



HAL
open science

KnobSlider: Design of a Shape-Changing UI for Parameter Control

Hyunyoung Kim, Céline Coutrix, Anne Roudaut

► **To cite this version:**

Hyunyoung Kim, Céline Coutrix, Anne Roudaut. KnobSlider: Design of a Shape-Changing UI for Parameter Control. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Apr 2018, Montreal QC, France. pp.1-13, <10.1145/3173574.3173913>. <hal-03015844>

HAL Id: hal-03015844

<https://hal.science/hal-03015844v1>

Submitted on 20 Nov 2020

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

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



HAL Authorization

KnobSlider: Design of a Shape-Changing UI for Parameter Control

Hyunyoung Kim^{1,2}

¹Université Grenoble Alpes
CNRS, LIG, France
{hyunyoung.kim, celine.coutrix}@univ-grenoble-alpes.fr

Céline Coutrix^{1,2}

²University of Stuttgart,
Stuttgart, Germany

Anne Roudaut³

³University of Bristol
Bristol, UK
roudaut@gmail.com

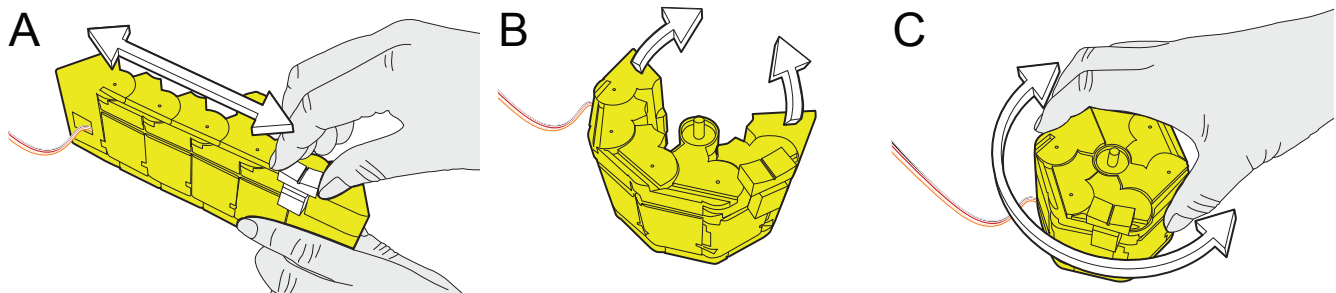


Figure 1. *KnobSlider* is a shape-changing device that changes between a rotational knob and a linear slider to accommodate users' needs. In the situation depicted (a) a sound engineer uses it as a slider to coarsely control a sound volume. He then presses the central button to trigger the change into (b) a low control-display (CD) gain knob, and (c) he can use it for fine adjustment.

ABSTRACT

Physical controls are widely used by professionals such as sound engineers or aircraft pilots. In particular knobs and sliders are the most prevalent in such interfaces. They have advantages over touchscreen GUIs, especially when users require quick and eyes-free control. However, their interfaces (e.g., mixing consoles) are often bulky and crowded. To improve this, we present the results of a formative study with professionals who use physical controllers. Based on their feedback, we propose design requirements for future interfaces for parameters control. We then introduce the design of our *KnobSlider* that combines the advantages of a knob and a slider in one unique shape-changing device. A qualitative study with professionals shows how *KnobSlider* supports the design requirements, and inspired new interactions and applications.

Author Keywords

Shape-changing interfaces; knob; slider; contextual inquiry.

ACM Classification Keywords

H5.2 [Information interfaces and presentation]: User Interfaces.

INTRODUCTION

Many professionals (e.g., sound and light engineers,

graphic designers, camera operators and pilots) use physical controls to interact with a large number of parameters. The interfaces have evolved little in the past 30 years, and these still use physical controls despite touchscreen technology being widely used. In fact, physical interfaces are ideal for such professions as they provide haptic feedback and thus eyes free manipulation. Each type of controls has different interactive advantages: the most prevalent are knobs for fine adjustment and sliders for absolute positioning. Knobs, or dials [24], are buttons controlled via rotation. Sliders are linear control elements consisting of rails and cursors. There is a variety of controllers, varying in angular or linear range, size, shape, torque or friction, with or without detents, and implemented via diverse technologies (of various resolution). Their interfaces allow users to simultaneously access a large number of parameters.

As a consequence of exploiting the advantages of physical controls, such interfaces are inevitably bulky and crowded. For instance, one of the sound systems we observed in this work offers more than 400 parameters through 3 banks of 112 controls —28 sliders with 4 layers each— and 65 knobs (Figure 2, P5-6). Such large interfaces are thus not portable, which can hinder users in many ways: e.g., sounds engineers cannot move around the stage to test sounds while adjusting parameters.

Furthermore, they are also cognitively demanding: for example, users must remember and reach the position of each parameter control. Touchscreen GUIs, which offer more flexibility by providing consecutively different interfaces on a surface, could solve some of these issues. However, they lack haptic feedback and hinder eyes-free interaction.

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from Permissions@acm.org.

CHI 2018, April 21–26, 2018, Montreal, QC, Canada.

© 2018 Association for Computing Machinery.

ACM ISBN 978-1-4503-5620-6/18/04...\$15.00

<https://doi.org/10.1145/3173574.3173913>

As a result, there is a tradeoff between the space occupied by input devices (e.g. sliders and knobs) and the number and types of controls they offer. Current solutions such as remappable banks or GUIs force users to choose either sticking to one type of device or losing physicality. In this paper, we offer *KnobSlider*, which provides both a physical knob and a slider through shape changing. It decreases the interface size and gains portability without losing the different types of controls or their physicality. We believe this is a strong advantage which was additionally suggested by our user population. Our bottom-up research procedure described below has the following contributions:

1. Through a formative study, we gain an **understanding of professional users' needs regarding parameter control**. We conducted contextual inquiries to learn about use of physical and touch screen controllers.
2. We derive **design requirements for a flexible physical interface element** based on the formative study. Users need fast, precise, eyes-free and mobile interaction with a large number of parameters. They also need retro-compatibility with current interaction.
3. We present **KnobSlider, a shape-changing physical control** that shifts between a knob and a slider (Figure 1). It combines the advantages of both types of controls while increasing the flexibility of the interface.
4. We report a **qualitative study with professional users interacting with a KnobSlider**. Results reveal that they appreciate the flexible control, and suggest promising applications for shape changing parameter controls.

RELATED WORK

Our work aims to provide flexible physical interaction for the control of continuous parameters, through knobs and sliders. We survey previous works that investigated flexible and physical continuous input devices.

Flexibility of a Single Device

An early height-changing knob was proposed by Hemmert *et al.* [18]. It was dedicated to cell phone notifications such as missed calls. Button+ [34] also changed the knob height to give distinctive control access to different users or to change the level of control difficulty for games. Haptic Chameleon [24] was a shape-changing knob that changed its function according to its deformed shape to control videos. InGen [1] was a passive knob with dynamic detent, stiffness and abrupt stops to help users scroll a list.

