# ExpanDial: Designing a Shape-Changing Dial

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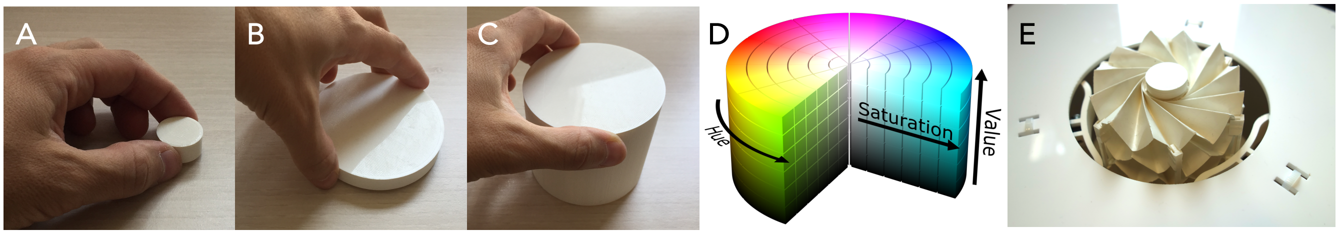

**Figure 1. (A-B-C) A conceptual shape-changing dial that changes the circumference and height. (D) The dial can be used for instance for color adjustment (Image by SharkD). (E) Our working prototype of a shape-changing dial using expandable origami.**

## ABSTRACT

We investigate the design of a shape-changing dial, i.e. a dial that can change its circumference and height to adapt to different contexts of interaction. We first explore how users grasp 3D printed dials of different heights and circumferences in order to inform the form factor of shape-changing dials. We then design a prototype, ExpanDial, inspired from morphing origami. We then use our prototype as a probe within design sessions and use the participants' feedback to devise a set of applications that can benefit from such reconfigurable devices. We also used the design sessions to better understand what kind of interaction and manipulation could be harnessed from such device.

### Author Keywords

Shape-Changing Dials; Reconfigurable Dials; Grasp; Interaction Techniques.

### CSS Concepts

• Human-centered computing~Empirical studies in interaction design • Human-centered computing~Haptic devices • Human-centered computing~Gestural input

## INTRODUCTION

Shape-changing interfaces are more and more widespread within the HCI community and many papers have already highlighted the advantages of bringing reconfigurability to interactive devices [1][29][33]. More particularly there is a growing trend in transforming standard input devices into reconfigurable ones to attribute them additional functionalities: e.g., dials and sliders [20][29][40], buttons [41] mouse and keyboard [21][2] and desktop [3].

Our work contributes to the same direction of augmenting conventional input controls with reconfigurabilities, particularly focusing on cylindrical dials. A dial, also called round knob or rotary control [22], is a control device for "analogue (infinitely variable) adjustment of a one-dimensional variable" [4]. It is controlled through its rotation around the axis that is perpendicular to its support surface. Dials allow precise and rapid control that is not achievable with other tangible devices [4]. Design handbooks and previous research explore different ranges of width and height: e.g., between 10 and 30 mm (height and width) [4], 25 and 75 mm (width) [22], or 10 mm and 8.25 mm (width) [7]. Despite being widespread, there have been few researches on opportunities and challenges of dials that can change their size automatically.

Within the HCI community, there have been height-changing dials [38] or width-changing dials [29] but none doing both at the same time. These papers also focus on certain applications, e.g., music or temperature control. This thus motivated us to explore shape-changing dials in a general perspective with a design changing both height and width. We set out to systemically investigate the needs and advantages of shape-changing dials to understand how to design such devices and to provide users with augmented control and/or display in different applicative contexts. We particularly focus on round and cylindrical dials, as these are most commonly found in many domains, from music producing to industrial machines.

Our approach first started with a controlled study in which we explored how users grasp the dials of different heights and widths in order to inform the form factor of shape-changing dials. We collected data on users' hand postures when they rotate static 3D printed dials with difference sizes (two heights and four width). It helped us draws design

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guidelines for shape-changing dials. We then implemented ExpanDial, a shape-changing dial that allows height and width changes (Figure 1). We then used the prototype as a probe during design sessions with participants to explore what applications can benefit from such device and what interaction and manipulation could be harnessed from this device to enrich the input bandwidth. Using the participants' feedback, we draw a space of potential application and interaction for shape-changing dials. We also gathered feedback on our prototype and conclude by discussing design implications for future shape-changing dials.

## RELATED WORK

Our work relates to shape-changing dials, user defined gestures for shape-changing interfaces, future applications for shape-changing interfaces, and grasping studies.

Previous work in shape-changing interfaces explored dials that can emerge from a flat surface [32], or dials that can change to another tangible control, like a slider [20]. In this paper, we focus on a different area, where shape-change happens within a single device, i.e. a change in shape that does not significantly affect the user's manipulation.

