Button+: Supporting User and Context Aware Interaction Through Shape-Changing Interfaces

Jihoon Suh
Department of Human Centered Design and Engineering, University of Washington
Seattle, WA, 98195, USA
jihoons@uw.edu

Wooshik Kim
Department of Mechanical Engineering, KAIST
Daejeon, Republic of Korea
briankim13@kaist.ac.kr

Andrea Bianchi
Department of Industrial Design, KAIST
Daejeon, Republic of Korea
andrea@kaist.ac.kr

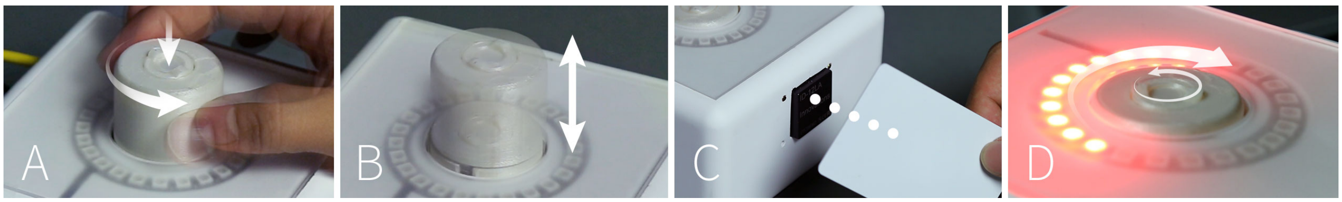

Figure 1. Components of Button+: A) rotary knob and pushbutton, B) actuated shaft with input capabilities, C) RFID reader, D) LED circular array and rotary haptic display.

ABSTRACT
Shape-changing interfaces are an emerging topic in HCI research: they merge the simplicity of tangible interfaces with the expressiveness of dynamic physical affordances. However, while prior work largely focused on technical aspects and proposed classifications of shape-changing interfaces based on the physical properties of the actuators and the user's levels of control, this work presents a classification of shape-changing interfaces based on the context and identity of the users. After introducing a new prototype for a shape-changing pushbutton, we conducted a series of workshop studies with designers and engineers to explore the design space and potential applications for this interface. We used the result of our workshops to propose a generalized taxonomy of interactions, and built two applications that reflect the proposed model. The paper concludes by highlighting future possible research directions for *context and user aware* shape-changing interfaces.

Author Keywords
Button interface; shape-changing interface; context-aware; design; personalization.

TEI '17, March 20-23, 2017, Yokohama, Japan
© 2017 ACM. ISBN 978-1-4503-4676-4/17/03…$15.00
DOI: http://dx.doi.org/10.1145/3024969.3024980

ACM Classification Keywords
H.5.2. Information interfaces and presentation (e.g., HCI): User Interfaces

INTRODUCTION
Shape-changing interfaces are becoming an increasingly interesting topic of research in HCI, mostly because they combine the intuitiveness of tangible interfaces [15] with the capability (typical of purely digital graphical interfaces) of displaying adaptive and dynamic content over time [14]. In the past, researchers have studied shape-changing interfaces with different form factors [12, 22], made from mechanical or deforming materials [7, 24, 25, 33], with both input (e.g., controllers) and output (e.g., physical displays) capabilities. Moreover, researchers have also acknowledged the advantage of shape-changing interfaces for different types of interactions through the use of dynamic affordances [32] and proposed numerous classifications [27, 29].

However, while most of prior work focused on various technological actuation methods for physical transformations and novel interaction techniques, this paper identifies a research opportunity in exploring the design space of shape-changing interfaces depending on the users and the context of use. Through a sequence of design workshops with designers and engineers, we explored in detail the benefits and design opportunities of dynamic physical affordances, and propose a novel taxonomy of interaction with shape-changing interfaces. In order to gather the most generalized results from the workshops, we designed and developed Button+, a custom-made simple shape-changing interface in the form-factor of an augmented pushbutton (arguably the most familiar and ubiquitous input interface in commercial products [1, 17]).

This paper contributes to prior work by proposing an alternative framework for classifying interactions with shape-changing interfaces, that is not based on technology [27], physical shapes [29], emotional expressiveness [20], or levels of control [28], but rather on the context of interaction (situation and users). The rest of the paper is organized as follows: we introduce prominent related work about shape-changing interfaces, and we describe the Button+ prototype. We present the workshop studies and their results, and a classification of the design space under two main dimensions. Based on this framework, we implement and present two applications that showcase the spectrum of these interactions. Finally, we discuss limitations and future avenues of research.

