MobiLimb: Augmenting Mobile Devices with a Robotic Limb

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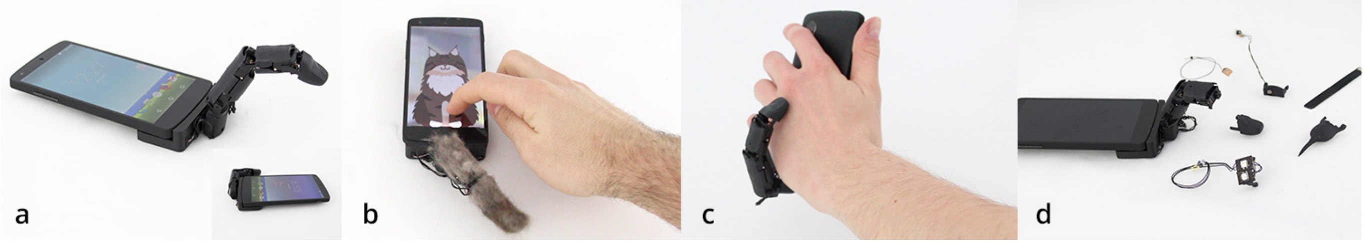

Figure 1: **MobiLimb is attached to a mobile device to extend its I/O capabilities while keeping a small form factor when folded. MobiLimb can be used, for instance, a) as a tool to display notifications, b) as a partner to foster curiosity and engagement, c) as a medium to perform rich haptic feedback. d) MobiLimb also supports several modular tips (e.g. LED, shells, proximity sensors) to create new forms of interaction.**

ABSTRACT

In this paper, we explore the interaction space of MobiLimb, a small 5-DOF serial robotic manipulator attached to a mobile device. It (1) overcomes some limitations of mobile devices (static, passive, motionless); (2) preserves their form factor and I/O capabilities; (3) can be easily attached to or removed from the device; (4) offers additional I/O capabilities such as physical deformation and (5) can support various modular elements such as sensors, lights or shells. We illustrate its potential through three classes of applications: As a *tool*, MobiLimb offers tangible affordances and an expressive controller that can be manipulated to control virtual and physical objects. As a *partner*, it reacts expressively to users' actions to foster curiosity and engagement or assist users. As a *medium*, it provides rich haptic feedback such as strokes, pat and other tactile stimuli on the hand or the wrist to convey emotions during mediated multimodal communications.

ACM Classification Keywords

H.5.2. Information interfaces and presentation: User Interfaces Haptic I/O, Input devices and strategies

Author Keywords

Mobile device, Actuated device, Robotics, Mobile Augmentation, Robotic limb

UIST '18, October 14–17, 2018, Berlin, Germany

ISBN 978-1-4503-5948-1/18/10. . . $15.00
DOI: https://doi.org/10.1145/3242587.3242626

INTRODUCTION

Shape-changing interfaces are part of Ivan Sutherland's [60] or Ishii's visions [31] about changing the way users interact with computerized systems. By using the visual, haptic and kinesthetic senses, shape-changing interfaces leverage our real-world abilities to better interact with systems. For instance, they can provide adaptive affordances, favor communication or increase user's enjoyment [2]

Shape-changing mechanisms have been shown especially relevant for mobile devices. For instance, they have been used to increase performance [34] or to improve interaction or interpersonal communication [46, 48, 49]. However, while smartphones or tablets provide a ubiquitous platform to promote shape-changing interfaces, current technology tends to be bulky, expensive and to not fit the form factor of mobile devices [2], making difficult a wide adoption of this technology.

We present *MobiLimb*, a new shape-changing component with a compact form factor that can be deployed on mobile devices. *MobiLimb* is a small 5 DoF serial robotic manipulator that can be easily added to (or removed from) existing mobile devices (smartphone, tablet). In the spirit of human augmentation, which aims at overcoming human body limitations by using robotic devices [53], our approach aims at overcoming mobile device limitations (static, passive, motionless) by using a robotic limb. This approach preserves the form factor of mobile devices and the efficiency of their I/O capabilities, while introducing new ones: (1) the users can manipulate and deform the robotic device (input), (2) they can see and feel it (visual and haptic feedback), including when its shape is dynamically modified by the mobile device. Moreover, as a robotic manipulator, (3) it can support additional modular elements (LED, shells, proximity sensors).