In this area, Button+ [38] shows a height-changing dial representing different access level to the system or game difficulties. The haptic chameleon [26] presents a dial whose shape can be changed between a circular shape, a half-circular shape and a wedge-shaped dial to change in a discrete way between three modes of control: continuous, discrete or semantic playback of a video. Dynamic knobs [15] on mobile phones change their height as a way to provide haptic feedback to the users through tactile exploration. Vázquez et al. [45] introduced dials embedding pneumatic actuation to enable the programming of different levels of actuation force from users. Lakatos [23] and Daniel et al. [8] demonstrate stacks of width-changing rings for dynamic sculpting and energy forecasting. Both however do not support direct manipulation of the dial-shaped devices. Ripple thermostat [29] explores the emotional experience when interacting with a dial that can dynamically change its force feedback and width. In contrast to these works, we aim at exploring independent width- and height-change of dials, for both control and display. We also want to investigate the different kind of benefits for users, whether it is performance, aesthetics, pleasure, affect, etc.

### Grasping studies

Early grasping studies (e.g., [22][27]) showed how users grasp objects. They also investigated how users grasp tangible controls, like dials (e.g., [13]). More recent work explored how users grasp tangible tokens on a surface [12]. While the authors explore different shapes and sizes (3, 4 and 5 cm), they do not vary the height of the tangible tokens. We wish to extend the width range to all common and usable dial widths [1][7][22]. We also would like to avoid constraining the users grasp (e.g., forcing a grasp with 3 fingers [12]). Hoggan et al. [16] studied the hand position on a dial shape displayed on a touchscreen. Although the device is not graspable, the study explores, among others, the width between the fingers and it would be interesting to see how the findings for a touchscreen compare to a graspable dial. We, however, want to avoid constraining the users grasp (e.g., forcing a grasp with 2 fingers [16]).

### Origami-inspired shape-changing interfaces

Origami has inspired many shape-changing devices. Previous work explores how differently folded states of foldable screens and smartwatches can activate certain viewpoints or functionalities [10][11][39]. Other work explores how different origami patterns can resemble certain 3D shapes and how to actuate the shape changes by using shape-memory alloys or inflation [30][33][42][46]. This paper uses an origami pattern that was used to make shadow for space telescopes [28][34] but has not been used in HCI. We use mechanical actuators (i.e., motors) and the tension of the folded material to activate shape-changes.

### User-defined gestures for shape-changing interfaces

Studies have been performed to find user-defined gestures for an elastic screen [43], for bendable surfaces [25] and for deformable displays [24]. It is not clear how these would apply for a novel shape-changing device like ExpanDial. For such a low-fidelity prototype (Figure 1E), it is hard to conduct a formal gesture elicitation study and to generalize its results to later prototypes. As a way to inform the design of a prototype, we rather perform an early exploration of deformation gestures by end-users. This more exploratory approach is close to the one of Strohmeier et al. [36] where they used a piece of fabric instead of a shape-changing interface to learn what kind of gestures shape-changing interfaces can use to convey emotions.

### Future applications for shape-changing interfaces

Finding relevant applications to shape-changing interfaces was found to be a grand challenge of the domain by HCI researchers [1]. Rod-based displays were used as a probe in an ideation study with the general public in order to find future applications [37]. ShapeCanvas [9], a rod-based display, was also provided for the general public to generate content. From this study applications ideas emerged, e.g., board games. But the extent to which these applications apply to a shape-changing knob is not straightforward.

Closer to ExpanDial, the authors of previous work on shape-changing dials – rather than end users – proposed applications for their devices [8][15][23][26]. Taking a different approach, Suh et al. [38] studied future applications of Button+ with end-users. Kim et al. [20] performed contextual interviews and found that dials are widely used by sound and light engineers, camera operators, graphic designers, photographs and pilots. The applications from these works might be relevant applications domains for ExpanDial. However, even though previous work explored possible applications that could apply to shape-changing dials, the extent to which these applications apply to a novel device is not straightforward. In addition, a novel device might inspire new, or more focused, ideas.

**Figure 2. Study setup with two webcams and one thermal camera above the dial placed on a turntable. Participants were sitting in front of the setup and were asked to stay seated.**

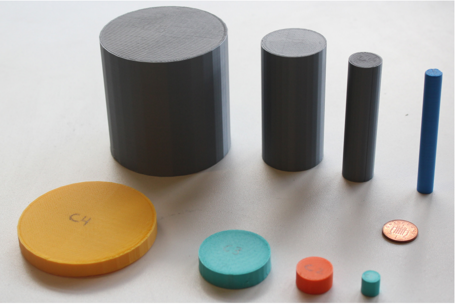

**Figure 3. The dials used in the study: width (1, 2, 4 and 8 cm in width) and height (1, 8 cm width)**

## GRASP STUDY

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

### Participants

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

### Task

Participants were presented 8 cylinders of different heights and widths (Figure 3). They were asked to grasp the dials in order to perform three different tasks: turn the dial by 10º, 90º and 360º clockwise. They did not have to turn the dial but rather to grasp the dial and hold it in position while the data was recorded. They thus had to first think about how to hold it to perform the rotation. They had to keep the position for 10 seconds to leave a thermal print on the dial for the thermal camera (see below for details).