RELATED WORK

Shape-changing interfaces can act both as input devices and output displays, with different levels of control [28]. Therefore, it is difficult to draw a line between the input and output modalities, as changes in the physical form factor impact both on the abilities of users to manipulate the interface through affordances [5] or to understand notifications and ambient information. Though prior extensive classifications exist [29], in our review we simply present prior works categorized according to whether emphasis was on the input or output modality.

Shape-changing interfaces as output displays

Shape-changing output displays described in the literature span over a variety of physical interfaces with different mechanical properties (e.g., changes in volume, orientation, form, textures [20]), form factors (e.g., table-alike surfaces [21], robotic avatars [27], mobile devices [11]) and applications (e.g., ambient displays [e.g., 13], wearable notification systems [e.g., 10] and communication devices [26]). From the technical point of view, most shape-changing displays are made of mechanical components or special materials. For example, Surflex is a shape-change display that uses shape-memory alloys to alter its surface [4], while PneUI uses pneumatically actuating soft materials [34].

Among mechanically actuated systems, Hong et al. introduced an ambient flower-shaped avatar that changes depending on the sitting posture of the user [13], while Park et al. [26] presented Wrigglo, a peripheral smartphone avatar for interpersonal communication. More complex shape-changing displays require multiple actuators in order to render complex geometries with greater accuracy. For example, FEELEX [16] is an array of linear actuators that deforms its shape. This work influenced several similar systems which provide technical improvements and refinements, though they substantially belong to the same family of kinetic surfaces (e.g., Lumen [27], Relief [21], inFORM [7], PocoPoco [18], Dynamic bar chart [32]). A notable system in this same category, although one-dimensional, is LineFORM [24].

Shape-changing interfaces for input

Similar to output displays, shape-changing input interfaces come in a variety of forms, complexity and usages. Among the most common usages, computer assistive input controllers are a particularly popular application domain.

DO-IT is an early example of a deformable input interface [23]. Deformation was later further explored by Michelitsch et al. [22] with an interface that switches the mode of interaction depending on the way it is held or squeezed. The Inflatable Mouse [19] is a computer mouse which enables different modes of interaction through changes of volumes, while Métamorphe is a computer keyboard made of vertically actuated keys with augmented capabilities [2]. Other shape-changing input controllers have the shape of buttons or dials, such as the actuated buttons described by Snibbe et al. [31], the pneumatically actuated buttons by Harrison et al. [9], and the dynamic button-knob for mobile devices by Hemmert et al. [12]. Tiab et al. [33] recently empirically explored the affordances for various shape-changing buttons.

BUTTON+

Button+ is a shape-changing button interface with input and output capabilities (Figure 2). Because physical buttons are easy to understand, pervasive and ubiquitously found in commercially available products [1, 17], we explicitly designed Button+ with the form factor of a pushbutton so that it may be suitable for a wide range of possible interactions. Specifically, because the physicality of traditional buttons can provide implicit information to users, researchers have suggested to adopt buttons with dynamic adjustments for novel interaction techniques [1]. Button+ is our attempt to create a customizable interaction with an augmented and expressive shape-changing pushbutton interface.

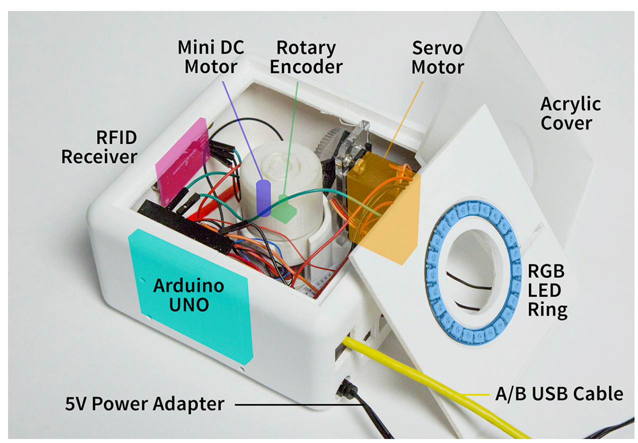

Figure 2. Button+ internal components and assembly.

PROTOTYPE

The prototype of Button+ not only mounts a regular pushdown button (Figure 1A), but it also includes a protractible/retractable knob that can be spun, pushed or pulled (Figure 1B), an RFID reader for identifying users or commands (Figure 1C), and a visual and haptic display for notifications and feedback (Figure 1D).