In this paper, we explore the design space of MobiLimb. We first describe its implementation and its integration on a mobile device. We then discuss human factors worth considering when augmenting a mobile device with a robotic limb. We also illustrate how MobiLimb leverages three primary interaction paradigms [6] as a *tool*, as a *partner* and as a *medium*.

As a *tool*, MobiLimb offers an expressive mean of manipulating objects, interacting with the physical environment, delivering notifications or providing guidance. 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 behaviors 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. 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.

Finally, we report on a user study investigating the role of MobiLimb in term of likeness, usefulness and fun through 13 scenarios.

RELATED WORK

Mobile Devices and Haptic Feedback

The popularity of mobile devices has encouraged researchers to explore various ways of augmenting their input and output capabilities.

For input, MobiLimb is related to projects augmenting the touchscreen with tangible objects providing both physical interaction and additional degrees of freedom. For instance, TouchToken [42] or GaussBricks [40] allow to move, squeeze and stretch tangibles at the surface of the screen, whereas Capstones [9] also provides an extra dimension by detecting stackable elements. Input methods external to the screen are also designed to interact with the back [5] or the sides of the mobile device [8]. Input accessories located next to the device provides a new way to interact with the device [30, 7, 36].

For output, several approaches have been proposed, including using advanced vibration motors [65], additional screens [23] or shape-changing interfaces [34]. A notable advantage of many of these approaches is that they augment the back or the side of the phone, which preserves the efficiency of the I/O capabilities of the original device.

To communicate emotions, current commercial mobile devices mainly rely on the audio and visual channels (voice, text, emojis) and somewhat neglect the tactile/haptic modality. Some previous studies have addressed this issue because the haptic modality has been shown to enable communicating more affective feedback [18, 61, 57]. For instance, text messages have been augmented with "haptic icons" [56]. However, the vibration motors that are commonly used on mobile devices have limited capabilities [27, 39, 65] and can convey only a limited range of emotions [27]. Moreover, the spatial resolution of human skin makes this technology not well suited for this purpose [47].

MobiLimb is not limited to tactile feedback (vibrations). By allowing directly touching the user, MobiLimb also provides kinesthetic feedback. This capability should enhance communication because it mimics what humans do. Moreover, MobiLimb enables direct manipulation and support various interactions with the surrounding environment.

Shape-Changing Mobile Devices

Shape changing interfaces have been used as a way of augmenting mobile devices to adapt them to their context of use [60, 2]. To enhance output capabilities, the device can take the shape of a controller when playing a mobile game [55] to transform the phone into a flexible surface [16]. Shape-changing phones are also used to explore more organic interfaces, by providing subtle life-like notifications [19], fostering engagement through proxemic behavior [32, 20] or conveying emotions [50, 59, 49].

MobiLimb builds upon this literature and also provides the benefits of physically interacting with the environment. Our approach makes use of an additional device, that can easily be added to/removed from the mobile device, which preserves the form factor of the mobile device and the efficiency of its I/O capabilities.

Some shape-changing mobiles devices are designed to maintain the form factor of the smartphone [48, 46, 34]. Haptic edge [34] provides moving elements on the side of a smartphone. Wrigglo [48] and Come Alive! [46], which are aimed at improving mediated communication, also follow a similar approach by using movable antennas at the top or side of the device. But they offer fewer degrees of freedom than MobiLimb and do not provide rich haptic feedback.

Robotics and HCI

MobiLimb lies at the intersection of HCI and robotics such as SixthFinger [29], ChainForm [44], Lineform [45], Zooids [37], LivingDesktop [4] or LuminAR [41], where robotic elements enhance interactions.

In particular, MobiLimb is related to the research area of *Supernumerary Robots* (e.g. sixth finger), which aims at augmenting the human hand with additional fingers or limbs [29, 62, 63, 26]. This field has been recently explored as a way of helping users to perform tasks when using a PC or a smartphone. Such systems can, for instance, help users grasp objects or provide additional tools [38]. To some extent, MobiLimb provides similar functionalities but does not require wearing specific equipment because it augments the mobile device rather than the human body. Lines interfaces [45, 44] and other actuated systems [37, 4, 41] also explore new tangible visualizations and interactions, but their current implementation does not make them usable for mobile devices and for handling expressive behaviors.

