luke Skywalker replaces his missing hand by a prosthesis, which features skin-like texture, accurate sensitivity (Figure 4.4-b) as well as a precise actuation capability.

Figure 4.5: A Game Pod, Anthropomorphic game controller, from Cronenberg's movie *eXistenZ*

Fictitious anthropomorphic interfaces are not limited to robot and prosthesis, as suggested by the richness of terms that describes interfaces that are a mix between alive interfaces and mechanics. For instance, a *Biological* spaceships, introduced in 1953 the short story "Specialist" by Robert Sheckley, are fully biological living organism that is alive and that grows

or *Symbiotes*, alive entities composed of several organisms that collaborate in the same interface. *Biomechanoids* (or *Cyborgs*) is the term often used to describe H. R. Giger's works, the designer of Aliens (4.4-c). It consists of an organic organism that visually borrows elements from the living, such as organic curves with anthropomorphic proportions, but that is a mechanical system.

The movie *eXistenZ* (1999) by David Cronenberg proposes a radical vision of future interfaces, both in term of interaction and aestheticism. Instead of traditional game consoles, players use organic "game pods" (Figure 4.5), to enter an alternate "game" reality (or Virtual Reality). These pods are covered with skin and the players interact by touching them. The "game pods" are connected directly to the players' bodies via "bio-ports" located in their back of their spines. The director, David Cronenberg, conjectures that because people already have non-mandatory surgeries to improve their abilities, such as laser eye surgery, they would also be willing to have "bioports" installed (Figure 4.6). Whereas robots mainly focus on anthropomorphization through movement and speech, this interface uses the human skin as anthropomorphic affordance. Anthropomorphization is not only present through a physical humanlike form. *Hal 9000* from Stanley Kubrick's movie *2001: A Space Odyssey* is an Artificial Intelligence embodied by a minimal eye-like interface (Figure 4.7). In the science-fiction movie *Her* by Spike Jonze, the interface is incarnated through a voice, as realistic as a human's voice. It allows the user to interact with a vocally transparent interface and rationalize its personality.

Figure 4.6: In the movie *eXistenZ*, the Game Pod has to be connected to the "*bioport*" interface, on the back of humans.

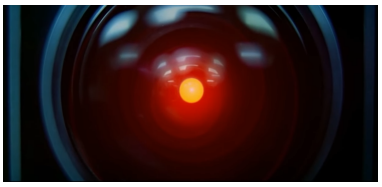


Figure 4.7: *Hal 9000* from Stanley Kubrick's movie *2001: A Space Odyssey* is an artificial intelligence whose eye we can only perceive.

There is a variety of examples of fictitious interfaces in science-fiction that use anthropomorphic features. The available creative interfaces are source of inspiration and feed the imagination and creativity of other artists, but also of researchers and especially HCI researchers. The use of science-fiction prototypes has been presented by Bell et al. [2013] and Johnson [2010] as a research tool, and researchers draw inspiration from this mediums to design of the next generation of interfaces.

4.1.2 *What is Anthropomorphism*

The underlying psychological reasons behind anthropomorphism not yet clear. Anthropologists studying human behavior such as Caporael and Heyes [1997] suggest that the anthropomorphic mental model results from

the cognitive ability of humans to apply analogies and patterns between ourselves and the observed phenomena. Two main theories are proposed to explain the reasons we use anthropomorphism. The first one is related to our emotional motives, also called the *Comfort thesis* and the second one to the primitive cognitive aspect, also called *Familiarity thesis*.

The *Comfort thesis*, which has been proposed by researchers such as Hume [2003], argues that different motives leads to Anthropomorphic thinking. First, this theory is linked to emotional motives, and suggests anthropomorphism arise because *"we are mistrustful of what is nonhuman but reassured by what is human"*. This is related to our emotional needs, and the desire to know when we fear the unknown. Later on, Guthrie completed his theory by suggesting that anthropomorphic thinking arises from a *bet* when we face the unknown, which is not part of a rational process but happens unconsciously when we believe that attributing humanlike properties to an unknown event is a good strategy because "*if we are right, we gain much by the correct identification, while if we are wrong we usually lose a little*" [Guthrie, 2002].

The *Familiarity thesis*, proposed by Guthrie [1997], suggests that anthropomorphism is an involuntary process that is part of our perceptual strategy as humans: *"We use ourselves as models of the world, because we have good knowledge of ourselves but not of the nonhuman world and, looking for an explanation of the world, resort to the knowledge that is easiest and most reliable."*. Contrarily to the *Comfort thesis*, this thesis is more centered on the perceptual reaction than on the emotional reaction.

> In this thesis, I adopt the point of view of the *Familiarity thesis*. When interacting with an unknown anthropomorphic interface, I build the interfaces in order to leverage familiarity and made the hypothesis that the perception of the interface plays an important role.

Anthropomorphism generates debates in the scientific communities, between researches that think it can benefit human perception and those who don't.
On the one hand, some scientists in the psychology literature are critics of anthropomorphic thinking. They believe that anthropomorphization is an evolutionary mistake [Mitchell et al., 1997] which removes the objectification of the experience, and that this behavior has to be eliminated from the scientific process. It is especially the case when users interact with a non-interactive inert object. According to this vision, anthropomorphization

thinking might lead the user into overthinking functionalities giving him a wrong understanding of the functioning of the object.

On the other hand, some researchers believe anthropomorphism can be a good process for the design and the understanding of new interactive systems. Indeed, Anthropomorphism has a fundamental 'sense-making' function, this unconscious process can be used by researchers and designers to leverage interactivity thanks to the familiarity of the appearance. In design, research suggests that when observing or interacting with an interface, we automatically project human and animal attributes, such as personality or traits [Scholl and Tremoulet, 2000]. Anthropomorphism is complex, and using it efficiently in HCI requires a good understanding of the underlying perceptive mechanisms. If we translate these concepts in HCI terms, we identified two mechanisms. First, the anthropomorphization of interfaces can be applied to the *physical* aspect, where an interface that look anthropomorphic can trigger similar effects. It is related to the affrodaces concept [Norman, 1999] and is presented in the following sub section. The *actions and behaviors* of such interfaces can also be rationalized with the attribution of cognitive and emotional models based on our previous experiences of interaction with humans or animals.

4.1.3 Anthropomorphic Affordances

The visual appearance of an object plays an important role in how we perceive possible interactions. This relates to *Affordance theory*. First proposed by Gibson [1977], it is initially defined as *"the quality of an object or an environment, that allows an individual to act"*. This concept was later introduced in HCI by Donald Norman, and is defined as *"the quality of the object suggesting the way of using it, and the intuitively recognised relation between attributes of an object and possible actions or operations, depending on the physical capabilities, goals, plans, values, beliefs and past experience of the actor"* [Norman, 1999]. Affordances are used to suggest how we should manipulate the object, as well as their interactive modalities and capabilities. The notion of affordance relates to the *"past experience of the actor"*, or how actor usually interacts with other objects during his life. If the actor has already interacted with the handle of a mug, he will know that a handle serve to hold the object, regardless of the shape of the object.
This notion is most often limited to the interaction with objects, and is usually based on mechanical and physical laws. In HCI, it rarely take into

consideration how the actor interacts with other humans beings or animals. *Anthropomorphic affordance* relates to the impact of an anthropomorphic aspect on the shape of the object. This concept is also connected to the embodiment paradigm. Proposed by Fishkin et al. [1998], embodiment is based in the concept of *"treating the body of the handheld device as part of its user interface"*. This notion emphases the relationship between the perceived physical properties of the device and the physical manifestations of its functionality.

In real life, we couple body parts to different senses, for instance, the skin can feel touch, the eyes can see, etc. If an interface looks like a finger, the actor will refer to his past experience with a finger: a finger can touch, feel contact and bend. The actor will then likely project this experience to the capabilities of the interface. Anthropomorphic affordances can also trigger feelings and emotions. An object with an infantile and childish aesthetic and look conveys cuteness, which shapes the interaction we can have with it, so that we will tend to care and protect it. This is particularly true for the appearance of the face and the body, where the expression relates to our experience of face-to-face communication. For instance, big eyes convey surprise or frown eyes anger.

> In this thesis, we are mainly interested in the touch anthropomorphic affordances, mainly connected to the skin and limbs. Connecting the visual appearance of objects with their interactive modalities is a design opportunity for the designer. Anthropomorphic or zoomorphic affordances can lead to a new type of object design, where the interaction is perceived thanks to our past experience and expectation of the animated *alive* world.

4.1.4 Layers of Anthropomorphism

Anthropomorphism for interfaces or objects is inspired by physiological and behavioural aspects. The **physiological** aspect is related to the look and feel of the objects, as well as their physical capabilities. The **behavioural** aspect corresponds to how the devices interact in their environment and with the users. The study by Persson et al. [2000] clarifies the user's expectations when interacting with an anthropomorphic interface. The authors argue that anthropomorphism is multilayered phenomenon, and propose to divide anthropomorphic perception as six different layers.

Layer 1: Primitive categorization.
Primitive categorization is considered as the most basic level of anthropomorphism. It involves the perception, at first sight, of an object or an interface being alive or inert. Most often, it is conveyed through actuation and movement that seem to be controlled by the entity itself. The visual features and appearance are also an important part of primitive categorization, such as interfaces with parts that look like faces or limbs that convey anthropomorphic perception. Finally, the presence of voice is also an important cue that is used to convey life likeness. The initial categorization and perception of an interface as an anthropomorphic interface by the users creates an effect of projection of various aspects of a living thing.

Layer 2: Primitive Psychology
The second layer is related to the knowledge and expectations we have about needs, drives, and sensation. This knowledge is acquired through the experience of interacting with other humans and animals. For instance, we know that the sensation of hunger disappears after eating and tiredness after sleeping.

Layer 3: Folk-Psychology
Psychology literature has developed theories about how the mind of other works. These theories and models, also called folk-theories and folk-models explain the inner behavior and explain their influence on our actions. The inner state includes perceptions, beliefs, goals, and intentions, and the action relates to how the individuals act (or not) in the real world. For instance, desires and goals motivate intentions and actions while beliefs constraint actions. The folk-psychology also encompasses the ability to attribute emotions. The attribution of emotion results from the evaluation of situations and events; it creates a reaction in people where each situation causes a different emotional response based on the individual evaluation of the situation.

Layer 4: Traits
The impressions of a person or of a system one forms is considered as traits. The traits relate to the perception of the personality. We use traits commonly in everyday life to describe others, with adjectives such as curious, aggressive, shy or confident. Traits are shorthand terms for complex processes on the folk-psychological level of anthropomorphism. Whereas *folk-psychology* is focused on short-term perception, traits are considered as a more stable and long-term characteristics of an individual.

Layer 5: Social Roles
In everyday life and encounters, we apply and use social roles to explain behavior of others and help understanding a situation. The different roles are connected to social schemas. Psychologists and sociologists have explored different types of social schemas that constitute our social and cultural environment. The *occupancy roles schemas*, linked to the activities such as doctors, waiters, police officers or academics, provide us with normative expectations. The *family role schemas*, such as father, mother, children or uncle convey expectations on how we should interact with each other daily. The *social stereotypes* are probably the most important constituent of the social roles. They are defined by a mix of assumptions we have about others. The stereotypes can be influenced by gender (women considered as more emotional and empathic) or job position (scientists are considered as rational). The stereotypes are formed during the first encounter with an individual and can be influenced by emotional and moral judgment.

Layer 6: Emotional Anthropomorphism
Finally, the last layer of anthropomorphism is emotional anthropomorphism, linked to the perception of affect. In contrast to the other levels, this layer does not involve expectations but involves an emotional perception. In a short timeframe, emotional anthropomorphism is related to the identification with another individual and moral judgment. People or users project an emotional stance towards other individuals or animals. This projection is often stereotypical and we not only understand why other acts as they do by attributing *folk-psychology*, traits, and social roles but also we tend to categorize them in terms of moral judgment, often Manichean (good and bad) that aligns with a character. In a long timeframe, it is connected to a strong bonding, involving processes such as love and friendship. These two phenomena are typically human, and as of today, the evolution and dynamics of these relations are not clear in psychology and anthropology literature.

These layers can be used as a tool for designers and HCI researchers to better understand the anthropomorphic processes that are triggered by anthropomorphic interfaces and systems. One key feature is that the system has to look alive at first sight (*Layer 1*), and users have to eventually perceive the intentions (*Layer 2*), motivations (*Layer 3*), personality (*Layer 4*) and perceived social role (*Layer 5*) of the interface. An interface that

is capable to create an emotional link with its user also reinforces the anthropomorphic perception (*Layer 6*). The first impressions are crucial to define perceived affordances and stereotypes, so that *Layer 1* might be the most important layer to create an anthropomorphic interface.

> In this thesis, we are particularly interested in the affordances that arise during primitive categorization. Using human affordances can leverage expressive and natural interactions. I used this layer to develop the form factor of the devices I developed (Chapters 5, 6 and 7). However, the other layers also have importance when designing an interface that have to seem alive. I used layers 3 and 4 to implement the application scenarios presented in Chapter 6.

4.2 *Anthropomorphic Interfaces*

Using anthropomorphic affordances can change how users make sense of an interactive object, by projecting expectations of human functioning and behaviour. Designers and researchers have used it to develop anthropomorphic interfaces. In this section, I present how anthropomorphism is used in the design of today's interfaces. Currently, anthropomorphism is particularly investigated in the field of robotics. However anthropomorphism is also inspiring product design and other user interfaces.

4.2.1 *Product Design*

When designing a product, industrial and product designers usually focus on creating a visually pleasant and aesthetic product while responding to user needs. Since products now embed electronics such as a screen, LEDs or actuators, designers have the possibility to develop new interactive user experience, and anthropomorphism is also explored in product design. There are two main motivations to use anthropomorphism in product design: visual aestheticism and to convey interactivity. More generally, human body parts are good candidates to express anthropomorphism because they have a particular salience to humans [Persson et al., 2000]. As example, the Minoru webcam (Figure 4.8-a) is a face-shaped interface that serves to record images. The form is linked to the function, as the two cameras present on this device have the same spacing as the human eyes. As this spacing allows us to see in three dimensions, the anthropomorphization

of this interface serves the function of seeing in 3D. Paro is another example using zoomorphic affordance: by adding some soft material such as fur, the object looks soft and the user wants to pet it [Yohanan and MacLean, 2012] (Figure 4.8-b).

(a) (b)

Figure 4.8: Anthropomorphism in Product Design. a) Minoru Webcam has an anthropomorphic face. b) Paro Zoomorphic stuffed animal for emotional communication [Yohanan and MacLean, 2012]

Researchers highlight the fact that anthropomorphism influences the mental model we develop when interacting with an object [Wasinger and Wahlster, 2005]. In their work, Wasinger and Wahlster found that users don't like to discuss directly with a simple object like a bar of soap while they are more generally willing to converse out loud with a personal computer or a car. This result suggests that interacting with an object through speech feels natural only when the object is perceived as complex, i.e. electronics or a computing system. This highlights the fact that it seems more natural for the user to build a mental models of interaction with an object that already conveys a complex behaviour, and that it is possible to attribute more capabilities to it, in this case, speech.

4.2.2 *Interfaces for HMI*

Figure 4.9: The visualisation of *Siri* voice interface by the designers of Apple demonstrates the difficulty of visually representing a voice interface. The colour and the shape help to personify the interface

Transferring the anthropomorphic concept to devices has been mostly explored in Human-Machine Interaction, both in academia and industry, especially for the design of robots. However, anthropomorphism has been more rarely used in HCI, although the computing power present in our devices makes them capable to interpret user's actions and react to it. It is natural for designers and researchers to draw inspiration from humans to design and develop new robots.

Some interfaces in industry have been developed with anthropomorphic features. Voice assistants are one popular example, such as Apple's *Siri* (Figure 4.9 or Amazon's *Alexa*. These interfaces are personified and use

a realistic voice to interact with the user. Other examples include the Nazbatag Internet of Things interface, or in academia shape-changing mobile devices that move to convey emotions [Lee et al., 2018, Hemmert et al., 2013]. In the following, I focus particularly on two systems that use physiological and behavioural anthropomorphisation: Software Agents and Robots.

Virtual Agents

Computer software is being more and more complex for the user, with an increasing number of functionalities, and interaction relies mainly on direct manipulation. Software agents were introduced as a new interaction paradigm [Maes, 1995]. They consist of computer programs that can work autonomously and can perform tasks on the behalf of the users or to assist them to perform tasks on the software. Anthropomorphic features are not necessarily present in virtual agents. However, the fact that they are perceived as independent and autonomous actors instead of traditional tools quickly lead to their embodiment. One popular example is *Clippy* (Figure 4.10), the virtual agent present in early versions of Microsoft Word. This agent was talking through text to user, and to personify it, the designers added humanlike features, eyes and eyebrows, to create expressive facial expressions. *Clippy* was reacting to the user interaction and tried to provide relevant solutions to the user and to anticipate his needs.

More recently, software agents can be personified with body and face to create a seamless interaction with humans during conversation. Embodied Conversational Agents, or ECAs, already introduced in Chapter 3 are representative of this anthropomorphization. These agents have similar physiological and communicative characteristics as humans: a face, a body, clothes, can talk and understand speech. The animation transform these agents in life-like humans replicas, their body action and movement can help reinforce the discourse or build a relationship with users.

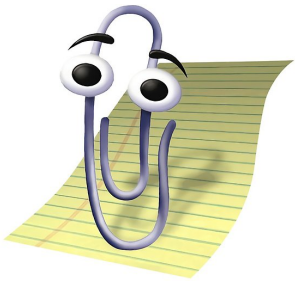


Figure 4.10: Clippy, the infamous Software agent from *Microsoft Word*.

Robots

In the previous section, we highlighted the fact that there are expectations driven by science-fiction literature of what a robot should look like and

how it should behave [Love, 2001]. Humans want robots to be lifelike companions, not necessarily human-looking (flesh-like) androids [Brooks, 2003] but with a coherent reasoning and the capacity to interact with the environment, including objects, humans or other robotic devices. The field of robotics draw inspiration from the human capabilities to guide the design of actuated interfaces. This is especially the case in the field of social robotics, where anthropomorphized technologies, in the form of both humanoid and animal creatures, support emotional bonding and increase social interaction with humans [Yohanan, 2012, Li and Chignell, 2011]. Anthropomorphic robots implements the **physiological** aspect and a **behavioural** aspect with different mechanisms.

Figure 4.11: Different expressions of the Probo social robot [Saldien et al., 2010]

For the **physiological** aspect, roboticians draws inspiration from human physical characteristics and capabilities including the actuation, the sensing as well as their physical appearance.

Actuation

Robots are capable of movement thanks to complex actuation mechanisms. The actuation mechanisms can serve to act on the environment, to act on the human or to display information signals [Saldien et al., 2010] (Figure 4.11). To interact with the environment, researchers tend to draw inspiration from human movements. For instance, they often use two legs to make the robot move like a human. Or they use a hand as end-effector, composed of fingers with three joints, which are capable of grasping objects (Figure 4.12). One advantage of using anthropomorphic features is that it feels natural for us, because we know their degree of freedom, and we can anticipate their movements. The actuation method itself can also be inspired by humans mechanical properties. For instance, a robotic arm, the Shadow Dexterous Hand [Tuffield and Elias, 2003] (Figure 4.12) with muscle-like pneumatic actuation is more compliant and can provide a force similar to humans.

Figure 4.12: *The Shadow Hand* by Shadow Robotics, a hand with five fingers and a pneumatic muscle-like actuation

Figure 4.13: Nao Robot being touched on the head, where a touch sensor is located.

Sensing

Robots are designed with different sensors, inspired by human senses. The sense of sight and the sense of touch are frequently implemented. They are crucial as they are the primary sense to explore our environment. For instance to sense the environment in 3D, robots may use two cameras located in their eyes – similar to humans' visual sensing.
The user can also interact directly with the robot if it supports

touch interaction with its robotic skin. Artificial skin sensors (see Chapter 3) try to replicate human sensing acuity. They are positioned at socially accepted locations, such as pressure sensors positioned on the arms, legs and head, as on the Nao Robot [Andreasson et al., 2018] (Figure 4.13). Other sensing capabilities include audio devices in the ears for speech recognition, or a loudspeaker in the mouth.

Look and Feel The visual appearance plays an important role for the primitive categorization *(Layer 1)* and is, therefore, a focus for designers. To promote social interaction with a robot, designers use human features (eyes, mouse) to foster familiarity. For instance, robots with realistic skin, such as Sophia from Hanson Robotics (Figure 4.15), convey affordances (the skin is made to be touched), in this case pinching the cheek. Figure 4.14 The eyes often serve as emotional display as eyes are an important trait for anthropomorphism [Duffy, 2003]. Other examples include robotic stuffed animals with fur, which is a material soft to touch and that can convey comfort [Saldien et al., 2010].

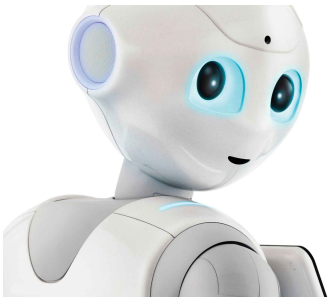


Figure 4.14: Pepper Social Robot, his eyes have a cosmetic function. No actual sensors are embedded.

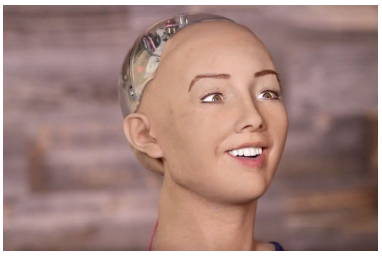


Figure 4.15: Sophia, the realistic robot from *Hanson Robotics* looks like human

To implement the **behavioural** aspect, robots are designed to have a behaviour that matches the user's expectations in order reinforce their life-likeness. This is achieved by assigning typical human characteristics and behaviour through movement or speech. It enables the users to have familiar interactions with the robot, and unconsciously derive traits and personality. Three main types of behaviours can be used to impact primitive psychology perception.

Autonomous Behaviour Robots are proactive when they can take decisions autonomously. The decisions rely on internal stimulation states. These changes of states can be reflected through the robot actions. For instance, actuators can be autonomously controlled to perform the determined movements, e.g., to initiate interaction with the user. Usually, several patterns of predefined poses and movements are used to imitate lifelike behaviour [Wada and Shibata, 2007]. For instance, a robot that looks around can be perceived as curious: This impacts the perception of the robot's identity and emotional state.

Reactive Behaviour This occurs when robots react to external stimulation. For instance, the Paro robot [Yu et al., 2015] (Figure4.8-b) reacts to loud noise and moves in its direction. This reactive behaviour can also help matching social norms, like greeting when meeting a stranger or bowing to demonstrate respect in Japanese culture (Figure 4.16).

Figure 4.16: Pepper robot bowing to demonstrate respect

Physiological Behaviour The robots can express physiological needs, that match the robots real needs, like recharging their batteries. To express these needs, we can refer to humans needs, like sleeping, such as Nao's robot or Sony's Aibo robot that lay down next to the electric charger. This physiological behaviour makes the robot more lifelike, and the user can empathize with its needs.

4.2.3 *Traditional HCI interfaces*

Designing with anthropomorphic affordances is a common practice for robotic devices and ECA because they are physical or embodied entities. It is somehow logical to develop such systems with humans requirements in mind. However, anthropomorphic affordances have been less explored for traditional HCI devices, such as smartphones or laptops.This might comes from the fact that these devices are not embodied, but are seen as tools [Beaudouin-Lafon, 2004]. They are more rarely actuated and animated.

Nevertheless, several projects in the HCI literature draw inspiration from anthropomorphic affordances. More generally, these projects are related to the Shape-Changing Interfaces or Organic User Interfaces (See Chapter 2):The anthropomorphism is conveyed through the actuation of these interfaces. Anthropomorphic affordances have been used for persuasive technologies in traditional objects, for instance with a faucet that can move and behave in life-like manners to communicate with the user [Togler et al., 2009].

Figure 4.17: Wriggloo, two ears for smartphones [Park et al., 2014]

A large body of work explores shape change of mobile devices to convey aliveness [Pedersen et al., 2014] or emotions [Strohmeier et al., 2016b]. The project Wriggloo [Park et al., 2014] (Figure 4.17) consist of two actuated ears to a smartphone to improve mediated communication between remote

users. The movement that one user performs on an ear is remotely reproduced on the other smartphone. Other mobile devices are augmented with smart hairs [Ohkubo et al., 2016]. Inspired by human hairs, they are capable to blend but their height and diameters of 3mm x 50mm is much larger. Hemmert et. al. [Hemmert et al., 2013] created a mobile device capable to react to proxemic interaction with different body postures. When the user is getting close to interact with the device, it can physically display behaviour such as attention or anxiousness. This related to the 3rd layer of anthropomorphism of *Folk-Psychology*. The device can also autonomously simulate breathing in the pocket [Hemmert, 2009].

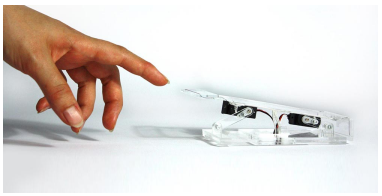


Figure 4.18: Actuated mobile phone by Hemmert et.al. [Hemmert et al., 2013] that reacts to proxemic interaction

> Overall, the work presented here use some anthropomorphic affordances to convey emotions or personality with the user. These projects don't have physical realistic humanlike embodiment. We explore this aspect in the next chapters of this thesis.

4.2.4 *The limits of Anthropomorphism*

Every new technology that comes with a radical approach is prone to face critics and reject from the public. One possible reason why it's not very much used is because anthropomorphism quickly reaches two limits: Uncanny Valley and Social acceptability.

Uncanny Valley

Humanoids robots are often perceived as *almost* humans. In this *almost* lies a big perception gap, first suggested by Mori in 1970 [Mori, 1970]. He suggested that as the appearance of robots become more humanlike, the viewer's level of comfort drops as a simulation approaches the realism of a human; he called this dip in liking the "Uncanny Valley" (Figure 4.19). For instance, if the robot has realistic skin and facial features but the actuation is not as realistic as the humans' movements, this will create the sensation of something wrong and *"off"*. An example of Uncanny valley is represented in Figure 4.20. Different robotic faces are presented in ascending order of mechano-humanness.

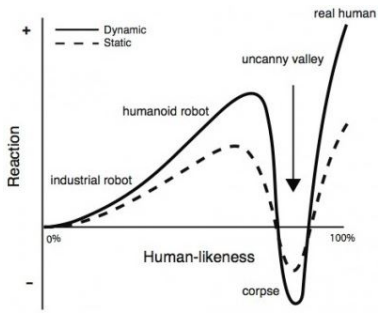


Figure 4.19: Uncanny Valley plot

Uncanny Valley is well known by researchers and science-fiction authors, but Uncanny valley has been principally a no-go zone in HCI [Bartneck

Figure 4.20: Different robot faces, ordered from the more mechanic to the more humanlike [Mathur and Reichling, 2016]

et al., 2009]. It has generally a negative impact on interaction and creates a sensation of reject of the interface from the user. Gray and Wegner [2012] suggest that *"machines become less realistic when people ascribe to the experience (the capacity to feel and sense) rather than agency (the capacity to act and do)"*. Using anthropomorphic affordances for the design of new interfaces will face the Uncanny Valley. To minimize rejection, one has to consider the degree of realism and project what would be the social acceptability of such interfaces.

Social and cultural acceptability

Another limit of anthropomorphic interfaces lies in the social acceptability by the users himself as well as the acceptability by others. The social acceptability by the user himself is reached when the behaviour of the interface mismatches his expectations. *Clippy*, the infamous virtual agent from Microsoft Word presented earlier is a good example of this limit. This software agent was programmed to give advice very often to the user. The result felt by the user was something that constantly interrupted his actions. In this case, the anthropomorphic layers of *traits* (layer4) and *social roles*

(layer 5) attributed to anthropomorphic interfaces were unacceptable.

Our interactions with technologies in the society are influenced by the perception by others: The social acceptability of a device or a technology usage is impacted by a combination of factors such as its appearance [Goffman et al., 1978]. The feedback is gathered by users by taking into consideration the reaction of the external observers and their existing knowledge. Social acceptability has to be evaluated when the motivations to use a specific device is limited by social norms, as often it happens in a public setting. Interacting with a radical interface such as an anthropomorphic device will have to face the judgement of social acceptability. However, every technology had to face social acceptation. Talking out loud to a mobile device was not socially accepted in the early 90's, and is now part of the social norm but not accepted. Technology adoption always follows a similar path, where few early adopters are the first willing to take risks to test a new technology, then possibly followed by a majority of late adopters [Katz and Shapiro, 1986]. In robotics, social acceptability is also limited by the fear of robots: Robots should not harm humans. Historically the research in robotics has been more focused on the transmission of positive pro-social emotions [Hanson et al., 2005] while avoiding physical contact with humans for reasons of security.

Social and culture acceptability is a challenge as well as an opportunity for the designers and researchers to reflect on the look of the interface, and how its perceived appearance can condition the social acceptance of technology. It is related to the context where the interface, and the social acceptability is impacted if the interaction is performed in a public or private context.

4.2.5 How can we use anthropomorphism in this thesis

In this thesis, we want to use anthropomorphic affordances in the design of HCI interfaces dedicated to touch. One goal is to explore how anthropomorphism can be used in our daily devices to convey and detect touch, by fabricating tools than can make it easily accessible. Anthropomorphic design applied in the context of affective touch raises new design challenges and considerations. The challenges presented below inform the design of anthropomorphic interfaces in the remaining of this thesis. Every design challenge has underlying technical challenges and considerations, that are

likely to impact the user experience.