Many studies have explored the flexibility of sliders focusing on dynamic haptic/force feedbacks. Some motorized slider cursors have been proposed for physics education [33], haptic cues of sound amplitude [33, 35], and creating music loop [14]. Vázquez *et al.* [40] changed the haptic feedback of knobs and sliders by changing pressure in air chambers around the knob/slider axes. Zoomable TUIs explored physically zoomable sliders to balance between device footprint and pointing performance [8]. In addition to knobs and sliders, a volume-changing mouse

was designed to allow zooming and scrolling through the control of the pressure [23].

Space-Multiplexing

One approach to enable flexibility is to provide multiple devices in different locations simultaneously. There have been two approaches taken in spatially arranging controls. First, next to each other, like on sound mixing boards. Here, users manipulate sets of physical controls, including sliding and rotating joints [3]. Their drawback is their footprint when space is a critical resource. Second, on top of each other, like in Zebra Widgets [6] and a rotary knob control for microwave oven [9]. They required less surface than the first arrangement. However, Zebra Widgets do not allow stacking a dial on a slider or vice versa. With the microwave control, moving one device might cause unwanted movement of the other device.

Time-Multiplexing

Another approach is to have knobs and sliders in a sequence at the same location. With Paddle [28], users can make a flat surface for swipe (linear input), then deform it to a ring for rotational input. inFORM and Emergeables [12,29] provided a slider and a knob at the very same location. With ForceForm [39], users molded a placeholder to make a slider or knob on a touch surface. ChainFORM [25] provided a linear or a round shape with actuation and touch sensing. However, in these implementations, the manipulation of the sliders was very different from that of the physical sliders, either lacking a physical cursor [12,25,28,39] or continuity [29].

Both Space- and Time-Multiplexing

Some research approaches allowed both spatial and temporal multiplexing. With inFORM and related approach [12, 29, 39], it was also possible to provide several sliders and knobs sequentially in one place and simultaneously in different places. Our approach incorporates a combination of spatial and temporal multiplexing. In contrast to using widgets on touch surfaces [21, 43], we want to avoid the need to place widgets on surfaces. In contrast of using discrete control points on a slider [12, 29, 39], we allow for both continuous and physical manipulation of the cursor.

Balancing between Space- and Time-Multiplexing

Space- and time-multiplexing provide different advantages. Space-multiplexing allows spatial arrangements [11], persistence of attachment between devices and parameters [1,11], exploiting spatial memory [31,32], simultaneous control of several parameters [1,11], and specialized physical form factors [11]. Time-multiplexing lowers hardware and maintenance costs [11] and avoids physical clutter [32]. Two extremes of these different multiplexing approached are “hundreds of potentiometers” and a “single mouse” [1]. Fitzmaurice *et al.* [11] and Beaudouin-Lafon [1] say that the challenge lies in finding the optimal balance between the two types of multiplexing. We aim to fill in this gap and combine both multiplexing.

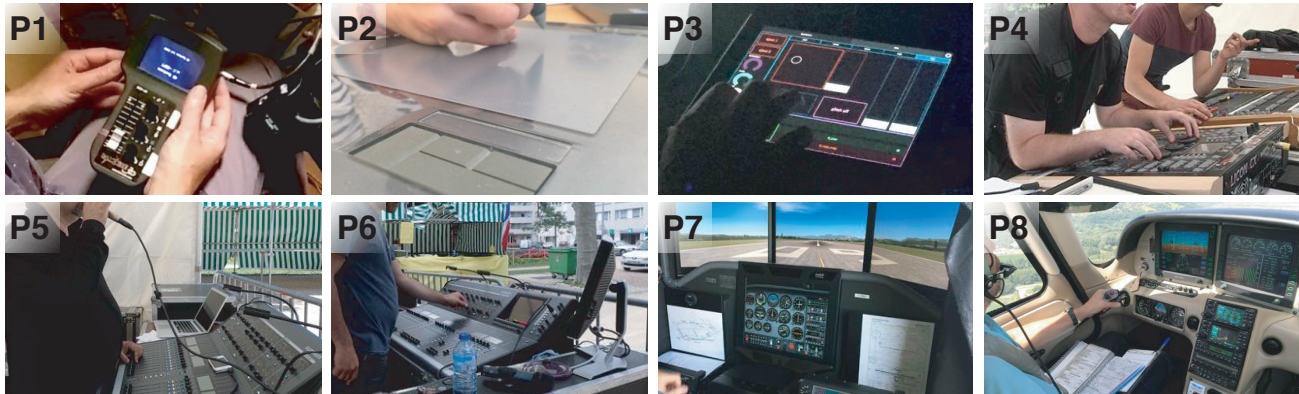


Figure 2. Participants using knobs and sliders in their professional activity: (P1) a cameraman with 4 knobs and a slider on a custom made device; (P2) a graphic designer using a graphic tablet and a slider placeholder; (P3) a light artist using custom knobs and sliders on a tablet in a dark environment; (P4) a light engineer using physical knobs and sliders while observing a stage; (P5) a sound engineer communicating with musicians on the far stage while using sliders; (P6) a sound engineer controlling a knob while watching a screen; (P7) a pilot using flight simulator for his training; (P8) a pilot using physical controls in a flight.

FORMATIVE STUDY

We used contextual inquiry [19] to gather users' requirements. Our observation and interviews of experts targeted specifically unresolved usability problems related to physicality and flexibility of devices for continuous parameters control —mostly knobs and sliders.

Participants

We first identified the most widespread professions extensively using physical input control. According to the US Bureau of Labor Statistics¹, in 2014 there were approximately 261,600 graphic designers, 119,200 pilots, 117,200 sound engineers, 20,060 camera operators, 11,930 exhibit designers (including light engineers). This approach allowed us to seek *importance* through a large population of users (e.g., graphic designers) and whose performance is critical to others (e.g., pilots); as well as to seek *generality* through diverse professions.

Through our extended social network and calling/emailing local professionals, we recruited 8 participants (ages 25-63, 2 females, Figure 2) using knobs and sliders in their professional activities: 1 movie operator (P1), 1 graphic designer (P2), 2 light engineers (P3, P4), 2 sound engineers (P5, P6), and 2 pilots (P7, P8). All participants were voluntary and consented to photo and video recording. The interfaces participants were using were mainly physical, although a few recently started using touchscreens.

Procedure

All sessions took place in ecologically valid settings and we observed all participants doing live activities, e.g., shooting a movie (P1), drawing (P2), preparing a show (P3-6) and piloting (P7-8) (Figure 2). We asked them to explain what was happening each time a sequence of actions was not clear. We interviewed them after the activities. At the end, we asked for situations where they needed to balance flexibility and tangibility. When the activities required concentration or silence (P1, P3) and it was not possible to ask a question, we asked questions during the follow-up interview. Each session took around 2 hours.

