An Exploration of Mobile Shape-Changing Textures

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ABSTRACT
This paper describes the development and evaluation of *Undulating Covers* (*UnCovers*), mobile interfaces that can change their surface texture to transmit information. The *Pin Array UnCover* incorporates sinusoidal ridges controlled by servomotors, which can change their amplitude and granularity. The *Mylar UnCover* is a more organic interface that exploits the buckling properties of Mylar, using muscle wires, to change the texture granularity. The results of two user studies show that very low frequency texture changes, using amplitude or granularity, can be distinguished with high levels of accuracy. Since small changes are perceptible, it is possible to incorporate such interfaces into mobile devices without drastically increasing their size or actuation requirements. Finally, ratings from participants indicate that UnCovers would be appropriate for attention-grabbing, or caring and supportive interpersonal messages.

Author Keywords
Shape Changing Interfaces; Haptic feedback; Mobile Communication; Mylar; Texture.

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

INTRODUCTION
Haptic feedback is often incorporated into interactive systems to provide information to our sense of touch [1,6]. However, this feedback is not usually static, especially in mobile devices. Existing research on mobile haptic feedback tends to make use of vibrotactile stimuli, which is transitory. The user's hand must be in contact with the device at the exact moment the feedback is provided otherwise the vibration may not be perceived. Previous research has shown that tactile perception differs depending on the body location [2]. So, even if the device is in contact with the user's skin, the detection threshold will be higher if it is in contact with less sensitive areas of the body. Research has shown that many users miss alerts from their mobile devices because of these perception issues [10].

TEI '17, March 20-23, 2017, Yokohama, Japan
© 2017 ACM. ISBN 978-1-4503-4676-4/17/03…$15.00
DOI: http://dx.doi.org/10.1145/3024969.3024983

Figure 1: Left - Pin Array UnCover, Right - Mylar UnCover.

The research reported here will demonstrate the potential of alternative forms of haptic feedback inspired by concepts from Organic User Interfaces (OUIs) and shape-changing interfaces [8] to address these perception issues. Unlike vibrotactile feedback, haptic feedback from shape-change can be static and continuous. Research in shape-change and OUIs has produced interfaces that can change their orientation, form, volume, texture, viscosity, spatiality, adding/subtracting and permeability [17]. To use shape-changing parameters [19] (size, shape, amplitude, porosity, granularity, speed, and strength) as a communication channel, it is important that users can distinguish, and identify multiple levels of these parameters. So far, these parameters have received little psychophysical attention, and, therefore, require some experimental investigation in order to understand how they are perceived.

In terms of mobile interaction, one of the most promising shape-change parameters is texture because the overall shape of the device is not affected [4], meaning that it is possible to augment an already existing rigid device, such as a mobile phone. In this paper, we evaluate the effectiveness of two techniques for dynamic and distinguishable texture displays, using shape-changing mobile interfaces, called *Undulating Covers* (*UnCovers*), shown in Figure 1. UnCovers dynamically alter the amplitude or granularity of surface control points to create different textures. Through two user studies we evaluate the distinguishability of different low frequency textures, and compare user perception, with and without visual feedback.

BACKGROUND

One of the most relevant publication for our research is Dimitriadis and Alexander's paper on shape-change notifications [3]. They developed several different types of shape-changes for mobile alerts. The most successful of which was the protrusion device. In this prototype a small arm protrudes from the display. The amplitude of this protrusion was 10mm or 15mm. The protrusion was presented either as a static stimulus or with a slow or fast pulse. The results showed that participants could detect 100% of these alerts in their pocket. Our experiment prototypes (the UnCovers) were inspired by Dimitriadis and Alexander's findings. Unlike the protrusion prototype described above, the UnCovers make use of multiple control points with much smaller amplitude changes, and include granularity control.