Touch Generation

Typical technology to convey touch use vibration motors or force feedback systems (See chapter 3). The touch signal transmitted by these devices to the user is over-simplified and the user can *interpret* it as specific emotions [Rovers and van Essen, 2004a]. My hypothesis is that if a device performs touch in a realistic and humanlike fashion, with an anthropomorphic interface designed for touch interaction, the user will interpret the touch similarly to a touch performed by another individual. I argue that there are some benefits to combining anthropomorphic affordances with functional capabilities that match these affordances. The underlying technical challenge lies in the reproduction of a realistic actuation, i.e. reproducing arm and fingers. The fingers have a precise actuation, limited joint orientation. We explore this challenge in the chapter 5 of this thesis.

Touch detection

Currently, the detection of touch is performed on interfaces that do not resemble the human skin (See Chapter 3). The aspects of the interface or the resolution of the sensors don't make them adequate to detect subtle touch nuances. Designing an interface with skin-like affordance and capabilities is an opportunity for the user to benefit from his knowledge of previous social experiences and interactions with humans, and to transfer this knowledge to the interface to interact more naturally with it. The combination of anthropomorphic affordances and functional capabilities can inspire new interactions typically performed on humans, such as pinching. The underlying technical challenge lies in the production of a realistic skin, capable of detecting touch and with similar physiological properties, such as its colour and surface texture. We explore this challenge in the chapters 7 and 8 of this thesis, and follow a biomimetic [Paulson, 2004] approach.

Visual stimuli

The feeling of touch is almost always multimodal. In real-life, a touch contact is usually accompanied by other stimuli. For instance, our visual perception reinforces the feeling of touch. It is an opportunity to combine tactile feedback with other modalities and anthropomorphic cues, to reinforce the tactile

perception. In the chapter 5, we combine touch with facial expressions to explore how it impacts perception of emotion from touch.

Considering the user's context

Another challenge lies in the understanding of the user's context. Existing devices are either worn (e.g. vibration sleeves [Huisman et al., 2014b]) or require the user to enter willingly in interaction with them (e.g. force-feedback devices [Smith and MacLean, 2007]). Having an interface that is in constant contact with the user involves the challenge of determining what are the right moments for interacting. A touch stimulus must not interfere with the user's main activity by perceptually overloading him. Continued or unwanted solicitations or notifications could lead to a rejection of the technology (anthropomorphic interfaces that implement Proactive Behaviour should not interfere with the user's actions such as *Clippy* did).

This challenge involves designing interactions that take into account the seamless transition between normal activities and activities related to communication through touch.

The challenges presented here raise an opportunity to design interfaces that uses only some humanlike features dedicated to touch. In our case, we can draw inspiration from the human touch capabilities, both in term of input and output. This requires to observe and have a good understanding of the human body to reproduce similar features and capabilities.

4.3 Conclusion

Anthropomorphism has been widely used in science-fiction literature and cinema. It is integrated in research in two main domains. First in Human-Machine Interaction, anthropomorphism motivates the development of humanoid Robots that resemble humans. Anthropomorphism is not needed to design a functioning robot, but it motivates the choice of form factors and actuation methods. Researchers reproduce similar movement mechanism (two arms, biped, etc.). Social robots are combined with a realistic appearance including facial movement. Their technology is usually very complex and expensive. Another context is the design of virtual agents. In these cases, anthropomorphism is related to verbal communication and

appearance. These interfaces are virtual, i.e., on a screen, and are often much more realistic and humanlike than the physical robots. However they are not incarnated in the physical world. The primitive categorization (anthropomorphic layer 1) might be the lost important aspect to consider when designing an anthropomorphic device. It is at the first sight the we build expectations towards a system, and infer the possible interactions matching our mental model [Duffy, 2003, Shneiderman and Maes, 1997]). If the object familiar, and the device appears like a physical system as we directly know how to use and manipulate, the users don't have to learn any metaphor to interact with it.

Other important anthropomorphic aspect are the behavioural aspect. Actuated zoomorphic toys who have the same behaviour as animals (breathing, curiosity, etc) uses a lot this aspect. This implies that the interactive object is autonomous and has its own model of action, which is not needed to design an interface for mediated communication.

WHAT YOU MUST REMEMBER

Positioning:

- Science-Fiction is a source of inspiration for the design of new interaction paradigm.
- Among the layers of anthropomorphism, the *Primitive Categorization* plays a crucial role.
- Anthropomorphic affordances can change how users make sense of an interactive object, by projecting human functioning and behaviour to the attributes of an object

Part II

Interfaces for touch output

5

Device Initiated touch with a Robotic Arm

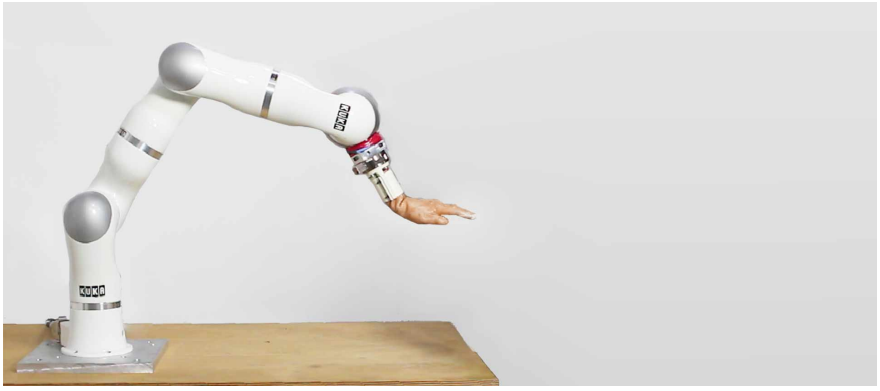


Figure 5.1: This device is capable to generate humanlike touch with different velocities, contact force, and amplitude.

Psychological studies have explored how people use touch to communicate distinct emotions [Hertenstein et al., 2006a]. However existing technological devices that reproduce touch usually rely on simple stimuli, such as vibration patterns or thermal feedback. As seen in the Chapter 2, affective touch is a complex phenomenon, and our ability to perceive a believable touch contact is influenced by different mechanoreceptors. It

is not clear yet if a device is capable to reproduce a believable affective touch and if such touch stimuli can be linked to emotions. It is also not yet clear how a designer or HCI researcher can use device-initiated touch in an application context.

[1] Main portion of this chapter was submitted in ACM Transaction for Affective Computing. Thus, any use of "we" in this chapter refers to the author of this work: Marc Teyssier, Gilles Bailly, Catherine Pelachaud, and Eric Lecolinet.

In this chapter, we [1] present an exploratory study that investigates the impact of touch generation performed by an artificial system to communicate emotions to users. More precisely, we study the effect of single and combined factors involved in touch (Force, Amplitude, Duration, Velocity and Repetition) on the perception of pleasantness (valence) and arousal. To this extent, we developed an anthropomorphic system made of a robotic arm augmented with an artificial hand as its extremity that touches the user's forearm. To assess both the device and the impact of touches on the perception of emotions, we designed a series of experiments testing each individual factor presented before and their combination. Finally, we illustrate several envisioned scenarios that can take advantage of conveying emotions through such touch movements. These scenarios include mediated communication, virtual reality or human-robot interaction wishing to enhance the sense of immersion or to augment human senses involved in the interaction.

5.1 *Objectives and Approach*

The objective of this chapter is twofold and is a first step towards the PROBLEM 1 of this thesis: *Can actuated devices produce humanlike touch?*.

During face-to-face communication, touch gestures that communicate affect are diverse (see chapter 2). For instance, the emotion Anger can be perceived through a short and localized gesture (*hit*) whereas Comfort can be perceived with a slow and protracted gesture with back-and-forth movements (*stroke*) [Hertenstein et al., 2006a]. Our first objective is to understand the characteristics of human touch and how to reproduce them. This corresponds to the PROBLEM 1.1 of our thesis: *What composes human touch and how can we transpose that to a device.* Taking into account previous literature on human-to-human interaction, we propose a set of factors characterizing touch.

We presented in Chapter 3 a variety of devices and technologies that are used to perform a generated touch. Some studies suggest that a

robot-initiated touch can be perceived as human contact [Willemse et al., 2016], and others report that people prefer touching robots than being touched [Hirano et al., 2018]. Our approach draws inspiration from these studies and also focuses on robot-initiated touch, where the device performs protracted and dynamic contact with the user's skin. In order to reproduce touch factors such as the velocity, force, movement and repetition, we chose to use a robotic arm. This robotic arm is augmented with an artificial hand that touches the user's forearm (Figure 5.4). Another benefit of using a robotic arm is that it can perform both tactile and kinesthetic feedback.

The second objective is to perform a humanlike device-initiated touch that conveys emotions. This corresponds to the PROBLEM 1.2 of our thesis: *is it possible to perform a humanlike device-initiated touch that conveys emotions?*. Our overall approach consists of transposing emotional perceptual experiments conducted in human-to-human interaction studies to machine-to-human interaction. This approach is frequently used in ECA literature, for instance to understand and reproduce the effect of smiling during conversation [Ochs et al., 2017, Whitmire et al., 2018]. The approach is developed in three steps, described below:

Step 1: Selecting Touch Characteristics and Device. The objective of this first step is to select the characteristics that will be explored in controlled experiments (Steps 2 and 3). Generating touch requires considering its various characteristics and their associated parameters. It raises the challenge of choosing an appropriate device. These two aspects need to be considered together as current technology limits the set of factors that can be implemented, thus investigated. For instance, controlling force, temperature, and skin moisture simultaneously might be technically difficult. These choices (set of touch parameters and device) were performed iteratively, by considering previous literature on human-to-human interaction and the characteristics of touch-generating device. Section 5.2.1 describes the set of touch parameters we chose (AMPLITUDE, VELOCITY, FORCE and TYPE) and Section 5.2.2 presents the device that we selected (a robotic arm augmented with an artificial hand).

Step 2. Perceptive Study on Context-Free Generated Touches. From the result of the previous step, we retained three characteristics (AMPLITUDE, VELOCITY and FORCE). The next step was to conduct an experiment

that investigated how humans perceive eight device-initiated touches (the combination of the three characteristics executed with two, small and large, parameters). It allowed us to select certain touch parameters that tend to have distinct effects in the perception of emotions. This study was done context-free, meaning that no information other than the touch stimuli was given to the participants. We applied a methodology similar to [Ochs et al., 2017] that is often used in perceptual studies. A context-free experimental design allows us to measure how each touch stimulus conveys specific emotions and what is the influence of touch parameters on perception of emotions.

Step 3. Perceptive Study on Generated Touches with Context Cues. In Section 5.5 we describe an experiment that investigates how context modulates the perception of machine-generated touch [Kertay and Reviere, 1998]. Context is defined here by textual scenarios and facial expressions of a virtual agent. The scenarios have been designed following the methodology proposed by Scherer et al. [Scherer and Ellgring, 2007]. They correspond to one (non ambiguous) emotional situation and have been used in other studies [Bänziger et al., 2012, Fourati and Pelachaud, 2018, Ochs et al., 2017]. The visual cues correspond to the facial expressions of a virtual character of the emotions associated to the scenarios. This study brings us closer to examining the perception of emotions through multimodal signals, namely facial expressions, text and touch in view of endowing emotional ECAs with touching capabilities. In the following section, we provide further in-depth details on the three aforementioned steps.

This chapter is structured as follows. We present the experimental design, apparatus and tasks conducted in three studies. The results of each studies are then presented and discussed. Finally I present use cases and scenarios.

5.2 *Step 1. Selecting touches and device*

In this section, we explain the choice of touch parameters and of the device. While reported sequentially in this section, these choices followed an iterative process. It's important to point out that our investigation was not technologically driven and did not focus on a specific device (e.g. smartphone [Wilson and Brewster, 2017]), which is common in the HCI

community. In contrast, we started by considering human factors.

5.2.1 *Selecting touch characteristics*

Touch can be characterized by several spatio-temporal characteristics. **Spatial characteristics** include the *location* where the touch is applied on the body [Nguyen et al., 1975]. The forearm, the shoulder and the back are the locations that are generally the most socially and culturally accepted [Hertenstein et al., 2009] and are most suited for social and intimate relationships [App et al., 2011]. The *touching area* or surface of contact depends on the kind of touch gesture (e.g. a hug vs. a touch with the fingertip) [Walther and Burgoon, 1992].

Temporal characteristics characterize the dynamics of touch movements. They include the *duration* of a touch [Connor et al., 1990], the *velocity* of a touch movement [Essick et al., 1999, 2010], and the *repetition* of spatio-temporal patterns which can either involve a succession of strokes (e.g. pats) or back-and-forth movements on the skin [Huisman et al., 2013b, MacLean, 2000]. Finally, **other characteristics** impact the perception of emotions through touch such as **force intensity** through variation of pressure [Cascio et al., 2008], **texture** [Essick et al., 1999] or the **temperature** of the end-effector [Salminen et al., 2013, Wilson et al., 2016].

These individual characteristics have an impact on the perception of emotions. Low velocities are more associated with pleasant emotions. Negative emotions tend to involve a short duration, and high velocity, high pressure [Hertenstein et al., 2006a]. Studies on the impact of temperature on the perception of emotions report contradicting results. Yoo et. al. [2015] found that the cooling is perceived as having a positive valence, while Wilson et. al. [2016] found the opposite results. Regarding the texture of the end-effector, smooth, soft materials received higher pleasantness ratings than rough, coarse materials [Essick et al., 1999].

To select the relevant touch characteristics for the study, we broke down touch movements present in the human-to-human literature [Essick et al., 1999, 2010, Hertenstein et al., 2006a, 2009] by considering them as a composition of simple characteristics. Given the numerous characteristics of touch, we retained four of them: Amplitude, Velocity, Force and Type. We chose these four characteristics because they allow us to generate a wide range of

gestures including Hitting, Stroking, Patting, Contact or Tapping. These gestures are often associated with a wide range of emotions [Essick et al., 1999, 2010, Hertenstein et al., 2006a, 2009]. We excluded some gestures for the reasons explained below, but that are worth exploring in future studies. For instance, we excluded gestures that require holding on to someone (e.g. Grabbing, Lifting the arm) or protracted touching on the back (Hug), as they would require complex interweaving between the machine and the participant. We also did not consider touch characteristics such as temperature or skin moisture. These characteristics do not seem to have a clear effect on the perception of emotions [Yoo et al., 2015, Wilson et al., 2016, Wilson and Brewster, 2017]. Moreover they are not easily reproduced on devices. Finally, we decided to consider gestures performed only on the forearm. This location is generally suitable in most cultures [Krahe et al., 2016, App et al., 2011] and commonly used in human-device studies [Huisman et al., 2013a,b].

5.2.2 *Selecting the device*

Our primary motivation when choosing a device was its ability to produce humanlike touch, i.e. its capacity to generate touches similar to those generated by humans. We thus quickly excluded vibration motors and focused on technologies providing kinesthetic feedback as well as tactile feedback close to those produced by the palm and fingers of the human hand.

Force feedback actuators [Bailenson et al., 2007] have been investigated to convey emotions. They are rated as more natural, and show a greater emotional interdependence with a stronger sense of co-presence than vibrotactile touch [Ahmed et al., 2016]. They are also more adapted to perform large-scale haptic feedback [Gosselin et al., 2008] as they can go around the user and produce contact at various body locations. Robotic devices have been used to provide passive haptic feedback [Yokokohji et al., 1999, Vonach et al., 2017, Araujo et al., 2016]. Using these devices in a virtual reality environment is relevant as the physical robots are hidden from the user's sight when wearing an HMD.

Inspired by these works and the robot-initiated touch in human-robot interaction [Essick et al., 2010, Gosselin et al., 2008, Chen et al., 2011, Kim and Follmer, 2019, Willemse et al., 2017] and by anthropomorphism (see

Chapter 4), we decided to use a robotic arm augmented with an artificial hand.

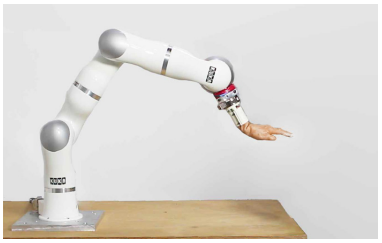


Figure 5.2: KUKA augmented with a rubber artificial hand.

Regarding the robotic arm, we chose to use a 7-degree-of-freedom KUKA LWR4+ compliant robotic arm (Figure 5.2), originally designed for safety with collaborative robotic applications in mind. This robot enables accurate motion and ensures the security of the participant. The workspace of the robot is around $1.5m^3$, the amplitude can be precisely controlled, and the end-effector can be reliably positioned in a 3D space ($\pm$0.05mm). The velocity of the end-effector can be accurately varied from 2cm/s to 40cm/s. We used a Microsoft Kinect V2 to track the anatomy of the user's arm, to ensure the robot's hand follows the user's arm morphology, and to adapt the force intensity along her arm. The force is measured with a dedicated apparatus connected to the end-effector of the robot (ATI F/T Sensor Mini45). Masses and spring constants of the lower arm skin are similar between individuals and are around 40 N/mm [ISO, 2016]. Hence the touch was applied along the surface of the human arm with an offset of the position of the end-effector relative to the target force ($\pm$0.1N).

Regarding the artificial hand, we used a silicon human hand attached to the robot (inspired by prosthetic hands bionics).

5.2.3 *Selecting touch parameters*

Once the choice of touch characteristics and device were finalized, we selected the parameters for each characteristic. In the following paragraphs, we use the term velocity (V) as the velocity projected on the axis of the forearm. We distinguish between dynamic movements ($V \neq 0$) and static movements ($V = 0$). Dynamic movements, such as a pat on the participant's arm, are characterized by the change of location of the end-effector (here, the hand attached to the robotic device) over time. In contrast, a static movement is performed at the same location (but can also have different duration and repetition characteristics) [Hertenstein et al., 2006a]. The selected touch parameters are presented in Figure 5.3 and are all in range with the mechanical constraints of the robotic arm.

Dynamic touch movement

We monitor four characteristics in the dynamic condition:

AMPLITUDE (labeled A) represents the length of the movement performed on the arm. We consider two amplitudes, 5cm (labeled *A*-) and 20cm (*A*+), which are commonly used in the human-touch literature [Essick et al., 2010].

VELOCITY indicates how fast the gesture is performed. We consider two velocities, 16cm/s (*V*+) and 3.8cm/s (*V*-). Their difference (diff=12.2cm/s) is similar to the values used in previous human touch experiments (diff=15cm/s), and seems to be sufficient to signal different emotions [Essick et al., 2010].

DURATION of a movement can be derived from its amplitude and velocity. It varies between short (0.3s) and long (5.2s).

FORCE we consider two levels, low <0.3N (*F*-) and strong >1.2N (*F*+). The FORCE range varies slightly from participants due to their forearm morphology, but still ensures a perceptible difference between the two values and remains small enough not to hurt the participant's arm [Cascio et al., 2008, Van Erp et al., 2010].

TYPE we consider three repetitions of movements: *Simple* (*To*), *Pat* (*Tp*), and *Stroke* (*Ts*) [Jones and Yarbrough, 1985, Hertenstein et al., 2006a]. A *Simple* gesture is a one-directional movement from one position to the another on the forearm. *Pat* is a 4-time repeated gesture and *Stroke* a 2-time back-and-forth gesture.

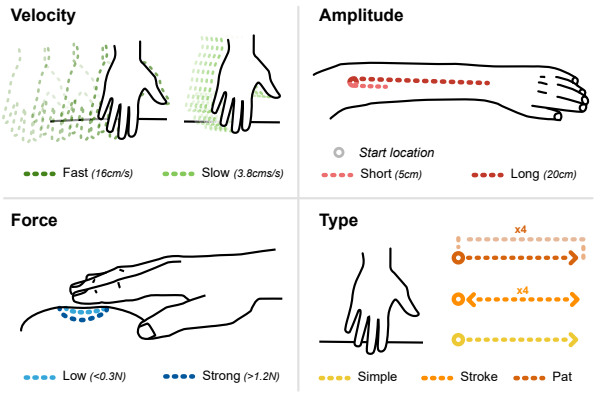


Figure 5.3: Touch factors used in the dynamic study. Factors include Velocity, Amplitude, Force and gesture Type.

Static touch movement

When considering static touch movements, AMPLITUDE and VELOCITY are null. We thus only consider FORCE and DURATION characteristics in this

case. The values for DURATION (Labelled *D*) are 0.3s (*D-*) and 1.3s (*D+*), in order to be comparable in static and dynamic conditions. Regarding the TYPE of the movement, we consider *Simple* (*To*) and *4-Tap* (*Tp*). *4-Tap* is an adaptation of *Pat* without movement on the arm. The *Stroke* gesture is removed because there is no displacement.

5.2.4 *Generated touches*

In total, there are 24 dynamic generated touches (2 AMPLITUDE x 2 VELOCITY x 2 FORCE x 2 TYPE) and 8 static generated touches (2 TYPE x 2 DURATION x 2 FORCE). The generated touches are labeled with the acronyms of the touch parameters. For instance, *V-A+F+Ts* corresponds to a generated touch with the smallest VELOCITY (3.8cm/s), the largest AMPLITUDE (20cm), the highest FORCE (>1.2N) and a Stroke TYPE.

In conclusion, we drastically reduced the size of the design space of touch by considering four characteristics and two different parameters per characteristic. The device is able to reproduce all of these characteristics. Our next step is to conduct a pilot study to understand the pertinence of the 32 generated touches in conveying emotions.

5.3 *Pilot study*

The objective of this pilot study is to compare the 32 previously defined machine-generated touches in order to identify the most promising characteristics and parameters for conveying emotions. No contextual cues are used in this experiment.

Figure 5.4: Setup of the experiment. a) The robotic arm is hidden behind an opaque screen and touches the user's forearm. b) A Kinect sensor tracks the user's forearm to follow her arm anatomy. c) Participant wears both earphones emitting white noise and a noise-cancellation headphone to hide the sound of the robotic arm.

Apparatus

The setup is illustrated in Figure 5.4. Participants are seated at a table, in front of a computer screen, wearing earphones that produce white noise as well as noise-cancellation headphones to hide the sound of the robotic arm. The left arm of the participant is laid on the table with the palm oriented downwards so that the stimuli are applied on the back of the forearm.

The experimental software for controlling the robotic arm is implemented within Unity. The tracking device, a Kinect, allows us to place the starting point of the touch movement near the elbow (Figure 5.3, Amplitude) and to follow the anatomy of the user's forearm in order to apply a constant force. Several layers of security are implemented to ensure the participant's safety, including robust user arm tracking, precise inverse kinematics, as well as the definition of a limited and well-identified interaction zone.

5.3.1 Experimental design

For comparison purposes, the procedure is similar to other studies investigating human-to-human touch [Essick et al., 2010, Hertenstein et al., 2006a] and assessing emotion perception [Wilson and Brewster, 2017]. The study contains sixteen volunteers (7 F) who are all right-handed students and staff members from the same academic institution, with a mean age of 26.4 (σ=1,9). They are provided with a description of the task, "*This study will measure which emotional content you think is being represented by each stimulus*". Once participants are ready, they can interact (with a mouse in their right hand) with the experimental interface to start the study. The experimental device then executes the stimulus, i.e a generated touch composed by a combination of parameters. Once the generated touch is executed, the participants fill in a questionnaire displayed on the screen about the touch they perceived and its associated emotions [Ravaja et al., 2017]. We measure the perceived emotions and overall user experience using the dimensional representations of emotions (Valence-Arousal emotional space [Russell, 1978]), presented in Chapter 2. We explained to our participants that "*arousal refers to physiological arousal or excitement: a low value indicates calmness while a high value indicates excitement; valence is related to emotional pleasantness: a low value indicates unpleasantness while a high value indicates pleasantness*". The first part of the questionnaire assesses the arousal/valence rating on a

7-point Likert scale (e.g. 1: "not at all", 7: "very"). :

– *"Was the emotion conveyed by touch pleasant?"*
– *"Was the emotion conveyed by touch intense?"* (We explained to the participants that "*intense refers to physiological arousal or excitement*".)

At the end of the experiment, participants are given another questionnaire (on a 7-point Likert-scale) about their overall experience and their perception of the robotic arm and their sensibility to touch. They are asked to indicate how much they agree with the following statements:

– *You touch the other speaker during a conversation*
– *You enjoy being touched during a conversation*
– *This device is adapted to perform touch*
– *The touch stimuli presented are efficient to convey emotions*
– *The touch stimuli were humanlike*
– *It was difficult to associate touch stimuli with an emotion*
– *You accept to be touched by a robotic arm*

The pilot-study follows a within-participant design, with the order of presentations of each condition counter-balanced between participants. Each stimulus is repeated three times during the experiment. We obtain a total of 96 stimuli ratings per participant (8 *static* + 24 *dynamic movements*) x 3 *repetitions*). Participants are given a break of 10 seconds between each trial and a longer break after 12 stimuli to let their arm rest. Overall, the study lasts about one hour to 90 minutes. To avoid cultural confound factor, participants in the studies are all from Western countries. For this study we collected results from 16 participants (1152 data points).

5.3.2 *Results*

We remove 3.0% (35/1152) outliers based on arousal and valence ratings using the Wilks' method [Caroni and Prescott, 1992] on the dataset containing the dynamic movements and 1.3% (5/384) on the dataset with static movements. Our results suggest that fatigue did not impact Arousal/-Valence (A/V) ratings; both MANOVA and ANOVAs reveal no effect of presentation order of stimuli (1,2,3) on Valence and Arousal.

To determine effects on individual measures (effect sizes are shown as η_p^2), we analyze the ratings using a two-way repeated-measure MANOVA

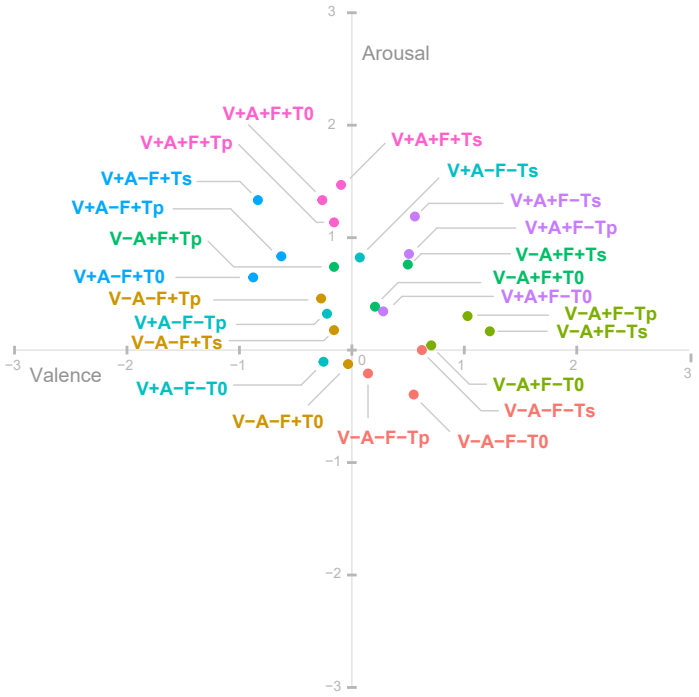


Figure 5.5: Results of arousal/valence distribution for the pilot study with all touch factors.

with valence and arousal as combined dependent variables. For the dynamic movements, MANOVA finds significant main effects for the characteristics Velocity ($F(2,1127) = 100.56$, $p < 0.001$; $Wilks'\Lambda = 0.86$, $\eta_p^2 = 0.13$), Force ($F(2,1127) = 54.78$, $p < 0.001$; $Wilks'\Lambda = 0.86$, $\eta_p^2 = 0.12$), Amplitude ($F(2,1127) = 29.67$, $p < 0.001$; $Wilks'\Lambda = 0.95$, $\eta_p^2 = 0.05$), but not effect on Type.

For static movements, MANOVA reveals a significant effect on Force ($F(2,375) = 16.78$, $p < 0.007$; $Wilks'\Lambda = 0.92$, $\eta_p^2 = 0.08$) and a small effect on touch Type ($F(2,375) = 7.12$, $p < 0.001$; $w'\Lambda = 0.96$, $\eta_p^2 = 0.04$) and no effect on Duration nor interaction effects. The distribution of arousal/valence rating for each stimulus (*static* and *dynamic touch*) is illustrated in Figure 5.5.

5.3.3 *Discussion*

Our results suggest effects of *dynamic* touch (involving the characteristics Velocity, Force, Amplitude). While we anticipated a strong effect of the Type characteristic on the perceived emotions when performing *dynamic* touch, this was not the case. This hypothesis was influenced by previous research that has reported on the impact of repetitive sequences of touch

to convey different meanings [Jones and Yarbrough, 1985]. Our study does not completely reproduce results from a number of previous studies [Hertenstein et al., 2006a], especially in the *static* condition. But these studies considered some touches (e.g. grab, hug) that our device could not produce. The effect of *static* touch on emotions (involving the characteristics DURATION, FORCE, TYPE), the impact is less clear for participants in our experiment.

Considering the result of this pilot study, and the fact that some results were not significant, we decided not to consider the TYPE characteristic and *static* touches in our next studies. We therefore focus on eight machine-generated touches which are a combination of the parameters AMPLITUDE, VELOCITY and FORCE. These combinations still enable us to perform touch gestures such as Hit, simple Stroke or Pat, but exclude prolonged bi-directional strokes or multiple taps.

This first step answers the first objective of this chapter. We decomposed human touch in a serie a factor and found that they can convey different emotions.

5.4 *Step 2: Investigating Context-Free Generated Touches on emotions perception*

The objective of the experiment described in this section is to confirm the findings of the step 1 pilot study to precisely understand the impact of the characteristics and parameters of touch on perception of emotion in a context-free situation. This is a step toward our end-goal of producing a humanlike touch.