Finally, MobiLimb is related to robotic systems for videoconference [24] or social interaction [1] that take advantage of the versatility, availability and low cost of smartphones. For instance, MeBot [1] is a small humanoid robot for videoconference systems whose face has been replaced with a smartphone to display the remote user. In contrast, our approach

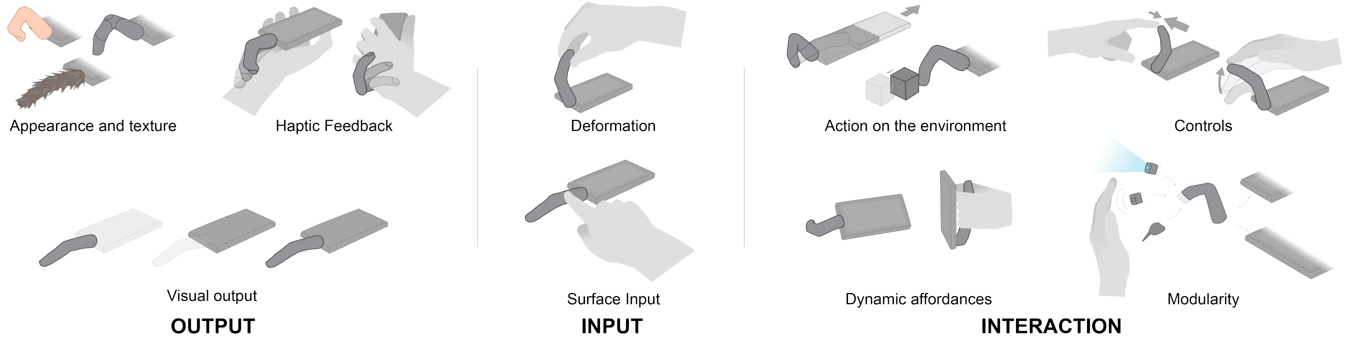

Figure 2: Design space of MobiLimb.

focuses on the smartphone and aims at augmenting its functionalities with robotic elements. Mobilimb is also related to zoomorphic toys (robotic stuffed animals) [64] and small wearable robots like Teroos [35], which can react through movement or direct touch and can improve affective communication between humans and robots.

MOBILIMB

MobiLimb consists of a robotic manipulator mounted on a mobile device. We first describe its input and output capabilities and its interaction space (Figure 2). We then present our implementation and discuss the main human factors we considered for building this device.

Output

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 5-e). MobiLimb can also provide dynamic notifications by moving or shaking the robotic device, for instance when incoming mail is received (Figure 5-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-a).

Haptics. Haptic feedback is most often limited to vibrations on commercial mobile devices [65]. 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 [22] or perform a physical contact on the inner wrist (Figure 7-c) or on the back on the hand (Figure 7-a,b). Both the wrist and the hand are "social organs" [22], 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 [12]. The texture and material covering the device can also enrich the type of tactile and visual feedback [3]. For instance smooth fur (Figure 6-a) or human-like skin (Figure 7-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-b).

Input

MobiLimb adds two input capabilities – physical deformation and touch detection – for controlling the mobile device (or connected devices such as remote displays), to increase 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 then use it like a joystick to manipulate 3D articulated objects (Figure 5-b). MobiLimb also detects when the users are *touching* or patting it and be used for instance as a tangible slider.

Interaction

By combining I/O capabilities, MobiLimb provides a rich interaction space.

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 the user's movements [58].

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 [34, 14, 55, 54, 49]. MobiLimb can model its shape (Figure 5-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 5-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 move in its environment, by making it crawl like a caterpillar (Figure 5-f).

Modularity. In contrast to pure design explorations such as those conducted by Pedersen et al. [50], MobiLimb requires no modification to current mobile devices, it does not alter its I/O capabilities (Figure 3 left) or its form factor. MobiLimb can simply be added to most of existing smartphone and tablets (with a micro USB) depending on the users' needs and constraints.

The input capabilities of MobiLimb can also be used in combination with those of the mobile device. For instance, users can manipulate the robotic [**?**] with one hand while interacting on the screen with the other hand (Figure 5-b).

Additional components, such as sensors or actuators, can easily be fixed to the "tip" of the device [38]. 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 1-d). The user can also attach physical objects to the device, as for instance a pen (Figure 7).

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 [62] or pneumatic actuation [11]. 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 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 3, right side). A 3D printed plastic structure was designed to hold together the servo motors without constraining motion at the different joints. It is thin enough to be covered with different outer shells.