### Apparatus

We used three cameras placed at different angles to gather videos of the grasp positions. Two were RGB cameras placed as illustrated in Figure 2. We used a simple program to record the input of the two cameras simultaneously. The third camera was a thermal camera placed as illustrated in Figure 2. The dials were placed on a Lazy Susan that we manually rotated once the participants finished assuming their grasp position after holding the grasps for ten seconds. A visual marker on the Lazy Susan (unobservable in Figure 2) helped measuring its rotation. This allowed the thermal camera to record the finger traces all around the dial. We used the eight 3D printed dials shown on Figure 3. We chose widths ranging from 1cm to 8cm based on previous studies of optimal dial widths [7] and current commercial dials that reach down to 1cm[1]. For the heights we used a range from 10-80 mm which goes above recommendations for dials height (e.g. 10-30mm [4]) but we wanted to cover a large range of heights to identify differences in grasping.

### Experimental design

We used a within subject design. The variables were the *Width* of the dial (1, 2, 4 and 8 cm in width), its *Height* (1, 8 cm) and the *Angle* of rotation (10º, 90º and 360º) of the task. The conditions were counterbalanced among participants to avoid learning or order effects. Sometimes the thermal camera would freeze so we asked the participant to assume the same grasp again and recorded a new video. The experiment lasted around 12-16 minutes per participant.

### Hypothesis and research questions

We had hypothesis and questions we wanted to evaluate.

*Q1 overall posture*: we first wanted to list the different types of grasps observed. We assumed some patterns would emerge to reflect the theory of the grasping hand by Napier [27], i.e., the position of the fingers would follow a classical pattern where the thumb opposed the other fingers.

*Q2 hand roll*: additionally, we wondered what hand roll (Figure 4) the users would prefer, i.e., approaching the dial from its side or its top. We did not have any assumptions on this question although our assumption was that they would approach it mainly by the side because they were sited in front of the setup and not standing.

*Q3 hand yaw*: we wanted to observe the hand yaw (Figure 4), i.e., the angle made by the hand at the start of the movement relatively to the user. We assumed that when users were asked to perform a larger Angle of rotation of the dial, the hand yaw would be larger too, as the users need to prepare their hand to achieve a larger motion without clutching.

*Q4 number of fingers*: we wanted to observe how many fingers were used. We assumed that the larger the dial, the more fingers would be used. We also hypothesize that the smaller the Angle of rotation of the dial, the less fingers would be used. This would corroborate with Napier's theory of hand grasping, suggesting that precision grasps involve using the index and the thumb [27]. It would also corroborate with observations from [44] showing that users make as most

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[1] E.g., https://www.adafruit.com/product/2057

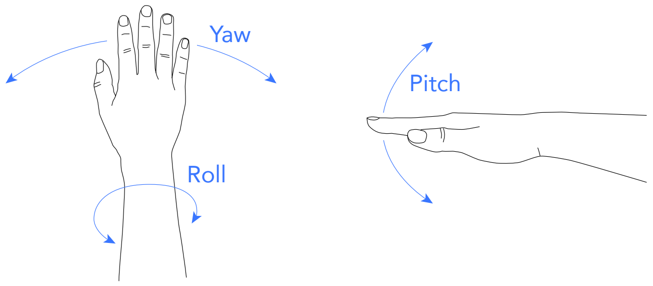

Figure 4. Hand yaw, roll, and pitch.

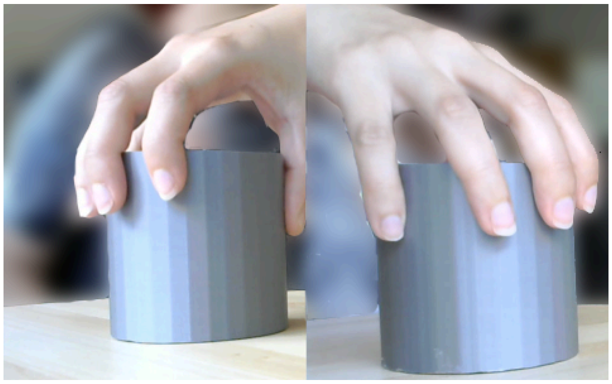

Figure 5. Images from the web camera. Here the hand comes from the top (hand roll).

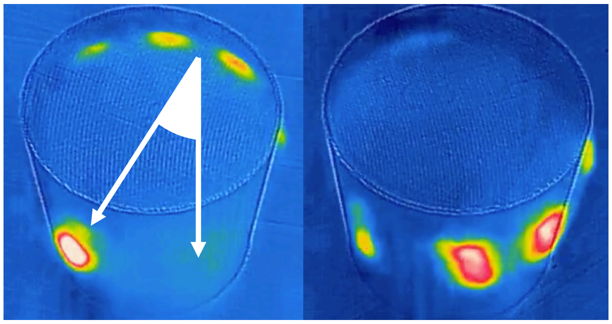

Figure 6. Thermal camera images from the beginning (left) to the end (right) of the Lazy Suzan rotation. The angle shows the hand yaw computed from the thumb to the centroid of the other fingers relatively to the user's position.

contact as possible with the fingers on TUI, probably to reach better performance.