5.4.1 *Experimental Design*

The apparatus and the experimental design of this study are similar to the pilot study. As a result from the pilot-study, we did not consider *static* generated touches and the TYPE characteristic. The experiment of study 2 consists of $2^3 = 8$ different stimuli corresponding to the combination of two parameters (low / high) for each of the three characteristics (VELOCITY, AMPLITUDE, FORCE). Each stimulus is repeated twice. The experiment

lasts for about 15 minutes. Thirty-two volunteers (14 F, 18 M) of the same European culture participate in the study, with a mean age of 26.5 (σ=6).

5.4.2 *Results*

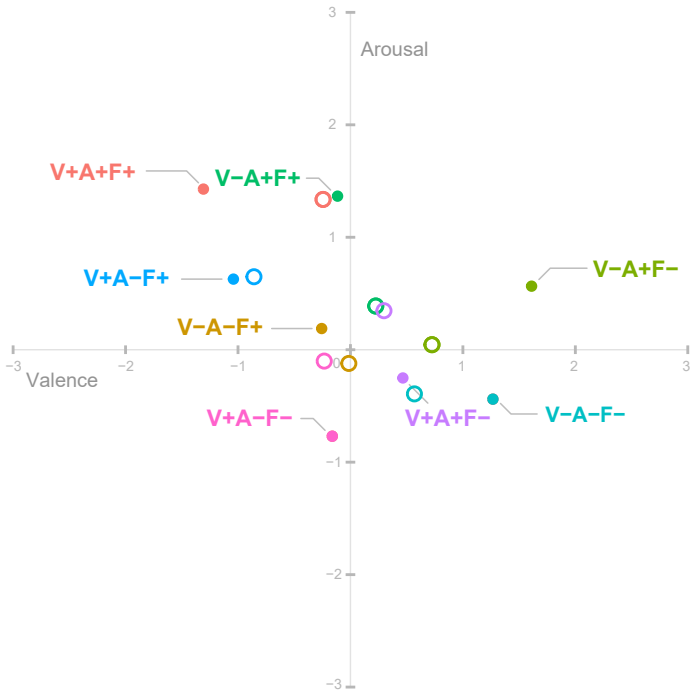


Figure 5.6: Results of arousal/valence distribution for all the context-free studies with the relevant three characteristics (Velocity, Amplitude, Force). Larger circles are the stimuli from the pilot study. We can see in this figure that some points are located near the center of the circumplex model. Those correspond to the neutral stimuli. The points the more far from center in each quadrant are considered as distinct emotions.

We map the average arousal/valence results obtained for each individual stimulus onto the circumplex model [Russell, 1989]. To fit the two dimensions of the model, we convert the 7-point Likert-scale ratings to -3 to +3 scales; each pair of arousal and valence values is taken as a coordinate in the 2D space. The values for the majority of the stimuli (Figure 5.6) lay within the 'high arousal, low valence' quadrant (*top-left*), associated with emotional states such as anger or frustration. There are a smaller number of points in the 'low arousal, high valence' quadrant (*bottom-left*: satisfaction, calm) and one point found within the 'low arousal, low valence' quadrant (*bottom-left*: depression, sadness, tired) and the 'high arousal, high valence' quadrant (*top-right*), associated with emotions such as excitement, happiness, and amusement.

Arousal/Valence ratinRgs

We analyze the results in two steps by conducting 1) a two-way repeated-measure MANOVA with Valence and Arousal as combined dependent variables and 2) two 3 x 3 repeated-measure ANOVA, on the Valence and on the Arousal data to determine effects on individual measures (effect sizes are shown as η_p^2). The confidence intervals of standard deviations per trial and per participant on the arousal (*ci = 0.31*) and on the valence (*ci = 0.34*) indicate that individual's ratings of the same stimulus are consistent.

The MANOVA indicates significant main effects on the individual characteristics VELOCITY ($F(2,32) = 45.12$, p < 0.001; $Wilks'\Lambda = 0.91$, $\eta_p^2 = 0.09$), FORCE ($F(2,32) = 120.1$, p < 0.001; $w'\Lambda = 0.67$, $\eta_p^2 = 0.32$), AMPLITUDE ($F(2,32) = 24.2$, p < 0.001; $w'\Lambda = 0.91$, $\eta_p^2 = 0.09$). The MANOVA reveals significant interaction effects for VELOCITY x FORCE ($F(2,32) = 6.23$, p < 0.001; $Wilks'\Lambda = 0.98$, $\eta_p^2 = 0.02$) and AMPLITUDE x FORCE ($F(2,32) = 3.0$, p < 0.001; $w'\Lambda = 0.98$, $\eta_p^2 = 0.01$).

Valence: Individual ANOVAs find a significant main effect of VELOCITY on Valence ($F(1,8) = 90.1, p < 0.001, \eta_p^2 = 0.15$), with the 16cm/s parameter resulting in a lower average valence (μ=-0.6, σ=0.8) than the 3.8cm/s parameter (0.6, 1.0). FORCE also has a significant effect ($F(1,8) = 144.5, p < 0.001, \eta_p^2 = 0.23$). A low Force results in a higher valence (0.8, 1.3) than a strong Force (-0.7, 1.3). The effect of AMPLITUDE on the valence is not significant, with close results between long (0.12, 1.2) and short amplitude (0.0, 1.0). An interaction between AMPLITUDE x FORCE is revealed ($F(1,8) = 5.6, p < 0.001, \eta_p^2 = 0.01$).

Arousal: There is a significant effect of AMPLITUDE on arousal ($F(1,8) = 45.9, p < 0.001, \eta_p^2 = 0.08$). A short Amplitude results in a lower arousal (μ=-0.2, σ=1.4) than a long Amplitude (0.7, 13). There is a significant effect on FORCE ($F(1,8) = 85.1, p < 0.001, \eta_p^2 = 0.15$), with an arousal stronger with a high Force (0.8, 1.3) than low Force (-0.3, 1.3). No effect is found for VELOCITY, with an arousal similar for low and high velocity (0.3, 1.4). Finally, ANOVA reveals an interaction effect on arousal of the combined factors VELOCITY x FORCE ($F(1,8) = 11.2, p < 0.001, \eta_p^2 = 0.02$).

In Figure 5.7, we report effect sizes of dynamic movements with 95% confidence intervals of individual ratings for both valence and arousal. The x-axis shows the mean effect of each factor on arousal and valence. Intervals indicate all plausible values, their midpoint being about seven

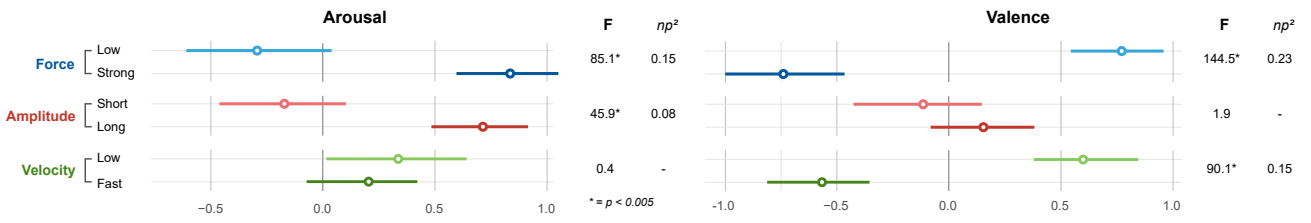


Figure 5.7: Effect sizes with 95% confidence intervals of individual ratings for valence and arousal. The x-axis shows the mean effect of each characteristic on arousal and valence, with their bootstrap confidence intervals.

times more likely than their endpoints [Cumming, 2013].

Individual Differences

Individual differences in touch perception may have an impact on the perception of the emotions [Seifi and Maclean, 2013, Wilson and Brewster, 2017]. The fact that participants declare liking to be touched during social communication (μ=3.6, σ=1.8) *(1:Don't like at all, 7:Like a lot)*, or like to communicate through touch (μ=3.4, σ=1.7) does not impact their arousal/-valence rating. ANOVA does not reveal an effect of gender on arousal ($F(1,253) = 1.5$) but reveals an effect of Gender on valence ($F(1,253) = 9.4$, p < 0.001, $\eta_p^2 = 0.01$). Participants were also asked to give confidence ratings for *"Globally, how difficult was it to perceive emotions?" (1: Not difficult, 7: Very difficult)*, which they found the perception task globally difficult (μ= 5.0, σ=1.5).

5.4.3 *Discussion*

This study investigates the impact of generated touch on the perception of emotions in a *context-free* situation.

From Figure 5.6, we observe that low Force is mainly associated to emotions with low arousal while a strong Force is linked to emotions with high arousal and negative valence. Similarly, Amplitude mainly influences arousal while touch Velocity tends to mainly influence valence ratings. Our results (Figure 5.7) further suggest that:

– Increasing the Amplitude seems to mainly increases arousal,
– Increasing the Velocity seems to reduce the valence
– Increasing the Force augments the arousal and reduces the valence.

Our results match previous studies. First, positive emotions (high valence) are conveyed through softer touch (low FORCE, slow VELOCITY) [Essick et al., 1999]. Then, negative emotions involve strong touch (high FORCE) [Essick et al., 2010]. Finally, high positive or negative excitement is communicated through strong dynamic touch (high FORCE, high VELOCITY, high AMPLITUDE) [Hertenstein et al., 2006a].

None of our generated touches convey emotions corresponding to the bottom-left quadrant, which is inline with previous studies between humans, as well as with technology-oriented studies [Wilson and Brewster, 2017, Wilson et al., 2016]. Clearly, the emotions with low Arousal/Valence are characterized by physiological *deactivation* [Reisenzein, 1994] and are generally less conveyed through touch in human-human communication (e.g., we don't communicate our *sadness* through touch, but may use touch to express our empathy to a friend feeling sad). These emotions are usually communicated through other non-verbal communication cues, such as facial expression [Ochs et al., 2017].

We also observe that three stimuli (*V+A-F+*,*V-A-F+*,*V+A+F-*) are close to the center of the circumplex model and can be considered as conveying "neutral" emotion. The other stimuli cover three of the four quadrants. In particular, the generated touch *V-A+F-* is in the Top-Right quadrant and can be associated with a positive emotion such as *Happiness*. The generated touch *V-A-F-* is in the Bottom-Right quadrant and can be associated with emotions such as *Calm* or *Boredom*. Finally, three generated touches (*V+A+F+*, *V-A+F+*,*V+A-F+*) are in the Top-left quadrant which is linked to emotions with high arousal and low valence such as *Anger*.

On Figure 5.6 we circle the points for the *Simple* TYPE stimuli that were obtained during the pilot study. We can observe that the stimuli stay within the same quadrant as in the pilot study. Stimuli that were perceived previously as "neutral", that are located in the -1/1 range on arousal and valence, are still perceived as such.

This study confirmed the results of the pilot study. To the research question *is it possible to perform a humanlike device-initiated touch that conveys emotions*, the results of our study allows us to respond positively. Our results suggest that, from the analysis of the position of the emotional rating in the circumplex model, three distinct areas in the circumplex model emerge. They roughly correspond to the emotion labels *Anger*,

Happiness and *Calm* as well as *Neutral*. Given our results, the smallest set of generated touches to convey distinct emotions are respectively *V+A+F+*, *V-A+F-*, *V-A-F-* and *V-A-F+*. We thus keep these four generated touches for further analysis in the next study.

5.5 Step 3. Investigating Generated Touches with Context Cues

We now explore how *context* cues and touch parameters influence the perception of emotions (arousal/valence). Embedding context in a perceptive study is difficult as it introduces many factors that can create bias. To circumscribe the information provided by the contextual cues, we follow a scenario-based induction technique [Bänziger and Scherer, 2010]. This technique, which is often used when conducting perceptive studies [Ochs et al., 2017], uses multi-modal corpora [Allwood, 2008, Bänziger and Scherer, 2010] and allows specifying non-ambiguous contexts. Each context is simple enough to correspond to one emotion. It may lack in naturalness and may not correspond to ecological settings, but since it corresponds to one value, this makes it possible to manipulate one variable at a time.

We use the four representative generated touches found in Step 2. From their position in the circumplex, they can be associated to four distinct emotions [Russell, 1978]: *Anger* (*V+A+F+*), *Happiness* (*V-A+F-*), *Calm* (*V-A-F-*) and *Neutral* (*V-A-F+*).

Each context was associated to one emotion through a textual scenario and a facial expression (associated to the emotion) of a virtual agent (Figure 5.9). Using facial expressions of emotions allows us to study the emotion congruence between facial and touch stimuli [Huisman et al., 2013a, Huisman, 2017]. The four chosen emotions conveyed by the contexts were identical to those conveyed by the generated touches from study 2: *Anger*, *Happiness*, *Calm* and *Neutral*. The scenarios were adapted from Banziger et al. [Bänziger and Scherer, 2010] and Dael et al. [Dael et al., 2012]. We considered 8 scenarios: two different textual scenarios illustrate each of these emotions.

We also selected one facial expression for each of these emotions [Niewiadomski et al., 2013], which is displayed on a female 3D character (Figure 5.8). We validated the facial expressions through a survey with 16 participants.

(a) (b) (c) (d)

Figure 5.8: Facial expression of the visual agent. a) Neutral, b) Calm, c)Happy, d)Angry

We presented static images of facial expressions and for each of them asked two questions on a 7-point Likert scale to assess Arousal/Valence perception: *Is the emotion conveyed by this avatar pleasant? (1 - Not pleasant at all, 7 - Very pleasant)* and *Is the emotion conveyed by this avatar intense? (1 - Not intense at all, 7 - Very intense)*. This survey confirms that each facial expression lies within a different quadrant of the arousal/valence space and corresponds to the expected emotion. The *Angry* facial emotion lies in the top-left quadrant, the *Happy* in the top-right and *Calm* in the bottom-right.

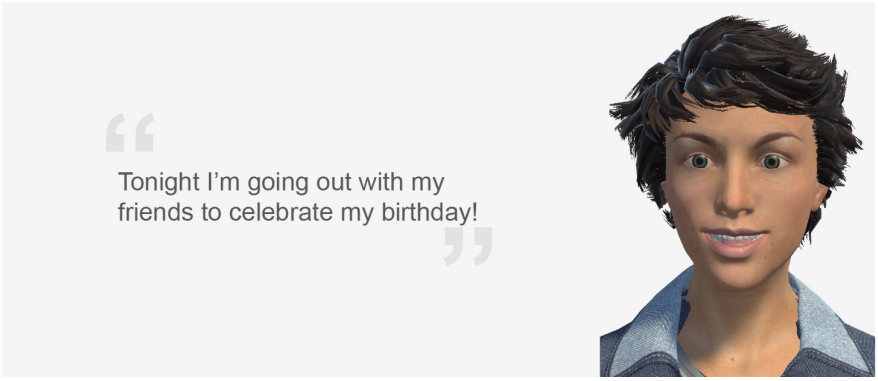


Figure 5.9: Context cues as presented to the user. Text scenario on the left side and facial expression on the right (here *Happy*)

5.5.1 *Experimental Design*

The device and experimental apparatus are similar to the one described in the previous studies, but the protocol differs slightly to introduce the context cues. First, the textual scenario is shown on the screen. Then, the tactile stimulus is presented at the same time as the facial expression of the virtual agent. The facial expression is static, it is an image, and its display lasts the time of the touch. In total, there are 16 conditions. Each combination of the four stimuli (generated touches), Touch Stimuli with

four context pairs (Congruent scenario + facial expression), Context are presented in Latin-square order to the participants. Finally, 16 right-handed volunteers (6 F), from the same European background participated in the study, with a mean age of 28 (σ=3.7). We told the participants that the touch was coming from the virtual agent present on the screen.

5.5.2 *Results*

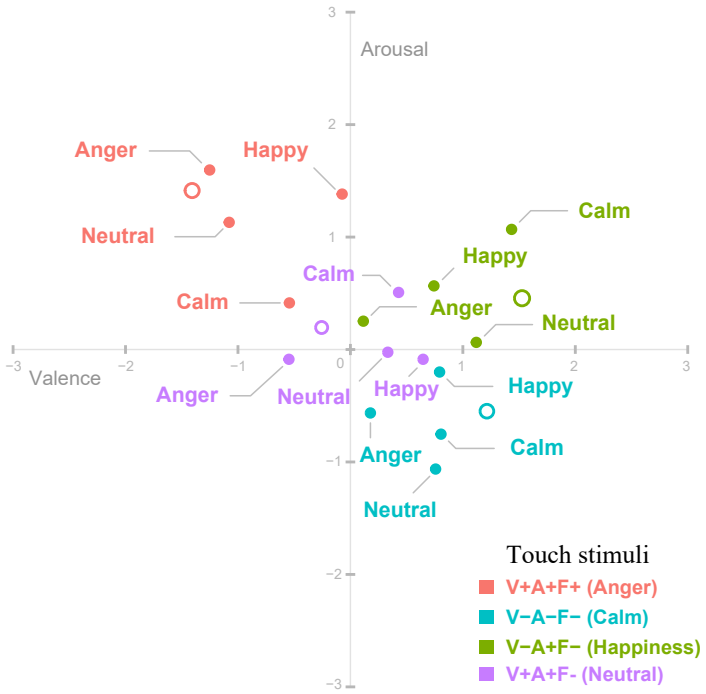


Figure 5.10: Results of arousal/valence distribution for the study with context Step 3, showing the effect of context cues on generated touch stimuli. The context cues are labeled on each point, the color corresponds to a touch stimulus. Larger circles are the stimuli from the context-free study.

Figure 5.10 illustrates the position of the perception of the stimuli on the circumplex. Labels on the point indicate the Context (scenario and facial expression) while the colors are associated to Touch Stimuli.

Arousal/Valence Ratings

The confidence interval of standard deviations per stimulus on the arousal ($ci = 0.21$) and on the valence ($ci = 0.16$) are relatively low. To determine effects on individual measures, we analyze the results with the same methodology as in Step 2.

The MANOVA finds significant main effects on all the factors Context

($F(2,32) = 4.48$, p < 0.001; $Wilks'\Lambda = 0.90$, $\eta_p^2 = 0.53$) and TOUCH STIMULI ($F(2,32) = 17.1$, p < 0.001; $w'\Lambda = 0.67$, $\eta_p^2 = 0.18$). The MANOVA does not reveal significant interaction effect of the combination of TOUCH STIMULI x CONTEXT .

Valence: Individual ANOVAs find a significant main effect of CONTEXT on valence ($F(1,4) = 9.9, p < 0.001, \eta_p^2 = 0.09$), with the *Anger* context resulting in lower average valence (μ=-0.3, σ=1.2) and *Calm* and *Neutral* the highest valence (0.6, 1.3). TOUCH STIMULI also have an effect on valence ($F(1,4) = 11.7, p < 0.001, \eta_p^2 = 0.21$), with a higher valence for the touch stimulus *V-A+F-* (Happy) (0.9, 1.3) and a lowest one for touch stimulus *V+A+F+* (Anger) (-0.6, 1.2). No interaction was found.

Arousal: An interaction is found between CONTEXT and TOUCH STIMULI ($F(1,4) = 3.1, p < 0.001, \eta_p^2 = 0.06$). ANOVA does not reveal a significant effect of CONTEXT on arousal (μ=0.3, σ=1.6). TOUCH STIMULI has a significant effect on arousal ($F(1,4) = 8.1, p < 0.001, \eta_p^2 = 0.17$), with the*V+A+F+* (Anger) touch stimulus having the highest arousal (1.1, 1.4) and the *V-A-F-* (Calm) stimulus the lowest (-0.6, 1.4).

Individual Differences

Similarly to our previous studies, the individual differences such as Gender or the participant's response on whether they like to be touched during social communication (μ=3.5, σ=1.2) do not impact the arousal/valence ratings. Participants find the task of detecting emotions equally difficult (μ= 5.1, σ=1.5) as in the previous studies. We find individual differences, when rating the touch stimuli, with some participants perceiving touch as more pleasant or more intense.

Position on the Circumplex Model

We can notice that the positions for each generated touch are consistent with the results obtained in Step 2. They remain in the same quadrant as when perceived in a context-free setting. Stimuli with *V-A+F-* touch sit within the 'high arousal, high valence' quadrant (top-right). Stimuli with *V+A+F+* touch sit within the 'high arousal, low valence' quadrant (top-left). Stimuli with *V-A-F-* touch are in the 'low arousal, high valence' quadrant. The stimuli with *V+A+F-* touch are located around the arousal

axis (arousal= 0) and within the -1/1 range of valence.

While the perceived emotions of a given generated touch remain in the same quadrant in the Arousal/Valence space regardless of the context cue, we observe nevertheless that the context cues modulate its perception. For instance, the *Calm* CONTEXT lowers the perception of the generated touch corresponding to *Anger* (*V+A+F+*) along the arousal dimension, while increasing the perception along the valence dimension. This result is also present for the three other generated touches. The results in the top-right quadrant (high arousal/high valence) show some confusion in the perceived emotions when the context cues and touch stimuli don't match. When the TOUCH STIMULI *V-A+F+* is performed, the *Calm* context has a higher arousal/valence than the *Happy* context cue.

5.5.3 Discussion

Our results suggest that touch has a higher impact on emotion perception than context cues, but that context modulates touch perception. This finding is inline with the literature indicating that when conflicting cues (e.g "*Anger*" touch with *calm* context cue) are presented, participants do not seem to merge stimuli but rather consider them independently and select one cue as the dominant one [Stein and Meredith, 1993]. This choice depends on a variety of factors such as individual differences or the task being performed [Stein and Meredith, 1993].

Our results show that there is some confusion between high valence/high arousal touch and contextual cues, i.e between Calm and Happiness. This is in line with the literature. The perception of non-verbal positive emotional cues often shows a higher level of confusion than for negative emotions [Sauter et al., 2014]. Facial expressions of positive emotions often share the same signals (smile, raised eyebrows, crow's feet, etc.) and several studies suggest that smile dynamics might be more important to discern those expressions [Ochs et al., 2017].

Other studies that present tactile stimuli with facial expressions of an ECA suggest that participants seem to rely on the visual modality for the evaluation of the valence and on the kinesthetic modality for the arousal [Gaffary et al., 2015, Bickmore et al., 2010]. Our results do not reproduce this finding. This might be explained by the fact that our tactile stimuli are different than those used in these studies (moving the partici-

pant's arm in [Gaffary et al., 2015] or inflating an object in a participant's hand in [Bickmore et al., 2010]). The robotic arm we used in our study has a strong physical presence and the touches it generates are closer to human touch than in these studies as it combines amplitude, velocity, and contact force against the participant's arm.

5.6 Discussion

In order to build devices capable to convey emotional cues though touch, we discuss the results of our studies, distinguishing the results of the touch parameters in a context-free setting and with context cues.

5.6.1 Selecting relevant touch factors

Our experiment investigates device-to-human touch movements. It relies on the literature on human-to-human touch for the choice of the touch factors and their values. While our system has limited tactile capacities in comparison with a human hand, and that complementary work is needed to consider additional dimensions (culture, touch location), our results suggest that similar emotions that are usually conveyed through touch during human-to-human communication can be perceived with our device. Our results are similar to those found in human-to-human touch studies [Essick et al., 2010] and suggest that robotic devices are able to perform social touch. For instance, a real-life "*hit*" with strong force is perceived as Anger [Hertenstein et al., 2006a]. Similarly, in our experiment, touch with strong force is perceived as less pleasant and more intense than touch with light force. Moreover, participants indicate that the device is adapted to perform touch gestures.

5.6.2 A device for humanlike touch

One of our research questions is to select a device capable to perform affective social touch. Our results suggests that a device with an anthropomorphic end-effector and some carefully picked touch factors is capable to perform a touch that can convey emotions. Using a realistic rubber hand as end-effector might be crossing the Uncanny Valley, as discussed in the

Chapter 4. However, we argue that if a generated touch is performed in the *same way* a human would do a real touch, the physical perception would be the same, hence creating a seamless and transparent interaction. Our system was initially designed to explore the design space of social touch and to study how touch movements influence the perception of emotions. Our system reveals potential benefits, especially for Virtual Reality applications. Indeed, in such environment, the user does not see the device and might focus more on the perceived touch.

However using this device has some limitations. Increasing/decreasing the intensity of one factor might reinforce/attenuate the level of the corresponding emotion but this is not always feasible due to technical limitations of our device. For instance, it might be impossible to increase the amplitude of a touch movement due to the size of the forearm. Similarly, the maximum velocity corresponds to the limit of the robotic arm speed. In contrast, the range of the force value can be increased within the limit of not hurting users. Future work is necessary to conclude on the upper limit for each factor. Moreover, sharing the workspace of a large robotic device is subject to safety norms (ISO 15066) which cannot be ignored. Other spatial characteristics such as "*surface in contact*" should also be investigated. This factor could have an impact on the perception of valence as physical interactions, such as a hug, involve a long mutual contact. The *location* of a touch movement on the body can also influence the perceived emotion. Other types of gestures should also be considered, such as "*Grabbing*". Social communication also involves gestures such as tapping someone's back to convey affect without being too intimate. Finally, we plan to study how the temperature [Wilson et al., 2016] combined with our touch parameters can influence the perceived emotions.

Although the meaning of touch varies depending on the cultures [Suvilehto et al., 2015], the impact of culture for emotional touch perception is not clear. Some results suggest that emotions conveyed by touch might be similar between cultures [Hertenstein et al., 2006a, 2009], but others [Cranny-Francis, 2011, Silvera Tawil et al., 2012] suggest the opposite. Although we expected a negative perception due to a general negative attitude toward robots [Nomura et al., 2004], participants report that it is more acceptable to be touched by a robotic arm than by a human (μ= 5.81, σ= 1.06). For instance, one participant indicates: *"I know that such a device can't have mean intentions, hence I prefer to be touched by it rather than by a human"*. Our work has some implications in Human-Robot Interaction and might help

improve affective grounding between a robot and a human [Jung, 2017].

5.6.3 *Conveying emotions in a context-free setup*

A designer might ask which factors s/he should control to maximize the range of perceived emotions. The Force factor changes drastically the perception of the touch. A low Force conveys positive and calm emotions while a strong Force conveys energetic and negative emotions.

One result of our study is the lack of observed interaction effects between the different factors. When a designer aims to convey an emotion that has not be designed through device-initiated touch, a possibility is to apply a linear combination of touch factors of known emotions as it has been proposed for facial expression of emotions [Ochs et al., 2017]. Approaches developed for the creation of facial expressions [Albrecht et al., 2005, Tsapatsoulis et al., 2002] could be used when a designer needs to convey an emotion for which no touch factors have been defined yet. In such studies, facial expressions for expressing a given emotion are obtained through a linear combination of known facial expressions of the closest emotions. Similarly, the designer could combine the values of the touch factors corresponding to the closest emotions to convey a given emotion. Perceptual tests will then be needed to validate this combination.

Moreover, we can observe variability between the participants on their perception of emotions from touch stimuli. Some users only use a small region of the circumplex model while others use the whole area. While participants may not perceive the same arousal/valence for a given stimulus, they will perceive a similar change in emotion perception (e.g., a more aroused emotion) when one touch factor is modified (e.g., a stimulus with faster velocity). So the results across participants are better explained by looking at the differential in the perception of emotions. This is a common result for emotion perception from multimodal cues [Yannakakis and Martínez, 2015]. The variability between individuals has to be considered and could be resolved by performing an initial calibration phase, where users rate example stimuli.

5.6.4 *Using context cues as additional modality*

Our results suggest that the combination of touch stimuli and context opens up a wider range of emotions (Figure 5.10), but that context cues do not drastically change the emotional perception of the touch stimuli. During an interaction with ECAs in a game, the facial expression of the character can be used to overcome the physical limitations of the touching device. Depending on the user's body posture, some touch movements performed on the user could be inconvenient. To convey emotion such as tenseness (high arousal middle valence), it might be easier to perform a touch close to *Anger V+A+F+* and to modulate it with a positive facial expression rather than reducing the velocity *V-A+F+* (Figures 5.13). The designer can choose the best way to convey emotion by modulating the context while performing a coherent touch.

In our experiment, we used minimal context cues (textual scenario and facial expression) to elicit the context in which the touch is performed. However, during interaction, these contexts cues might not be sufficient to drastically change the perception of emotions. Users' perception of the context vary in regards of their current emotional state, their relationship with their interlocutor, or the global experience (is it a stressful environment, etc.) [Ekman et al., 2013]. These parameters have to be taken into consideration when designing touch interactions. Other elements can influence the perception context such as sound or color, which we did not explore in our experiments. Further research and exploration need to be conducted to see whether the results of Study 2 can be reproduced, for instance, in a stressful virtual environment.

5.7 *Use Cases and Scenarios*

The results of this chapter demonstrated that it is possible to convey some emotions through a device-initiated touch. Although empirical, these results can be applied directly in applications and scenarios. Video games [Baños et al., 2004], mediated communications [Hertenstein et al., 2006a, Van Erp and Toet, 2015], care-related (companionship, nursing) [Broekens et al., 2009] or social robotics [Cabibihan et al., 2009] often lack emotional communication through the touch channel and are thus good candidates to benefit from our findings. In this section, we propose examples of use

cases as illustration.

5.7.1 *Improving communication between people*

Human-to-human mediated communication interfaces would benefit exploiting the touch channel to communicate emotions as it can reinforce and maintain bonds between people, convey one's emotional state or comfort the other one, etc. [Van Erp and Toet, 2015] [Gallace and Spence, 2010, Field, 2010]. For instance, text-based communication systems (Figure 5.11) can send smileys accompanied with a touch stimuli to amplify the displayed emotion. Video communication which takes advantage of non-verbal cues such as facial expression could benefit from touch stimuli as additional social and affective cues.