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 × 65mm × 8mm*) attached at the bottom and on the back of the phone, or at the back of the tablet (Figure 1-a). An integrated female pin header allows connecting/disconnecting the servo-motors and 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.

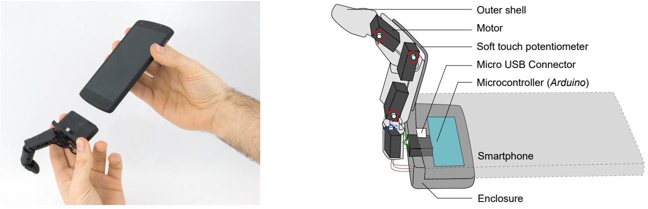

Figure 3: Left: MobiLimb is plug and play and can easily be connected to most of existing device. Right: Current implementation.

API and applications. We developed an Android/Unity API providing two main control methods to drive MobiLimb. Because it provides much freedom, *Forward-kinematics*, which allows controlling each motor individually, is better suited to control animation. In contrast, *Inverse-kinematics* determines the joint angles from the desired position of the end-effector of the device and controls each motor accordingly. This solution is preferred to control actions where the tip of the appendix has to follow a precise path, e.g., when touching the user. We built a Unity application to enable rapid prototyping. This application makes it possible to create, record and play animations easily. To compose a fluid animation, it is possible either to use keyframes or to manipulate the physical robotic limb (using motor sensing) or its virtual representation on the device screen.

Human factors

MobiLimb raises several *technical* challenges related to robotic technologies such as miniaturization, speed, precision, robustness, torque, autonomy or cost, which can alter the usability and utility of such a device. 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 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 (Figure 1-a) to use less space, e.g. for inserting the phone in a pocket or a bag.

We conducted an informal study with seven participants from our research laboratory to compare the impact of three classes of textures on pleasantness. The textures were attached to a non-interactive but articulated device and were individually presented to the participants, who could see and touch them. We then engaged in a discussion to know how they were perceived. The first texture looks like a classic *robotic* shell (in plastic). The second one is in fur (Figure 6-a) and the third one is a "finger-like" skin (Figure 7-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.

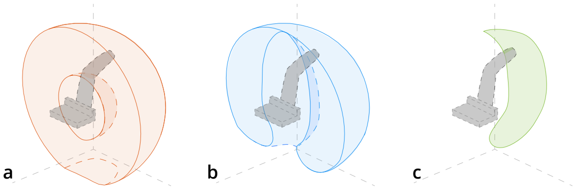

Figure 4: Reachable volume of the prototype from the bottom of the device; a) 5-DOF, b) 4-DOF, c) 3-DOF.

We observed strong reactions regarding the "finger-like" skin, which may be related to the uncanny valley effect [43]. 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. Except for some dedicated use cases where the goal is to trigger curiosity (art) or for specific mediated communications, our recommendation is thus to avoid using too 'realistic' textures as they might make some people feel uncomfortable. However, participants liked when the shell (and its motion) was mimicking the appearance and behavior of animal limbs (e.g. a moving fur cat tail or a scorpion tail).

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 the hand and (2) still have rotation freedom. Figure 4 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, this 5 DOF kinematic structure was sufficient to obtain a large variety of motions and interactions while maintaining a small footprint. In particular, it can illustrate our envisioned scenarios involving haptic feedback because the wrist and the back of the users' hand are the closest available skin surface when users are using a common grip (Figure 7-a) and can thus be reached by the tip of the device.

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 [6].

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.

3D interaction. Users can manipulate the articulation hinges of MobiLimb to control the 3D joints of a virtual character skeleton for 3D animation (Figure 5-b) [33]. 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 5-c).

Holder. Shape changes can be used to create new affordances and improve ergonomics [14]. Pre-defined positions can be reached: MobiLimb can for instance facilitate grasping the phone by taking the shape of a handle (Figure 5 -d).

Off-screen notifications. MobiLimb can produce physical notifications that can leverage different modalities. When the device is laying 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 5-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 [19]. Private notifications can be obtained by moving the device along the thigh.

Plotter. MobiLimb can be extended with a pen to draw messages on a physical support such as a post-it (Figure 7-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 5). 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 localize an object in a 3D model of the environment, which can be captured with, for instance, ARCore platform [17].