Button+ is shaped as a squared 132 x 132 mm 3D printed box (height: 73 mm) with rounded edges containing electro-mechanical parts, and an Arduino UNO development board wired to a controlling computer. The Button+ case hosts a cylindrical 70mm high by 38ø mm vertical shaft that can extend up to 30 mm from the top of the box. The shaft can be used as a rotary knob capable of continuous 360° spinning, sensed by a 24 step rotary encoder. The protraction of the knob was achieved by means of a custom-made rack-and-pinion geared mechanism (Figure 3). The pinion (60 teeth gear, 38ø mm) and the rack (20 teeth, height 40 mm) were laser-cut from 4mm thick acrylic sheets and are actuated by a 180° servo motor (HES-288, speed: 0.22sec/60°, torque: 2500 gf-cm at 5V) mounted on the box. Inside the box, a hollow cylinder was used to constrain the shaft to only vertical movements.

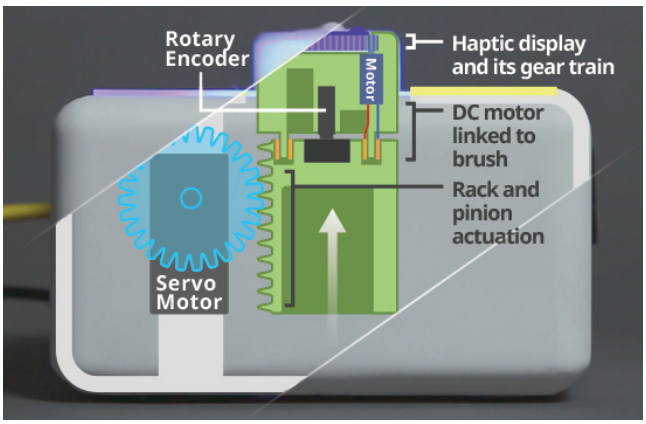

Figure 3. Rack and pinion actuation, brushing, and gearing required for the haptic display.

The servo motor was modified to be position-readable, by attaching additional wires to the internal potentiometer. This allows sensing push and pull forces applied on the knob by the user (~5.3 to ~6.3 Newtons), which results in a vertical displacement (servo motor *backdriving*). The knob is surrounded by a circular array of 24 RGB LEDs (Adafruit Neopixel ring) and it houses a custom-made rotary haptic display mounted on a small DC motor (200rpm, 0.1W at 3V). A 125 kHz RFID reader (ID-12LA) is mounted on the side of the Button+ box. The DC motor and the LED ring were powered separately by an external power supply (5V, 2A). Finally, 3D printed parts were post-processed using Tetrahydrofuran and polished with sand paper, while the top of the box was covered with a 112 x 112 mm clear sand-blasted acrylic sheet.

DESIGN WORKSHOP

To understand the design space and practical opportunities of physical shape-changing interfaces as a consumer product, we organized a series of design workshops with interaction designers and engineers. Prior studies with shape-changing interface used design workshops to collect participants' feedback and generate ideas for applications [8, 6]. Similarly, our workshop's main objective was to generate numerous applications for the Button+ interface and to describe specific input/output interactions that would take advantage of the shape-changing capabilities.

Participants

We recruited 12 volunteers (5 female) from the authors' affiliated institution (*KAIST,* South Korea*),* aged 21 to 29 (M: 25.0, SD: 2.09) of which 6 were designers and 6 engineers. All participants had a minimum of four years of study in their disciplines, with expertise in product or interaction design, mechanical or electrical engineering, and computer science. All participants were compensated with USD 10 in local currency for their time.

Method and material

We conducted a total of three design workshops. Each design workshop took approximately 90 minutes with a team composed of two designers and two engineers. It took place in a designated meeting room with a large TV screen and a table. Participants sat in a circle and were provided a pen, handouts, and paper for scribbling. A moderator (one of the authors) and a staff helper supervised the workshop sessions at all times. Workshops were also video recorded for subsequent analysis.

At the start of the workshop, after a brief welcoming session and after signing a consent form, the participants were given an introduction to the concept of shape-changing interfaces. They were then given a 5-minute demonstration of Button+, placed on the center of the table, and were encouraged to try to use it. A software with minimal GUI was used to display the numerical values from each input modality of the prototype (pushbutton state, knob rotation and vertical position). For the output modality, a computer keyboard was used to issue commands and demonstrate the visual and haptic notifications, and the protraction/retraction of the knob.