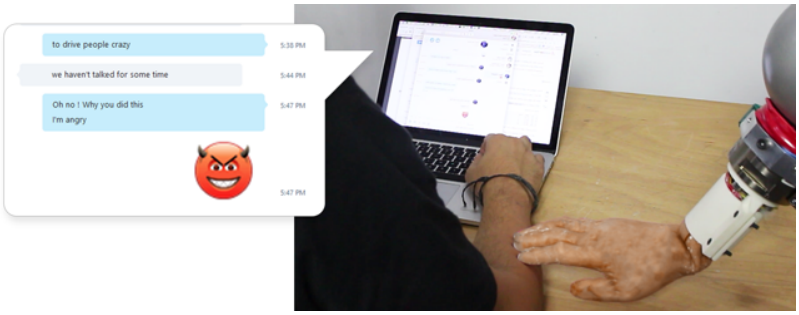


Figure 5.11: Touch movements for mediated communication, Augmenting emojis to amplify perceived emotions.

Haptic feedback also help increase immersion and presence in a co-located virtual environment [Sallnäs, 2010, Ahmed et al., 2016]. In particular, in a co-located virtual environment, a remote user can mimic a stroke on the arm during a collaborative task. The gesture is captured by the system and reproduced on the local user's arm with the robotic arm (Figure 5.13) to increase immersion and presence.

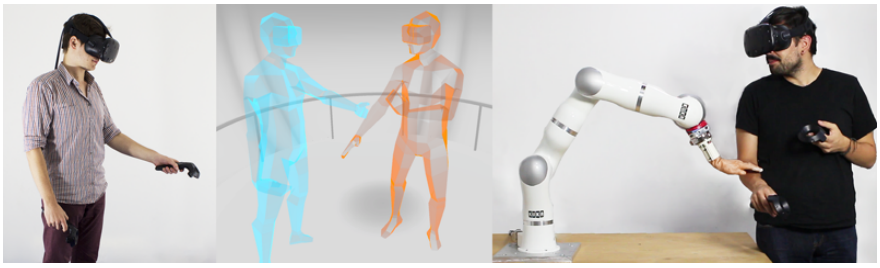


Figure 5.12: Using device-initiated touch in a remote virtual reality communication system to increase virtual presence.

5.7.2 *Increase realism of Robot-Human Interaction*

Figure 5.13: Combination of a VR visual (left) and Haptic (right) feedback to increase the communicative capabilities of a virtual agent.

In addition to communicating emotions through facial and body expression [Niewiadomski et al., 2013], we propose to endow virtual expressive characters such as Embodied Conversational Agents (ECAs) with touch capabilities to augment their *non-verbal cues* (Figure 5.13). Our findings about combination of touch factors and facial expressions give some insights on how to choose the proper combination of touch stimuli and facial expressions. The same approach can be transposed to *physical* social robots to increase their expressiveness [Shibata and Tanie, 2001]. While they usually convey positive emotions [Hanson et al., 2005] through touch, our findings seem to indicate that robots encompassing a variety of touches could express a large panel of social and emotional cues.

5.7.3 *Implementation*

Among these envisioned scenarios, we implemented two proofs-of-concept: the communication system augmented with touch movements (Figure 5.11) and the scenario of a virtual agent communicating emotions through facial and body expressions as well as touch movements (Figure 5.13). We used the same setup as our experiment. The virtual scene of the second prototype was implemented in Unity with HTC Vive, using the Morph3D Character suite to animate the virtual agent. The movements of the agent's hand are reproduced in real time by the robotic arm. The arm of the user was tracked both with a Kinect depth sensor and the Vive controllers. These proofs-of-concept demonstrate the feasibility of our envisionned scenarios.

5.8 Conclusion

In this chapter I presented different studies and a system that explore the generation of artificial touch with humanlike characteristics. The main contribution of this chapter is the choice of relevant touch characteristics and their evaluation and characterization for conveying emotions. The combination of the relevant touch factors and system developed for their study respond to the PROBLEM 1.1 of this thesis, of how complex and rich touch gestures can be reproduced through interactive systems and devices. Our results suggest that fast and ample stimuli are perceived as more pleasant than short and slow stimuli. While the Velocity factor is positively correlated with the perception of arousal, the force factor is negatively correlated with valence. More generally, this chapter demonstrates that it is possible to reproduce a variety of gestures with a device that performs different touch contacts with the user body.

The analysis of the emotional perception while being touched as well as the addition of the visual modality with the touch stimuli, respond to the PROBLEM 1.2 of this thesis *Is it possible to perform a humanlike device-initiated touch that conveys emotions?* Although not all emotions can be conveyed through touch, pro-social emotions with high arousal seems the best suited for touch communication.

Overall, these results raise opportunities to improve various robot-human interactions and suggest that using non-verbal emotional cues through touch might help improve affective grounding between a robot and a human [Jung, 2017]. The system we used in this chapter is quite big, but we believe the results presented here can be transposed to other devices capable of performing a touch contact against the user. Our envisioned scenarios reveal potential benefits, especially for Virtual Reality applications. Indeed, in such environments, the user does not see the device and might focus more on the perceived touch.

The main limitation of using such a device is its size and the fact that it requires a dedicated setup to convey touch. Although great in a lab setup, this device is not adapted to a mobility context. A next step will be to design small-scale interfaces with the same capabilities of touching the user but more adapted for a nomadic use (PROBLEM 1.3 of this thesis). We will further investigate this aspect in the following chapter of this thesis

WHAT YOU MUST REMEMBER

Contributions:

- Definition of a set of touch factors (*Velocity*, *Amplitude*, *Speed* and *Type* (or repetition)) compatible with a device that applies touch on users.
- Evaluation of device-initiated touch on the arousal valence emotional perception.
- Evaluation of the impact of context on perception of emotions through touch

6

MobiLimb: Augmenting Mobile Devices with a Robotic Limb

Figure 6.1: MobiLimb is a robotic interface is connected to a smartphone, and can provide haptic feedback to the user.

In the previous chapter, we[1] showed that a large-scale robotic device can initiate touch and convey emotions through touch. While working with large-scale robotic device in an experimental setup in a research laboratory is appropriate to conduct research, such a system is not suitable for a

[1] Main portions of this chapter were previously published in [Teyssier et al., 2018b]. Thus, any use of "we" in this chapter refers to the author of this work: Marc Teyssier, Gilles Bailly, Catherine Pelachaud, and Eric Lecolinet.

mobility context.

In Chapter 3, we presented different technologies that can perform touch on the user. They usually consisted in new devices, that the user has to wear or use in addition of his usual devices. Smartphones are widely used for remote and social communication. Although the smartphone is a perfect tool for conveying voice, pictures and text, its capabilities regarding touch are quite limited. Thus, our research question is how to make small-sized devices, like smartphones, able to convey emotional touch. Hence, we designed MobiLimb, a small 5-DOF serial robotic manipulator that is fixed to a mobile device. In line with human augmentation, which aims at overcoming human body limitations by using robotic devices [Rocon et al., 2005], our approach aims at overcoming mobile device limitations (static, passive, motionless) by using a robotic limb capable to touch.

One inspiration to further explore this direction comes from Ivan Sutherland's [Sutherland, 1965] and Ishii's visions [Ishii et al., 2012] about Shape-changing interfaces. By using the haptic and kinesthetic senses, shape-changing interfaces can provide adaptive affordances, favor communication or increase user's enjoyment [Alexander et al., 2018] and leverage our abilities to better interact with interactive systems. Shape-changing and actuated mechanisms have been shown especially relevant for mobile devices to improve interaction or interpersonal communication [Ohkubo et al., 2016, Park et al., 2014, 2015].

In this chapter, we explore the design space of MobiLimb (Figure 6.1). We first present its hardware implementation and illustrate how it could be used. We then present our implementation and discuss the main human factors we considered for building this device. Finally, we illustrate the potential of MobiLimb through three classes of applications. We first present scenarios that would benefit from the haptic capabilities of the device and show how it could be used to enhance interaction.

6.1 *Objectives and Approach*

In this chapter, we continue to explore the PROBLEM 1 of this thesis: *Can actuated devices produce humanlike touch?*, and more particularly PROBLEM 1.3: *how can we design a portable device or artefact that can touch the user?* The main objective of this chapter is to develop a small-scale device able

to provide kinesthetic feedback from a mobile device. The design and development of MobiLimb was driven by our findings from Chapter 5. We also drew inspiration from other studies in the HCI literature.

The popularity of mobile devices has encouraged researchers to explore various ways of augmenting their output and input capabilities. For output, several approaches have been proposed, including using advanced vibration motors to convey emotions [Yoo et al., 2015], additional screens to wider the output space [Hinckley et al., 2009] or shape-changing interfaces [Jang et al., 2016]. A notable advantage of some of these approaches is that they augment the back of the phone and not obstruct the screen, which preserves the efficiency of the I/O capabilities of the original device.

Some robotic systems developed for social interaction [Adalgeirsson and Breazeal, 2010] take advantage of the versatility, availability and low cost of smartphones. To design a small-sized anthropomorphic interface, we turned our attention to the research areas of *Supernumerary Robots* (e.g. sixth finger), which aims at augmenting the human hand with additional fingers or limbs [Hussain et al., 2016, Wu and Asada, 2014, 2015, Hu et al., 2017]. These devices are used as tools [Leigh et al., 2018] to help users to perform tasks using a PC or a smartphone but require to be placed on the human body. Lines interfaces [Nakagaki et al., 2015, 2016] and other actuated systems [Le et al., 2016, Bailly et al., 2016, Linder and Maes, 2010] have explored tangible visualizations and interactions, but their current implementation does not make them usable for mobile devices and for handling expressive behaviors. Moreover none of these projects have been applied to mediated communication. More generally in HCI research, shape changing interfaces have been used to design interfaces with a variable form factor and size [Sutherland, 1965, Alexander et al., 2018]. Some shape-changing mobiles are designed to maintain the form factor of the smartphone [Park et al., 2014, Ohkubo et al., 2016, Jang et al., 2016]. With this approach, shape-changing phones can be used to explore organic interfaces, by providing subtle life-like notifications [Hemmert, 2009], foster engagement through proxemic behavior [Jabarin et al., 2003, Hemmert et al., 2013] or convey emotions [Pedersen et al., 2014, Strohmeier et al., 2016a, Park et al., 2015].

The design and development of such a device implies several objectives and challenges. In the previous chapter, we used a hand as end-effector of the robotic device. Using a hand is not possible for a mobile device as it is

bigger than the mobile device itself. Thus, reducing the size means using a smaller-sized anthropomorphic interface; for this purpose, we chose to explore a finger-shaped robotic actuator. The first challenge is technical as we need to create a finger-like anthropomorphic interface that is actuated, reactive and that can be connected onto a mobile device. This interface should be able to perform movement on the wrist of the user. To explore this challenge, we rely on DIY and easy Fabrication tools and methods.

A secondary objective is *How the prototype can be used in other contexts, for other use cases?* Although mediated communication was the main motivation for the design of this device, its capabilities are not necessarily limited to this context. This objective can be explored through a design space as well as the design of new application scenarios. This raises a final research question, which is the relevance and the perceived usefulness of such a device.

This chapter is structured as follows. We first present our prototype MobiLimb and its design space. We continue by detailing the technical implementation and its fabrication method. Finally, we present and discuss applications scenarios and their evaluation.

6.2 *MobiLimb*

(a) (b) (c)

Figure 6.2: MobiLimb is attached to a mobile device to extend its I/O capabilities while keeping a small form factor when folded. MobiLimb can be used, for instance, a) as a medium to perform rich haptic feedback, b) as a partner to foster curiosity and engagement, c) as a tool to display notifications

MobiLimb is a new shape-changing component with a compact form factor that can be deployed on mobile devices. This finger-like 5 DoF serial robotic manipulator can be easily added to (or removed from) existing mobile devices (smartphone, tablet). Following human augmentation direction, our approach aims at overcoming mobile device limitations

(static, passive, motionless) by using a robotic limb.

MobiLimb proposes a new way of implementing actuated interfaces that lower technical difficulties while enabling a rich set of interactions and preserving the form factor of mobile devices. It augments the efficiency of their I/O capabilities and also induced new ones. The users can see and feel the robotic device (visual and haptic feedback), including when its shape is dynamically modified. Moreover, as a robotic manipulator, the users can manipulate and deform MobiLimb to perform input. Finally, it can support additional modular elements (LED, shells, proximity sensors). MobiLimb offers tangible affordances and an expressive controller that can be manipulated to control virtual and physical objects. We not only focus on the touch and mediated communication possibilities and illustrate how MobiLimb leverages three primary interaction paradigms [Beaudouin-Lafon, 2004]:

- As a *medium*, MobiLimb can enrich voice, video or text communication between users with haptic feedback. It is capable of emitting strokes, pat and other tactile stimuli on the back of the hand or the inner wrist of the user to convey feelings or emotions (Figure 6.2 - a).
- As a *partner*, it can have various looks and feels to embody different characters, by covering the appendix with different textures. Through its motions MobiLimb can physically and haptically express behaviours and emotions "out of the screen", thus conveying curiosity and engagement. It can react to user's actions and assist novice users or users with special needs(Figure 6.2 - b).
- As a *tool*, MobiLimb offers an expressive mean of manipulating objects, interacting with the physical environment, delivering notifications or providing guidance (Figure 6.2 - c).

6.3 *Implementation*

MobiLimb is a robotic manipulator with a kinematics structure of five revolute joints in serial. In this section, we describe the four main parts of the system: the actuators, the sensors, the embedded electronics and the controller.

Actuators. Various technologies are available for providing continuous

actuation, such as using wires as tendons [Wu and Asada, 2014] or pneumatic actuation [Deimel and Brock, 2013]. However, such technologies are not compatible with the compact form factor of a smartphone. Other solutions such as shape memory alloys (SMA) or piezo components bring additional complexity in control and kinematics. We thus use servo motors because they allow reaching a specific position quickly and do not require continuous power to maintain their position. We used five PZ-15320 servo motors ($3) capable of rotating 170° at a max speed of 0.06s/60° at 4.7v. They provide a torque of 85g/cm at 4.7v, which is sufficient to support the weight of a smartphone (130g) and can apply a contact force of about 0.8N. Their arrangement, illustrated in Figure 6.3, provides five degrees of freedom (DOF). Two motors, mounted on two orthogonal axes on the base, carry the first link. Every other link has its own revolute joint parallel to each other (Figure 6.3, right side). A 3D printed plastic structure holds together the servo motors without constraining motion at the different joints. It is thin enough to be covered with different outer shells.

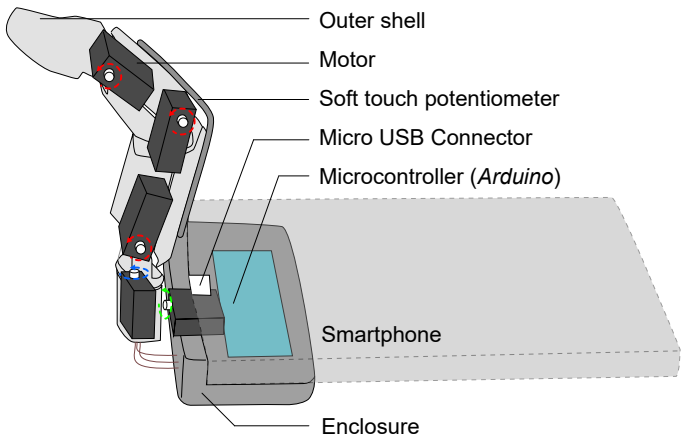


Figure 6.3: Hardware implementation of MobiLimb . The device is composed of 5 chained servo motors connected to an Arduino Leonardo pro.

Sensors. Servo motors provide their own angular position as feedback. This allows calculating the shape of the device. A flexible potentiometer (under the shell on the back of the device) detects when and where the user is touching MobiLimb.

Controller and smartphone integration. MobiLimb can be easily connected to a smartphone, with a plug and play mechanism. The motors and an Arduino Leonardo Pro Micro microcontroller are packed within a thin 3D-printed base ($34mm \times 65mm \times 8mm$) attached at the bottom and on the back of the phone, or at the back of the tablet (Figure 6.16). An integrated female pin header allows connecting/disconnecting the servo-motors and

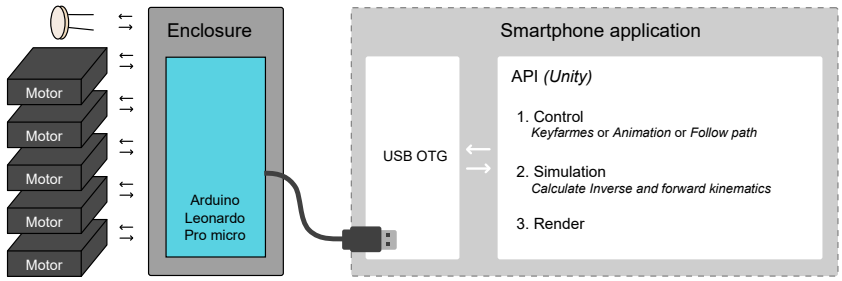


Figure 6.4: Control system of MobiLimb. The motors are connected to an Arduino Leonardo. The smartphone integration uses USB OTG to communicate with the Arduino and the Unity API propose several ways of controlling the device.

additional input and output components from the tip. The micro USB connector serves for the serial communication (60Hz) between the mobile device and the microcontroller. MobiLimb takes its power from this micro USB connector and thus does not require additional batteries (the sleep mode only consumes 20mA, 150 mA when moving). The compact size of MobiLimb allows to comfortably grasp the phone.

Motor control. We developed an Android/Unity API providing three main control methods to drive MobiLimb, enabling both rapid prototyping of applications and precise control. Because it provides a lot of freedom, *Forward-kinematics*, which allows controlling each motor individually, is better suited to control animations. To compose a fluid animation, it is possible to use a timeline with keyframes, to set step by step the desired joint angles (Figure 6.3). Another control method is to record and play animations by manipulating the physical robotic limb using motor sensing. When the designer orients the finger, the angles are displayed on the screen (Figure 6.3) . He can then record the movement and save it as an animated sequence. In contrast, *Inverse-kinematics* determines the joint angles from the desired position of the end-effector of the device and controls each motor accordingly (Figure 6.3). This solution is preferred to control actions where the tip of the appendix has to follow a precise path, for instance to draw a shape or touch the user.

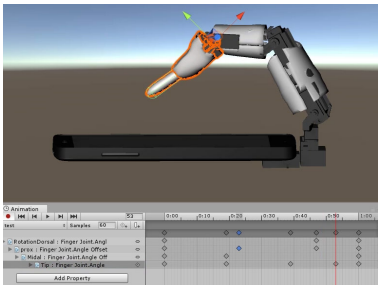


Figure 6.5: Control using keyframes

Figure 6.6: Control using direct manipulation

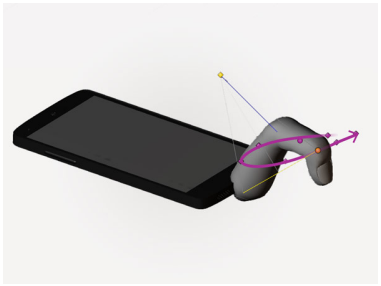


Figure 6.7: Control using Inverse-kinematics to follow a target

6.4 *Design Space*

In this section, we describe the design space and interaction potential of MobiLimb. With the ability to physically extend the capabilities of the device: input, output and interactions, that can be performed on the user

or the environment. can be connected to any device.

6.4.1 Output

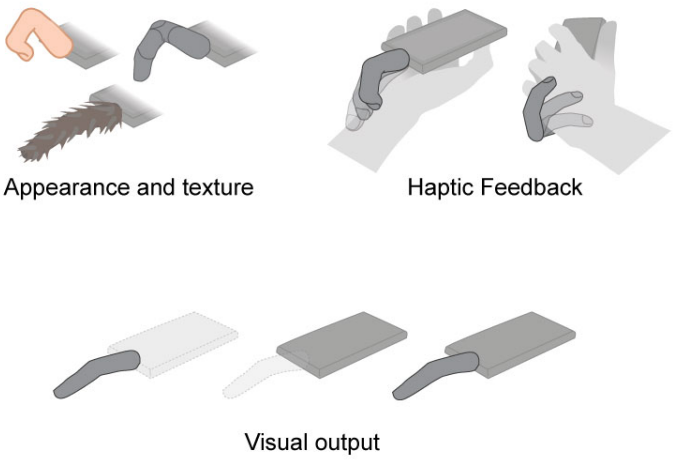


Figure 6.8: Design Space of Mobilimb for Output. Mobilimb provide haptic feedback and different visual output(change appearance and texture).

Visual output. MobiLimb can display visual information by modifying the shape and the motion of the robotic manipulator. For instance, it can be used as an *alternative* of the screen to display static information such as the current state of the phone (e.g. flight mode, battery level, etc.) or to indicate a direction or an object in a 3D space (Figure 6.17-e). MobiLimb can also provide dynamic notifications by moving or shaking the robotic device, for instance when incoming mail is received (Figure 6.17-a). Such notifications are well suited for attracting users' attention when other modalities are not appropriate: audio is not always suitable in public space and vibrations requires the user to carry on the device. In addition, MobiLimb can also serve to extend the screen by displaying additional information physically "out of it" (Figure 6.15-a).

Haptics. Haptic feedback is most often limited to vibrations on commercial mobile devices [Yoo et al., 2015]. In contrast MobiLimb provides active kinesthetic feedback through dynamic motion of the device at the surface of the user's skin. It can generate taps or strokes with various spatial and temporal patterns [Hertenstein et al., 2006a] or perform a physical contact on the inner wrist (Figure 6.14-c) or on the back on the hand (Figure 6.14-a,b). Both the wrist and the hand are "social organs" [Hertenstein et al., 2006a], which make them appropriate for communicating feelings and emotions. Moreover, the back of the hand provides a large and sensitive

surface that can receive other types of information such as notifications.

Appearance and texture. MobiLimb can be covered with various membranes to modify its appearance and its degree of anthropomorphism or zoomorphism, which may engage interaction [Duffy, 2003]. The texture and material covering the device can also enrich the type of tactile and visual feedback [Araujo et al., 2016]. For instance smooth fur (Figure 6.15-a) or humanlike skin (Figure 6.14-b) can be used. Depending on the use case, the modular tip of the device can be changed to convey specific meanings (for instance a stinger in Figure 6.15-b).

6.4.2 *Input*

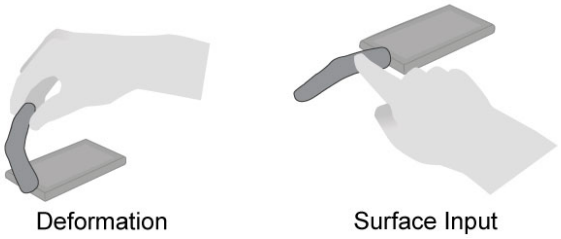


Figure 6.9: Design Space of Mobilimb for Input. Mobilimb can detect the manual deformation of the joints as well as the surface touch input.

MobiLimb adds two input capabilities – physical deformation and touch detection – for controlling the mobile device (or connected devices such as remote displays), to augment expressivity or avoid occluding the touchscreen. For this purpose, users can *manipulate* the shape of the limb by changing the orientation of its joints. Users can use it as joystick to manipulate 3D articulated objects (Figure 6.17-b). MobiLimb also detects when the users are *touching* or patting it and be used for instance as a tangible slider.

6.4.3 *Interaction*

By combining I/O capabilities, MobiLimb provides a rich interaction space (Figure 6.10).

Controls. Beyond (1) manual (user) and (2) automatic (system) control, MobiLimb can offer two intermediate modes of control: (3) Semi-manual control occurs when the user is manipulating MobiLimb and the system reacts to this action, for instance by applying a resistance; (4) semi-autonomous control occurs when the system actuates MobiLimb to guide

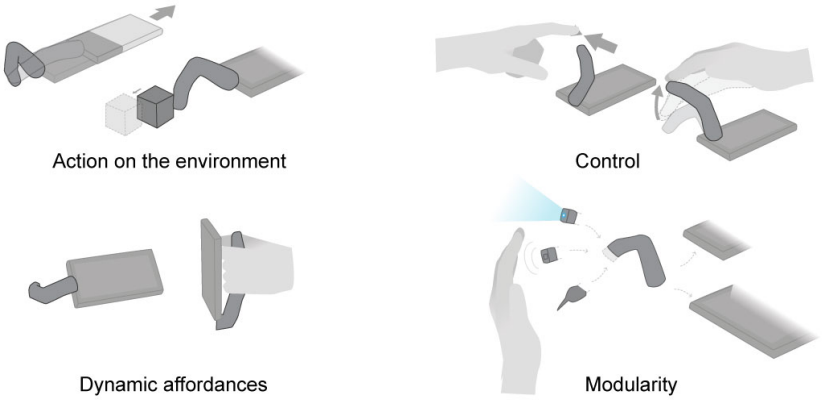


Figure 6.10: Design Space of MobiLimb for interactivity. Mobilimb is capable to perform action on the environment, provide dynamic affordances, and degrees of controls, and is modular.

the user's movements [Seifert et al., 2014].

Dynamic affordance. Dynamic affordances benefit interactions as they can inform how the device can be manipulated. They can then provide new controls over the device and its parts [Jang et al., 2016, Follmer et al., 2013b, Roudaut et al., 2016, 2013, Park et al., 2015]. MobiLimb can model its shape (Figure 6.17-d) to communicate how to grasp the device by dynamically changing the physical aspect of the device. It can also change the orientation of the mobile device so that users can better see its screen (Figure 6.17-c).

Action on the environment. While mobile devices are currently only able to vibrate, MobiLimb can physically interact with its environment. It can push or grab objects in its surrounding. It can also make the smartphone moves in its environment, by making it crawl like a caterpillar (Figure 6.17-f).

Figure 6.11: MobiLimb is plug and play and can easily be connected to most of existing device.

Modularity. In contrast to pure design explorations such as those conducted by Pedersen et al. [Pedersen et al., 2014], MobiLimb requires no modification to current mobile devices, it does not alter its I/O capabilities (Figure 6.11) or its form factor. MobiLimb can simply be added to most of existing smartphone and tablets (with a micro USB).

The input capabilities of MobiLimb can also be used in combination with those of the mobile device. For instance, users can manipulate the robotic limb with one hand while interacting on the screen with the other hand (Figure 6.17-b).

Additional components, such as sensors or actuators, can easily be fixed onto the "tip" of the device [Leigh et al., 2018]. These components are automatically recognized by the system. For instance, LEDs (output)

or proximity sensors (input) can be added to MobiLimb to extend its interaction space (Figure 6.12). The user can also attach physical objects to the device, as for instance a pen (Figure 6.14).

Figure 6.12: MobiLimb supports several modular tips (e.g. LED,shells, proximity sensors) to create new forms of interaction.

6.4.4 *Human factors*

MobiLimb raises several *technical* challenges related to robotic technologies such as miniaturization, speed, precision, robustness, torque, autonomy or cost, which can alter its utility and its usability. In this section, we describe the main *human* factors we considered and how they informed the design of MobiLimb. These factors concern aesthetic, acceptance and the degrees of freedom.

Aestheticism and acceptance. MobiLimb is thin (diameter 1.5*cm*, length 8*cm*) and small enough to be well integrated with a mobile device. In particular, when it is inactive, the appendix rests along the side of the device to use less space, e.g. for inserting the phone in a pocket or a bag.

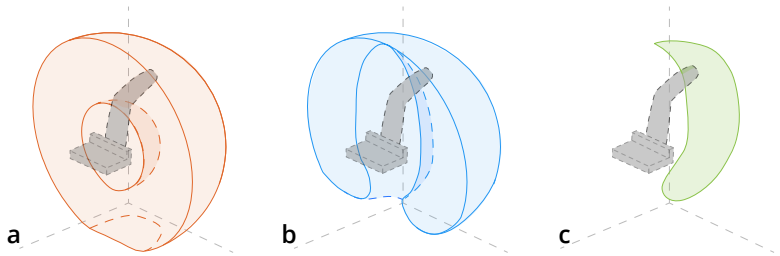


Figure 6.13: Reachable volume of the prototype from the bottom of the device; a) 5-DOF, b) 4-DOF, c) 3-DOF.

Degrees of Freedom (DOF). We used five servo-motors as a compromise between the number of DOF and the form factor (length, weight) of the device. A key design factor is the wide volume the robot can cover, so that (1) the system can reach the back and wrist of user's hand and (2) still have rotation freedom. Figure 6.13 shows the volume covered by MobiLimb when using 5, 4 or 3 degrees of freedom. This diagram was obtained by doing a forward kinematic simulation (15000 simulations) of the 3D model, avoiding self-collision. After several trial and error searches, the 5 DOF kinematic structure was sufficient to obtain a large variety of motions and interactions while maintaining a small footprint.

Quality of actuation. To maintain a high level of interactivity, the device should quickly react to the system instructions. It should also provide enough strength and torque to maintain a static position and hold the

weight of the smart phone. The motions of MobiLimb should also be fast (no latency) and precise enough to target a specific position, for instance on users' skin. The finger tip should cover a large volume.

Deployment. The autonomy, weight, cost and robustness of the powered skeleton should accommodate widespread adoption.

6.5 *Applications and scenarios*

In this section, we present several applications that showcase various aspects of MobiLimb. We foresee several ways of using this new device: as a tool, as a partner and as a medium [Beaudouin-Lafon, 2004]. Applications explore actuation, sensing and explore several degrees of anthropomorphism, from object to incarnated interface.