Directional Light: Inspired by Pixar's famous lamp character [41], MobiLimb can act as a robotic lamp if a light is added at the tip of the appendix (Figure 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 extend the previous one to spot a given target in the environment regardless of the orientation of the mobile device.

Figure 5: MobiLimb as a tool: a) Notifications display, b) 3D joint manipulation, c) Video preview, d) Improve grasping, e) Directional light, f) Self-actuated movement

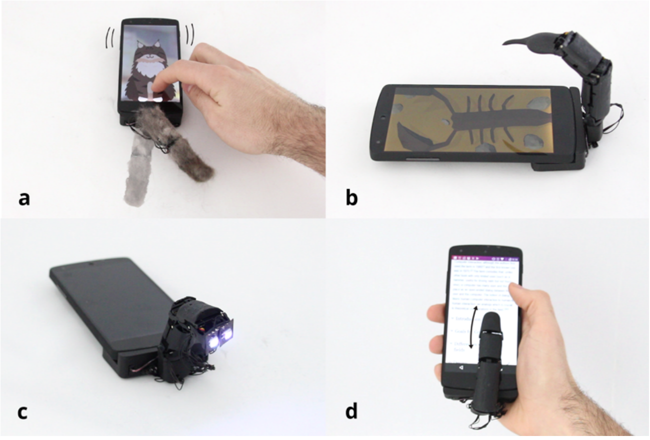

Figure 6: As a *partner*, MobiLimb can express behaviors and embody virtual agents. a) Cat with a tail, that reacts to users' actions. b) Hostile scorpion. c) Curious device. d) Assistive guide showing how to scroll on a page.

MobiLimb as a Virtual Partner

Virtual characters can take the appearance of a human-like 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 [66, 52, 51]. With a smile, a head movement, a gesture, etc. they can display empathy, affect or show their willingness to interact. Such characters usually communicate using verbal and nonverbal behaviors, but lately, some tentatives have been made to endow them with haptic capabilities [28].

Virtual characters can (1) display expressive behaviors, (2) react to user's actions and (3) assist users in their tasks. 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 [25]. Emotions are not only communicated through facial expressions and voice but also through body movements and tactile signals [10, 15]. 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-a) or a scorpion companion (Figure 6-b). By moving around with different expressive qualities it can communicate different emotional states [20]. 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 attached 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 [20]; 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 should also react to users' actions. They 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.

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 in real life on the screen rather than to metaphorical interfaces, without modifying the screen content. It can also imitate a scrolling movement to help users understand the action they should undertake (Figure 6-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.

MobiLimb as a Medium

The primary function of a smartphone is mediated communication using either voice, video or text. While touch plays an important role in co-located communication [21], this modality is often limited to simple vibrations [65]. Its low resolution and fidelity make it a poor candidate for human-like mediated communication, as it does not imitate touch as human does. The haptic channel can be an unobtrusive communication modality [21]. MobiLimb can directly touch the user with different motion qualities to convey a variety of emotions.

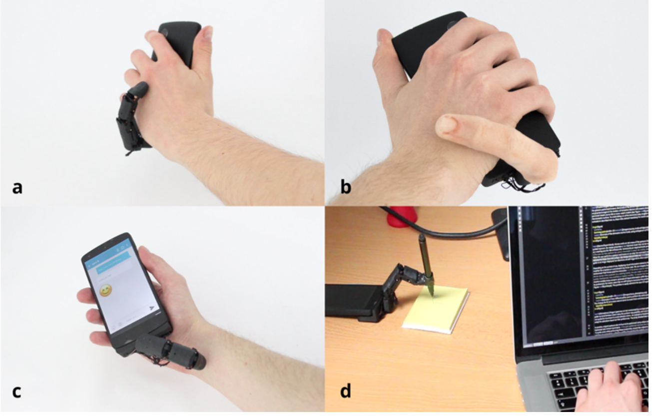

Figure 7: MobiLimb can serve as haptic interface and touch the user on a) the hand or c) the wrist. b) A human-like skin texture can cover the device. d) Physical text messages can be sent between users.

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 7-a-b) or on her/his wrist (Figure 7-c). This tactile communication can be used to express emotions such as comfort (through *stroke*), excitement (*gentle tap*) or anger (*repeated strong taps*) [21, 27]. 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 [21]. 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 [13] during mediated communication.