After the introduction, a 4-3-5 *brain-writing* session (a variation of the 6-3-5 brain-writing method [30]) was used to collect participant's ideas. The brain-writing method is a popular technique focused on generating a large quantity of collaborative ideas in written form. Initially, each of the four participants simultaneously drew on paper three different ideas within five minutes, then passed the sheet of paper to another participant, who further developed them. This process repeated four times, with each participant adding three ideas that refined and built upon previous ones. After 20 minutes each team produced 12 complete ideas documented on paper, each composed by four iterations (48 sketches in total). During the 4-3-5 sessions participants were allowed to ask clarifications to the moderator and to other team members.

After the 4-3-5 session, the moderator guided a discussion among the participants about the ideas that they drew on paper. Each participant was given the time to voice his/her favorite ideas, and rank them for functionality and novelty. Then, the team unanimously nominated the best four ideas and filled out the final concept sheets, with changes reflecting the team discussion. The workshop was concluded with a short debriefing, and for each team we collected the sheets containing the sketches generated during the 4-3-5 sessions and the final nominated ideas.

WORKSHOP RESULTS AND CLASSIFICATION

We reviewed all the sketches collected from the design workshops, and extracted 10 unique application ideas by merging similar concepts. Using an affinity diagram and the recordings of the discussions in the workshops, we clustered ideas according to whether emphasis was put on the identity of the users or on the context of interaction. We also considered whether the users had control over the shape-changing capabilities (e.g., customizable functions mapped to different shapes), or whether changes were system-controlled and users could simply react to them.

Following this process, we present a taxonomy of interaction with shape-changing interfaces with two orthogonal dimensions: *user-context awareness* and the *active-passive role* of the user. The resulting four areas correspond to four different interaction styles, which we named as *Situational*, *Role-based*, *"Swiss Army Knife"* and *Personalized*. The following sections describe in detail these areas and the ideas composing them.

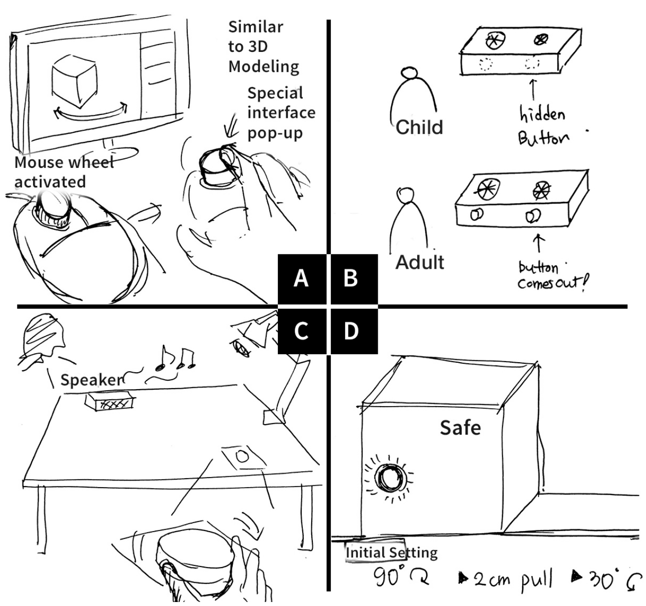

Figure 4. Sketches from the design workshops, showing possible applications of Button+: A) App Specific Mouse, B) Hidden Stove, C) Desk Universal Controller, D) Safer Safe.

Context Aware Interaction

The category *Context Aware* describes those interactions that require the interface to change shape depending on the context of use. For example, the interface could implicitly change depending on the specific types of activities that the user is performing (*Situational*), or could be explicitly changed by the user to select a specific functionality out of many ("*Swiss Army Knife*").

Situational

Situational interaction depends on which activity the user is engaged with or the peripheral information available. For example, S1 is an idea for a game keypad that changes shape depending on the state of the game. As the game becomes more complex and the game-character evolves, the controllers available to the users dynamically change. S2 presents a computer mouse-like device that changes shape to support different types of input depending on the PC application used. Similar to previous work [19, 23], our participants described an interface that looks like a computer mouse but "acts as a more sophisticated tool when dealing with minute adjustment such as computer-aided modeling or drawings" (Figure 4A). Finally, S3 is a car navigational and audio wheel-like interface, similar to the BMW iDrive [3], that hides itself when the vehicle is in motion to minimize distractions for the driver and unintentional input.