6.5.1 *MobiLimb as a Medium*

We designed an application using MobiLimb to transmit haptic touch for mediated communication. When chatting with another user, one can send a *tactile emoji* that will be felt directly by the other user, on the back of her/his hand while holding the phone (Figure 6.14-a-b) or on her/his wrist (Figure 6.14-c). This tactile communication can be used to express emotions such as comfort (through *stroke*), excitement (*gentle tap*) or anger (*repeated strong taps*) [Hertenstein et al., 2009, Huisman et al., 2013b]. Texture can also affect the perception of touch. Being touched by a cold vs warm, a soft vs rough object will have an impact on the perception of the touch quality [Hertenstein et al., 2009]. With MobiLimb it is possible to cover it with different materials. The choice of material (e.g a soft and fluffy cover) can impact emotional perception and reinforce the emotional link [Etzi et al., 2014] during mediated communication.

Other applications for mediated communication have been implemented. For example, when MobiLimb can be extended with a pen, it can draw tan emoticon that was just received or any other messages. This capacity expands communication beyond the screen (Figure 6.14-d).

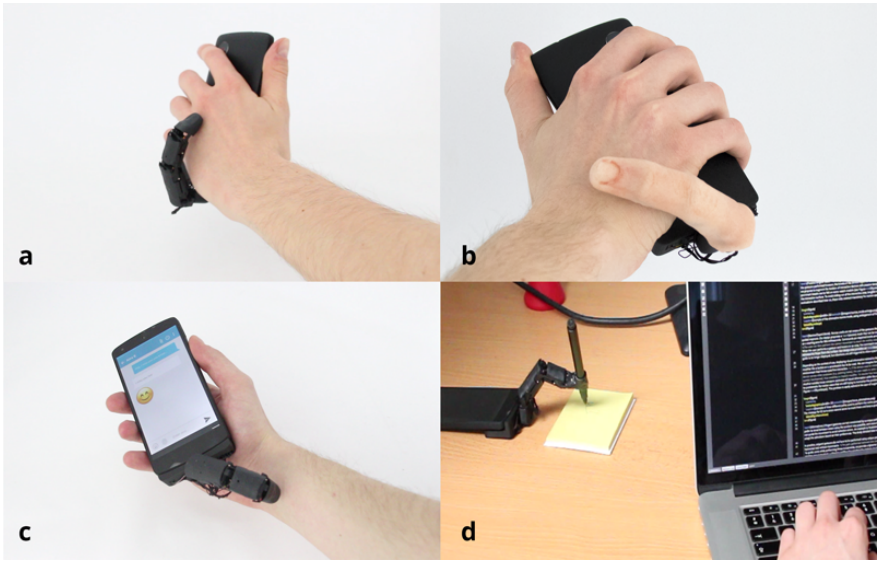


Figure 6.14: MobiLimb Can serve as haptic interface and touch the user on a) the hand or c) the wrist. b) A human-like skin texture can cover the device. d) Physical text messages can be sent between users.

6.5.2 *MobiLimb as a Virtual Partner*

Virtual characters can take the appearance of a humanlike figure or an animal; they can be realistic or cartoonish. Among various things, they can be avatars of remote users, emoticons augmenting a SMS, animals in a virtual farm game. They can be controlled by a user, or be autonomous. In the latter case, they are often referred to as Embodied Conversational Agents (ECAs). Such characters can be very expressive socio-emotional interaction partners [Zhao et al., 2014, Rizzo et al., 2016, Ring et al., 2016]. They can display empathy, affect or show their willingness to interact with a smile, a head movement, a gesture, etc. Such characters usually communicate using verbal and nonverbal behaviors, but lately, some tentative have been made to endow them with haptic capabilities [Huisman et al., 2014b].

Virtual characters can (1) display expressive behaviors (2) react to the user's actions and (3) assist users in their tasks. As talking agents on handheld devices are more and more presents (Siri,..), we see an opportunity in the physical embodiment of virtual characters. Through its physical embodiment MobiLimb can act upon these three aspects that we detail now.

Expressive behaviors. Emotional display with physical and tangible motion can enhance interaction [Hoffman and Ju, 2014]. Emotions are not only communicated through facial expressions and voice but also through

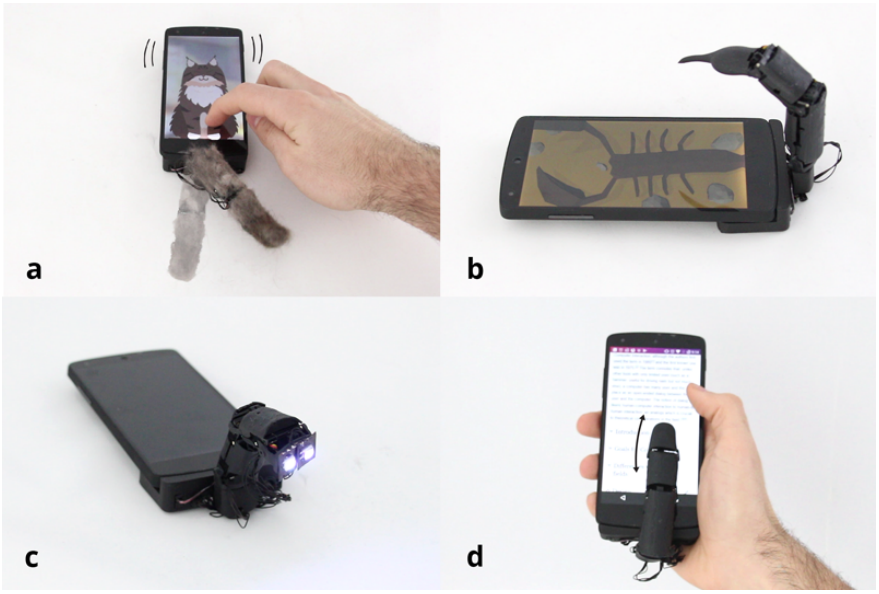


Figure 6.15: As a *partner* MobiLimb can express behaviors and embody virtual agents. a) Cat with a tail, which reacts to users' actions. b) Hostile scorpions. c) Curious device. d) Assistive guide showing how to scroll on a page.

body movements and tactile signals [Dael et al., 2012, Gaus et al., 2015]. MobiLimb can be used as a 3D movable and haptic extension of virtual characters. For instance, it can mimic the physical tail of a virtual cat companion (Figure 6.15-a) or a scorpion companion (Figure 6.15-b). By moving around with different expressive qualities it can communicate different emotional states [Hemmert et al., 2013]. For example, through gentle movements, it can communicate a tender stroke, while rapid and more forceful movements correspond to negative emotional states.

These expressive signals may be linked to different meanings and functions. Rather than signaling an emotion, they can have the value of an emotional emblem that corresponds to a given state. For example, MobiLimb can express life cycle and battery state [Hemmert et al., 2013]; the more the device looks down and depressed the less battery it has. When an important message has been received but is not yet read, it can start taping and shaking around to express the need of attention.

Expressive reaction. Virtual characters interact with users by interpreting their actions. During an interaction, both partners are continuously active; when one has the speaking turn, the other one provides feedback, for example by responding to the other's smile. To be a full-interaction partner, the virtual characters can act in response to user's touch using the physical extension of their virtual body. For example, if a user pets the cat character, it can show its contentment and react by moving its physical tail and by

purring using built-in phone's vibration motor. A variety of scenarios and contexts can be divided in two types of *physical display*: the *autonomous movements*, and the *semi-autonomous movements*. We consider an *autonomous movement* when it is started by the device itself and express some internal state or need. For example, when the device wants to convey boredom, it can start moving, taping and shaking around to express its need of attention. *Semi-autonomous* actions can be started with user input but the device respond. A virtual cat can have its tail prolonged in the real world, to physically embody the virtual character. When we pet its tail,to demonstrate contentment, the cat on the screen can purr which can be represented by different tail movements and phone vibrations.

Eyes Light: Inspired by Pixar's famous lamp character [Linder and Maes, 2010], MobiLimb can act as a robotic lamp if a light is added at the tip of the appendix (Figure 6.5-e). Its color and intensity can be controlled manually or by the system depending on, for instance, the ambient luminosity. This feature can be used to spot a given target in the environment regardless of the orientation of the mobile device, and look at elements in the physical space.

Assistive guide. Some users (e.g. a novice or someone with special needs) may require help to interact with the mobile device and its applications. MobiLimb can be used as a didactic device, pointing to the place the user should look at on the screen or touch to select an item. MobiLimb relates to actions performed on the screen rather than without modifying the screen content. It can also initialize a scrolling movement to help users understand the action they should undertake (Figure 6.15-d). As a physical tutor, assistance could be triggered by a vocal command asking to show a function of an application. Thus, assistive technologies and interactive tutorials can take advantage of this capability to indicate a useful location to the user and thus help in learning how to use an application.

6.5.3 MobiLimb as a Tool

These applications extend the I/O capabilities of a regular mobile device; some are inspired by the literature on shape-changing interfaces and applied robotics. They afford new input controls or display additional information visually or haptically. Using MobiLimb as tools benefits expressiveness while interacting with the device and provides new range of

Figure 6.16: Mobilimb connected to a tablet

possible feedbacks.

3D interaction. Users can manipulate the articulation hinges of MobiLimb to control the 3D joints of a virtual character skeleton to create 3D animation (Figure 6.17-b) [Jacobson et al., 2014]. Tangible input allows more expressiveness and gives more freedom than traditional pointing. Users can select the desired bone on the multitouch screen and deform it with the 5-DOF controller. The mechanical constraints of the controller make it adequate to manipulate articulated figures such as humans and animals body limbs in an intuitive manner.

Viewer. MobiLimb can serve as an adaptive stand when the user is watching a video or a slideshow. The system can track the head of the user (with the front webcam) to maintain the phone in an ergonomic landscape mode (Figure 6.17-c).

Figure 6.17: MobiLimb as a tool: a) Notifications display, b) 3D joint manipulation, c) Video preview, d) Improve grasping, e) Directional light, f) Self-actuated movement

Holder. Shape changes can be used to create new affordances and improve ergonomics [Follmer et al., 2013b]. Pre-defined positions can be reached: MobiLimb can for instance facilitate grasping the phone by taking the shape of a handle (Figure 6.17 -d).

Off-screen notifications. MobiLimb can produce physical notifications that can leverage different modalities. When the device is lying on a table, a visual notification can be produced by moving the robotic limb in the air or by tapping it gently on the table (Figure 6.17-a). When the user is holding the device, a tactile notification can be emitted by tapping on the user's hand. Physical notifications can also be performed when the device is inside the user's pocket [Hemmert, 2009].

Plotter. MobiLimb can be extended with a pen to draw messages on a physical support such as a post-it (Figure 6.14-d). It can then copy drawings from a mobile device onto paper. It can also write down emoticons sent by SMS. Our current implementation allows drawing on a surface of about 5 cm^2. MobiLimb can move (by crawling) to draw on a larger surface,

Navigation. MobiLimb can indicate a point in space or on the device screen. It can be used as a guidance technique to help users find a given target in the surrounding environment (Figure 6.17). Contrary to a regular on-screen guidance technique (e.g. virtual maps, instructions or compass), the 3D orientation of the appendix can be perceived in peripheral vision. This scenario requires to locate an object in a 3D environment, which can be captured with, for instance, ARCore platform [Google, 2018].

6.6 *Preliminary study*

6.6.1 *Appearance*

We conducted an informal study with seven participants to measure the impact of appearance of Mobilimb on user's perception. Seven participants from our research laboratory to compared three classes of textures covering Mobilimb.The textures were individually presented to the participants, who could see and touch them. We then engaged in a discussion using traditional brainstorming tools. The first texture looks like a classic *robotic* shell (in plastic). The second one is in fur (Figure 6.15-a) and the third one is a "finger-like" skin (Figure 6.14-b) with a high degree of realism. This texture is made of painted Plastil Gel-10 silicon used in the movies industry to make fake limb and skin.

For use cases not related to haptic feedback, participants liked the shell appearance. It was seen as neutral when connected to a mobile device, as the color of the prototype was the same as the color of the device. Participants enjoyed the scenarios related to zoomorphism, they enjoyed that the appearance and behavior of animals are linked, as the moving fur cat tail or a scorpion tail.

We observed strong reactions regarding the "finger-like" skin, which may be related to the uncanny valley effect [Mori, 1970]. This illustrates that using 'realistic' skin is not neutral and changes the perception of the

mobile device from an inanimate object to an *'almost'* human entity.

6.6.2 Scenarios

We conducted a video-based evaluation to (1) collect feedback about the system and (2) provide directions on the most promising scenarios to be investigated in future work. To achieve this, we deployed an online survey (mainly sent to the mailing list of a design school) to evaluate the 10 scenarios presented above. After each scenario, we asked how much the participants liked the presented scenario, found it useful and fun (a 7 item Likert scale was used). At the end of the survey, participants were free to write down comments.

Results

51 participants (11 female) aged 21 to 38 years (mean=26, sd= 3.5) completed the survey. The results of the study are reported in Figure 6.18. The figure shows a high tendency of positive results. In summary, 86% of the participants found the device amusing , 67% liked the device and 59% found it useful. The results reveal that participants were particularly enthusiastic regarding five applications.

The **Plotter** scenario received the highest subjective evaluation. 84% of the participants found it amusing and 78% found it useful. A high number (88% and 86%) of the participants found the scenarios with expressive behaviors fun (the **Pet the cat** scenario and the **Crawling** scenario). The participants (94% and 82%) also found the **Ergonomy** (dynamic affordances) and **3D edition** scenarios particularly useful

Surprisingly, using MobiLimb for **Notification** was not very well appreciated. 45% of the participants disagree or strongly disagree with the usefulness of this scenario. The participants do not think that MobiLimb motion would efficiently attract visual attention. MobiLimb also allows haptic notifications (e.g. when the phone is in the pocket), but this scenario was not part of the video because it is difficult to illustrate visually.

Haptic touch for **Mediated touch communication** received positive opinions (59% of the participants liked it). The video showed the robotic shell rather than the finger-like prototype not to bias participants with uncanny

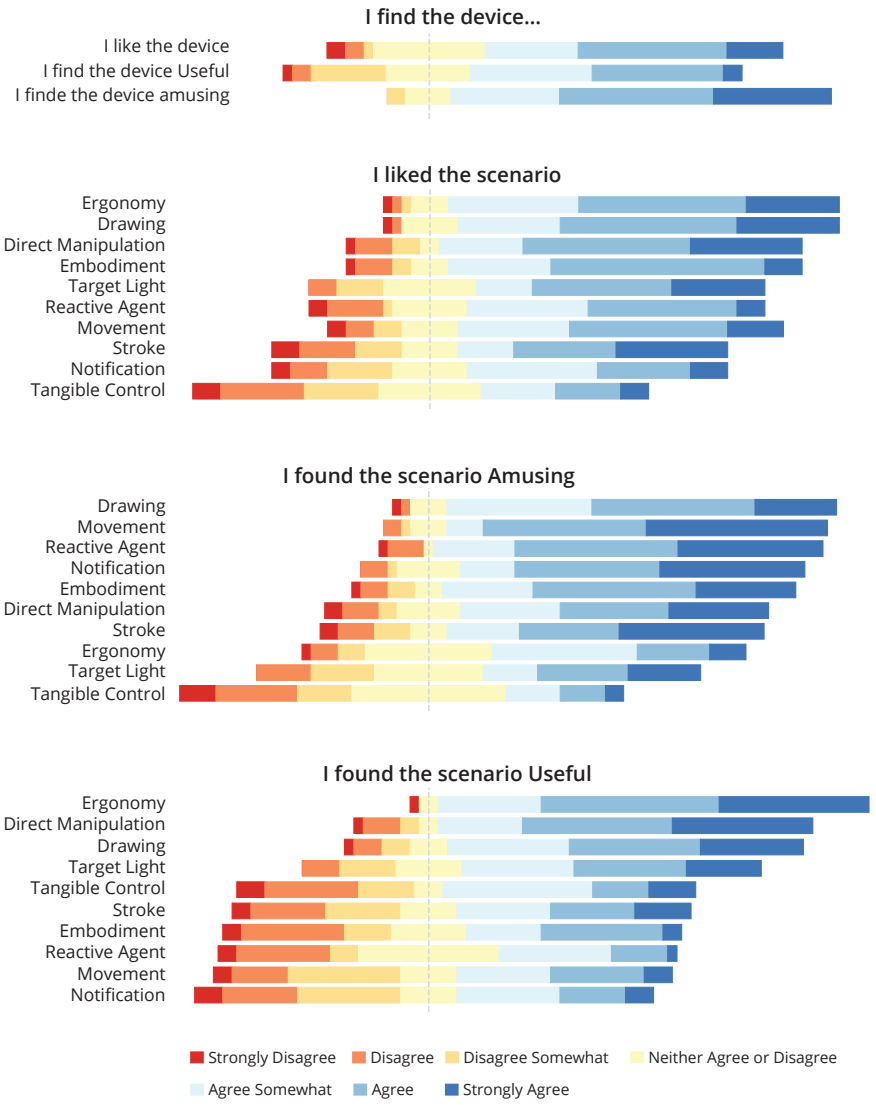


Figure 6.18: Summary of participants responses to the 7-point Likert scale questions.

effect (see section on Human factors). This somewhat mixed result can probably be explained by the fact that the acceptance of this sort of haptic feedback strongly depends on the identity of the emitter and his degree of familiarity (a partner, colleague, etc.)

In the free comments space, some participants suggested additional applications. Among them, one participant suggested attaching a "*camera* [to the appendix] *with a gyroscopic stabilizer allowing the user to film without shaking*". Two participants would like to use the device to "*scratch inaccessible points of their back*". Seven participants mentioned applications related to hedonism.

Two participants suggested applications described in the paper but not shown in the video: The navigation scenario using the device in "*GPS mode to point at a direction*", the ergonomic scenario where the appendix applies a force strong enough on the back of the hand "*for the phone not to drop*" and the assistive guide scenario for "*visually impaired people*".

In overall, the scenarios were well perceived in terms of likability, usefulness and amusement. Further evaluation studies ought to be conducted along different dimensions such as the appeal of the device, its functionalities and also its ergonomy and usability. In particular, we aim to evaluate the potential of haptic feedback to convey emotions.

6.7 Conclusion

In this chapter, we presented MobiLimb, a finger-like robotic actuator that can be connected to a mobile device that is capable to perform output and input. We presented the design space of this interface, its implementation as well as some use cases. This prototype is a response to the PROBLEM 1.3 of this thesis, *how can we design a portable device or artefact that can touch the user?*.

Our proof-of-concept comes out of several compromises. Despite the advances in robotics, we are not aware of technologies allowing rapid prototyping of such environments. Introducing actuated devices within the desktop workstation raises several long-term challenges such as (1) the miniaturization of the actuators to keep devices with the same form factor and weight; (2) the quality of the actuation (for instance, the device should quickly react to system instructions to maintain a high level of interactiv-

ity and provide enough strength to guide/resist to the users' motions); Finally, (3) for deployment, the autonomy and cost should accommodate widespread adoption. Our implementation of different scenarios highlights the interest of augmenting a mobile device with a robotic manipulator.

Our device is capable to provide kinesthetic feedback on the user wrist in a mobility context and we went further by exploring the input capabilities of the device as well as scenarios for interface control that leverage expressivity. These scenarios were enjoyed by the participants of our preliminary study. The design is simple and based on robotic actuation, which enables the easy exploration of the potential and most desirable types and shapes of robotic actuators attached to devices. There are technological limitations stemming mostly from miniaturization. An actuation solution which could provide higher torque would be useful to push heavy physical objects, have smooth motions even with thick shells and increase the force precision applied on the users' skin (within a bearable limit). The last point is especially important to convey emotions through touch. For instance, a strong force is generally perceived as conveying more negative feeling. Mobilimb is open-source which allows other HCI researchers to adapt this principle to different classes of applications such as smartwatches, the mouse or everyday objects.

We see MobiLimb as an example of the synergy between HCI and robotics, and as an example of Anthropomorphic interfaces. When interacting with a system, we build expectations towards system reactions, and interactions should match user's mental model [Duffy, 2003, Shneiderman and Maes, 1997]). MobiLimb aims to explore nearby or *full embodiment* interface [Fishkin, 2004], where users do not have to learn any metaphor to interact. This implies that the device appears like a physical system as we directly know how to use and manipulate. MobiLimb also illustrates that shape-changing technologies are ready to be integrated into commercial ubiquitous devices without radically changing their form factor. Not only this can accelerate the development of such systems but it makes them robust enough for in-depth evaluations (a major challenge of shape-changing interfaces [Alexander et al., 2018]). Moreover, most mobile devices provide tactile feedback (vibrations) at the price of a reduced expressivity, whereas complex robotic systems provide kinesthetic feedback, but they are bulky and expensive. Combining both types of feedback into a small and mobile interface seems a promising approach; our device demonstrates its feasibility. Such a combination can lead to a novel generation of smartphones and

interactive systems.

MobiLimb is conceived as an anthropomorphic interface, which is capable to perform Output like a human finger will do. The touch input capabilities of MobiLimb was limited to a 1-Dimensional touch sensor under the realistic skin, which far from being similar to human skin. It raises the challenge of developing an anthropomorphic touch interface, that looks like skin and that has the same visual-tactile capabilities of human skin.

WHAT YOU MUST REMEMBER

Contributions:

- Design and development of a finger robotic actuator for mobile devices
- Applications and scenarios that demonstrate its use as a medium, as a tool and as a virtual partner
- Initial evaluation of perception of the appearance and the relevance of scenarios

Part III

Interfaces for touch input

7

Skin with humanlike mechanical properties

Figure 7.1: In this chapter I present the reproduction of artificial skin.

In the previous part of this thesis, I have proposed devices capable to generate affective touch using anthropomorphic touch interfaces. These devices cover one part of the mediated communication loop: the need for

the receiver to feel tactile stimuli. However, an interface or a device adapted for emotional input is also needed to complete the communication loop. In the case of co-located touch, it is the skin that serves as this communication interface. Skin is a fundamental biological interface to sense the world and communicate with others (Chapter 2). Different mechanical properties allow users to perform expressive gestures: its elasticity allows others to pinch it, while its thickness ensures a soft contact in case of prolonged touch, such as stroking.

Artificial Skin has been explored in robotic literature and is usually designed with aesthetic and safety requirements in mind, rather than for harvesting interactive properties that are specifically useful for Human-Computer Interaction. This chapter presents studies that contribute towards this direction. It aims at selecting the best factors to create artificial skin reproducing the visual, tactile and kinesthetic aspects of the human skin, with interaction in mind [1]. I first motivate the choice of the material used to reproduce different skin layers (Figure 7.1), then present three studies that explore the replication of different skin properties: pigmentation, surface texture and thickness. I finally propose a set of gestures that can be performed on the skin.

[1] Main portions of this chapter have been published in [Teyssier et al., 2019]. Thus, any use of "we" in this chapter refers to the authors of this paper: Marc Teyssier, Gilles Bailly, Catherine Pelachaud, Eric Lecolinet, Andrew Conn and Anne Roudaut.

7.1 *Objectives and Approach*

While artificial skin has been largely studied in robotics for reproducing the sensing capabilities of the skin [Dargahi and Najarian, 2004], few studies have considered the human skin as a source of inspiration. Our objective is to understand how to reproduce skin that looks and feel like real skin, has similar bio-mechanical properties and can convey anthropomorphic affordances. We thus follow a bio-driven approach to design artificial skin and explore Problem 2.1: *what are the requirements to replicate a realistic human skin*. We also further explore what type of gestures can be performed on such surface. The end goal is to create a skin capable to convey anthropomorphic affordances.

To achieve this objective, we first draw inspiration from the design of sensors in robotics. There is a long history of research into the design of artificial skin in the field of Robotics. In Robotics, an "*artificial sensitive skin*" [Lumelsky et al., 2001] imitates the sensing capabilities of human skin. Typically it is used for replicating the sensing capability of the human

fingertips [Hosoda et al., 2006, Yousef et al., 2011a, Wettels et al., 2008], and thus often covers a small surface ($2cm$). An example is BioTac [Fishel and Loeb, 2012] (Figure 7.2), which consists of a fingertip sensor covered with an elastic liquid-filled skin that replicates finger viscosity. The materials used to design the skin depend on the sensors underneath. Robots such has the Nao [Gouaillier et al., 2009] don't even have artificial skin and integrate sensors directly under their plastic cover, which the user can directly touch. Others humanoid robots are covered with a thick artificial skin. A layer of silicone rubber is positioned on top of the capacitive sensors [Cannata et al., 2008, Schmitz et al., 2010]. The advantage of this approach is that this type of skin provides a sense of depth when interacting with it. However, it does not allow interactions such as pinching on its surface. Textile sensors have also been used to cover robots [Fritzsche et al., 2011, O'Neill et al., 2015]. The interaction on this type of surface is close to touching clothes, hence does not have the physiological aspect of skin.

Figure 7.2: BioTac robot finger, with an extremely high sensing acuity that uses different viscosity to reproduce human's viscosity

Creating realistic looking artificial skin has also been explored in the artistic field since a long time. Artists such as Duane Hanson, John de Andrea or Ron Mueck are "hyper-realistic" sculptors (Figure 7.3) present realistic human sculptures. Creating realistic skin texture is a long manual process, which require using traditional sculpture tools to crave texture and texture sheets, such as leather. The sculpture is then painted and hair is often added to reinforce realism. Olivier Goulet propose clothing and bags made out of realistic artificial skin (Figure 7.4). These objects are made of colored latex and resin. Replicating humans is still extensively used in the movie industry to create props and special flesh-like prosthetic effects. In particular, humans limbs covered with blood or scars[2] are often used for special effects. Because, prostheses should look and behave like human flesh when filmed, artists need to recreate the mechanical properties of the limbs. To this extent, they use a combination of different silicones with various viscosity to simulate the different layers of the skin (dermis, hypodermis, muscles), and solid structures for the bones. A cast of the actor limb allows a perfect replica of the limb but also reproduces the thin surface texture of the skin.

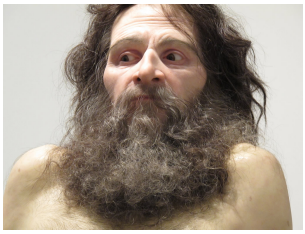


Figure 7.3: *Wild Man* scupture by Ron Mueck.

[2] During the winter 2018, I visited FX artists at clsfx [CLSFX, 2019] as well as Cyprien Mur, who taught me about the fabrication process of a cinema prosthesis.

Figure 7.4: SkinBag fashion bag, a bag made with resin

In this chapter, we take inspiration from the human skin to design artificial skin. Bio-inspired research is common in fields such as Robotics or Material Engineering, where it aims to abstract principles and structures from nature (e.g. mechanical abilities) to create new interfaces [Oliver et al., 2016, Dargahi and Najarian, 2004]. As it seeks to reproduce the

physiological aspect of biological skin, our approach shares similar goals but focuses on interactive aspects. We use artistic methods and tools to create our artificial skin.From a perceptive point of view, we study how to reproduce the visual, tactile and kinesthetic aspects of the human skin. We motivate the use of silicone to mimic the deformability of skin with reference to relevant literature. Then, through three user studies, we investigate how visual factors (color and texture) and haptic factors (texture and thickness) impact user experience and the perception of realism.

7.2 *Design Choices*

In this section, we present our design choices regarding the composition and fabrication of artificial skin. We first consider human skin properties, then the appropriate materials.

7.2.1 *Human Skin properties*

To select the properties we wanted to reproduce, we looked at the physiological layers that compose skin and their biomechanical aspects [Edwards and Marks, 1995, Hussain et al., 2013, Joodaki and Panzer, 2018]. The skin is divided into three primary layers [Edwards and Marks, 1995] (also see Chapter 2):

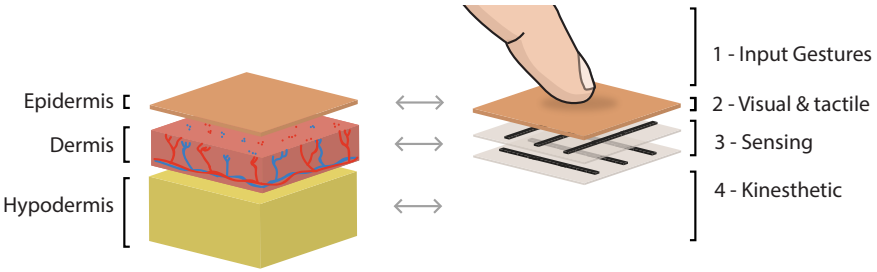


Figure 7.5: Our goal is to replicate the three layers of the human skin: the *epidermis* layer provides both visual and tactile perception (e.g. texture); the *dermis* layer is the sensory layer embedding nerves to detect mechanical contact; the *hypodermis* layer provides kinesthetic feedback thanks to its soft mechanical properties (viscosity, thickness, etc.).

– The *epidermis* is the outermost layer. It hosts multiple layers of renewed cells, with a turnover time in the order of a month. It provides both visual and tactile feedback (typically pigmentation and texture).

– The *dermis* is the middle layer. It hosts most of the sensory receptors responding to tactile and kinesthetic feedbacks that compose touch [Ko-

larsick et al., 2011]. It also hosts receptors for pain and temperature, as well as veins, hair bulbs and sweat glands.

– The *hypodermis* is the thicker part of the skin located between the skin and the muscles and is principally used for storing fat. It provides depth and resistance when human interacts with the skin, thus providing kinesthetic feedback.

In this chapter, we focus particularly on factors that are present in the *epidermis* and *hypodermis* layers of the skin, which impacts interaction and that are not related to sensing: The *pigmentation*, *texture* and *strain/thickness*. These factors varies between individuals (age, gender) and body location. We excluded properties such as the semi-impermeable barrier or the heat regulation capabilities, which are out of the scope of our study.