*Q5 placement of finger*: we wanted to observe where the fingers were placed on the length of dials (not its circumference). With taller dials, we assumed that users would place their finger either on the top (if the hand comes from the top) or on the middle of it. The reason is that those positions ensure that the dial is more stable.

### Data generation

We manually annotated all the videos to retrieve the position of fingers (placement on the circumferences of the dials and on the length) as well as the orientation of the hand (roll and yaw) and the type of grasp. To measure the yaw of the hand we measured the angle made from the thumb to the centroid of the other fingers relatively to the user position (Figure 6-left). As we will see later, we choose this measurement because participants had consistent posture where the thumb always opposed the other fingers. Figure 5 and Figure 6 illustrate the type of images we captured as well as specify the hand roll and yaw metric we used.

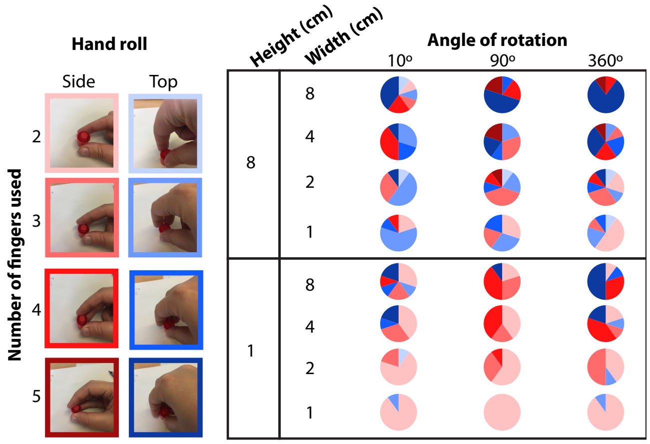

Figure 7. Overall postures observed.

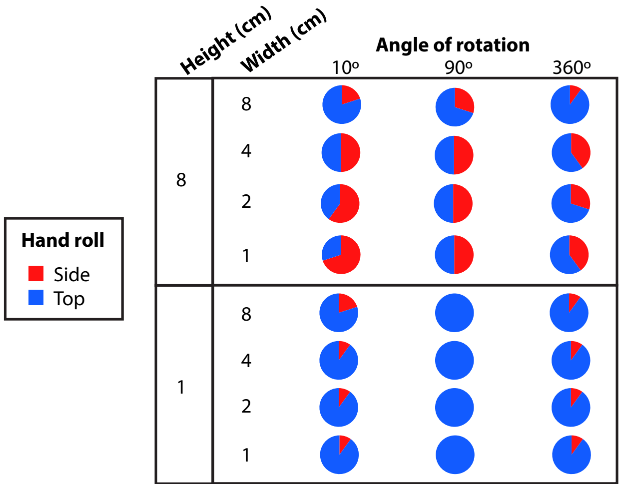

Figure 8. Hand rolls per dial Size and Angle of rotation.

### Results

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

*Q1 overall posture*

As we hypothesized, there was a finite number of postures assumed by the participants, in total eight corresponding to the number of fingers used (2, 3, 4 or 5) and two hand rolls (coming from the top or the side). Those postures are illustrated on Figure 7. We observed very little variations on the positions of the fingers on the circumferences of the cylinder, i.e. the positions always matched the typical patterns of the thumb being diametrically opposed to the other fingers, which corroborated previous work [27].

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

*Q3 hand yaw*
The data revealed a lot of variation in term of hand yaw angle, thus why we used the continuous value of the angle measured. Figure 9-left shows the distribution of hand yaw angles across the different dials and Angles of rotation. We can observe that the size of the hand yaw angle seems to correlate with the size of the Angle of rotation but there is a lot of variability across dials size. A Friedman's analysis of variance confirmed a significant difference on the yaw angle between 10º and 360º Angle of rotation, i.e. the angle is bigger with 360º, suggesting that our hypothesis is true (the participants prepared their rotation movement by assuming a larger hand yaw at the beginning of the movement). We did not find any significant differences for the other comparisons (dial width and height).

*Q4 number of fingers*
Figure 9-right shows the mean number of fingers used across the different sizes of dials. A Friedman's analysis of variance showed no significant difference between dial Height and Angle of rotation but showed an effect on dial Width. All pairwise comparisons showed a significant difference for the dial Width ($p<0.05$). Smaller cylinders thus correlate with smaller number of fingers, which make sense as they have less surface for the users to use.

*Q5 placement of finger*
Figure 10 shows the distribution of vertical placement of fingers across the different dials' Width and Angles of rotation. We only looked at the 8cm dials that actually offer different alternatives for vertical placement. The data revealed very few variations in term of hand roll angle, thus why we coded this metric in three categories only: placed at the top, bottom or middle. Although the top of the dials is clearly more used overall we did not find any significant differences between dial Width and Rotation.