Other applications for mediated communication have been implemented. For example, when MobiLimb is extended with a pen, it can draw the emoticon that was just received or any other messages. This capacity expands the communication beyond the screen (Figure 7-d).

PRELIMINARY STUDY

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 illustrated in the accompanying video. 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 8. 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 to not bias participants with uncanny 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.)

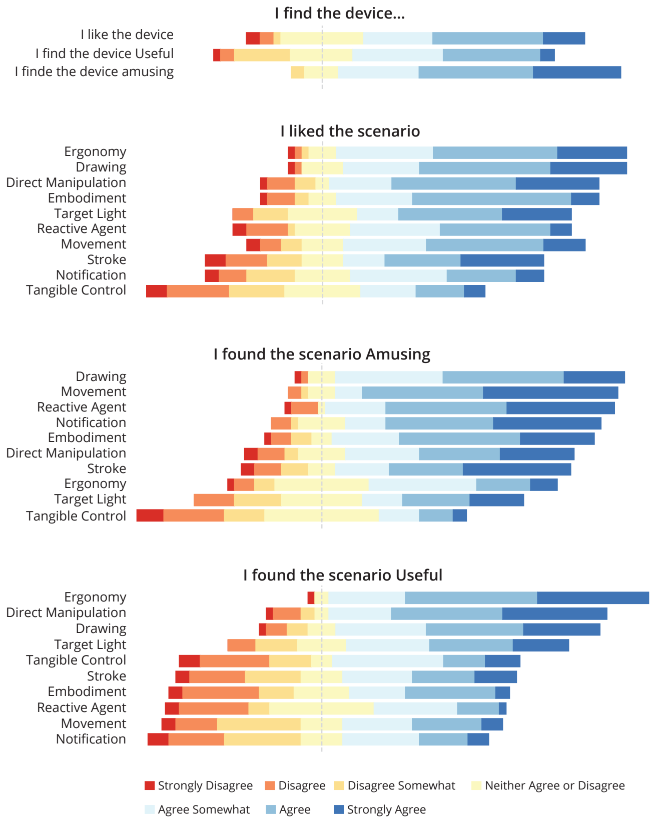

Figure 8: Summary of participants responses to the 7-point Likert scale questions.

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*".

DISCUSSION AND FUTURE WORK

In line with augmenting humans with robotics, we have explored the design space of augmenting mobile devices with a robotic device. We have implemented MobiLimb and used it in different scenarios. We now discuss directions for future work, which focus on technical challenges, evaluation and applications.

Technical challenges. Our implementation of different scenarios highlights the interest of augmenting a mobile device with a robotic manipulator. There are however 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. Although high-torque actuators are currently available, they are based on considerably more expensive components, or on exotic materials requiring specific implementations of position and force control schemes. Another issue is the power source, as they require more energy.

Evaluation study. The preliminary study showcased 10 of our envisioned scenarios to collect initial feedbacks. 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. The choice of movements (type and quality) to convey emotions has to be carefully picked not to create confusion in their interpretation. Stereotyping those movements or getting inspiration from animals show potentials as those movements are easier to distinguish and more likely to be interpretable. We also aim to further explore how MobiLimb can interact with the environment. For instance, information on the surrounding context, using the integrated camera or sound detection, would allow MobiLimb to act more autonomously (thus being more life-like).

Applications. Using an existing device to attach a robotic manipulator enables the exploration of potential and most desirable robotic actuators. We plan to transpose the concept of MobiLimb to different class of devices such as smartwatches, the mouse or everyday objects. This work also opens the venue for a possible anthropomorphization of interactive devices, which could then range from simple robotic actuators augmenting the smartphone to organic user interfaces where technology is barely noticeable. This could radically change our perception of interactive devices.

In conclusion, we see MobiLimb as an example of the synergy between HCI and robotics. MobiLimb 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 [2]). Moreover, most mobile devices provide tactile feedback (vibrations), at the price of a reduced expressivity, whereas complex robotic systems provide kinesthetic feedback, but 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.

ACKNOWLEDGMENTS

This work has received partial support from ANR, with the references ANR-17-CE33-0006 (SocialTouch) and ANR-16-CE33-0023 (GESTURE). Authors wish to thank all the participants of the study. They also thank Y. Jansen, A. Roudaut, E. Dimara, I. Avellino and V. Padois for their constructive feedback.

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