Pigmentation The visual aspect (or *color*) informs on the perception of age, attractiveness, mood, ethnicity or health [Fink et al., 2006].

Texture The skin texture impacts visual and cutaneous haptic perception. The skin texture is created by the wrinkles and skin pores. Wrinkling is responsible of the haptic cutaneous (or tactile) perception of the smoothness of the skin (along with the self-lubrication and the hair, which increase friction) [Quatresooz et al., 2006].

Strain/Thickness Strain is a measure of the deformation and is dependent on a material thickness which, in skin, varies between individuals (age, gender) and body locations (*epidermis* from 0.3mm to 1mm [Hwang et al., 2016] *dermis*: 0.9mm to 2.5mm [Laurent et al., 2007, Rodnan et al., 1979]; *hypodermis* from 1.9mm to 12mm [Hwang et al., 2016]). Given these variations, it is not surprising to find a large variation in the elastic modulus [3] (between 0.02 MPa to 57 MPa [Diridollou et al., 2001]).

[3] or Young's Modulus, which is the tendency of an object to deform along an axis when opposing forces are applied along that axis.

Skin *texture* and *pigmentation* are the main factors that determine the visual realism of the skin [Bando et al., 2002]. The surface texture provides subtle tactile cues, while the *strain and thickness* of the skin enable elasticity and depth perception during interaction.

In an interaction context, it is unclear whether visual similarity to human skin is an important factor. For example, using similar *pigmentation* as

human skin may not be ideal because human likeness is tight to the Uncanny Valley effect [Mori et al., 2012] and can elicit feelings of eeriness and revulsion in observers. Black or white colors (representative of usual device colors) might be more relevant for communicating interactivity. It is also unclear which *texture*, and which thickness is the most appropriate for interaction (as users may prefer interacting with thick viscous layers). All these questions sparked our interest in understanding how to adapt artificial skin to our interactive context. We address these points in the following section through three user studies.

7.2.2 *Choice of Material*

To reproduce the properties of the skin described above, we looked at common materials used in other fields of research as well as in art pieces. Silicone is the material most frequently used (Figure 7.5). It is cheap, easily available and durable. Moreover, it can be molded in any shape and be pigmented. Different viscosity and elasticity can be obtained with this material. This material is for example used to create skin simulators for medical training [Kang et al., Sparks et al., 2015, Dąbrowska et al., 2016] because of its mechanical properties.

We used different silicone products from Smooth-On Inc. to reproduce the skin properties listed above. In particular, we used *DragonSkin Pro-FX* [Smooth-On, 2019a] platinum cured silicone to create the *epidermis* layer. We combined it with *Silc pig* pigments for the pigmentation and used a mold technique for generating specific textures. We use *Ecoflex Gel* [Smooth-On, 2019b] for the *hypodermis* layer. This silicone has a different viscosity, is highly soft and flexible silicone presenting mechanical properties close to human fat [Wang et al., 2018, Geerligs, 2006].

Figure 7.6: The three fabrication steps to prepare the silicone [Smooth-On, 2019b].
1) Part-A of the silver cured silicone is poured onto the container.
2) An equivalent volume of Part-B Ecoflex silicone is poured.
3) Finally, the two parts are mixed thoroughly with silicone pigments.

7.2.3 *Artificial Skin Samples*

We created different samples. These samples are composed of a colored top layer (to recreate the epidermis) and a bottom layer (to recreate the hypodermis). Different thickness is used for each layer as in the human body [Edwards and Marks, 1995]. We followed the fabrication procedure protocol for each of them.

1. **Preparing the top layer**. We start by preparing the top layer, as it will be the first one poured into the mold. This top layer is prepared by mixing two parts of *DragonSkin Pro-FX* [Smooth-On, 2019a] with *Silc pig* pigments (Figure 7.6).

2. **Pouring the top layer**. The mix is poured into a rectangular mold of 80x40mm. To reach the desired thickness, the target volume is calculated and weighted during the pour. To create the surface texture, the bottom of the mold is eventually covered with a texture sheet. To ensure an even thickness, the silicone is left on a flat surface before curing.

3. **Curing**. Once set, the silicone layer is cured with 90° for 5 minutes.

4. **Preparing the bottom layer**. The bottom layer is prepared similarly to the top layer with the vicious *Ecoflex Gel* [Smooth-On, 2019b].

5. **Pouring the bottom layer**. The bottom layer is poured into the same mold, on top of the top layer. The volume is precisely measured to reach the target thickness.

6. **Curing**. We let the layer cool at room temperature for 2 hours.

7. **Demolding**. Finally, the sample is demolded from its case and flipped upside-down. The layer thicknesses are measured, to ensure they have the desired height. It is then eventually presented to the participants of the studies.

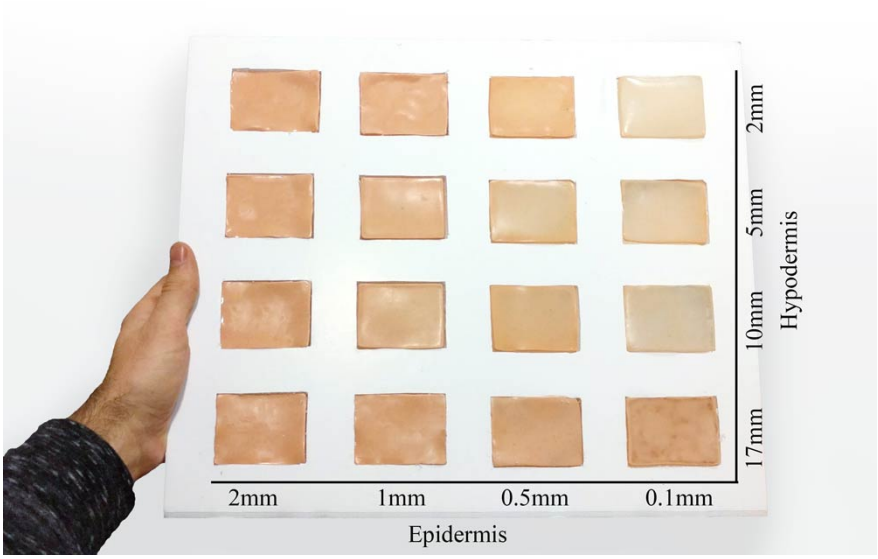


Figure 7.7: Different samples. Each of them has different epidermis thicknesses (from 2mm on the left to 0.1mm on the right) and different hypodermis thicknesses (From 2mm on the top to 17mm on the bottom)

As an initial test and in order to reduce the design space, we designed a matrix of 4x4 skin samples and did a focus group with 8 HCI professionals. The focus group was conducted over 1 hour, and the participants were free to manipulate the samples. Each sample presented had different epidermis thicknesses, from 2mm on the left to 0.1mm on the right. They also had different hypodermis thickness, from 2mm on the top to 17mm on the bottom. The participants suggested that that the samples with a too thin layer of epidermis (0.1mm) were not comfortable to touch (too sticky) and could not be used in an interaction context. We removed them from the following studies.

7.3 *Replicating Pigmentation*

Our first experiment aims at understanding the impact of *pigmentation* on skin humanlikeness perception and comfort and at detecting possible negative anthropomorphic effects. We believe that pigmented artificial skin could benefit interaction. Our research question was to explore if an interface that look like skin affords natural interactions. Because participants are used to interacting with flat surfaces (smartphone, touchpad), our results can reflect that black and white colors are more suited to suggest interaction.

Figure 7.8: *Left*: Representative usual device colors: White and Black; *Right*: Organic, but not human pigmentation (e.g. Alien or reptiles). *Right*: Realistic human skin colors: Beige and Brown.

7.3.1 *Samples*

Figure 7.8 illustrates the five different pigmentation we compared. We selected the colors to range from devices to human. The black and white colors are more representative of the usual device colors; the beige and brown colors are representative of realistic human skin colors; the green pigmentation suggests something organic, but not necessarily human (e.g. alien or reptilian).

7.3.2 *Participants and Experimental Design*

We recruited 15 participants (10 males, mean age 21) from our university to test each sample. The order of presentation of the samples was counter-balanced between participants using a Latin-Square design and a session lasted around 10 minutes. For each sample, participants indicated their levels of agreement regarding the three following affirmations, using a 5-point Likert scale:

1. *This interface looks like an interactive device*
2. *This surface looks like human skin*
3. *It looks comfortable touching this surface*

We also asked participants to rate their impressions of the samples according to the following scales: *fake/natural*, *machinelike/humanlike*, *artificial/lifelike*, which are often used to assess anthropomorphism [Bartneck et al., 2009].

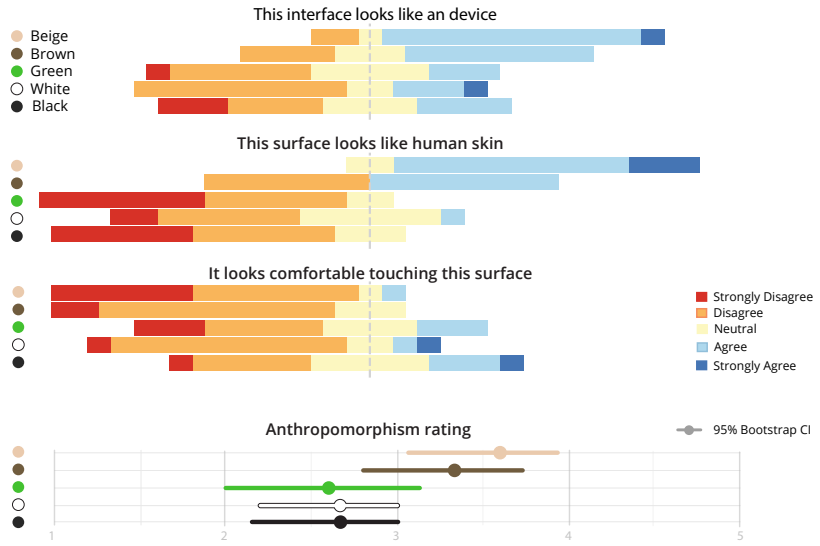


Figure 7.9: Results of study 1 investigating the impact of pigmentation on human likeness, comfort perception and anthropomorphism.

7.3.3 *Results*

The results are illustrated on Figure 7.9-top. Non-parametric Friedman tests were conducted followed by post-hoc comparison tests for all the questions asked and the effect was found on all questions: interactive (Chi-square = 13.6, $p<0.05$); and look like humans (Chi-square = 36, $p<0.05$).

The results suggest that the two human skin colors (beige and brown) better communicate interactivity than the others ($p<0.05$), in particular the usual white/black device pigmentation. They also confirm that beige and brown pigmentation significantly ($p<0.05$) increase the skin human likeness in comparison with other samples. The result of the anthropomorphism questionnaire (Figure 7.9-bottom) indicates that the skin pigmentation (beige and brown) provides a higher level of anthropomorphism than the other colors. Finally, the results did not suggest that the two human skin colors are perceived significantly less comfortable than the other colors.

We expected that the black and white colors would be perceived as more interactive because of their similarity to existing devices, but natural skin pigmentation was associated to a higher degree of interactivity. For the following, we keep the beige pigmentation and study different textures to investigate whether it can change the opinion of users regarding comfort.

7.4 *Replicating Texture*

We studied different surface textures to create wrinkles of different body locations. We compared their effect on comfort as well as the perception of the skin human likeness. Wrinkles are important for visual perception as it impacts the surface texture. Their 3D shape impacts the specularity of the object and change the material perception. Moreover the finger is capable of differentiating different textures easily [Delhaye et al.], hence a surface that looks like skin but doesn't feel like skin can create a cognitive dissonance.

7.4.1 *Samples*

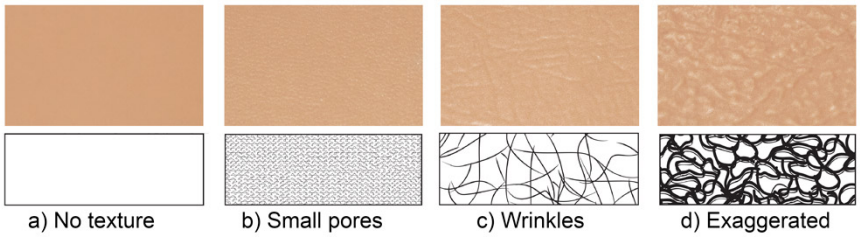


Figure 7.10: Textures samples considered in Study 2

Figure 7.10 illustrates the four samples of texture we compared. We considered two realistic human skin samples (Fig. 7.10-b, -c) which varied

both in terms of the size of the pores and the depth of the wrinkles: the skin of the back with small pores and no wrinkle (b) and the skin of the hand with small pores and wrinkles (c). We also considered two extreme samples which are less realistic: one without any pores and wrinkles which is very smooth (a), and one with exaggerated pores size and wrinkles.

7.4.2 *Participants and experimental design*

The design was similar to study 1. We recruited 16 participants (10 male, mean age 21) from our university. The experiment was divided into two phases: in the haptic phase, the task consisted of touching lightly the different samples without seeing them avoiding any bias of the beige pigmentation. After each sample, participants indicated their level of agreement about the two following affirmations using a 5-point Likert scale:

1. *Touching this surface feels comfortable*
2. *This surface feels like human skin*

In the visual phase the task was similar except that participants could only rely on the visual modality. The participants then indicated their level of agreement about this affirmation:

3. *This surface looks like human skin.*

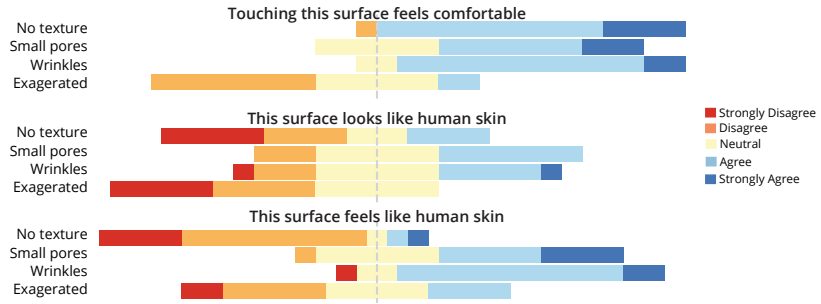


Figure 7.11: Results of the study 3 investigating the impact of the thickness on comfort and skin human likeness

7.4.3 *Results*

Non-parametric Friedman tests were conducted followed by post-hoc comparison tests for all the questions asked and the effect was found on all questions: comfortable (Chi-square = 21.8, $p<0.05$); feel like humans (Chi-

square = 12.3, p<0.05); and look like humans (Chi-square = 18.6, p<0.05). The results (Figure 7.11) suggest that the exaggerated sample is less comfortable than the three other samples (p<0.05). They also confirm that the two realistic samples are perceived more like a skin than the two other samples both tactically (p<0.05) and visually (p<0.05). The main finding is that an appropriate skin-like texture is important both for comfort of manipulation and humanlikeness perception. In the following experiment, we use the texture with small pores.

7.5 *Replicating Thickness*

We study the impact of the *strain/thickness* on easiness and comfort of interaction, as well as human likeness. During interaction, this layer thickness is responsible for the perceived depth and elasticity of the skin and impacts the different gestures one's can perform. It provides kinesthetic feedback and depth perception.

Figure 7.12: Different skin thickness considered in Study 3

7.5.1 *Samples*

The repartition of fat is different in human's body. The thickness of the top layers (epidermis+dermis) is 1.2mm as it is the average value of the dermis over the body [Lee and Hwang, 2002, Tan et al., 1982]. For the hypodermis thickness, we considered four values corresponding to different body areas (Figure 7.12): *2mm* (face [Rohrich and Pessa, 2007]), *5mm*, *10mm* (forearm [Hwang et al., 2016]), *17mm* (mean body [Kanehisa et al., 2004]).

7.5.2 *Participants and experimental design*

We used a similar design than previous studies. We recruited 16 participants (10 males, mean age 22) from our university. The task consisted of freely touching and manipulating each sample such as it was the skin of someone else. After each trial, participants indicated their level of agreement regarding the following affirmations with a 5-point Likert Scale:

1. *It was comfortable doing gestures on this sample*
2. *It was easy to perform gestures on this sample*
3. *This surface feels like human skin*

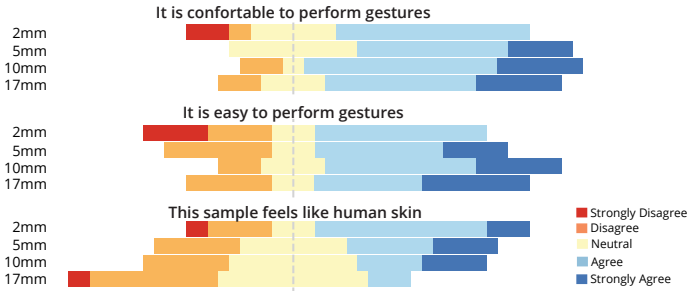


Figure 7.13: Results of the study 2 investigating the impact of textures on comfort and skin human likeness

7.5.3 *Results*

Non-parametric Friedman tests were conducted followed by post-hoc comparison tests for all the questions asked and found a main effect on the look alike question (chi-square = 7.4, $p<0.05$). Figure 7.13 illustrates the results. The sample with the thicker hypodermis layer was perceived as the less human like, as this value is usually present in body location not accessible for social touch, such as the belly ($p<0.05$). The graph also shows that samples with a thicker layer are perceived slightly more comfortable and easier to perform gestures or manipulate although this was not significantly different. Participants naturally compared the *5mm* and *10mm* with their own skin (respectively hand and forearm) suggesting that these surfaces are perceived as comparable to their skin.

From the results of the three studies, the participants seem to prefer humanlike and realistic-looking skin for interaction. The results suggests that the skin-like color looks like an interactive surface, a subtle wrinkle texture as well as the fat layer is more comfortable to perform gestures. Some anthropomorphic affordances (see chapter 9) might be conveyed with this interface, suggesting a touch interaction.

7.6 *Anthropomorphic interface*

The approach presented above propose a homogeneous surface. This facilitates the replication and ensures similar results when an artificial skin

is reproduced. However, the human skin is not flat and smooth. It is influenced by the bones, the muscles and the veins; the skin has volume and wrinkles of different depth.

As a creative and side exploration, we created another artificial skin, with a stronger anthropomorphic stance. For that purpose, we aimed to reproduce a rendering close to the human hand. Compared to our previous samples, this required adding more wrinkles and more volume. We created different artificial skins using the same base material but worked on the surface to render a different aspect. This process is based on artistic techniques, such as sculpting or casting. The final render is presented on figure 7.14

Figure 7.14: The new artificial skin on the front have a different look and feel than the previous artificial skin, on the back

7.6.1 Fabrication

To fabricate this artificial skin render, we followed a similar approach as with the previous samples. The main difference is that, rather than using a textured surface for the top layer, we fabricated a custom mould. The fabrication steps as are follows:

1. **Sculpting the mold**. A sculpture of the final shape was made with Monster Clay used with platinum silicone moulding compounds. The sculpt was done manually, including every wrinkles and details. To get close from the real skin, we used reference from pictures and from our skin. We sculpted two different samples, shown in Figure 7.15-a and -b.
2. **Casting the mold**. We poured some RTV Resin casting over the mould

to make a negative of the sculpt (Figure 7.15-c) in order to have a mould. The impression can be as precise as 0.01mm and can be used to cast an unlimited number of replicas. The mould is set overnight, and removed the sculpt is removed (Figure 7.15-d);

3. **Preparing the top layer**. We mixed the Dragon Skin silicone with some beige pigments. To create blood vessels, we used some red flocks.

4. **Pouring the top layer**. We applied some mould release and then poured the top layer (epidermis) layer into the mould. The volume was not carefully measured, as our objective was to fill the asperities with a layer of around 1mm. Once set, the silicone layer was cured for 30minutes.

5. **Preparing the viscous layer**. The viscous layer is prepared similarly to the previous artificial skin. We used the vicious Ecoflex Gel [Smooth-On, 2019b] mixed with some beige pigments.

6. **Pouring the viscous layer**. The viscous layer was poured over the top layer, and dried overnight.

7. **Demolding**. Finally, the sample was carefully demolded (Figure 7.15-e)

Overall, this process took much more time to fabricate than the previous samples. The base sculpt takes around 2 hours to sculpt, while the casting of the mold requires additional waiting time (4 hours).

(a) (b) (c) (d) (e)

Figure 7.15: Fabrication steps for a realistic skin interface. a) Sculpt of the pad in clay b) Skin of the phone in clay c) Casting of the mould d) The three different moulds with various shapes and forms e) Removing the finished skin from its mold

7.6.2 *Towards Anthropomorphic Artificial Skin*

We built two samples. One looks like a smartphone case and is built to be held by the user (Figure 7.16), the other is shaped as a laptop touch-pad (Figure 7.17) and is built to be placed on a surface.

These samples explore different techniques and have different visual properties. On the smartphone case, we tried to put forward different

Figure 7.16: New artificial skin shaped as a skin smartphone

volumes, while the touch-pad we reinforced the wrinkles. The pigmentation is closer from the human skin tone, and the different volumes make the overall interface more anthropomorphic. By showing the skin around, we had a strong reaction from the individuals. Moreover, the temperature interface is relatively cold (not at body temperature). When touched by the individuals, they mentioned that is was feeling odd. We interpreted this aspect as crossing the Uncanny Valley, and this should be further investigated.

Figure 7.17: Closeup of the anthropomorphic skin-like touch-pad. We can see the details of the wrinkles.

In terms of fabrication, this new artificial skin reveals some challenges. The previous fabrication method was more rigorous. The epidermis layer had an even shape on all its surface. With the new fabrication method, the mould was not flat, as the wrinkles and the volume impact its shape. When the silicone is poured, its distribution is not be even along all the outer layer of the skin. Thus, some part are be more stiff than others. This can impact interaction as these zones cannot be pinched easily. However, it is great from an artistic point of view. Indeed, the difference of thickness of the surface layers creates transiency, as with the human skin, and natural sub-surface scattering. Hence, the hypodermis layer colour has an impact on the perceived colour. Moreover, the talc layer plays a more important role as it highlights the asperities and wrinkles of the skin.

Some research work suggests that natural skin landmarks impact on-skin interaction [Steimle et al., 2017]. For instance, users tend to touch zones with beauty spots or wrinkles. Future work around these interfaces should investigate how the wrinkles or the shape of the skin influence the interaction. For instance, how stiffness impacts gestures, or how volume affords touch.

7.7 *Interactions*

Our next step in the design of the artificial skin was to identify the types of gestures which can be performed on such artificial skin. According to social literature [Hertenstein et al., 2006a, 2009] and On-Skin literature [Weigel and Campus, 2014], the human skin affords two main types of gestures: 1) gestures from mediated communication between individuals and 2) 2D multi-touch gestures from interface control. Our design space (Figures 7.19 and 7.18) summarizes the relevant gestures. This list is not exhaustive and only represents gestures that are most often considered in the literature .

Gestures from emotional communication

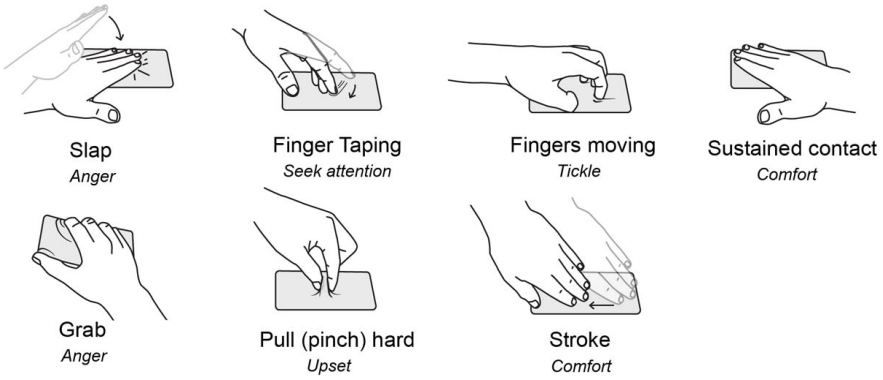


Figure 7.18: Design space for interactions, inherited from emotional communication

Skin leverages expressive gestures and tactile expression of pro-social emotions. Common gestures to convey positive emotions include stroking or rubbing gently to show affection or stroking harder to comfort someone. Patting is often used to convey sympathy. Negative emotions are also conveyed though touch. Most frequent gestures are slapping or hitting to convey Anger. Gestures can also be used to communicate an internal state, such as squeezing or grabbing to demonstrate fear, or pulling or pinching to demonstrate envy or jealousy or as taping on a surface to show impatience. Finally, signaling intent is also performed on the skin, usually through short and repeating touches, such as poking to attract attention. A simple touch contact with no movement can also signify a presence or a active listening [Hertenstein et al., 2009].

Gestures from interface control

In command selection, traditional input paradigms consist in pointing to hover items, and click or touch to select through a list of items. The same commands are used on a desktop or in mobile devices but are performed with fingers rather than a pointing device. The skin being a surface, it presents similar characteristics as conventional multi-touch devices. It can be used to control interfaces by interacting with the finger, but adds an extra dimension, the depth of the skin. The main advantage of skin input compared to traditional 2D input is that it takes advantage of the depth to provide passive tactile feedback. Traditional gestures for input include one-finger or multi-finger gestures. Artificial skin can serve to empathize metaphors such as pinch and stretch to zoom. The depth leverages analog capabilities: a press can be performed with variable levels of pressure; a light press or finger rotations can serve to perform micro interactions [Roudaut et al., 2009], for instance for interacting as with a joystick. Moreover, some input gestures can rely on the physical affordance of skin, as for instance pinching and twisting the skin to use it as a controllable knob.

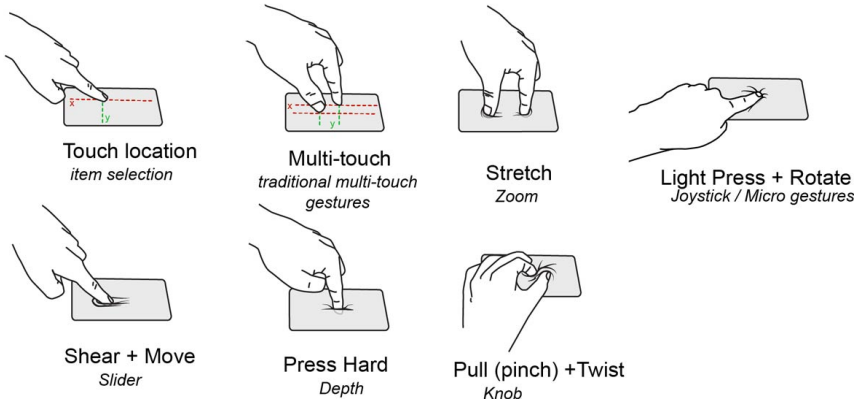


Figure 7.19: Design space for interactions, inherited from interface control

We could observe that users spontaneously performed such gestures during the studies. While participants performed gestures such as pointing or rotating with two fingers, as with regular interfaces, the most frequent gestures were pulling the skin (pinching), stroking and slapping, which are skin-specific gestures. These findings corroborate with the gestures proposed in existing literature surveys [Weigel and Campus, 2014, Hertenstein et al., 2006a, 2009]. The participants did not propose additional new gestures.

Users tend to transpose the interactions they are doing with real skin to artificial skin. Artificial skin leverages expressive gestures and tactile expressions of pro-social emotions, such as stroking or pinching. Gestures with similar characteristics to conventional multi-touch devices and traditional input paradigms suggest that users transpose conventional multi-touch gestures onto other interactive surfaces, like artificial skin.

7.8 Conclusion

In this chapter, I presented various studies that explore the sensory replication of the artificial skin. I draw inspiration from the human skin to choose relevant factors that can impact the perception of artificial skin. Our exploration let us form a series of guidelines for mimicking human skin for an interactive setup. This is a step towards the answer PROBLEM 2.1 of our thesis: *what are the requirement to replicate a realistic human skin.*

Our results suggest that the skin-like pigmentation samples convey interactivity, hence highlight skin affordance. The texture of the surface seem to play an important role. A texture with skin pores and wrinkles is feeling more comfortable and more humanlike. The thickness seem crucial for the comfort of interaction. Using a fat layer of 5mm to 10mm and a thickness of dermis of 1.2mm is the best combination for the comfort of interaction. Overall, our user preferred interacting on an interface with the human skin features. This is in line with the literature presented in the chapter 4: The *primitive categorization* plays a crucial role in anthropomorphic perception and in the perception of the affordances. The fact that some users wanted to touch even if they were not instructed to further reinforces this aspect.

Realistic skin prototypes are Uncanny and go a step further forwards anthropomorphism. They are less flat, have visual landmarks thanks to subtle colour changes and an even texture with deep wrinkles. I believe that a realistic skin can benefits interaction, however, such interfaces are hard to reproduce and to study in an HCI context as many factors can impact their perception. The human skin surface also involves other elements such as body hair, veins that inflate, different colours, a changing temperature, or even sweat, that were not taken into consideration in this study.

We followed a bio-driven approach which is singular in HCI. One challenge we faced was to conciliate an holistic approach and an iterative design.

In *theory*, the different parameters of the skin should be investigated altogether, e.g. we observed that it was difficult to study the colour of the skin independently from its texture. However, in *practice*, there are too many dimensions to investigate, which requires making design choices at each iteration. Further investigations are needed to provide clearer guidelines to follow a bio-driven approach in HCI, and we believe that exploring synergies with other fields such as Material engineering or Robotics will be a powerful means to further the development of advanced interactive devices.

One remaining challenge is to embed sensing capabilities into the skin. This challenges the fabrication of such a device and the development of relevant scenarios for artificial skin-based interaction. We explore this aspect in the following chapter.