### Lessons learned

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

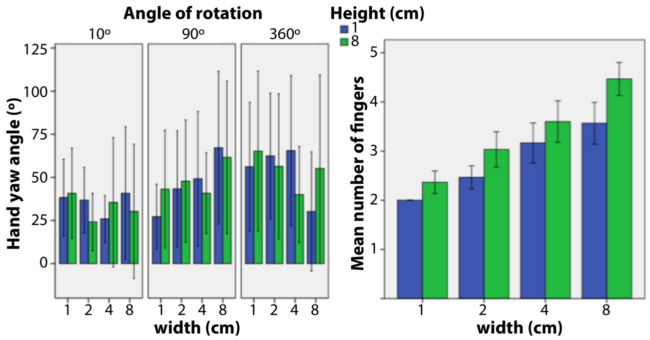

**Figure 9. (Left) Hand yaws per Width and Height of the dials and Angle of rotation. (Right) Number of fingers per Width and Height of the dials.**

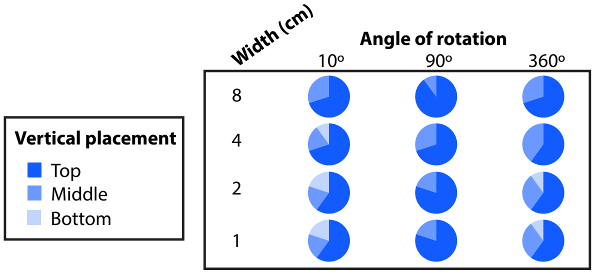

**Figure 10. Placement of the fingers on the length of the 8cm dials per Width and Angle of rotation.**

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

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

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

Lastly, based on the eight postures of Figure 7, we need to figure out if it is ok for users to deform the dial from the very same postures, or if they would prefer to deform the dial from a different, explicit posture/gesture so that deformation does not happen when turning the dial. We explore gestures to activate shape changes of shape-changing dials in a following section.

## EXPANDIAL PROTOTYPE IMPLEMENTATION

Following the first study, we implemented ExpanDial, a dial that is able to change its width and height (Figure 1E,11,12). We first explain how we built the prototype and then show how the prototype brings off the lessons we learned from the grasp study.

### Design

We used NASA's Star Shade pattern [28][34] (Figure 11A) for the resizing mechanism of a round paper piece. The pattern allows the folded piece of paper to change width while keeping the round circumference. The ratio between the minimum and the maximum width varies depending on the design and the paper material [28]. We tried various patterns and chose the one working well with simple paper.

We grooved the pattern on paper by using a vinyl cutter. We then stacked five pieces of the folded paper to make a cylinder and connected the edges of the sheets using 3D printed connectors (Figure 11B). As the height of the folded paper changed along the change of the width, we connected only one side of the creases (mountains or valleys) to the connectors. We then fixed the stack on a Palette[2] sensor that senses rotational movement and click.

Below the sensor, we placed three linear actuators that enable height changes (Firgelli L12-50-100-6-R, Figure 12). To change the width, we placed the three identical linear actuators around the circumference, with walls at their extremities. They could evenly push and release the circumference. When the walls push the stack, its width is reduced. When released, the stack goes back to its maximum width thanks to the paper tension.

The size of the case below the dial was around W360×L305×H230mm. For clarity, we call the stack of folded sheets of paper *the dial*, and the box that accommodates the shape-changing mechanism *the case* in the rest of the paper. The current version of prototype can change its width from 3.6cm to 9cm and its height from 2.3cm to 6.3cm. Users can use 2-5 fingers when rotating it, and they will be more likely to use 3-5 fingers (Figure 9).

### Rationale

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

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

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

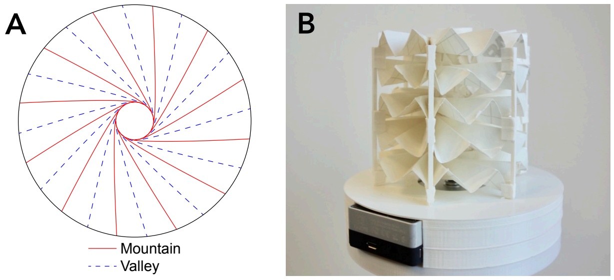

**Figure 11. (A) The folding pattern. (B) The paper pieces folded along the pattern, stacked, and connected through 3D printed connectors.**