"Swiss Army Knife"

Following the metaphor of a Swiss Army Knife, a multi-purpose knife-kit that includes multiple tools in one, our workshop participants envisioned situations in which the user can modify the shape of the interface to select specific actions among many possibilities. For example, K4 is a remote light controller that specifies the intensity or colors of different lamps located in the room. K5 is a multi-device universal remote controller for the desk (Figure 4C). Using this controller, a user can switch on/off any device in the room, as well as control other parameters of specific appliances (e.g., changing orientation and speed of a fan).

	Context Aware	User Aware
PASSIVE *REACT*	*Situational*	*Role-based*
	S1 1Btn Game Controller	**R6** Hidden Stove
	S2 App Specific Mouse	**R7** A/C Admin Controller
	S3 Drive & Car Control	**R8** Biometric Safe
ACTIVE *CUSTOMIZABLE*	*"Swiss Army Knife"*	*Personalized*
	K4 Light Controller	**P9** Safer Safe
	K5 Desk Universal Controller	**P10** Instrument Effector

Figure 5. Taxonomy of Button+ interactions: *Situational, Role-based, "Swiss Army Knife",* and *Personalized.*

User Aware Interaction

The category *User Aware* describes those interactions that depend on the identity or the role of the user. With Role-based interaction, access-privilege rules can be assigned to all users, limiting the subset of possible input that they can perform. With personalized interaction, different users can configure and customize a shared shape-changing interface to match with specific working styles or to save preferences.

Role-based

Role-based interaction means that the interface changes shape according to the current user. For example, R6 (Figure 4B) is a dial for a stove that retracts itself to hide from unauthorized users (e.g., children) and only pops out when an adult is present. R7 is a controller for a centralized air conditioning unit. The controller has minimal functionalities for most users (e.g., on/off, fan speed) but discloses the full set of input options to building managers and administrators. R8 is a dial-shaped biometric sensor embedded in a jewelry safe that is graspable and can be rotated only by authorized users.

Personalized

Different users can also choose to personalize the way they interact with a shared device by identifying themselves before usage. As an analogy, users of modern luxury cars often have the ability to save in memory their personal preferences for the settings of the seats, mirrors and other features. Similarly, our workshop users discussed ways for personalizing the settings of a shared interface and recalling these preferences upon usage. P9, for example, is a lock for a safe that allows multiple owners to create a secret combination using both the height and the rotation of a dial (Figure 4D). In this way, multiple users can make their own secret combinations for accessing private compartments of a shared safe using the same input interface. P10 is an instrument effector that can save the settings for all members of a music band (typically guitarists and bass players). One of the participants remarked that "having a dial to visually and tangibly change the controls for a guitar effector can be helpful since different members in the band usually have different preferences for their instruments."

DISCUSSION

This is not the first work that attempts to classifying the types of interaction with shape-changing interfaces: numerous interpretations have already been proposed, including the prominent work of Rasmussen et al. [28, 29]. However, while previous classifications mainly focused on the technological aspects or material properties of shape-changing interfaces [27], the emotional expressiveness of the input and output modalities [20], and the user's level of control [28], this work takes a slightly different perspective by empathizing the context of interaction.

In our framework, an interface can change shape to reflect a specific situation or the types/identities of users engaged. Examples from the workshops include those interfaces that change shape depending on *what activity* the user is performing (S1, S2, S3), and those interfaces that, through implicit affordances, prevent or grant input to *specific users* (R6, R7, R8). The common characteristic of these applications is that the shape-changing capabilities are triggered by the system and the user mostly reacts to them.

Diametrically opposite, there are interactions that still depend on the context (users or situations) but for which the user has active control over how the interface changes shapes. Examples from the workshop include interfaces that are used to *control different functionalities* or devices through shape alterations (K4, K5), or devices that are shared by multiple users and provide, by means of different shapes, a way *to specify and view custom settings and options* for each individual user (P9, P10).

Interestingly, many of the application ideas from the workshops are arguably falling into multiple groups, because, as in previous work, the categories proposed in our analysis are not mutually exclusive. It is also interesting to note that the context/user aware model proposed in this paper does not contrast with classifications from previous work, but rather complements them. For example, the concept of level of control, (system vs user control) proposed by Rasmussen et al. [28] is also described in our model in terms of passive vs active interactions (the vertical axis of Figure 5), but it is augmented by an additional dimension (user vs context awareness).