WHAT YOU MUST REMEMBER

Contributions:

- Proposition of bio-driven approach to inform the design of artificial skin.
- Evaluation of the perception of properties of the skin, including pigmentation, surface texture and thicknesses.
- Fabrication method of a realistic looking artificial skin
- Definition of a set of gestures adapted for interaction on an artificial skin

8

Skin-On Interfaces: Realistic Artificial skin for Devices

Figure 8.1: In this chapter I present Skin-On interfaces, artificial skin to cover existing devices.

In the previous chapter, I presented how to reproduce some of the mechanical properties of the skin in order to develop an artificial skin. This step is important for the development of a sensitive artificial skin, as it provides a substrate similar to human skin, capable of deformation such as stretch and strain. The unique properties of the skin (e.g. size, stretchability,

etc.) motivated HCI researchers to develop On-Skin technologies to allow users to interact directly with their *own* skin [Harrison et al., 2010, Nittala et al., 2018, Weigel and Steimle, 2017]

Skin-On interfaces consist of augmenting interactive systems with anthropomorphic artificial skin. In this chapter, I[1] argue that the benefits of human skin should not only be used for On-skin interfaces but also for what we call Skin-On interfaces. To create Skin-On interfaces (Figure 8.1), we based our approach on the findings from the previous chapter (Chapter 7), which presented the replication of the *epidermis* and *hypodermis* layers, and extended it by focusing on the sensing capabilities that compose the *dermis* layer of the human skin.

[1] Main portions of this chapter have been published in [Teyssier et al., 2019]. Thus, any use of "we" in this chapter refers to the authors of this paper: Marc Teyssier, Gilles Bailly, Catherine Pelachaud, Eric Lecolinet, Andrew Conn and Anne Roudaut.

Skin-On interfaces mimic real human skin. Thanks to anthropomorphic affordances, these interfaces might better communicate the interactivity of the interactive systems and facilitate the discoverability of gestures. Such interface is adapted for interfaces for mediated communication of emotions but also for interface control. For instance, the back of a mobile device could be covered with artificial skin sensing user gestures (e.g. grab, twist, scratch, etc.) and provide tactile and kinesthetic feedback to enhance user expressiveness and user experience.

In this chapter, I present first the types of gestures than can be performed on Skin-On interfaces. I then present a new technological method to perform sensing inside the artificial *dermis* of the device, as well as an open-source hardware platform. Finally, I present the implementation of several Skin-On interfaces and applications to demonstrate the added value of our approach.

8.1 Objectives and Approach

The objective of this chapter is twofold. First, we aim at exploring the challenge of creating realistic skin, but this time we focus on the layer we didn't explore in the previous chapter: the *Dermis layer*. This contributes to complete the answer of PROBLEM 2.1, *what are the requirements to replicate a realistic human skin*. We then aim at proposing a complete design of artificial skin in order to sense touch in a mediated communication context. For this purpose, we integrated an artificial skin into existing devices, which is an answer to PROBLEM 2.2) of this thesis.

To inspire the design of Skin-On interfaces, we build on the gestures presented in the previous chapter to propose a fabrication method to create an artificial dermis layer, with a spacial acuity high enough to detect them i.e. multi-touch, pressure and complex gestures such as stroke, stretching or grabbing. Reproducing the human tactile acuity is a challenge: the skin spatial acuity varies from 2.3 mm inside the palm, 7mm on the forearm up to 15mm on the thigh [Weinstein, 1968, Vallbo et al., 1984, Stevens and Choo, 1996]. This challenge requires to draw inspiration from the digital fabrication literature to explore the potential materials and fabrication methods.

Researchers have explored various fabrication methods to design flexible input. In some cases, the materials used are still rigid and do not allow for complex gestures such as the one presented above [Schwesig et al., 2004, Lo and Girouard, 2017, Rendl et al., 2016, Strohmeier et al., 2016a]. Other works have proposed to add thickness to sensors to enrich the vocabulary of gestures [Smith et al., 2008, Nguyen et al., 2015, Beven et al., 2016]. For instance, a thick silicone layer to provide a malleable input surface that can be used to detect stretching, bending and twisting using capacitive sensors [Follmer et al., 2012, He et al., 2017]. Most previous studies used silicone as a base substrate, with various techniques, to sense touch, stretch [Wessely et al., 2016] or deform the human body [O'Brien et al., 2014]. Our approach is to develop a fabrication method that is easy to reproduce and only requires low cost materials.

Finally, this chapter presents a series of use cases and prototypes, which illustrate how artificial skin can be used as a communication medium and how it can be integrated within existing devices. This responds to the Problem 2.2) of this thesis, how to integrate an artificial skin into existing devices?

8.2 Sensing

In this section, we focus on the reproduction of the human skin sensing acuity. We present different sensing techniques and materials and discuss which ones are more adapted to mimic human skin sensing layer.

8.2.1 *Implementing artificial mechanoreceptors*

Skin has a wide range of mechanoreceptors used conjointly to detect touch and deformations. Building skin-equivalent sensors raise two technical challenges: (1) choosing the sensing technique and the overall electrode pattern, and then (2) choosing electrodes material compatible with artificial skin's properties not to hinder its deformability. To inform our choices we have a series of requirements:

- *Strain/thickness*: we want to reproduce the deformability of the skin as described earlier. We are particularly focusing on sensing layers of thickness below 1.2mm to match the results found in our sensory exploration studies.
- *Accuracy*: we want to build accurate sensors that can reproduce the human skin sensing acuity and detect the gestures defined previously.
- *Accessibility*: we want to use accessible technologies, i.e. process should be easy to reproduce by HCI practitioners with affordable material and without high-end equipment.

8.2.2 *Choosing an electrode pattern*

We choose to implement our sensor using a matrix layout sensing mutual capacitance. To understand the reasons behind this choice we need to explain the different techniques that can be used. There are various ways to layout sensors to detect gestures. One frequent solution consists of using a matrix of discrete sensors, and another more accessible accessible technique use resistive or capacitive sensing.

Matrix of discrete sensors

To sense location, the most common approach in robotics is to use an array of similar sensors [Lee and Nicholls, 1999, Argall and Billard, 2010, Dahiya et al., 2013]. A discrete layout means that the skin sensing interface is made of several individual cells spaced out on the surface of the artificial skin. These sensors can sense capacitance, resistance, but are not limited to contact sensing. For instance, temperature or luminosity sensors can be used to infer touch or the environmental conditions [Argall and Billard,

2010]. This design is close to the reality of the nerve cells: dedicated elements provide information of various nature, which are used to interpret touch. However, like the human cells, one important constraint is that a lot of sensors require a complex wiring and instrumentation, which is difficult to integrate in an existing product.

Resistive sensing

The accurate detection of several levels of pressure requires a layer that changes its electrical properties when compressed. Piezoresisitve materials [Burns and Glenn, 1996, Dagdeviren et al., 2016] can be encapsulated between two layers of conductive material to perform this sensing. A low-cost DIY alternative is to use the Velostat type of piezoresistive films [Perner-Wilson and Satomi, 2009] or piezoelectric textiles [Parzer et al., 2017]. Resistance on a 2D sensor can be read from orthogonal electrodes with a piezoresistive material between them. This approach is often used for smart textiles [Donneaud et al., 2017, Freire et al., 2017] but requires large electrodes (>1cm) which does not fit with our requirement of spatial acuity, and requires several layers which complexifies the fabrication process.

Capacitive sensing

Capacitive touch sensing relies on the change of capacitance, which occurs when the body gets close to the electrode and changes the local electric field. Capacitive sensors can be used to sense basic contact, and are precise to detect an on/off state change. When the sensor has a low electrical resistance, it is possible to infer pressure information. Sensing complex modalities like stretch, bend or shear sensing often rely on the change of electrical resistance or capacitance when a material is deformed.

Techniques based on change in capacitance can be used to detect touch on a 2D surface. The mutual capacitance sensing technique uses the changes of the local electric field when a finger is near the surface. This technique is used in HCI [Nittala et al., 2018, Zhang and Harrison, 2018] as it allows multi-touch and only requires two orthogonal arrays of electrodes separated by a dielectric layer. The electrodes can be thin but requires a low electrical resistance. Location and pressure information can be extrapolated from the

mutual capacitive reading. The interlocking diamond pattern [Nittala et al., 2018] improves the accuracy when the resistance of the electrodes is too high. This technique provides an excellent spatial resolution and requires few instrumentation. It is also the easiest and fastest fabrication method as it doesn't require a lot of layers.

8.2.3 Choosing the electrodes material

To implement the electrode pattern described above, we needed a conductive material that fits our requirements. We excluded solutions that rely on complex machinery or a complex fabrication process to fit with our requirements. In particular, we excluded solutions such as depositing of hard conductive particles or liquid conductive metal in a microfluidic channel [Nagels et al., 2018, Lu et al., 2014]. We also tested the solutions described below before choosing to use conductive thread.

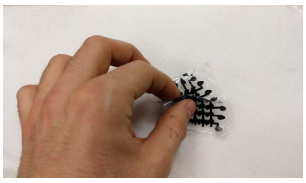


Figure 8.2: Test of conductive silicone traces encapsulated within a transparent silicone layer

Conductive silicone

A common approach is to use cPDMS, a silicone material filled with carbon powder or nanotubes [Lipomi et al., 2011]. We tested two conductive silicons. First, we prepared a cPDMS mixing carbon black, EcoFlex 00-30 silicone and D5 solvent. A 1:1:1 ratio ensured a proper consistency for coating over stencils, and an even distribution of the carbon black allowed conductivity and stretch. Once dry, the conductivity was about $500k\Omega/cm$. The second silicon we tested is a commercially available conductive silicone, Elastosil® LR3162 by Wacker [GmbH, 2019]. It has a theoretical conductivity of $2\Omega/cm$ when mixing manually, but we could not get a conductivity under $10k\Omega/cm$. This material allows a stretch up to 60% before breaking. Its electrical resistance is high and increases when stretched (Figure 8.2). The high electrical resistance of the electrodes makes it unsuitable for mutual capacitance sensing. Another drawback of this approach is that connecting the electrodes to cPDMS can be challenging to ensure a durable prototype [Wessely et al., 2016].

Conductive fabric

We also explored conductive fabric, which is used in the DIY wearable community [Donneaud et al., 2017]. We used a Silver plated stretchable conductive fabric (stretch-width:65%, stretch-length:100%) to create a composite fabric + silicone material by pouring a thin layer of silicon on top of the conductive textile. Once cured, we laser cut this composite material to the desired pattern and sealed it into another silicone layer. The weaving structure of the material makes it durable, very conductive ($<1\Omega/cm^2$), and an increased strain reduces its electrical resistance. However, its thickness was 0.8mm (about the same as the fabric thickness), which is over the size of the dermis thickness when using multiple layers (two layers are needed, plus the dielectric, which would make the sensor more than 1.2mm thick).

Conductive threads

Another approach is to use conductive threads that are sealed in a thin layer of silicone. We used conductive insulated *Datastretch* thread [Tibtech, 2019], which allows a strain up to 30%, is 0.2mm thick, and has a conductivity of 4.2Ω/m. It is less stretchable than conductive textiles or cPDMS, but 30% is sufficient compared to the skin maximum strain, which is approximately 40% [Bark et al., 2008]. The threads can be positioned with a specific pattern, and electrical insulation allows superposing multiple electrodes while keeping the layer sufficiently thin. The electrode pattern can only have a limited number of electric lines, but this technique remains the fastest to fabricate and requires few materials which makes it appropriate considering our requirements. As the threads are thin, the thickness of the sensing layer can be similar to the human's dermis and even smaller.

Other materials

The conductive layer can also be created with a deposit of hard conductive particles such as copper. To enable some strain, it requires a specific shoe-horse pattern layout, which allows a reasonable stretch (30%) [Sosin et al., 2008]. We didn't use this technique as these patterns require a precise material deposit or cutting machine which is not ideal for an easy DIY fabrication. But they have a very high conductivity and durability. Liquid-based conductive materials such as gallium or eutectic gallium-indium

Figure 8.3: Organic conductive ink PEDOT:PSS often used in HCI

(EGaIn) can be embedded with micro-fluidic channels in PDMS substrate and serve as wires [Lipomi et al., 2012, Lu et al., 2014]. These solutions provide a high conductivity but require many manufacturing steps to create different layers, including stencils, plotter cutting, casting, etc. Conductive ink based on PEDOT:PSS [Lipomi et al., 2012] (Figure 8.3) is more and more mainstream in fabrication research. However, the electrical resistance increases drastically after every stretch [Wessely et al., 2016], which makes it impossible to build an efficient deformable sensor. Thus, we discarded this solution.

8.2.4 Skin-On Fabrication Process

Inspiration and requirements

One fabrication constraint was that we wanted to use conductive layers within a flexible silicon substrate. As stretchable electronics often require several layers, the screen-printing technique is the most commonly used in HCI, to develop on-skin interface [Weigel et al., 2017] or stretchable interfaces [Wessely et al., 2016]. This process requires to make one silkscreen per layer, which can be tedious. We draw inspiration from these techniques to explore three alternatives to create our conductive and stretchable interface.

Conductive silicone stencil

(a) (b) (c)

Figure 8.4: Tests of conductive carbon over stencil. a) A two-layers grid of electrodes. b) After a stretch the layer is destroyed. c) Other type of sensor made with conductive silicone, a strain gauge

An easier approach consists of coating over a stencil, to spread the polymer following a specific pattern [Weigel et al., 2015]. We tried this

method with the following protocol: First, we spread a thin layer of silicon on the flat surface. Once dry, we cover it with a plastic book laminate, which will serve as a stencil. We crave the desired sensor pattern with a laser cutter and then apply the conductive paste by coating over the stencil. Finally, we seal the conductive pattern with an extra thin layer of silicon and cure with a heat gun for 10 minutes. This process is repeated for every layer.

Compared with on-skin interfaces such as [Weigel and Steimle, 2017], having the electronics encapsulated between two layers of silicon makes the interface more robust and durable. This method enables the prototyping of a thin layer while being easy to do with few equipment. It allows a stretch up to 80% before breaking the conductive traces (Figure 8.4-b). Single sensors with a low requirement in terms of electrical resistance, such as capacitive sensors or strain gauges (Figure 8.4-c) works great with this method. However, the electrical resistance is too high to use it with mutual capacitance sensing, and would require an array of sensors to sense location, which needs a lot of instrumentation and a low resistance. Moreover, the manual steps are still too complicated for a really easy and DIY fabrication process.

Casted conductive fabric

(a) (b)

Figure 8.5: Tests of casted conductive fabric. a) The fabric is encapsulated whithin a silicone layer. b) By using laser-cutted patterns, we can create complex patterns on several layers;

Another solution we explored is cast conductive textile (Figure 8.5) We tried this approach with the following protocol: Some stretchable conductive fabric was placed on a flat sheet. We then pour silicon on top of this fabric (Figure 8.5-a), and evenly spread it so that the silicone is encased within the weaves of the fabric. This fabric+silicone is then laser cut to a specific pattern. The patterns or electrodes are placed on a flat sheet. More

silicone is poured over the patterns to form the final layer (Figure 8.5-b). One challenge of this technique is to fabricate the patterns described above. The structure of the fabric constrain the possible width of the electrodes of 2mm. The height of the final sensing interface is quite high, around 2mm, which is thicker than the human dermis and not adapted to our bio-driven approach.

Casted conductive yarns

(a) (b)

Figure 8.6: Tests of conductive yarns. a) The first interface was designed with non-stretchable conductive yarns. b) Another test on a larger surface with stretchable yarns

After testing all the possible combinations, we found that the mutual capacitance sensing technique with conductive insulated yarns is the best technique to replicate the dermis layer. Our initial test was performed with silver-particle non-stretchable yarns (Figure 8.6-a). These yarns were difficult to connect to electrical circuits, and the interface was not stretchable. The final solutions uses stretchable yarns, electrically insulated (Figure 8.6-b). This technique offers several advantages: it provides an excellent spatial resolution with close electrodes, requires few instrumentation and allows inferring pressure information. It is also the easiest and fastest fabrication method which doesn't require a dielectric layer of silicon between two electrodes layers. As the threads are thin, the thickness of the sensing layer can be inferior or similar to humans' dermis.

Our fabrication method

We now present the steps needed to fabricate our artificial skin (Figure 8.7). As the choice of the material was detailed in the "Sensory Inspiration" section, we focus here on how embedding the sensing layer impacts the

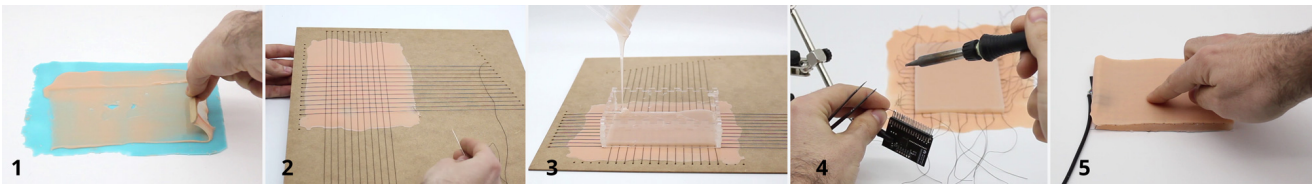


Figure 8.7: Fabrication steps of Skin-On artificial skin. *1.* Epidermis layer, *2.* Electrodes, *3.* Hypodermis layer, *4.* Electronics, *5.* Aesthetics

fabrication process.

1. **Creating the top textured layer**. The epidermis layer is built with a skin-like texture and a beige pigment (Figure 8.7-1). A thin-film applicator was used to achieve the desired thickness (about 0.6mm).

2. **Positioning the electrodes**. The top layer is positioned on a pane, with the texture facing down. The conductive threads are then placed in a perpendicular grid on top of the artificial epidermis to form the electrodes. To ensure an even spacing between the electrodes, we laser cut guide holes on the edge of the acrylic plate and then sew the thread, following the holes (Figure 8.7-2). The spacing between holes varies depending on the desired size of the interface and the spacial acuity. Once the electrode grid is positioned, we pour another thin layer of silicone to seal it in place. We ensure that the total interface is under 1.2mm.

3. **Adding the hypodermis.** We prepare a rectangular mould of the size of the desired artificial skin and place it on top of the sensing layer. The hypodermis silicone layer is poured inside the mould to reach the desired fat thickness, i.e. 10 mm in this example (Figure 8.7-3).

4. **Connecting the electronics.** The electrodes are then connected to the hardware sensing platform (Figure 8.7-4).

5. **Shaping the Skin-On.** This step consists in improving the visual appearance of the interface. The designer can manually trim the excess of silicon, fold it around the side of the hypodermis layer and glue it with silicon glue (Figure 8.7-5). For a permanent fixation on a device, either silicon glue or acetone can be used to smoothly blend the silicon with the underneath surface. Paint or makeup can be used to

shade the artificial skin with flesh-like tonal variation, thereby increasing anthropomorphism.

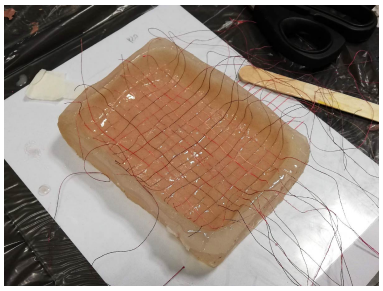


Figure 8.8: Wires manually positionned in the realistic artificial skin.

To integrate the wires in the realistic skin presented in chapter 7, the fabrication method has to be modified. Because we use a mould, it is not possible to lay flat the wires. Hence, we manually position the wires (Figure 8.8). With this method, the grid is not perpendicular, it favours human likeness and anthropomorphism at the expense of resolution and accuracy.

8.3 *Open-toolkit for touch and gestures detection*

The final step is to detect users' gestures. We present the implementation of our hardware and software toolkit and demonstrate its gesture recognition algorithm, which can detect all the gestures proposed in the previous chapter of this thesis.

Figure 8.9: *Left*. Open Hardware Mutual Capacitance breakout *Right*. Smartphone case prototype hardware.

8.3.1 *Hardware Platform*

[2] Available at https://github.com/muca-board

We developed an Open Source and Open Hardware multi-touch controller, available online[2] with a total cost of $4. This contribution enables DIY fabrication of multi-touch interfaces on non-conventional surfaces such as human skin [Nittala et al., 2018], walls [Zhang and Harrison, 2018] or, as in our case, flexible silicon. The breakout is composed of a *FT5316DME* controller, which allows for connecting 12 sensing electrodes and 21 transmitting electrodes. Any conductive electrode with an unusual shape or using unusual material can be used for sensing and transmitting. The touch controller can transmit the raw electrodes data or 5 multi-touch coordinates via i2C, to any micro-controller. In our prototypes, we used both Arduino Pro Micro board for sending the data via serial communication to a laptop,

and a Wemos D1 mini for transmitting information wirelessly to the mobile device. We now explain how we detect touch contact, then more complex gestures.

8.3.2 Data processing

The processing pipeline relies on OpenCV to convert the mutual capacitance readings to touch coordinates. This process removes the background noise and tracks the user's points of contact with the surface.

Using the data read (in serial or wireless) from the sensing and transmitting electrodes, we build a 2D image of 12x21 pixels. Each individual cross-point corresponds to the capacitance reading at a location on the sensor grid.

To minimize the background noise, we perform an initial calibration. After the board is detected, we create a calibration matrix, by averaging the individual value of each coordinate 10 times. The interface must not be touched during this period (Figure 8.10-b). Incoming capacitive data is transformed by the calibration matrix (Figure 8.10-b), and the values are normalized and stored in an image file. We apply a threshold to remove points under 0.1%, which we consider as background noise.

To support accurate spatial interpolation, we upscale the image 5x using the Lanczos-4 algorithm (Figure 8.10-c). The raw image of the transformed cross-points values is then converted into a binary image with a threshold of 55%. We apply contour detection to separate distinct elements on the image as *blobs*. We calculate the relative surface of each blob area and the nearest fitting ellipsoid to get its center and orientation (Figure 8.10-d). The electrodes are read 16 times per second and the data processing takes on average 4ms. An API is provided to share touchpoints and gesture events using Unity3d.

Multi-touch point detection.

The centre and the radius of an ellipsoid define respectively the location and the strength (or pressure) of the touchpoint (Fig. 8.10-top). From a pilot study, we defined the maximum radius (5mm) that a single finger press can have on this surface (Fig. 8.10-c). To determine and track the position

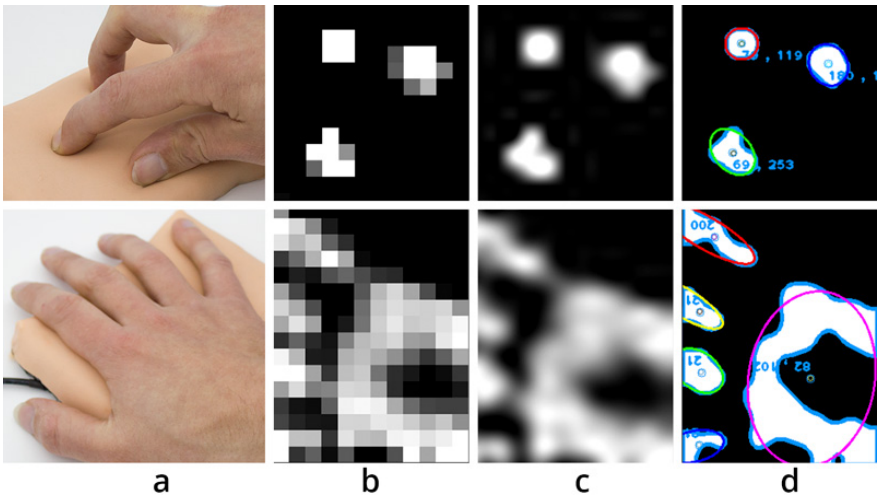


Figure 8.10: Data processing to detect multi-touch (*top*) or grab (*bottom*) gestures: *a*- Gesture, *b*-raw sensor data, *c*-5x upscale image, *d*- Contours and Blobs detection.

of the multi-touch points over time, we use the contour points (stored in a k-d tree), and find the closest blob position in O(log$n$).

Advanced gesture detection.

Advanced gestures differ from multi-touch gestures by their specific dynamic and/or the number and size of the contact area (radius larger than 1cm^2). For instance, a "stroke" is characterized by a simultaneous swipe contact of at least three fingers along all the surface and a "tickling" by repeated fast finger swipes in the same direction. When the user performs a "pinch" with two fingers, circular *blobs* merge into a single ellipse with a large eccentricity. Its rotation informs on the rotation and strength of twist. Other gestures are detected because of their large surface area. For instance, the detection of the palm of the hand has a very large surface area ($> 50mm^2$). A slap is characterized by the presence of a large *blob* for a very short amount of time. On the opposite, a grab gesture (Fig. 8.10-bottom) is characterized by a large *blob* on a side of the surface (palm) and four ellipses with large eccentricity at the center of the surface (fingers) (Fig. 8.10-d).

Our data processing algorithms provide a spatial acuity of 2mm, using an electrode spacing of 4mm. This is comparable to the acuity of the human skin on the forearm. The two-point discrimination threshold of our prototype is 10 mm, which is better on average, than with the human skin [Weinstein, 1968].

Gesture detection pilot study. We ran a preliminary study with 8 partici-

pants on a subset of 8 gestures. The selected gestures are representative of the capabilities of our device: they leverage skin depth, allow multi-touch interaction, and are not a combination of basic gestures. The participants performed 3 practice trials, then 5 test trials, for a total of 8*8*5= 320 tested gestures. The overall recognition rate was 85% (Light Press: 100%, Hard Press: 100%, Sustained Hand Contact: 88%, Stretch: 83%, Pinch: 80%, Stroke: 80%, Tickling: 78%, Slap: 73%). Although preliminary, these results are promising and demonstrate the feasibility of our approach and allows us to implement applications.

8.4 Use cases

We first describe the implementation of three Skin-on interface prototypes with different form factors as shown in Figure 8.11. We then present the applications we developed for these prototypes. These applications are divided into two categories: interface control and communication of emotions.

(a) (b) (c)

Figure 8.11: Different form-factors of Skin-On. a) On a smartphone as interactive case, b) on a laptop as touchpad c) on a smartwatch

8.4.1 Skin-On devices

We present three prototypes with different form factors. These prototypes have different sizes and are connected to or replace various devices: smartphones, touch-pads and smartwatch (Figure 8.11).

Skin-On Smartphones

We built a Skin-On smartphone case (Figure 8.11-a) providing advanced input and output capabilities on the back and the side of the mobile device [Le et al., 2018, Corsten et al., 2017, Shen et al., 2009]. The interface communicates via WiFi with the Android device and all the hardware (sensing breakout, battery and communication component) is self-contained within the case (Figure 8.9). This prototype has a dimension of 8cm x 15cm and could easily be extended to tablets.

Skin-On Touchpads

We also built a Skin-On interface for built-in and external touchpads. We created two interfaces with two different sizes and thicknesses (9cm x 12cm and 10cm x 14.5cm, thickness 7mm) that can be connected to a device via USB (Figure 8.11-b).

Skin-On Wristband

We also fabricated a Skin-On wristband to alleviate the limited input and output capabilities of smartwatches [Perrault et al., 2013] (Figure 8.11-c). The wristband (10cm x 2.5cm, thickness of 5mm) illustrates how wearable devices can benefit from Skin-On interfaces. The wristband is connected to a computer that processes the data and sends back the events to the smartwatch via WiFi.

8.4.2 Applications for interface control

Communicating interaction

Skin-On interfaces provide natural physical affordances. The characteristics of the material can motivate users to spontaneously explore the interface and discover novel controls. For instance, Study 3 demonstrated that several users spontaneously pulled the skin (to pinch) and twist it, a gesture that users would not naturally perform on rigid touchpads. Moreover, once users discover the skin metaphor (either by themselves or after communicating with others), they will be more inclined to explore additional

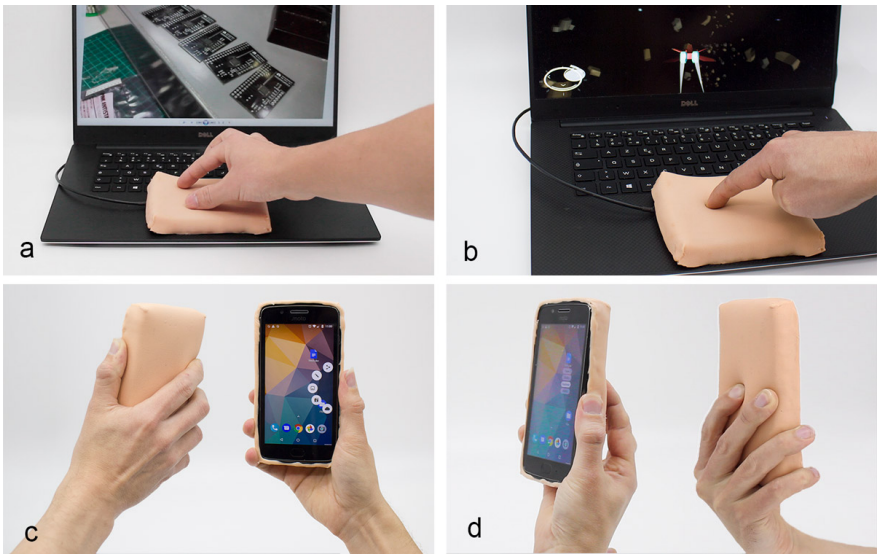


Figure 8.12: Applications for interface control. a) Leveraging physical interaction (pinch and stretch), b) Virtual joystick with micro-interactions, c) Grab detection to display an adaptive pie menu, d) a pressure menu

gestures and discover new controls.