Data collection and analysis

We collected 8640 words of written notes, 141 drawings and photos (i.e., finger posture or devices used), and 2h34m26s of video and audio recordings of particular sequences of actions or interview. When possible, we performed the analysis no later than 48 hours after the interview. First, we described every sequence of observed actions. We used the collected notes, photo and video recordings from our observations to help the description. We then used thematic analysis [4] to analyze user needs regarding their controllers. We started with a research question: “what is needed for the users to perform their task?” A coder first labeled the observations with initial categories (codes) answering the question. An additional two coders joined to discuss, and agreed on them as well as identifying particular topics to regroup codes by themes. Our final scheme had six final main themes.

Results

We identified six needs regarding the control of parameters. We illustrate them with examples of actions we observed or comments made by the participants.

Most knobs were potentiometers with no bounds or detents, of around 1cm diameter with small lobes on their sides. We observed fewer varied knobs: e.g., with position mark (P1), concentric ones (P8), discrete arrow-shaped ones (P8) or large knob with a concave notch for rotation with a single finger (P4). In the following, we focus on the requirements that encompass knobs and sliders.

Interaction with a large number of parameters

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

¹ <https://www.bls.gov>

Fast interaction

Fast access to parameters: In many situations, the users needed to quickly acquire the devices. For example, to quickly access the parameters of a fan and a fog machine during the show, P3 (light artist) chose to permanently display two dedicated knobs on the left-hand side of his interface (Figure 2). P2 explained that her desk is always tidy: she needed a clear space to go from one device to another without losing time. P5 told that he never used the sliders that are too far away, and preferred pressing a button to quickly switch the parameters associated with the sliders that are close to him.

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

Fast observations of parameters: For example, P1 was manipulating interaxial distance between stereoscopic cameras and the bounds of the slider were clearly showing her the physical constraints of cameras. She also used red tape to mark a particular value of the interaxial distance during the shooting (see Figure 2 P1, the left side of the slider). P5 and P6 sometimes quickly glanced at their interfaces to observe a parameter value during the show. During manipulation, the knobs of the cockpits (P7-P8) provided haptic feedback through haptic detents. For quick observations of parameters, P7-P8 looked or touched the corresponding devices. P7 explained that in emergency situations, quick observation of parameters is critical. Overall, sliders were preferred for rapid observation of parameters.

Precise interaction

For precise interaction, most participants used large sliders (~8-10cm), with very smooth friction to allow tiny movements. The only small slider we observed was a tactile one with a placeholder (Figure 2, P2), to zoom in on the screen. When operating a slider, P1 placed her hand carefully to avoid mistakenly moving the dials next to it (Figure 2).

Knobs, even when small, also offered high precision as most of them were multiturn. Using the knob for precise control was done by P2 who used her tactile dial with a placeholder to scroll webpages. We observed P4 (light engineer) using a knob before the show to very precisely set a projector angle (Figure 2, P4). For this, he performed many rotations on a knob with low control-display (CD)

gain. Similarly, P7 and P8 (pilots) used knobs to accurately input decimal values of radio frequencies. P7 related that the extremity of his aircraft’s throttle could be turned for precise adjustments. P6 needed to adjust the curve of sound level (dB) for each frequency (Hz) of each instrument and microphone on stage. He preferred using the physical knobs for this rather than the touchscreen. P1 (movie operator) used a knob to adjust, at pixel precision, the horizontal shift between stereoscopic images, by performing multiple rotations. Overall, knobs were preferred for precise interaction.

Eyes-free interaction

P1 needed eyes-free interaction because her screens were not collocated with her knobs and sliders. Similarly, P2 focused on her canvas on the screen and looked away to modify her tool, thus lost time finding her object on the canvas again. P3-P6 watched the stage while interacting (Figure 2). P5 explained that he preferred physical controllers, and never used the touchscreen of his console, which our observations corroborated. P5 and P6 said that interacting with bounded parameters on multiturn —i.e. unbounded— knobs was not comfortable, as they have to look away from the stage to watch the LEDs around the knob. Bounded knobs were not available on the mixing console we observed, and participants said that they also seldom find them on other mixing consoles.

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

P7 and P8 (pilots) used push/pull handle for power and mixture (of air and fuel) and often placed their hand on the handles to know their status without looking (Figure 2, P8). P7 said, “If you put your hand on [the control device], you know in which mode you are.” They commented that physical devices were particularly useful when visibility in the cockpit was altered by smoke. P7 and P8 both explained that aircraft manufacturers were introducing touch screen interfaces. Both agreed that the idea was dangerous. Their comments strengthened the cockpit design requirements in previous work [5, 41].

Mobile interaction

All users needed mobility. P1 used her cameras and control devices at different locations. P2 sometimes worked away from her desk, e.g., in a van during a vacation. P3 explained that moving around the stage was crucial for him: when not possible, he communicated with someone in front of the

stage as a proxy. Unfortunately, this person might not understand what he wanted or did not have the same demand on the final quality. To avoid losing time or quality, he used a tablet, but sub-optimally moved back and forth between his desk and the stage. P4 went on the stage to better see his projectors, and then came back to the console. We observed P5 going on the stage to ease the communication with musicians. He said this was the only reason he used the tablet, as he did not like using the sliders/knobs on touch screens. To avoid using the tablet, he communicated with musicians via a microphone (Figure 2, P5), or even shouted or signed. Sometimes a third person was necessary to help communication with drummers who did not have a microphone. Thus, all solutions were suboptimal. Mobility was also necessary during the show: P6 walked around the venue to hear the sound from other locations. He then had to come back to the mixing desk to adjust the parameters. P7 and P8 (pilots) had a compact interface that fits in the cockpit.

Retro-compatibility

The professional users needed to leverage their existing expertise with current interfaces. For example, P2 explicitly commented that she was not keen to change interface because her workflow was efficient and she was not ready to lose income for a short term. The only participant that explicitly showed no interest in retro-compatibility was P3. He built a new interface dedicated for each show and improved it with practice. Yet, his touchscreen controllers were mimicking physical ones (knobs, sliders, buttons, etc.).

DESIGN REQUIREMENTS

We derived the following six requirements directly from the themes of our formative study.

- R1. Interaction with a large number of parameters* was requested by all participants. The cameraman had the least (10). The sound and light engineers can deal with more than 100. Types of parameters were diverse: some were discrete (e.g., tool in Palette) or continuous (e.g., sound volume). Some were bounded (e.g., flaps' angle) or not (e.g., shift between cameras). Some were cyclic (e.g., projector's angle).
- R2. Fast interaction.* Quick access to parameters can be supported by placing devices within users' reach. Rapid manipulation of parameters can be supported through smooth trajectories. Fast observation of parameter value can be carried by visual and/or haptic display, including min/max value or value of interest.
- R3. Precise interaction* can be supported through a large interaction area (multiturn knob or large slider) and little friction. Enough space between devices prevents errors. A stable grip on the device also allows its operation without slipping.
- R4. Eyes-free interaction.* Eyes-free access to parameters can be supported by spatial stability of the device to leverage motor-spatial memory. Eyes-free manipulation of parameters can be supported through

physical trajectory guide (e.g., slider's rail, knob's rotational axis) and haptic feedback. Eyes-free observation of parameters' value can be supported through a physical cursor or haptic feedback (detent).