APPLICATIONS

Inspired by the results of the workshops, we developed two applications for the Button+ interface that showcase the four interactions proposed in our model. We developed a *user-aware* music player application that enables customized control for users with different access privileges, and a *context-aware* car simulation videogame that dynamically changes the input controller capabilities depending on the players' performance. For each of the two applications we considered situations in which the user is both passive (shape-changes are driven by the system and the user reacts to them) or active (the user perform input gestures by changing the interfaces shape).

Music Player

Our first application is a controller for a music player software running on a computer connected to the Button+ interface. The software was written using Java in Processing with the Minim library. The Button+ controller interface enables several functionalities, including playing/pausing music, track change, and volume control. It also provides both visual and haptic notifications. The behavior of the input interface was designed to allow interaction from multiple users who might share the control of a music player, but also have varied access privileges. By changing the shape of the controller, different physical affordances are provided to distinct users (identified by means of RFID tags) depending on their predetermined roles.

Our system acknowledges four distinct user roles (normal user, heavy user, administrator, and new user) with different abilities of controlling the system. For instance, a normal user can simply choose to play or pause a song using the pushbutton mounted on the top of Button+ knob. No other control is offered to a normal user, as the knob is completely retracted in the box. When a heavy user accesses the system, a knob controller appears from the box. The user can then change song tracks by spinning it. An administrator can, on top of these actions, also change the volume level of the music, by vertically pushing or pulling the knob. Finally, a new user has no ability to control the system: if a new user attempts to do any input, the haptic display on the of the top of the retracted knob gives feedback to signify that no input is allowed. In other words, a new user has a passive role.

Figure 6. Demonstration of music player application.

Car Simulation Videogame

Our second application is a controller for a car simulation videogame that changes upon context. The game runs on a computer connected to the Button+ controller, and it was developed using Java in Processing with the Fisica library. The game content is displayed on a computer screen, and the interaction requires the usage of both the Button+ interface and four RFID cards disguised as one ignition key (used to start the game), and three shift gears for changing the car speed.

The goal of this game is to drive the car as far as possible avoiding obstacles until the fuel runs out. The Button+ knob is used as a steering wheel for controlling the car's left and right position. The fuel level is indicated on the screen with a graphical bar, and it is also mapped to the height of the knob: as time passes by, the knob height is gradually decreased, making steering more difficult. When the fuel tank is empty, the knob is completely retracted and the car is not controllable anymore. Finally, if the car bumps into an obstacle on the road, a haptic feedback is rendered on the top of the knob and a gas consumption penalty is assigned. Also for this application, changes of shape in the interfaces are both system and user driven.

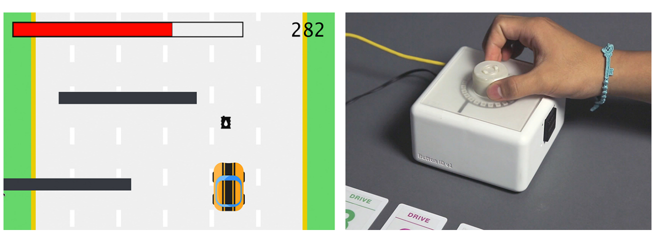

Figure 7. Demonstration of the car simulator application.

CONCLUSIONS

In this paper, we have explored the design space of a simple shape-changing button interface – the Button+ prototype. Based on this platform, we conducted a series of design workshops with the goal of generating ideas for practical products that could be enhanced by shape-changing capabilities. As a result, we collected and analyzed ideas from 12 participants and developed a taxonomy that describes user-aware and context-aware interactions. The simplicity of our prototype ensures that more complex shape-changing interfaces could still be described using the proposed model. Finally, we developed two applications that showcase the range of interactions described in our classification.

These results can be generalized for other shape-changing interfaces that do not necessarily share the same form factor of Button+. Indeed, the main motivations for choosing the current form factor is that physical buttons are among the most common and ubiquitous interfaces [17], and, as it was pointed out in previous work, they could benefit from innovative design that leverages on actuation to represent dynamic properties [1]. Button+ is only an example but we believe that the taxonomy presented in this paper can easily be applied to other shape-changing interfaces.