To fully understand the perception of shape-changes using the amplitude and granularity parameters, it is important to identify the difference threshold, also known as the Just Noticeable Difference (JND) [13]. Dimitriadis and Alexander [3] used fairly high amplitude levels of 10 and 15mm, reaching 100% detection, but did not examine the smallest perceivable changes. Since such large shape changes consume a great deal of power, as noted by Dimitriadis and Alexander, and may decrease the robustness of the technique for use in the pocket, we wanted to examine much smaller amplitude changes. According to work by Shimojo *et al.* [21] gaussian shaped ridges with amplitude levels as small as 2mm can be detected easily.

Pin arrays could be considered the first shape-changing tactile displays. For example, Lee *et al.* [12] built a 6x6 tactile shape display that uses servo-motors to control metal pins. Experiment results showed that participants could distinguish 3D vertical lines when the pins were covered with a rubber layer. However, given the large number of motors, the prototype is not suitable for mobile use.

Raffle *et al.* [16] developed an interactive membrane called Super Cilia Skin. The membrane is made up of an array of actuators, which oscillate in response to a magnetic force. This can display geometric patterns. Informal evaluations showed that users could distinguish different shapes. Somewhat similarly, the Hairlytop device [14] makes use of Shape Memory Alloy hair-like actuators to display geometric information.

Harrison and Hudson [4] proposed that texture displays could be used to provide passive tactile feedback on the surface of various different objects. User evaluations showed that participants could easily distinguish between two and four different states for different fabric prototypes. For example, there was a beaded matrix where the beads are threaded onto some elasticated material. When the material is relaxed, the beads form a set of ridges and when the material is stretched the beads become spaced out. These results are very promising but there is still work to be done to integrate the proposed texture displays with a mobile device and to determine the perceptual thresholds.

All of these findings along with related work on other types of shape-changing interfaces for mobile settings [5,18] suggest that texture-based deformations could be effective and perceivable in mobile environments, where a wide variety of applications could be developed.

THE UNCOVER PROTOTYPES

In this paper, we focus on two shape-change parameters: amplitude and granularity, both of which are key features that can help to differentiate textures. We created two prototypes, called *Undulating Covers* (*UnCovers*) [1], that can deform by altering the amplitude and granularity of surface control points on an interface. In the first prototype, the control points are based on a basic mechanical pin array. The second prototype is made from Mylar[2] and the surface buckles act as control points.

Prototype 1 – Pin Array

We selected a simple design where sinusoidal ridges, covered in a thin layer of 95% cotton 5% spandex, can be pushed and pulled through a porous surface using linear servomotors (see Figure 2). If we break the design down into the shape-changing parameters outlined by Roudaut *et al.*[19], we have:

- Area: 5.5 x 5.5cm^2;
- Granularity: 0 to 12 control points;
- Amplitude: 0.2cm;
- Porosity: 0 or 100%;
- Speed: 0.5 seconds.

The deformable section of the prototype is covered with a thin material layer because previous research has shown that such a layer acts as a spatial low pass filter [10].

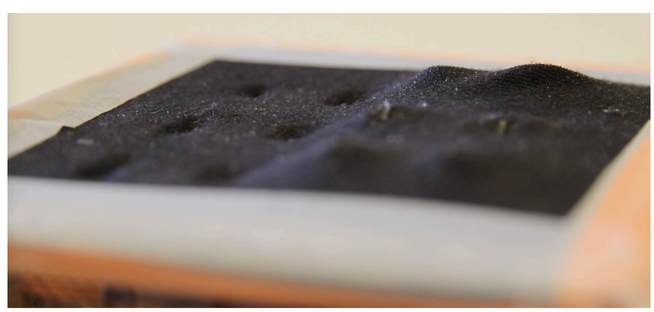

Figure 2: Pin Array UnCover, with 0 to 3mm amplitude levels.

[1] The 3D models and electronic schematics of the UnCovers are available at https://goo.gl/gVygTe

[2] http://www.dupontteijinfilms.com/filmenterprise/Datasheet.asp?ID=302&Version=US

It also prevents the mechanism from being exposed to dust or dirt that could prohibit its movement. The ridges can also be convex or concave. Previous experimental brain research has shown that detection thresholds for convex and concave stimuli are comparable [12]. This means that we can double the design space.