- R5. Mobile interaction* can be supported by small devices.
- R6. Retro-compatibility* with current interaction: it is arduous for users to give up current UIs — even though new ones can be beneficial in the long term [30]. This can be supported by standard operations of standard devices and customizability.

Some of these requirements are incompatible (e.g., a slider should be large for precision and small for mobility). As a consequence, a good design needs to find a compromise in order to maximize users' satisfaction.

KNOB SLIDER DESIGN

We first present the design space of the previous work to reveal space for improvement. We then present KnobSlider, a shape-changing device for rotary and linear input, and how it supports the target design space and requirements.

Design Space Exploration

We focus on the physical interfaces that have some retro-compatibility (R6) with physical knobs and sliders (rotational/linear interaction). They have different spatial and temporal combinations as shown in Table 1.

Table 1. Design space and related work.

	<i>No time-multiplexing:</i> Device(s) available all the time	<i>Time-multiplexing:</i> Devices available in sequence
<i>No space-multiplexing:</i> One device available at the workspace	A. A single knob or slider [8,24,34,40]	B. A knob and a slider in sequence [12,25,28,29,39]
<i>Space-multiplexing:</i> Multi-devices available at the workspace	C. Adjacent knobs and sliders and stacked knobs and sliders [3,6,9] and current systems	D. Knobs and sliders anywhere, anytime: [12,21,29,39,43] and current systems

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

- A. A single knob would hinder the fast and eyes-free operation of a parameter (R2,R4). A small single slider would either hinder precision (R3) and a large single slider would take too much space (R5) on a surface.
- B. A knob or slider sequentially morphing out of a surface currently lacks continuity (R1) or physical cursors (R4). Manually placing a knob or a slider on a surface is time-consuming (R2).
- C. Adjacent knob and slider are space-consuming (R5). A knob on top of a slider (and vice-versa) would cause unwanted movement thus lack precision (R3).
- D. Physical knobs and sliders anywhere, anytime are not fully supported yet. As in B, manually placing knobs and sliders on a surface is time-consuming (R2) and knobs and sliders morphing out currently lacks continuity (R1) or physical cursors (R4). Current systems partially support time-multiplexing through banks of sliders only.

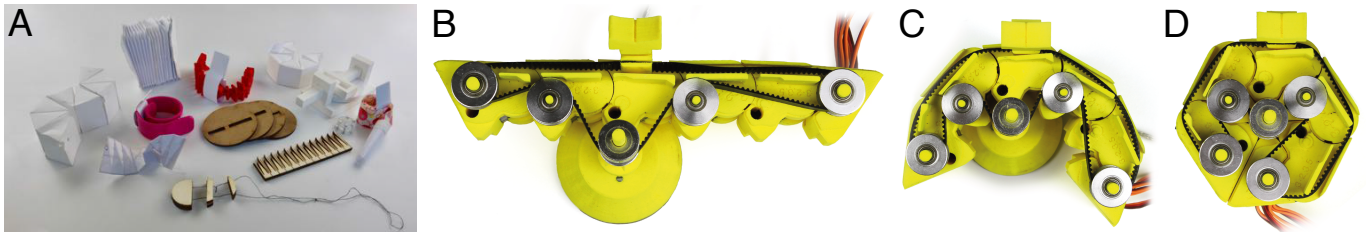


Figure 3. (A) Low-fi prototypes. (B-C-D) KnobSlider working prototype without the top cover to expose the slider’s timing belt and the slider mechanism. (B) In slider shape, the movement of timing belt is conveyed through the gears, (C) during transformation, the edges of blocks start to lock the bottom central gear, (D) the edges completely lock the bottom central gear, the rotation of the knob does not affect the timing belt.

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

Design Principle

After exploring with low-fi prototypes (Figure 3.A), we converged on a particular design that better supports the requirements. The design has six triangular prism blocks connected to each other (Figure 3 B-D). When folded (D) the prisms form a hexagonal prism (knob). When unfolded (B), the prisms are aligned, thus creating a connected surface. A cursor can move along the surface. The design is originally inspired by the Sensitive Rolypoly [13], and the final design looks similar to the InGen [1] when folded.

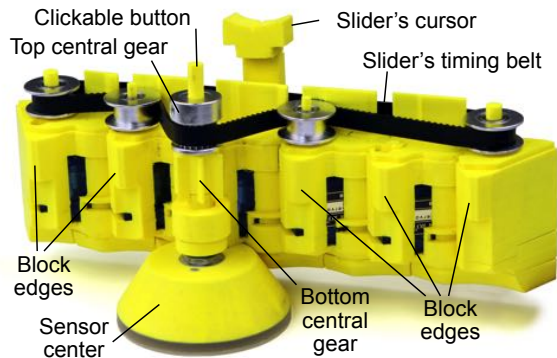


Figure 4. Different elements of the KnobSlider, here without the top cover to expose the slider’s timing belt.

Working prototype

To open/close each hinge between two blocks, we embed a servomotor (SG90) at each hinge between two blocks (Figure 3.B, block #1 to #5 from left to right). Each motor is individually controlled by an Arduino. The housing is 3D printed with ABS. For sensing the knob or the slider value, we place a manufactured clickable knob² at the base of the sensor center (see Figure 4). The sensor is connected to the bottom and top central gear, and used for both knob and slider states of the KnobSlider. When the joints are closed, the block edges interlock with the bottom central gear making a knob state. User’s rotation of the knob then translates to the sensor axis, and the device works as a knob. When the joints are open, the device makes a slider

state. The central block is supported on the bottom central gear, but the rotation of the block doesn’t affect the gear. Instead, the movement of the slider cursor is conveyed to the top central gear through the timing belt.

Table 2. Summary of the prototype specification

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

Table 2 summarizes how our prototype supports the requirements. The device can support two continuous parameters, and several can be used in parallel. The peak motor speed is 60° per $0.1s$, enabling the shape change in $\sim 0.1s$. The KnobSlider can reach similar precision than knob/slider on their own; in our prototype, knob has 100 control positions per rotation, and slider has ~ 237 control positions per 112mm (cursor traveling length). The knob diameter is $\sim 75mm$. The outer length of the slider is around 182mm, and the cursor’s traveling distance is 112mm due to the gears at the corners of slider. When it is a slider, the footprint is about 68.2 cm^2 . When it is a knob, the footprint becomes around 43.6 cm^2 . Additionally, the silicon base ensures stability. The KnobSlider has physical cursors for both knob and slider, but the slider friction varies because of the gaps between the blocks. Future engineering effort includes miniaturization, haptic feedback, cursor automation and cable removal to ensure better mobility and multiturn knob. Even though the prototype is low fidelity, it is suitable to collect early feedback from users.