This work has several limitations and possibilities for future improvement. The main limitation is perhaps related to the implementation of the Button+ proof-of-concept prototype. Our prototype is bulky and could easily contain additional shape-changing input and output elements. Future work will be devoted to build better hardware with refined capabilities, following the users' feedback. For example, workshop participants commented that the haptic actuator located on the top of the knob could be more useful and effective if it were placed on the side of the knob. Also some other participants commented that the box size was larger than they expected, limiting practical application scenarios.

Another limitation is the number of participants of the workshop studies: despite that we tried our best to give voice to a variety of users by recruiting people with both engineering and design backgrounds, future iterations of this work will require more participants with a greater variety of backgrounds. Future work will be required to validate this framework and to generate practical design guidelines that support user and context aware interactions through shape-changing interfaces.

ACKNOLEDGEMENTS

This paper was supported by the MSIP, Korea, under the G-ITRC support program (IITP-2016-R6812-16-0001) supervised by the IITP.

REFERENCES

1. Jason Alexander, John Hardy, and Stephen Wattam. 2014. Characterising the Physicality of Everyday Buttons. In Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14). ACM, New York, NY, USA, 205-208.

2. Gilles Bailly, Thomas Pietrzak, Jonathan Deber, and Daniel J. Wigdor. 2013. Métamorphe: augmenting hotkey usage with actuated keys. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13). ACM, New York, NY, USA, 563-572.

3. BMW iDrive: http://www.bmw.com/com/en/insights/technology/technology_guide/articles/idrive.html {Last access August 2016}
4. Marcelo Coelho, Hiroshi Ishii, and Pattie Maes. 2008. Surflex: a programmable surface for the design of tangible interfaces. In CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08). ACM, New York, NY, USA, 3429-3434.
5. Marcelo Coelho and Jamie Zigelbaum. Shape-changing interfaces. Personal Ubiquitous Computing 15, 2 (2010), 161-173.
6. Aluna Everitt, Faisal Taher, and Jason Alexander. 2016. ShapeCanvas: An Exploration of Shape-Changing Content Generation by Members of the Public. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). ACM, New York, NY, USA, 2778-2782.
7. Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation. In Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13). ACM, New York, NY, USA, 417-426.
8. John Hardy, Christian Weichel, Faisal Taher, John Vidler, and Jason Alexander. 2015. ShapeClip: Towards Rapid Prototyping with Shape-Changing Displays for Designers. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 19-28.
9. Chris Harrison and Scott E. Hudson. 2009. Providing dynamically changeable physical buttons on a visual display. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09). ACM, New York, NY, USA, 299-308.
10. Kate Hartman, Jackson McConnell, Boris Kourtoukov, Hillary Predko, and Izzie Colpitts-Campbell. 2015. Monarch: Self-Expression Through Wearable Kinetic Textiles. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15). ACM, New York, NY, USA, 413-414.
11. Fabian Hemmert, Susann Hamann, Matthias Löwe, Anne Wohlauf, and Gesche Joost. 2010. Shape-changing mobiles: tapering in one-dimensional deformational displays in mobile phones. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10). ACM, New York, NY, USA, 249-252.
12. Fabian Hemmert, Gesche Joost, André Knörig, and Reto Wettach. 2008. Dynamic knobs: shape change as a means of interaction on a mobile phone. In CHI '08 Extended Abstracts on Human Factors in Computing Systems (CHI EA '08). ACM, New York, NY, USA, 2309-2314.
13. Jeong-ki Hong, Sunghyun Song, Jundong Cho, and Andrea Bianchi. 2015. Better Posture Awareness through Flower-Shaped Ambient Avatar. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15). ACM, New York, NY, USA, 337-340.
14. Hiroshi Ishii, Dávid Lakatos, Leonardo Bonanni, and Jean-Baptiste Labrune. 2012. Radical atoms: beyond tangible bits, toward transformable materials. interactions 19, 1 (January 2012), 38-51.
15. Hiroshi Ishii and Brygg Ullmer. 1997. Tangible bits: towards seamless interfaces between people, bits and atoms. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97). ACM, New York, NY, USA, 234-241.
16. Hiroo Iwata, Hiroaki Yano, Fumitaka Nakaizumi, and Ryo Kawamura. 2001. Project FEELEX: adding haptic surface to graphics. In Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01). ACM, New York, NY, USA, 469-476.
17. Lars-Erik Janlert. 2014. The Ubiquitous Button. interactions 21, 3: 26–33.
18. Takaharu Kanai, Yuya Kikukawa, Tatsuhiko Suzuki, Tetsuaki Baba, and Kumiko Kushiyama. 2011. PocoPoco: a tangible device that allows users to play dynamic tactile interaction. In ACM SIGGRAPH 2011 Emerging Technologies (SIGGRAPH '11). ACM, New York, NY, USA, Article 12 , 1 pages.
19. Seoktae Kim, Hyunjung Kim, Boram Lee, Tek-Jin Nam, and Woohun Lee. 2008. Inflatable mouse: volume-adjustable mouse with air-pressure-sensitive input and haptic feedback. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '08). ACM, New York, NY, USA, 211-224.
20. Matthijs Kwak, Kasper Hornbæk, Panos Markopoulos, and Miguel Bruns Alonso. 2014. The Design Space of Shape-changing Interfaces: A Repertory Grid Study. Proceedings of the 2014 Conference on Designing Interactive Systems, ACM, 181–190.
21. Daniel Leithinger and Hiroshi Ishii. 2010. Relief: a scalable actuated shape display. In Proceedings of the fourth international conference on Tangible, embedded, and embodied interaction (TEI '10). ACM, New York, NY, USA, 221-222.
22. G. Michelitsch, J. Williams, M. Osen, B. Jimenez, and S. Rapp. 2004. Haptic chameleon: a new concept of shape-changing user interface controls with force feedback. In CHI '04 Extended Abstracts on Human