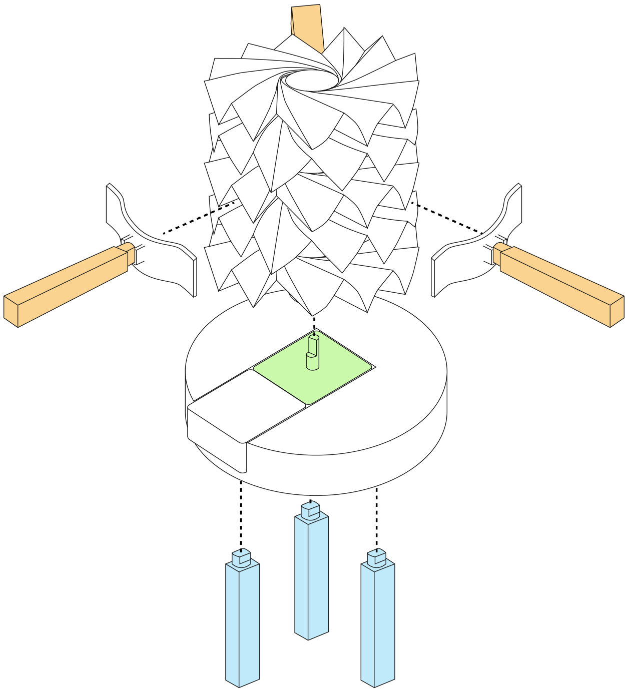

**Figure 12. The prototype schematic showing the shape-change mechanism. Three motors control the width (orange) and three motors control the height (blue). A rotational sensor (green) captures the rotation and click of the dial.**

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

## DESIGN SESSIONS

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

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[2] https://palettegear.com/

### Participants

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

### Procedure

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

For the second question, we asked the participants to think in the frame of application areas (*work*, *home*, *entertainment, others*) and modalities (*control* and/or *display*), where ExpanDial may be able to support current applications and replace existing current interfaces. It was also to guide the participants to focus on shape-changing dials as interfaces rather than as new devices (e.g., a shape-changing road in a public ideation [37]). By doing this, we expected the participants to generate application ideas that can reveal potential advantages and challenges of shape-changing dials.

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

### Results

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

#### *Q1 ExpanDial improvement*

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

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

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

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

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

#### *Q2 Envisioned application scenarios*

The participants suggested 44 application ideas (avg. 4.4 ideas per participant), and 41 of them were relevant to height or width changing dials. We used the 41 ideas in the analysis. We revisited all the ideas to categorize them into the *application areas* and control/display *modalities* (see Figure 13). We allowed multiple categories for the application areas (Figure 13-left). E.g., a participant categorized a 3D interaction idea to the work category, but it could also belong to the entertainment, for VR games. In this case, we allocated the idea to both categories. We did not allow multi-selection in the control/display modality categorization as it was mutually exclusive (Figure 13-right).

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

Ideas based on application areas

In total, 23 ideas were categorized into *work*, eleven were categorized into *home*, thirteen belonged to *entertainment*, and four belonged to the *others* (Figure 13-left).

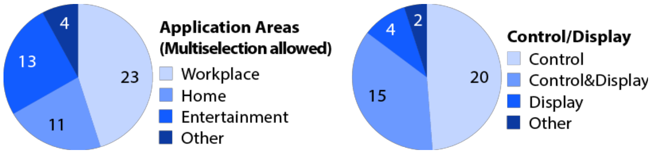

**Figure 13. The application areas and control/display modality of envisioned application ideas.**

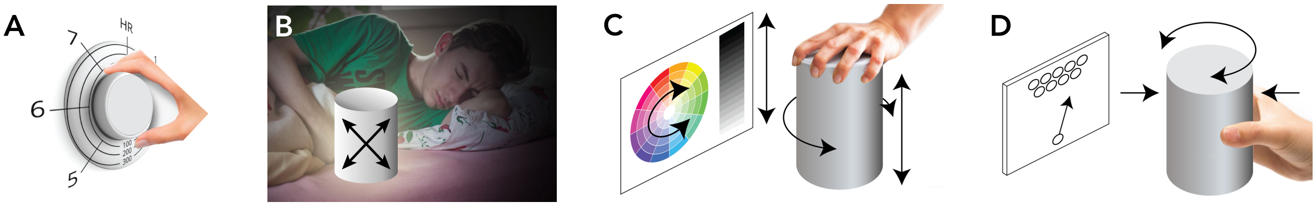

**Figure 14. Examples of envisioned applications of ExpanDial. (A) timer and temperature setting for an oven. (B) An alarm clock that gets bigger and brighter as the set time comes. (C) Using the dial to explore a color space. (D) A rehabilitation game.**

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

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

Many of the *home* ideas (7/11) were about controlling remote home appliances and displaying information about them, as in smart home scenarios. Three other ideas were changing the width and rotating the dial to set the temperature or the timer of an oven. The system changed the dial height and/or width to show remaining time (Figure 14a). The last idea was using the dial as a morning alarm clock. E.g., users set the time by rotating the dial, and the dial would become larger and larger until that users cannot ignore it anymore. The participant said that the dial would have light inside, and it would get brighter as the set time comes as well (Figure 14b).

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

Ideas in *others* category were general interaction methods and could be applied to any applications or systems. Two of them were using the particular design of ExpanDial (i.e. origami), e.g. using each paper layer for discrete control or display. For instance, each layer could set or display the temperature of each room in a house. Another idea was to change the dial size for better ergonomics, e.g., smaller sizes for small children or bigger sizes for elderlies who lack fine motor skills [17]. The last idea was to give force feedback when the system cannot perform a desired function. E.g., users try to squeeze the dial to reduce a Photoshop brush size while the size is minimum. The dial gets stiffen and prevents any further squeezing.