QUALITATIVE STUDY

We evaluate the KnobSlider and gather feedback of professional users in ecological setups. We also gather possible uses and future developments of the KnobSlider. For this, we use technological probing [20].

² griffintechology.com/us/powermate

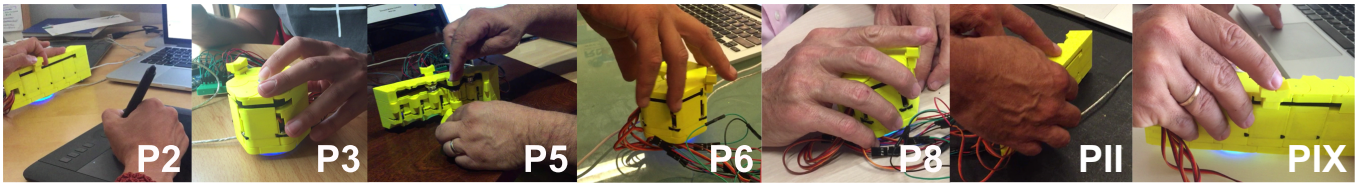


Figure 5. Seven out of our 10 participants interacting with the probe. P2, PII and PIX use the slider. P3 and P5 are about the change the shape by clicking on the central button. P6 and P8 use the rotary knob.

Note that we chose to conduct a qualitative study over a quantitative one for two reasons: First, previous work conducting performance evaluation of shape-changing UI [29] showed that a low-res prototype does not perform as well as the envisioned concept. For this reason, researchers seldom conduct quantitative evaluation of shape-changing UI [18,25,34,40,44]. Second, quantitative experiments are hard to generalize to real use as the tasks performed by participants might be too simplistic [10] or the participant groups can be artificial: often young students and/or colleagues of the authors. We wanted to avoid this by bringing the KnobSlider to its real target users for a task as real as possible. Accordingly, we conducted a qualitative experiment where we asked professionals to use the KnobSlider in a situation as close as possible to their actual work (Figure 5). This allowed us to gather diverse and real feedback on its benefits and drawbacks.

Participants

We recruited 10 participants: 6 from the first study (P2,3,5,6,7,8), and 4 new via our extended social network or calling/emailing local professionals: P1 and PII (light engineers), PIII (graphic designer), PIX (photographer using Photoshop like P2 and PIII). They (2 females) were between 32 and 63 years old. All participants were voluntary and consented to photo and video recording.

Procedure

Each participant was interviewed while interacting with the probe for ~1 hour at their workplace when possible (for P3 at a café and P7,P8 in their office). We demonstrated how the prototype worked. The participants were asked to perform given tasks in thinking-aloud protocol. We then conducted semi-structured interviews to assess our requirements. At the end, we asked them to explain a recent situation where the KnobSlider might, or not, be useful.

Apparatus

Most systems used by our participants³ had very diverse and/or proprietary communication protocols. Instead of investing a lot of resources for interfacing a low-fidelity KnobSlider with them, we wanted to gather early feedback and prototyped custom applications tailored for each profession. This enabled close-to-real world tasks while providing simplicity and flexibility as required by

technology probes [20]. One exception was Photoshop, used by three participants (graphic designers P2,PIII,PIX), which allowed us to easily interface the KnobSlider directly through mouse and keyboard events.

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

Tasks

To ensure each participant uses the KnobSlider in situations similar to their actual work, we implemented different tasks representing what each professional were frequently observed doing in our formative study (Table 3). We proposed a mapping between these tasks and the KnobSlider's inputs and shapes (Figure 5) in order to support the user requirements.

Table 3: Tasks performed in the qualitative study.

Participant(s)	Slider shape allows...	Knob shape allows...
P2,PIII,IX Graphic designers	Switching between tools	Adjusting a tool's size
P3 Light artist	Adjusting the size of a rotating laser	Adjusting the speed of laser dot's movement
PI,PII Light engineers	Controlling the intensity of a projector	Controlling the rotation of the projector
P5,6 Sound engineers	Controlling the sound volume	
P7,8 Pilots	Controlling the flaps angle	

For graphic designers (P2,PII,PIX), we implemented a script to control Photoshop functions through the KnobSlider. With the slider shape, users switched among tools in Tools Palette. With knob shape, users changed tool size, such as Brush and Burn tools. For the rest of participants, we implemented stand-alone Processing applications because their interfaces were not compatible with our device. The light artist's (P3) task was changing the size of a moving laser light with the slider, and changing its movement speed with the knob. The light engineers (PI,PII) were asked to control the intensity (brightness) of a projector with the slider and angle of the projector with the knob. Sound engineers (P5,6) could control volume of a song with both slider and knob. Pilots (P7,8) controlled two different flap angles with the slider and knob.

Data collection and analysis

We collected 313 words of written notes, 1 photo and 7h14m33s of audio and video recording of particular sequences of the interview and use of the KnobSlider. We

³ Allen&heath iLive T112, LICON CX, MA Scancommander et grandMA mixing consoles, CESSNA 172 aircraft and Cirrus Aircraft Avidyne Entegra SR20 with Avidyne FlightMax Entegra EX5000C R 6.2.1 software, custom hardware and software developed by the participant or by its company, etc.

transcribed the audio of the recordings. As in the first study, we used thematic analysis to analyze our results.

Results: Meeting the users' requirements

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

Interaction with a large number of parameters

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

Fast interaction

Fast access to parameters. Most participants said the change of shape was fast. Expecting a slow change of shape, we observed two participants (P3, P5) first holding down the button, instead of a short click on the button (Figure 5). We noticed that for some of them, the change of shape was scary at first: "it seems that it is going to explode" (PIII), "it scares me [...] because it moves" (P5). However, after a few trials they liked it and appreciated its speed: "it needs to be fast" (PIII), "it is not disturbing" (PIII), "it is fun, like an animal" (PII). We observed participants clearly playing with the shape-change capability and getting used to its speed. P7 even said that it might take too much time to change the shape: "There is a time between both [shapes], so it has to be two different steps of my work. [...] It is for two distinct tasks, two ways to work on the same data". This suggests that the change of shape can be even faster for an expert user.

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

Fast manipulation of parameters. All participants liked the smoothness of the knob. Seven participants mentioned or agreed that KnobSlider in slider shape (Figure 5, P2 and PIX) helps quickly reach the vicinity of a value. Even faster manipulation of parameters can be achieved through lower friction. Five out of ten participants complained that the slider had too much friction. For instance, PII said that "it needs to be smooth", like "velvet".

Fast observation of parameters. While the lack of smoothness of the slider was critical for sound and light engineers, P7 and PIII said that the detents of the slider are useful. P7 (pilot) said that army pilots use detents for feedback, as they focus on external elements for survival. PIII (graphic designer) suggested using them as haptic

feedback for switching between Photoshop tools with the slider. Further observation of parameters can be achieved through motorization: after the adjustment of a parameter with the knob, P6 (sound engineer) wanted the cursor of the slider to be updated.