Leveraging physical interaction

Skin-On interfaces leverage physical interaction by providing haptic feedback in line with gesture input. For instance, when users are pinching or stretching a virtual image (Figure 8.12-a), they physically pinch and stretch the artificial skin. Similarly, a twist gesture can be used to manipulate a tangible knob: the amplitude of the twist rotation controls the volume of a music player. Physical interaction metaphors can be especially useful in games, where they provide a sense of realism. For instance, users can perform a shear gesture thanks to the elasticity of the skin to execute a slingshot in the Angry-bird game.

Increasing the degree of control

Skin-On interfaces allow users to perform advanced gestures with a higher degree of control. Typically, pressure-based interaction can be difficult to control since rigid surfaces cannot communicate apparent stiffness to users. In contrast, Skin-On interfaces have a much smaller stiffness, providing a higher level of control. We implemented a pressure-based menu. When selecting an icon, a light touch opens a document, a medium touch shares it and a strong one deletes it. Rather than pressing on a flat plane, the

hypodermis layer provides another level of haptic. Similarly, users can perform micro-gestures [Roudaut et al., 2009] with a higher level of accuracy and control a 3D joystick by performing in-place rotations of the finger (Figure 8.12-b).

Increasing the input bandwidth

Skin-on interfaces allow a wide range of interaction that would otherwise require advanced technologies. For instance, the Skin-On Smartphone supports back-of-device interaction [Le et al., 2018], which lets users interact with the device without occluding the screen. It can also sense how users are grabbing the device [Eardley et al., 2017] as the artificial skin covers both the back and the side of the smartphone. For instance, Figure 8.12-c shows an adaptive Pie menu [Bailly et al., 2017] whose location depends on the handedness of the phone grasp.

Skin-on interfaces can also serve for improving small mobile devices such as smartwatches or connected objects. For instance the Skin-On wristband (Figure 8.11-c) can allow performing all the one-dimensional interactions (along the wristband) proposed in [Perrault et al., 2013], plus some additional interactions such as 2D scrolling or continuous rotations on the wristband, e.g. to change the volume of the music, navigate in applications or send simple gestural messages to others.

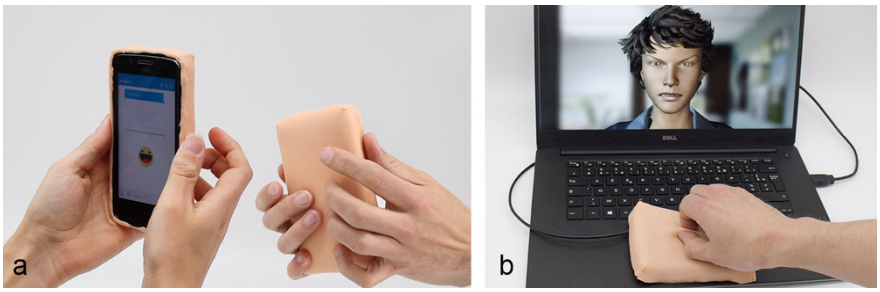


Figure 8.13: Examples of applications for emotional communication. a) Tactile expression for mediated communication, b) Communication with a virtual agent.

8.4.3 *Applications for emotional communication*

Touch gestures on Skin-On can convey expressive messages for computer-mediated communication with humans or virtual characters.

Mobile tactile expression. We implemented a messaging application where users can express rich tactile emoticons on the artificial skin. The intensity

of the touch controls the size of the emojis. A strong grip conveys anger while tickling the skin displays a laughing emoji (Figure 8.13-a) and tapping creates a surprised emoji. The distant user can then receive these emoticons visually, or haptically, for example using an interface like those proposed in the Chapter 6.

Virtual agent embodiment. Artificial skin can act as a mediated embodiment of an ECA or virtual character. The users can then perform social touch gestures on the skin, that is, on the virtual character, as they would normally do in human-to-human interaction. For instance, users can perform a stroke to convey their sympathy, small repeated taps to convey happiness, etc. [Hertenstein et al., 2009], or pinch to convey annoyance (Figure 8.13-b). Another example is to convey one is listening to what the ECA is saying. For example, a simple touch by the user can indicate she is paying attention to the ECA speech. The ECA then detects the touch gesture, interprets it and reacts accordingly through voice or facial expression.

8.5 Discussion and Future Work

This chapter presents a new fabrication method to create devices with anthropomorphic form factors that could be suitable for areas of research such as Shape Changing Interfaces [Alexander et al., 2018] [Kim et al., 2018] or Organic User Interfaces [Holman and Vertegaal, 2008]. However, there are still some limitations that need to be addressed in the future.

Technical evaluations. Further tests are needed to evaluate the robustness of our system. While preliminary studies indicate that we can recognize 8 touch gestures and multi-touch ones, taking individual variability into account and using better recognition algorithms (typically relying on machine learning) would improve the recognition rate and allow distinguishing variations of these gestures (e.g. soft grab vs. hard grab). We also plan to study the factors (e.g.the number of repetitions, gesture strength, etc.) that alter the sensing capabilities and the mechanical properties of the artificial skin. In particular, the orientation of stretch gestures seems to impact the maximum strength that can be applied. Indeed, the grid layout of the electrodes facilitates the stretch in diagonal directions, where the stretch is greater than 50% while it is limited to 30% on the horizontal and vertical axes. Thus, the orientation of the artificial skin should be preferably chosen

in such a way that frequent stretch gestures are performed on the diagonal of the grid. This work also brings technical challenges that are worth deepening and that are not covered in this chapter, including the impact of curvature on spatial sensing acuity and signal to noise ratio.

Additional Skin-On form factors. We see several directions to investigate other form factors. First, it would be interesting to consider larger surfaces, such as interactive tables or, as one participant spontaneously mentioned, a Skin-On wall. Larger surfaces introduce technical challenges as there is a trade-off between the acuity and the responsiveness of the interface. However, different areas could have different acuity, as it is the case with the human body. For instance, finger tips (2.3mm) are more sensitive than the calf (45mm) [Weinstein, 1968]. Similarly, the sides of an interactive table could have a higher resolution than its center, as more interactions occur in the vicinity of the user position.

While this chapter focuses on augmenting common interactive systems (PC, smartphones, smartwatches), Skin-On Interfaces could also be useful in a wide range of setups, including prosthetic, robots or connected objects. We envision interaction scenarios where Skin-On and On-Skin interfaces co-exist in a complementary way: the continuity of interaction across existing devices (mobile, desktop and skin-worn) would be maintained through similar skin-based interaction paradigms.

Skin-On interfaces with output abilities. Engagement in a social interaction can be defined as "*the value that a participant in an interaction attributes to the goal of being together with the other participant(s) and of continuing the interaction*" [Poggi, 2007]. It is a crucial vector to keep the interaction going on, so that participants continue exchanging information and establishing trustworthy relationship. Showing, perceiving, adapting to each other emotion are important cues of engagement. While, so far, we have focused on conveying different types of information with Skin-On interfaces, our future aim is to perceive affect through artificial skin to reinforce engagement between interaction partners. For instance, the color of the skin could change (using thermochromatic ink) to inform about a new message or to communicate the emotional state of the user. Similarly, the texture of the skin could change (sweat or goosebumps) to convey disgust or frustration. Shape-changing mechanisms such as air cavity [Follmer et al., 2013a] could be used to stiffen some parts of the skin (e.g. veins, muscles) to modify the relief of the skin epidermis, thus the gesture performed on the skin. More

generally, our goal is to further explore various types of anthropomorphism towards humanlike devices.

8.6 Conclusion

In this chapter, I presented Skin-On Interfaces, a prototype of anthropomorphic interactive artificial skin for devices. I presented the fabrication method as well as application scenarios that leverage affective and social touch. Skin-On Interfaces are capable to detect affective human touches, such as stroking or a pinching, which is a gesture not frequently detected by artificial skin.

The creation of a sensing layer that can sense touch with a fine acuity partially contributes to respond the PROBLEM 2.1 of this thesis: *what are the requirements to replicate a realistic human skin*. In this case, requirements are both physical and technical: The sensing method reproducing the *dermis* layer is flexible and thin enough to be combined with the realistic artificial skin. Combined with the findings of the previous chapter, Skin-On Interfaces provide a complete design of artificial skin, and can be used to sense touch in a mediated communication context. The addition of Skin-On to existing devices used for mediated communication (e.g. smartphone) answer the problem PROBLEM 2.2 of this thesis. The fabrication method we propose is simpler than existing artificial skin and the open-source software and hardware platform favors a replication by HCI practitioners and designers.

I believe this work extends the boundary of traditional interactive devices by opening up the user experience to anthropomorphic interfaces and new familiar organic interaction between humans and machines. As seen in the chapter 2, humans have a biological predisposition to form attachment with social partners, and even inanimate objects, including mobile devices [Konok et al., 2016]. Several studies on interactive stuffed animals and robots have shown that they increase human engagement [Yohanan et al., 2005, Yohanan and MacLean, 2012]. Using artificial skin on a device may create similar effects, and should be investigated in future work. It could change the engagement or affect that we have towards inanimate objects such as interactive devices, for instance by strengthening the personal bond with the device.

This work also explores the intersection between man and machine (human augmentation) from a new perspective: Instead of augmenting the human with parts of machines, we demonstrate how machines can be augmented with parts of human. Uncanny valley has been principally a no-go zone in HCI [Bartneck et al., 2009], and our work challenges this. Skin-On Interfaces is a step towards humanlike input interface and offers new perspective around technical and conceptual aspects.

WHAT YOU MUST REMEMBER

Contributions:

- Fabrication method for multi-touch sensing on artificial skin
- Open-Source hardware and software toolkit that enables simple multi-touch detection and advanced computer vision treatment.
- Application and scenarios that demonstrate how Skin-On Interfaces can be used with existing devices

Part IV

Conclusions and Perspectives

9

Conclusion and Perspectives

The direction I follow in this research is that the design of input and output capabilities of user interfaces should be inspired by the human's body. This dissertation is a first step toward this idea, through the prism of affective touch communication. Instead of relying on traditional input interfaces, in this thesis, I created interfaces that aim to replicate how humans communicate and that look and feel natural for the user.

For this purpose, I proposed to use anthropomorphic affordances to design interfaces. This paradigm was motivated by the fact that we are used to interact with others by using touch as an affective communication channel, but current existing devices neglect this channel. To address the research questions of this thesis and explore devices with anthropomorphic affordances, I built upon Human biological characteristics and digital fabrication tools and methods. The devices presented in this thesis propose new technical or empirical contributions around touch detection and touch generation. This thesis thereby contributes to the understanding of the value of new design paradigms for emotional touch communication. In

this chapter, I summarize the findings and contributions of the thesis, I discuss perspectives, future research and the implications of this work.

9.1 *Progress on Research Problems*

This thesis was originally motivated by the question *How devices for mediated touch communication can be more humanlike and integrated with our devices daily used*. From this initial problematic, I derived two research questions, PROBLEM 1 is related to the generation of affective touch, PROBLEM 2 is related to the detection of affective touch. I provide a summary of how I addressed these problems in the thesis.

9.1.1 PROBLEM 1 *Is it possible for an actuated device to produce humanlike touch?*

(a) (b) (c)

Figure 9.1: Devices created to explore PROBLEM 1: a) A robotic device with human hand as end-effector, b) MobiLimb connecting to a smartphone, c) MobiLimb with humanlike skin.

I addressed this question by designing two systems I used to observe how device-initiated touch can convey emotions and to explore possible scenarios.

The first step was to understand how touch is performed by humans. After analyzing the related work in different domains – from physiology to HCI –, I proposed to consider touch as a composition of different factors. To reproduce humanlike touch by a device (Figure 9.1-a), I selected and presented several parameters in Chapter 5: Velocity, Amplitude, Speed and touch Type (or movement repetition). I then performed a laboratory experiment to experimentally assess if a device-initiated touch can convey emotions. I used a device with a rubber human hand as the end effector and

presented different touch stimuli to the users. The experiment presented in Chapter 5 was performed in a controlled environment and raised some technical challenges such as knowing the user body position to apply a touch contact on the forearm. The system was effective to convey distinct emotions, suggesting that i) the choice of factors was relevant ii) a device initiated touch can convey emotions when the touches parameters are similar to a human touch. This work provides the foundations for further investigations on device-initiated touch by a large-scale device.

These initial results encouraged me to further explore how to use device-initiated touch with a small-scaled device in a context of mobility. I designed a robotic actuated device that looks like a finger and that can be plugged onto a smartphone. *MobiLimb* (Figure 9.1-b), presented in Chapter 6, is capable of touching the user on the wrist or the back of the hand. This *proof of concept* demonstrates that it is possible to perform affective touch in a mobility context with a small device. This prototype allowed me to experiment with other scenarios (non-touch-related), to design interactions, and to observe the users' reaction with such scenarios in a qualitative study.

In summary, the two systems are complementary. The first system and its study contribute in empirical knowledge and demonstrate that a device can convey affective touch. The second system provides a technical implementation and demonstrate the feasibility of a small scale device that conveys touch in a mediated or mobile context.

9.1.2 Problem 2 *How can we embed humanlike artificial skin into existing devices?*

To address this problem, I decided to rethink traditional input devices and to use anthropomorphic affordances to propose an interface that looks and feels like human skin.

I first identified the requirements to design artificial skin. I drew inspiration from the human skin. I found that the skin layers have different mechanical properties that influence the tactile and kinesthetic perception. To reproduce such properties, I used silicone with different pigmentation, texture and viscosity and performed perceptual studies presented in Chapter 7 (Figure 9.2-a). I demonstrated that for visual and tactile perception,

(a) (b) (c)

Figure 9.2: Devices created to explore PROBLEM 2. a) Different versions of artificial skin, b) Skin-On Interfaces augmenting existing devices c) Realistic Skin-On Interface on a mobile device

skin-like texture and pigmentation suggests interactivity. For the kinesthetic perception, the surface texture and fat layer influence the comfort and facilitate the execution of gestures. These results can be used for the design of other artificial skin. They suggest that anthropomorphic affordances convey interaction. The study also emphasizes the need to consider kinesthetic and tactile perception when designing artificial skin.

These considerations helped the design of an *interactive* artificial skin that can be added on top of devices. I presented in Chapter 8 *Skin-On Interfaces* over three different devices, a smartphone case, a smartwatch and a laptop touchpad (Figure 9.2-b). This artificial skin is able to detect gestures that are commonly used in human-to-human communication, such as pinching or tickling, but generally ignored by interactive devices. The proposed scenarios illustrate that we can embed humanlike artificial skin on a device. It can not only reinforce affective communication but also improve user input's expressiveness.

In summary, by mixing perceptual studies and digital fabrication, I provided a new approach for designing artificial skin and prototypes that augment existing devices. The proposed design can be used in other domains such as robotics for conceiving robotic skin.

9.2 *Scientific Contributions*

This research has contributed to the understanding of affective touch perception and the design of anthropomorphic devices for affective touch by exploring both the input and output capabilities of such devices. The contributions made in this thesis are related to the engineering, design and social sciences. They consist in Empirical, Artefact, Methodological and Opinion

contributions. The main contributions of this thesis are summarized below.

- Empirical Contributions
  - *Touch factors compatible with a device.* I defined a set of touch factors inspired by human touch movements compatible with a device that applies touch movements on users to convey emotions. I proposed to consider dynamic touch movements as a composition of Velocity, Amplitude, Speed and Type (or repetition). To validate the relevance of these touch factors, I conducted a study that demonstrated that their combination has an impact on the perception of emotions.
  - *Communication of emotions through device-initiated touch.* I conducted several perceptual studies to understand the impact of device-initiated touch on arousal and valence perception. I implemented the touch factors onto a device and created a set of stimuli that were performed on user's forearm. The results of these studies suggest that combination of touch factors can be perceived as conveying different emotions. When context, defined by a text and the facial expression of a virtual character, was provided, it modified slightly the perception of touch.
- Artifact Contributions
  - *Design and development of a robotic actuator for mobile devices*. I created a finger-like robotic device that can be plugged onto a mobile device to perform touch on the user's wrist. This contribution demonstrates the feasibility of a small scale actuator that can be combined with an existing device already used for mediated communication. I further explored the input and output capabilities of this device and presented application examples using it as a tool or a virtual partner.
  - *Design and development of artificial skin for devices.* I developed a novel hardware interface for multi-touch detection that can be fixed onto existing devices. This engineering contribution reproduces the dermis sensing capabilities of the skin. I developed hardware relying on mutual capacitance sensing technique and a low-cost open-source and open-hardware platform that enables simple multi-touch detection and computer vision treatment.
- Methodological Contributions
  - *Novel approach to design artificial skin*. I proposed a bio-driven approach inspired by bio-mechanical aspects and properties to inform the de-

sign of artifacts. This approach conciliates a holistic approach and an iterative design process, drawing inspiration from the analysis of the different layers of the human skin. It helped to select materials with adequate mechanical properties to reproduce the dermis, epidermis and hypodermis layers with appropriate visual and kinesthetic qualities.

  - *Fabrication of artificial skin*. I proposed a new fabrication method for multi-touch sensing on malleable surfaces that enable research practitioners to create a realistic artificial skin easily. To this extent, I encapsulated stretchable insulated conductive wires to create electrodes within a silicone substrate.

- Opinion Contributions

  - *Design for Anthropomorphic Affordances*. I promoted the design of devices with anthropomorphic affordances. I illustrated this by designing a device that looks like the human hands and fingers and can perform touch in a similar fashion. I also illustrated this approach with an interface that augments existing devices with artificial skin. By leveraging human tactile and haptic qualities this input surface not only supports existing input methods but enables exploring novel methods that are more natural and closer to human-human interaction.

9.3 Perspectives and Opportunities

This thesis is the first work to investigate anthropomorphic interfaces for touch communication in HCI. The prototypes were developed by following a strong *Critical Design* approach [Dunne, 2008], which opens more research questions, in short medium and long terms.

9.3.1 Short and Medium Term

- *Technical Evaluations*. The devices presented in this thesis are HCI prototypes and more *technical* work is needed to create robust interfaces. The robotic device presented in Chapter 5 shares the space with the user. In a deployed use case, it is crucial to ensure user safety. Hence, future tests should evaluate necessary measures to ensure participants' security,

including robust user tracking, precise inverse kinematics for the virtual human used as a predictor of the user's movement, explicit Cartesian force control (both for safety and performance reasons) as well as the definition of a limited and well-identified interaction zone.
For *Mobilimb*, one main technical challenge is the miniaturization and the robustness. An actuation method providing a high torque could be used to push heavy physical objects, and increase the force precision applied on the user's skin (within a bearable limit). This point is especially important to convey emotions through touch. Although high-torque actuators are currently available, they are based on considerably more expensive components, or exotic materials requiring specific implementations of position and force control schemes. For *Skin-On Interfaces*, some technical evaluations need to be conducted, such as how touch detection is impacted when the interface is stretched and to measure the impact of curvature on spatial sensing acuity and the signal-to-noise ratio.

– *User Evaluations*. Our results of device-initiated touch highlight differences in individual ratings. A system should be able to adapt to how people perceive touch stimuli as emotions. User evaluation needs to be conducted to assess the benefits of individual calibration when the interaction is started. Further evaluation studies need to be conducted with *Mobilimb* and *Skin-On Interfaces* to measure their appeal, functionalities, ergonomy and usability.
For *Mobilimb*, an evaluation could explore whether similar touch characteristics as found in our studies (see Chapter 2) would have similar meanings if conveyed on the wrist of the user.
Skin-On Interfaces can be used to analyse the efficiency of anthropomorphic affordances. We can study if, when no explanation is provided, users would interact with the devices as they interact with humans? In the different projects presented in this thesis, the users interacted over a short period with the systems. It would be interesting to assess how their way of interacting changes over time. Moreover, a longer interaction period will involve different contexts of use. Studies are needed to analyse how the context impacts user interaction with these devices.

– *Social Acceptability. MobiLimb* and *Skin-On Interfaces* received a lot of media attention. Both projects were published in more than **300** online and press articles (including *New Scientist*, *BBC*, *Fox*, *CNN*,..) and the

videos were seen more than **10 Millions** times on various platforms. This media exposure generated a lot of public discussion, and the article headlines revealed some social acceptability challenges. As an example, here are some headlines for *MobiLimb "Smartphone with a finger crawls across the table to stroke your wrist" – New Scientist*[1], *"Feely finger phone crawls across desk" – BBC* [2], and for *Skin-On Interfaces "Creepy humanlike skin makes your phone ticklish and pinchable" – New Scientist*[3], *"This phone case looks and feels like human skin " – CNN*[4]. The headlines use words from human interaction such as *"crawling"*, *"ticklish"*,*"pinchable"*, which suggest the anthropomorphic affordances are perceived. Most importantly, these headlines explicitly state that the projects are perceived as creepy. This is further empathized by the written comments from the viewers (more than **10000**). This amount of data is a great opportunity for qualitative research. The analysis of these textual reactions can help understand the public perception and how and why people had such a strong reaction. *Do the people share the same cognitive scheme of rejection? Is it linked to Uncanny Valley?* This knowledge can provide insight that might help us to create future anthropomorphic interfaces that are socially acceptable.

[1] By Douglas Heaven – link

[2] By Chris Fox – link

[3] By Donna Lu – link

[4] CNN – link

– *Supporting the HCI community*. *Mobilimb* and *Skin-On* are both low cost, DIY and open-source platforms. The media attention these projects received reveals that the HCI community is eager for accessible tools and platforms to develop new hardware, and wants to experiment and propose new interactions for anthropomorphic interfaces. I believe that creating accessible, low cost and DIY tools for designers and the HCI community opens many possibilities, such as replication and creative hacking, and can inspire other researchers working around the same ideas. It is also an opportunity to develop more uses cases and scenarios, for instance, the finger design of Mobilimb can serve in a robotic context for manipulating objects, while the artificial skin design proposed in Chapter 8 can serve to cover human prosthetic. Both projects are currently being used by engineering scholars as educational tools and for creative workshops on uncanny valley. Through the projects of this thesis, I promoted open-source and I want to continue providing hardware solutions for the HCI community. This perspective can be explored in the short term, by collaborating with other researchers with complementary knowledge and by providing new tools and fabrication method fabrication. To facilitate the accessibility of Skin-On sensing technology, I am currently mass-producing the breakout board.

9.3.2 *Medium and Long Term*

– *Bio-Inspired Methods*. In this thesis, the design of the prototypes was inspired by human. I used a bio-driven approach where I took inspiration from the human body and from human movements to design both the interactive and technical properties of Skin-on interfaces. Bio-inspired research is typical in fields such as Robotics or Material Engineering, with a particular aim at borrowing nature structure and mechanical abilities to create new mechanical material and interactions [Oliver et al., 2016, Dargahi and Najarian, 2004]. The work presented in this thesis only tackles the bio-driven approach and apply this principle only in the context of touch. Other aspects of the bio-driven approach can be further explored, such as inspiration from *humans*, inspiration from *animals* or inspiration for *plants*. Future work could explore other physiological characteristics of the *human* skin. For instance goosebumps, blushing or upright hairs serve as display for others. We can also draw inspiration from other senses. For instance, a realistic eye interface can serve to convey social information by using the movements of the eye, gaze or eyebrows shape. Some *animals* also have interesting physical properties that can inspire the design of interfaces to change shapes depending on context. For instance, the spines of a Hedgehog, or the Porcupinefish, that can inflate and serve as self-defence mechanisms, change radically of shape. Finally, the organic structures of the *plants* can inspire the design of the structure and the shape of a device. Overall, such bio-inspired approaches involve methodological, creative and technical challenges. They require to study and understand the biological mechanisms to replicate them in an interface, and their fabrication process requires collaboration from other research communities such as material science. Further investigations are needed to provide clearer guidelines to follow a bio-driven approach in HCI.

– *Critical Design.* The projects presented in this thesis have a strong stance on the design of future interfaces. I do not only explore the interaction with such devices but also propose a radical critical aesthetic experience of what could be the look and feel of the devices. One opportunity for future research is to explore how interactive systems with anthropomorphic affordances can be used as a critical medium to help reflect on our interaction with technologies. This raises critical design [Dunne, 2008] questions around the ethical, social, and cultural aspects of the impact

of technologies on our lives. Further research should also investigate the minimum cue from which the anthropomorphic affordance is conveyed to the user. Mobilimb (Chapter 6) or Skin-On Interfaces (Chapter 8) use full embodiment metaphor and try to replicate the biological, mechanical as well as the visual aspect of the humans. However, it could be possible to convey subtle metaphorical cues to represent human and anthropomorphism such as humanlike movements [Bianchini et al., 2016] to reproduce behavior. Overall, this works raises opportunities to emphasize the importance of the physical aspect of the product design and encourage reflection around devices with unusual shapes and aspects. Future work should investigate design as social research for interaction.

– *Transhumanist perspective.* The work around anthropomorphic interfaces has more profound implications for technologies in general. Transhumanists believe the future of humans is a mix between humans and machines. This concept of cyborgs considers that humans will augment themselves with devices [Brummett, 1999, Bostrom, 2005]. The design of anthropomorphic devices can be seen as having the same end goal. Rather than augmenting humans with machine parts, machines can be augmented with human parts. Similar to transhumanism, anthropomorphic interfaces can have different levels of aesthetics and functions, thus foster different interactions and perceptions. Anthropomorphic interfaces could range from a single anthropomorphic element attached device, e.g, a finger, where the shape and function of the device remains clear, to a fully organic user interface such as Cronenberg's Pods in *eXistenZ*, where technology is barely noticeable. I believe that thanks to anthropomorphic design, devices can be seen as independent actors and be perceived more as interaction partners than interaction tools [Beaudouin-Lafon, 2004]. Rather than creating a fully humanlike interface, using an existing device on which we plug anthropomorphic features allows us to explore the potential of these features gradually, thus to select their most desirable aspects. Practical work has to be conducted to develop new prototypes that probe different facets of anthropomorphic affordances. Theoretical work has to be conducted in parallel to better understand the perception, and to reflect on whether such a vision of technology is desirable or not.

9.4 Conclusion

In summary, this thesis contributes to the design and understanding of anthropomorphic devices for affective touch communication. In this thesis, I promote the use of anthropomorphic affordances to design interfaces that benefit from our knowledge of physical interaction with other humans. Anthropomorphism has received little attention so far in the field of Human-Computer Interaction, and its design space is broad and still largely unexplored. The studies, devices, fabrication processes and toolkits presented in this thesis facilitate its exploration and the development of interfaces that can convey and detect touch. It provides support for future research to explore how affective communication can be expressed with humanlike interfaces and allow further interfaces and scenarios to be generated. As illustrated by the prototypes presented in this thesis, it is possible to use simple and DIY approach to leverage anthropomorphic affordances. Ultimately, traditional devices would ideally be enriched with anthropomorphic affordances to provide another layer of expressivity.

The work in this thesis is a first step towards the design of prototypes based on this concept. It raises further questions that can be addressed with new experiments and studies. This approach offers an original perspective on interface design and proposes a critical design thinking view. The media exposure and public perception reveals that social acceptability is a challenge we should face. As communication is part of our daily lives, this topic is important to tackle, and a radical approach in the design of interfaces brings discussion around our relationship with the technology.

A

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Titre : Dispositifs Anthropomorphiques pour la Communication Tactile Affective

Mots clés : Toucher Affectif, Dispositifs Anthropomorphiques, Interaction Homme-Machine, Retour Haptique, Fabrication Digitale

Résumé : Le toucher, y compris le contact cutané entre les humains, déclenche une connexion physique et un attachement émotionnel. Alors que de nombreuses études ont considéré les modalités acoustiques et visuelles comme des moyens communicatifs, le toucher a été beaucoup moins exploré dans des situations où les humains interagissent avec des machines ou avec eux-mêmes par l'intermédiaire de machines. En outre le toucher permet une expérience intime comme on peut sentir le sentiment d'autrui et envoyer son sentiment sans avoir des étrangers le remarquer. L'objectif de ce projet est d'étudier le contact social. Il ne se concentre pas sur les technologies tactiles, mais sur la façon dont ces technologies peuvent être utilisées pour améliorer l'interaction humaine avec les petits appareils portables et les agents conversationnels incorporés (ECA). Ses objectifs sont (1) de comprendre les principes du toucher social et de prédire son impact sur l'engagement; (2) concevoir de nouvelles techniques d'interaction pour améliorer l'expérience de l'utilisateur. Son originalité est de se concentrer sur un moyen communicatif et émotionnel qui a été quelque peu négligé par rapport à d'autres canaux et à aborder des thèmes innovants tels que le rôle de la touche sociale pour favoriser l'engagement dans l'interaction homme-machine. Certaines applications incluent des jeux, des dispositifs portables, des ECA, des achats virtuels, des notifications discrètes, un biofeedback.

Title : Anthropomorphic Devices for Affective Touch Communication

Keywords : Affective Touch, Anthropomorphic Devices, Human-Computer Interaction, Haptic Feedback, Digital Fabrication

Abstract : The sense of touch, including skin contact between humans, triggers physical connection and emotional attachment. While many studies have looked at acoustic and visual modalities as communicative means, touch has been much less explored in situations when humans interact with machines or with themselves via machines. Moreover touch allows for intimate experience as one may sense other's feeling and send one's feeling without having outsiders notice it. The goal of this project is to study social touch. It does not focus on touch technologies but on how these technologies can be used to enhance human interaction with small wearable devices and Embodied Conversational Agents (ECAs). Its objectives are (1) to understand the principles of social touch and predict its impact on engagement; (2) to design novel interaction techniques to improve user's experience. Its originality is to focus on a communicative and emotional mean that has been somewhat overlooked compared to other channels and to address innovative topics such as the role of social touch to foster engagement in human-machine interaction. Some applications include games, wearable devices, ECAs, virtual shopping, discrete notifications, biofeedback.

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