Ideas based on the control and/or display modality

Twenty ideas categorized into *control*, fifteen into both *control & display*, four into *display*, and the last two into *others* (Figure 13-right). For these categories, we did not allow multi-selection as they were mutually exclusive.

Half of the *control* ideas (10/20) were controlling multiple parameters by using the shape-changing ability of ExpanDial. For example, users can explore a color space (Figure 14c), or change transparency and size of a brush by rotating, squeezing, and change height of the device simultaneously. There was no idea of controlling different parameters by changing the force or speed of interaction, which was suggested in Dynamic Knobs [15]. Two *control* ideas were combining the dial to existing devices, such as a joystick or Wii remote.

Fifteen ideas were in the *control & display* category. Among them, ten were to give haptic or force feedback with the width/height change of ExpanDial. They included to force users to use different forearm muscles (e.g., rehabilitation game, Figure 14d), to give immersive experience (e.g., force feedback for an airbrush interaction in VR), and to notify users when they are holding the dial (e.g., expanding the width when there is an urgent task while scrolling through a to-do list with rotation). A *control & display* idea was using the dial combined with a mouse, to scroll by rotating or to notify users of desktop events by expanding the width, similarly to the Inflatable Mouse [21].

One *display* idea was to use the device as a shape-changing ambient or peripheral display as in previous work [14][47]. The participant said that ExpanDial would animate air quality in a room with a breathing rhythm (i.e., slow breathing when the air quality is good and fast breathing in the other case). The other two ideas were changing the width or height to notify a new email or that a cooking timer has finished.

### *Q3 Gestures for shape-changing dials*

We collected 48 gesture ideas to increase or decrease the circumference width or height of ExpanDial (see Figure 15). After merging duplicated ideas, we got on average six types of gestures per interaction: increasing width, decreasing width, increasing height, and decreasing height. We describe the overall findings and discuss them in the below section.

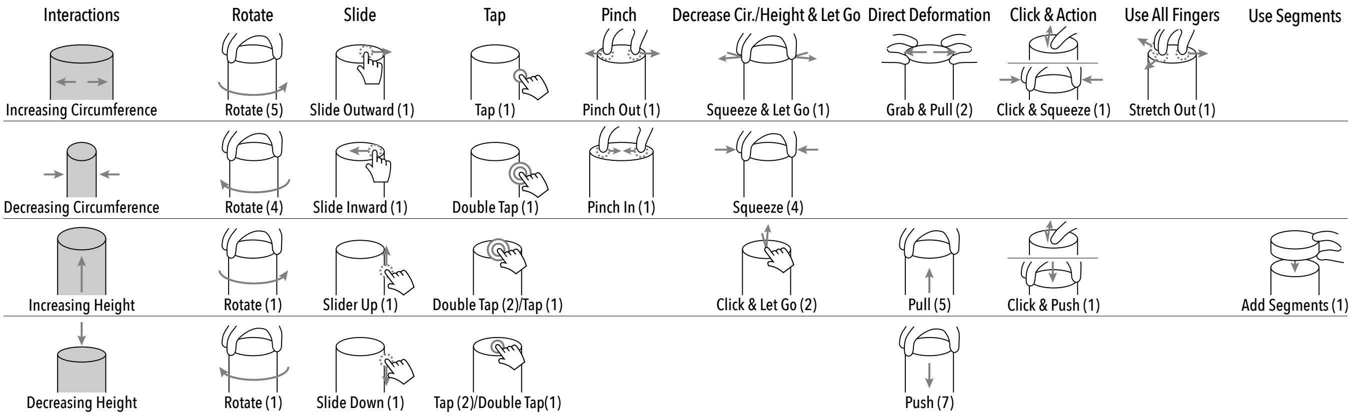

**Figure 15. Suggested gestures to increase/decrease circumference and height of dials. The numbers in the parenthesis show how many participants suggested the gesture. Left column: targeted shape-changes of the dial. Right columns: suggested gestures and how frequently they were suggested (in parenthesis). They are vertically aligned by their similarity with other shape-change gestures (e.g., Squeeze & Let Go for width increase and Squeeze for width decrease were suggested together).**

Changing the width

Nine ideas were to rotate the dial to increase or decrease the circumference width. Two participants explained that the interaction is the same with rotating screws, while one participant said it was using centrifugal force. To distinguish the rotation for width-change from the one for rotational input, the participants suggested three ideas: 1) using different speed (e.g., quicker rotation for width change), 2) rotating while pulling up the dial for width change, and 3) having two rotational modes of the dial such as a mouse scroll wheel that has friction and non-friction modes (e.g., on Logitech MX Master 2S).