Precise interaction

Seven participants mentioned or agreed to use the KnobSlider in knob shape (Figure 5, P6) for precisely reach a parameter's value. For instance, P7 said "[in a cockpit], rotary means precision" and P6 "and then I need precision and *shazam!* It transforms to a knob". P6 cited example of parameters that can be controlled on mixing consoles with either knobs or sliders, e.g., pan (whether the sound comes from left or right) or volume, depending on the required precision. In addition to multiturn with a low CD gain, the stability of the knob shape further helped fine adjustments: "I can rest my hand on it" (P7), "I feel I play with something solid" (PIX). Its shape further helped precision by preventing fingers from slipping: PII liked that the knob was not round, but provided edges for a secure grip.

More precise interaction can be achieved through longer slider shape. Light and sound engineers mentioned that they like sliders to be as long as possible. Stable slider would also help precise interaction. Eight participants said that the slider was not stable. In Figure 5, PII is holding it with his left hand. The rotation axis needs to be locked and supported on the surface when in slider state. Lastly, lower knob would increase precision in interaction. Sitting participants (PIII, PIX) found that the hand operating the prototype lacked support because the prototype is too high.

Eyes-free interaction

Probably because KnobSlider leverages standard physical interaction and its eyes-free capabilities [21], this requirement was less discussed. For example, three participants mentioned that the slider's shape allows for adjustment and haptic feel of bounded parameters. When in knob shape, the slider's cursor protrudes from the knob. P3 found it "efficient" to use it as a handle to rotate the knob.

Mobile interaction

Most participants saw the KnobSlider as a solution to bring a few physical devices on a mobile surface: "I take it, I go there and I do my balance for real" (P5), "If you need it to be transportable, then this is a solution" (P6). They saw its abilities for deciding on the go which device they want. Either for (1) a different parameter: "I have a volume slider, and when I adjust the pan, I have a knob. I gain space. Instead of having both a slider and a knob, I have two in one" (P6); or (2) for the same parameter, but with a different footprint: P5 wanted to have eight KnobSliders, and take them out of his mixing table to put them on a tablet-like surface and go on stage with the musicians or in the public with only the necessary channels to adjust. If eight do not fit on his surface, then he would change a few to knobs. Even more mobile interaction can be achieved through removing cables (as half of the participant suggested), and miniaturizing the prototype. Five

participants complained about the size of the prototype. Light and sound engineers (PI,PII,P3,P5,P6) were comparing the prototype to the sliders and knobs they daily use, and mentioned that they like knobs as small as possible.

Retro-compatibility

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

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

Results: envisioned interactions and applications

We now present feedback relative to possible future interactions and applications of the KnobSlider.

Envisioned interaction

Novel manipulation of the same prototype: Eight participants suggested novel interactions. E.g. P3 was holding the knob shape in one hand while turning with the other, and deforming the flexible slider. The additional rotational axis of the slider gave P8 (pilot) the idea to explore the surroundings’ visualization with polar coordinates, by orienting the slider (angle) and sliding the cursor (distance or scale). Two participants asked the interviewer if it was possible to use the slider’s cursor when in knob shape.

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

Beyond mixing tables: PI and P3 also thought about using the KnobSlider on a flat table and tracking its displacement on the table (PI mentioned the reacTable [22]). P3 also mention holding the KnobSlider in its knob shape in a hand, without any support.

Envisioned applications

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

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

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

Our participants also proposed new application domains based on their experience. For example, P6 proposed to use the change of shape in the manufacturing industry. It could indicate that a security requirement is met after a first adjustment – e.g. the pressure is low enough after rotating the knob – and that the worker can proceed to adjust the porosity with the slider if its shape is unlocked.

DISCUSSION AND FUTURE WORK

Implications for Shape-Changing Interfaces (SCIs)

This paper provides a solution for users with diverse professions that use linear and rotary controls, in contrast to previous work that has often targeted single professions (e.g., musicians [37] or cooks [41]) or the general public

[16]. From this study, we can draw implications for future SCIs for professional users.

First, the participants were excited by the reconfigurable aspect, suggesting they are open to adopting time-multiplexing through shape change. The current approach for time-multiplexing in the industry is to provide touchscreen interfaces (e.g., THALES Avionics 2020 or Slate Media Technology RAVEN MTi2), while others add back physical devices on GUIs (e.g., Microsoft Surface Dial or Neff Point and Twist dial). SCIs can be a next step to provide both tangibility and time-multiplexing. In addition, they can provide eyes-free situational awareness, which is useful in degraded work conditions [41].

Second, the retro-compatibility users require should be studied to ensure SCIs' adoption by professionals. Although KnobSliders could provide better retro-compatibility than touchscreen interfaces, the time-multiplexing of physical device introduced surprising feelings and waiting time for shape change. A follow up study can investigate the impact of shape change on users' perceptual response and find a compromising point. For instance, it can study the impact of proximity of device to users, speed of shape-change, and possibility of hurting users (e.g., device snaps on user's fingers) on user's subjective feelings.

Lastly, a long-term field study should be conducted to let more professionals adapt SCIs into their daily workflow. The interviewed users needed dynamic interaction in timely manner and mistakes could be critical. The long-term study should study how to design SCIs to support various context including emergencies. It can also study how to promote users' transition to expert functions, as SCIs will get more sophisticated. It can refer research in GUI, e.g., [30].

KnobSlider design and prototype

The qualitative study unveiled advantages and future directions of KnobSlider before a quantitative study.

Benefits of KnobSlider over current solutions

Small footprint is critical for both mobile interaction and mixing desks, as participants reported not using devices beyond arm's reach. Participants found that KnobSlider allows fast and coarse manipulation of the slider combined with slow but precise manipulation of the knob, with a smaller footprint than previous work [8,9]. This particular benefit needs to be quantitatively measured in future work. KnobSlider also allows users to only use a knob when space is limited. In addition, KnobSlider better supports customization to a preferred control. This is also important as participants reported that they want to leverage their expertise of their current interface.

Future high-fidelity implementation

Although the KnobSlider was enough for our study, several aspects of the device should be improved for quantitative study in comparison with commercial knobs and sliders. A future work can miniaturize the device to increase the spatial benefit of KnobSlider. Stability during the slider

status and shape change should be also improved for fast and precise interaction. The friction of slider needs to be low and even. Seamless joints between blocks can resolve this problem. It can be useful to motorize the slider cursor and the knob to improve retro-compatibility. Adjacent KnobSliders should not get in the way of each other. A central motor could ensure that the unfolded part always stays vertical. Most importantly, the device's safety should be improved as current design allows the device to collide with user's fingers.

Open issues and novel interactions

Even though we seek generality from the five professions, future work should study the applicability of our requirements to further professions, situations, and tasks.

Currently the ratio of slider length and knob diameter is limited to π at best. Considering that many participants preferred large sliders and small knobs, folding in spiral could be explored.