Factors in Computing Systems (CHI EA '04). ACM, New York, NY, USA, 1305-1308.

23. Tamotsu Murakami, Kazuhiko Hayashi, Kazuhiro Oikawa, and Naomasa Nakajima. 1995. DO-IT: deformable objects as input tools. In Conference Companion on Human Factors in Computing Systems (CHI '95), I. Katz, R. Mack, and L. Marks (Eds.). ACM, New York, NY, USA, 87-88.
24. Ken Nakagaki, Sean Follmer, and Hiroshi Ishii. 2015. LineFORM: Actuated Curve Interfaces for Display, Interaction, and Constraint. In Proceedings of the 28th Annual ACM Symposium on User Interface Software & Technology (UIST '15). ACM, New York, NY, USA, 333-339.
25. Ryuma Niiyama, Xu Sun, Lining Yao, Hiroshi Ishii, Daniela Rus, and Sangbae Kim. 2015. Sticky Actuator: Free-Form Planar Actuators for Animated Objects. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '15). ACM, New York, NY, USA, 77-84.
26. Joohee Park, Young-Woo Park, and Tek-Jin Nam. 2014. Wrigglo: shape-changing peripheral for interpersonal mobile communication. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 3973-3976.
27. Ivan Poupyrev, Tatsushi Nashida, and Makoto Okabe. 2007. Actuation and tangible user interfaces: the Vaucanson duck, robots, and shape displays. In Proceedings of the 1st international conference on Tangible and embedded interaction (TEI '07). ACM, New York, NY, USA, 205-212.
28. Majken K. Rasmussen, Timothy Merritt, Miguel Bruns Alonso, and Marianne Graves Petersen. 2016. Balancing User and System Control in Shape-Changing Interfaces: a Designerly Exploration. In Proceedings of the TEI '16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16). ACM, New York, NY, USA, 202-210.
29. Majken K. Rasmussen, Esben W. Pedersen, Marianne G. Petersen, and Kasper Hornbæk. 2012. Shape-changing interfaces: a review of the design space and open research questions. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY, USA, 735-744.
30. Bernd Rohrbach. 1969. "Kreativ nach Regeln – Methode 635, eine neue Technik zum Lösen von Problemen". (Creative by rules - Method 635, a new technique for solving problems)". Absatzwirtschaft 12: 73-53.
31. Scott S. Snibbe, Karon E. MacLean, Rob Shaw, Jayne Roderick, William L. Verplank, and Mark Scheeff. 2001. Haptic techniques for media control. In Proceedings of the 14th annual ACM symposium on User interface software and technology (UIST '01). ACM, New York, NY, USA, 199-208.
32. Faisal Taher, John Hardy, Abhijit Karnik, et al. 2015. Exploring Interactions with Physically Dynamic Bar Charts. Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems, ACM, 3237– 3246.
33. John Tiab and Kasper Hornbæk. 2016. Understanding Affordance, System State, and Feedback in Shape-Changing Buttons. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). ACM, New York, NY, USA, 2752-2763.
34. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneUI: Pneumatically Actuated Soft Composite Materials for Shape Changing Interfaces. Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology, ACM, 13–22.