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

Four ideas to decrease the width were squeezing the circumference, and the gestures to increase the width varied (Figure 15, four gestures on the top row right). They varied as four types of gestures: 1) squeezing the circumference quickly, to activate its expansion, and grasping it again, to stop the expansion at the desired width, 2) grasping and pulling the circumference outward, 3) clicking the top of the dial to reset it to the biggest width and then reduce the circumference, and 4) putting all five fingers on the dial and stretching out the fingers.

Changing the height

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

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

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

## Discussion

The participants were concerned about their own capability to control the width and height. This raises the question of the human resolution [5][6] for these deformation gestures. The participants were also concerned about their ability to properly perceive a change in width and height. The height of bars similar to dials can be recognized [19] but the question remains open for widths.

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

The participants proposed applications in *work* and *entertainment* domains. This suggests that performance, emotional and hedonic user experience [31] of shape-changing dials should be studied. Some of the *work* ideas were less error-tolerant and needed more concentration on the tasks (e.g., surgery robot interface) than others (e.g., desktop interaction). This raises the following questions: can the force/haptic feedback provided by the ExpanDial provide distinguishable warnings and notifications? How can such a shape-changing device balance between notifications and users' focus on their tasks?

In addition, some application ideas were using the height for display. These ideas take for granted that users would feel the height when manipulating ExpanDial. But we were not sure that users would be able to always feel the height change, especially when they are manipulating the device.

Interestingly, many of the suggested gestures were from touchscreen interactions. On the one hand, one of the aims of shape-changing interfaces is to fully use human's dexterity [18], and thus mapping touchscreen-based gestures to them might not fully exploit their capabilities. On the other hand, it could improve users' learnability and transition from touch interfaces to shape-changing ones. The challenge lies in finding a trade-off between gestures that are general and easy to be applied to all kinds of interfaces and gestures that leverage the input capabilities for each particular interface.

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

## IMPLICATIONS FOR SHAPE-CHANGING DIALS

From the results of both studies, we derive the following requirements for a shape-changing dial. ExpanDial requires a round basis, so that users can place their hand at any angle (yaw) before rotating it and support any number of fingers. A disk below the dial with a pointer to indicate the value at the bottom of the dial could also be added in order to allow for precise feedback on the angle value, avoiding parallax.

As participants of the design session were concerned about undesired movement when change the shape, the community should find a way to allow users to change the shape of the dial while not affecting the eight postures of Figure 7. Changing the shape can be done: (1) from a different posture with the same hand, forcing users to change shape and turn the dial in sequence, or (2) from different posture with the other hand, forcing two-handed interaction, or (3) from the very same posture. In this last case, great care should be taken to avoid undesired rotation of the dial, and conversely, undesired shape-change when users turn it.

ExpanDial can take advantage of height changes continuously while interaction happens. Users largely place their fingers on top of it, whether the dial is low (1cm) or high (8cm). If ExpanDial provides smooth sides, users will be able to keep their grasps at the bottom/middle while the device is raised or lowered. This is a grand challenge, because current implementation techniques for width-changing dials [8][23][29] do not provide a smooth surface at the circumference. Future work may use a different origami pattern with a smooth circumference, such as the one by Sternberg [35]. Using the height of the dial as haptic feedback might only be partially supported, as part of users grasped the high dial (8cm) from its m rather than its top.

Future work should address the design of the gestures to allow for manipulation of the angle, the width and the height, without affecting the users grasp(s). Some of the open research questions are: Is the simultaneous change of height, width and angle necessary? Or can the sequential manipulation of these physical parameters support the user's tasks? Is one- and/or two-handed interaction possible? Can we find a set of gestures that allows simultaneous change of angle, width and height while avoiding undesired input? A first intuition resulting from our design session is that different kind of pressures might be applied for turning vs. deforming the dial.

Future applications and studies should explore a wide range of expected benefits, from emotional and hedonic user experience to task performance. A grand challenge for such novel devices is to support simultaneously an easy transition from known interaction (e.g., touchscreen) to the new interaction techniques, while at the same time exploiting all its capabilities for an augmented input bandwidth. In order to be able to leverage the change of width as a way to provide feedback, future work should study the ability of users to accurately perceive the width of the dial.

Finally, our work lays the foundation for designing such shape changing input devices, but more work needs to be done to pursue this direction. We particularly wish to study additional morphing mechanisms and more complex form factors such as shuttle types of dials [4] that can be rotated by one finger or dials with different torque to provide force feedback.

## CONCLUSION

In this paper, we systemically explored how users grasp dials with different heights and widths and provide lessons for designing shape-changing dials. Based on the lessons, we designed ExpanDial, a shape-changing dial that can not only accept users' rotation and deformation to enable multi-parameter control on a single device, but also change its height and width to display information. The design session with ExpanDial revealed challenges on designing applications and gestures for shape-changing dials. Our work provides foundational knowledge on users' dial grasp and show how the knowledge can be applied in designing shape-changing dials. We believe that more shape-changing interfaces should consider human factors so that they can provide better ergonomics as well as fully leverage human's interaction capabilities.

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