Further work is needed where there was no consensus, e.g., 1) The presence of the slider's cursor when in knob shape that cause lower retro-compatibility (R6) but better eyes-free interaction (R4). 2) The locking of the slider's orientation, wanted by most, whereas it gave an idea of an interaction to a pilot.

New interaction techniques should be explored in future work. For instance, participants suggested bending the slider. This could allow physical implementation of the graphical corner by Tsandilas *et al.* [38], or changing slider length as suggested in Zoomable TUIs [8].

CONCLUSION

In this paper, we identified six requirements for a physical interface for flexible continuous parameters control. Based on these requirements, we designed a working prototype, KnobSlider. It combines the benefits of a physical knob and a physical slider through on-demand shape change. We evaluated the KnobSlider with target users. Results suggested future improvements of the KnobSlider and implications for shape-changing interfaces. In future work, we will iterate the design so that we can conduct a long-term field study with professionals. We will also explore novel interaction techniques based on this device.

ACKNOWLEDGEMENT

This work was supported by the French National Research Agency (ANR-11-LABX-0025-01, ANR-11-EQPX-0002, ANR-15-CE23-0011-01), the Leverhulme Trust, the Alexander von Humboldt Foundation, the German Research Foundation through the projects C02 & C04 of SFB/TRR 161, and the German Federal Ministry of Education and Research as part of the project Be-greifen (grant no. 16SV7527). The prototype has been partially made in AmiQual4home (<https://amiqua4home.inria.fr/fr/tools/cl/>) and MSTIC (<http://fabmstic.liglab.fr/>). We would like to thank the participants of both studies, and colleagues and reviewers for their feedback.

REFERENCES

1. Akash Badshah, Sidhant Gupta, Gabe Cohn, Nicolas Villar, Steve Hodges, and Shwetak N. Patel. 2011. Interactive generator: a self-powered haptic feedback device. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). ACM, New York, NY, USA, 2051-2054. DOI: <https://doi.org/10.1145/1978942.1979240>
2. Michel Beaudouin-Lafon. 2000. Instrumental interaction: an interaction model for designing post-WIMP user interfaces. In Proceedings of the SIGCHI conference on Human Factors in Computing Systems (CHI '00). ACM, New York, NY, USA, 446-453. DOI=<http://dx.doi.org/10.1145/332040.332473>
3. Alan F. Blackwell and Darren Edge. 2009. Articulating tangible interfaces. In Proceedings of the 3rd International Conference on Tangible and Embedded Interaction (TEI '09). ACM, New York, NY, USA, 113-118. DOI=<http://dx.doi.org/10.1145/1517664.1517693>
4. Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3 (2), pp. 77-101. <http://doi.org/10.1191/1478088706qp063oa>
5. Juan Angel Lorenzo del Castillo and Nadine Couture. 2016. The aircraft of the future: towards the tangible cockpit. In Proceedings of the International Conference on Human-Computer Interaction in Aerospace (HCI-Aero '16). ACM, New York, NY, USA, Article 11, 8 pages. DOI: <https://doi.org/10.1145/2950112.2964582>
6. Liwei Chan, Stefanie Müller, Anne Roudaut, and Patrick Baudisch. 2012. CapStones and ZebraWidgets: sensing stacks of building blocks, dials and sliders on capacitive touch screens. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY, USA, 2189-2192. DOI=<http://dx.doi.org/10.1145/2207676.2208371>
7. Corteville, Brecht, et al. "Human-inspired robot assistant for fast point-to-point movements." *Robotics and Automation, 2007 IEEE International Conference on*. IEEE, 2007.
8. Céline Coutrix, and Cédric Masclat. "Shape-change for zoomable tuis: Opportunities and limits of a resizable slider." *Human-Computer Interaction*. Springer International Publishing, 2015.
9. Tom Djajadiningrat, Ben Matthews, and Marcelle Stienstra. 2007. Easy doesn't do it: skill and expression in tangible aesthetics. *Personal Ubiquitous Comput.* 11, 8 (December 2007), 657-676. DOI=<http://dx.doi.org/10.1007/s00779-006-0137-9>
10. Augusto Esteves and Ian Oakley. 2011. Informing design by recording tangible interaction. *CHI Extended Abstracts*: 2011. <http://doi.org/10.1145/1979742.1979893>
11. George W. Fitzmaurice and William Buxton. 1997. An empirical evaluation of graspable user interfaces: towards specialized, space-multiplexed input. In Proceedings of the ACM SIGCHI Conference on Human factors in computing systems (CHI '97). ACM, New York, NY, USA, 43-50. DOI=<http://dx.doi.org/10.1145/258549.258578>
12. 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. DOI: <http://dx.doi.org/10.1145/2501988.2502032>
13. Johanna Fulda, Pieter Tierens, Teemu Mäntyharju, and Thomas Wimmer. 2014. Raising user impulse awareness: the sensitive rolypoly. In Proceedings of the 8th International Conference on Tangible, Embedded and Embodied Interaction (TEI '14). ACM, New York, NY, USA, 347-348. DOI: <https://doi.org/10.1145/2540930.2555205>
14. Romain Gabriel, Johan Sandsjö, Ali Shahrokni, and Morten Fjeld. 2008. BounceSlider: actuated sliders for music performance and composition. In Proceedings of the 2nd international conference on Tangible and embedded interaction (TEI '08). ACM, New York, NY, USA, 127-130. DOI=<http://dx.doi.org/10.1145/1347390.1347418>
15. Gibbs, C. B. "Controller design: Interactions of controlling limbs, time-lags and gains in positional and velocity systems." *Ergonomics* 5.2 (1962): 385-402.
16. Erik Grönvall, Sofie Kinch, Marianne Graves Petersen, and Majken K. Rasmussen. 2014. Causing commotion with a shape-changing bench: experiencing shape-changing interfaces in use. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 2559-2568. DOI=<http://dx.doi.org/10.1145/2556288.2557360>
17. 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. DOI=<http://dx.doi.org/10.1145/1518701.1518749>
18. 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. DOI=<http://dx.doi.org/10.1145/1358628.1358675>
19. Karen Holtzblatt, Jessamyn Burns Wendell, and Shelley Wood. 2004. *Rapid Contextual Design: A How-to Guide to Key Techniques for User-Centered Design*. Morgan Kaufmann Publishers Inc.
20. Hilary Hutchinson, Wendy Mackay, Bo Westerlund, Benjamin B. Bederson, Allison Druin, Catherine Plaisant, Michel Beaudouin-Lafon, Stéphane Conversy, Helen Evans, Heiko Hansen, Nicolas Roussel, and Björn Eiderbäck. 2003. Technology probes: inspiring

- design for and with families. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03). ACM, New York, NY, USA, 17-24. DOI=<http://dx.doi.org/10.1145/642611.642616>
21. Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2012. Tangible remote controllers for wall-size displays. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '12). ACM, New York, NY, USA, 2865-2874. DOI=<http://dx.doi.org/10.1145/2207676.2208691>
 22. Sergi Jordà, Martin Kaltenbrunner, Günter Geiger, and Marcos Alonso. 2006. The reacTable: a tangible tabletop musical instrument and collaborative workbench. In ACM SIGGRAPH 2006 Sketches (SIGGRAPH '06). ACM, New York, NY, USA, Article 91. DOI=<http://dx.doi.org/10.1145/1179849.1179963>
 23. 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. DOI=<http://dx.doi.org/10.1145/1357054.1357090>
 24. 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. DOI=<http://dx.doi.org/10.1145/985921.986050>
 25. Ken Nakagaki, Artem Dementyev, Sean Follmer, Joseph A. Paradiso, Hiroshi Ishii, ChainFORM: A Linear Integrated Modular Hardware System for Shape Changing Interfaces, to appear in Proceedings of ACM UIST'16.
 26. Napier, John R. "The prehensile movements of the human hand." *Bone & Joint Journal* 38.4 (1956): 902-913.
 27. Esben Warming Pedersen and Kasper Hornbæk. 2011. Tangible bots: interaction with active tangibles in tabletop interfaces. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '11). ACM, New York, NY, USA, 2975-2984. DOI=<http://dx.doi.org/10.1145/1978942.1979384>
 28. Raf Ramakers, Johannes Schöning, and Kris Luyten. 2014. Paddle: highly deformable mobile devices with physical controls. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '14). ACM, New York, NY, USA, 2569-2578. DOI=<http://dx.doi.org/10.1145/2556288.2557340>
 29. Simon Robinson, Céline Coutrix, Jennifer Pearson, Juan Rosso, Matheus Fernandes Torquato, Laurence Nigay, and Matt Jones. 2016. Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). ACM, New York, NY, USA, 3793-3805. DOI: <http://dx.doi.org/10.1145/2858036.2858097>
 30. Joey Scarr, Andy Cockburn, Carl Gutwin, and Philip Quinn. 2011. Dips and ceilings: understanding and supporting transitions to expertise in user interfaces. ACM CHI'11, 2741. <http://doi.org/10.1145/1978942.1979348>
 31. Scarr, Joey, Andy Cockburn, and Carl Gutwin. "Supporting and exploiting spatial memory in user interfaces." *Foundations and Trends® in Human-Computer Interaction* 6.1 (2013): 1-84.
 32. Orit Shaer and Eva Hornecker. 2010. Tangible User Interfaces: Past, Present, and Future Directions. *Found. Trends Hum.-Comput. Interact.* 3, 1-2 (January 2010), 1-137. DOI=<http://dx.doi.org/10.1561/1100000026>
 33. Ali Shahrokni, Julio Jenaro, Tomas Gustafsson, Andreas Vinnberg, Johan Sandsjö, and Morten Fjeld. 2006. One-dimensional force feedback slider: going from an analogue to a digital platform. In Proceedings of the 4th Nordic conference on Human-computer interaction: changing roles (NordiCHI '06), Anders Mørch, Konrad Morgan, Tone Bratteteig, Gautam Ghosh, and Dag Svanaes (Eds.). ACM, New York, NY, USA, 453-456. DOI=<http://dx.doi.org/10.1145/1182475.1182535>
 34. Jihoon Suh, Wooshik Kim, and Andrea Bianchi. 2017. Button+: Supporting User and Context Aware Interaction through Shape-Changing Interfaces. In Proceedings of the Eleventh International Conference on Tangible, Embedded, and Embodied Interaction (TEI '17). ACM, New York, NY, USA, 261-268. DOI: <https://doi.org/10.1145/3024969.3024980>
 35. Atau Tanaka and Adam Parkinson. 2016. Haptic Wave: A Cross-Modal Interface for Visually Impaired Audio Producers. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI '16). ACM, New York, NY, USA, 2150-2161. DOI: <https://doi.org/10.1145/2858036.2858304>
 36. Melanie Tory and Robert Kincaid. 2013. Comparing physical, overlay, and touch screen parameter controls. In Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS '13). ACM, New York, NY, USA, 91-100. DOI=<http://dx.doi.org/10.1145/2512349.2512812>
 37. Giovanni Maria Troiano, Esben Warming Pedersen, and Kasper Hornbæk. 2015. Deformable Interfaces for Performing Music. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 377-386. DOI: <https://doi.org/10.1145/2702123.2702492>
 38. Theophanis Tsandilas, Anastasia Bezerianos, and Thibaut Jacob. 2015. SketchSliders: Sketching Widgets for Visual Exploration on Wall Displays. ACM CHI'15. <http://doi.org/10.1145/2702123.2702129>
 39. Jessica Tsimeris. 2013. Achieving soft and directly deformable interaction on tabletop interactive surfaces. In Proceedings of the 2013 ACM international conference on Interactive tabletops and surfaces (ITS

- '13). ACM, New York, NY, USA, 475-480.
DOI=<http://dx.doi.org/10.1145/2512349.2514600>
40. Marynel Vázquez, Eric Brockmeyer, Ruta Desai, Chris Harrison, and Scott E. Hudson. 2015. 3D Printing Pneumatic Device Controls with Variable Activation Force Capabilities. In Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems (CHI '15). ACM, New York, NY, USA, 1295-1304. DOI: <http://dx.doi.org/10.1145/2702123.2702569>
41. Jean-Luc Vinot, Catherine Letondal, Sylvain Pauchet, and Stéphane Chatty. 2016. Could tangibility improve the safety of touch-based interaction?: exploring a new physical design space for pilot-system interfaces. In Proceedings of the International Conference on Human-Computer Interaction in Aerospace (HCI-Aero '16). ACM, New York, NY, USA, Article 8, 8 pages. DOI: <https://doi.org/10.1145/2950112.2964581>
42. Wen Wang, Lining Yao, Teng Zhang, Chin-Yi Cheng, Daniel Levine, and Hiroshi Ishii. 2017. Transformative Appetite: Shape-Changing Food Transforms from 2D to 3D by Water Interaction through Cooking. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (CHI '17). ACM, New York, NY, USA, 6123-6132. DOI: <https://doi.org/10.1145/3025453.3026019>
43. Malte Weiss, Julie Wagner, Yvonne Jansen, Roger Jennings, Ramsin Khoshabeh, James D. Hollan, and Jan Borchers. 2009. SLAP widgets: bridging the gap between virtual and physical controls on tabletops. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09). ACM, New York, NY, USA, 481-490. DOI=<http://dx.doi.org/10.1145/1518701.1518779>
44. Lining Yao, Ryuma Niiyama, Jifei Ou, Sean Follmer, Clark Della Silva, and Hiroshi Ishii. 2013. PneuUI: pneumatically actuated soft composite materials for shape changing interfaces. In Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13). ACM, New York, NY, USA, 13-22. DOI: <http://dx.doi.org/10.1145/2501988.250203>