Prototype 2 – Mylar

The second prototype was developed specifically with granularity in mind. We wanted to be able to change the granularity of control points without requiring one motor per control point. Mylar has a great deal of potential use cases in shape-changing interfaces because it buckles in a predictable manner and only requires a single actuation location. Recent research [20] has shown that Mylar buckles into a diamond-like pattern when axial compression is applied to a cylinder. The granularity of the diamond pattern depends on the difference in circumference between the Mylar sheet and the solid mandrel underneath (see Figure 3). We used differences of 0.5mm, 1mm, and 2mm. The shape-change parameter values are as follows:

- Area: 188.5cm^2 lateral surface (radius 1.5cm, height 20cm);
- Granularity: 0 to c. 1450 control points;
- Amplitude: 0 to 3mm;
- Porosity: 0%;
- Speed: 0.5 seconds.

EXPERIMENT 1 - AMPLITUDE

As a first step, an experiment was conducted to investigate the perception of the Pin Array UnCover's amplitude changes. We used an adaptive staircase method called the One-Up Three-Down method 31FC [13], commonly used in psychophysical research. 31FC involves the presentation of three amplitudes per trial. The target amplitude is randomly assigned to one of the three presentations. The participant has to identify the presentation containing the target amplitude. The magnitude of the amplitude is increased after one incorrect response, and decreased after three consecutive correct responses.

The experiment participants were required to complete all 31FC tasks and a post-study questionnaire. In each 31FC task, the participant could touch and explore the UnCover for as long as they wished. When the participant was ready, they pressed a button to initiate the second deformation. There was a preset 3-second inter-stimulus interval for each deformation.

Participants

We recruited 18 participants (9 female, 16 right-handed, with an age range of 18 to 35) through the University and social networks. All of the participants wore headphones to mask any noise from the servomotors.

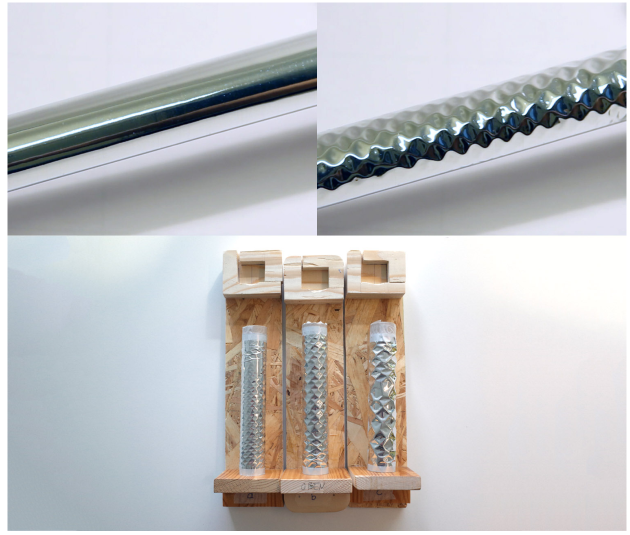

Figure 3: Mylar UnCover. Upper left: flat surface with granularity level of 0 when there is no pressure applied. Upper right: diamond-like pattern on the surface with granularity level of 1450 when Mylar is compressed. Bottom: Mylar sheets wrapped around mandrels attached to the wooden bases.

Conditions and Variables

In this experiment, the independent variable was the amplitude of the shape-change. We used seven different amplitude levels: -3mm, -2mm, -1mm, 0mm, 1mm, 2mm, 3mm. We chose our amplitude levels from within the perceivable range outlined in [11][12].

There were two modality conditions: with and without visual feedback. In the visual feedback condition, the participants were able to see the shape-change occurring. In the non-visual condition, a box covered the participants' hands so they could only feel the shape-change, not see it.

Figure 4: Experiment set-up for tactile only condition.

The experiment used a within-groups design where all participants completed tasks under all conditions. The order of the modality condition was counterbalanced. The experiment set-up is shown in Figure 4.

Results

The experiment system logged the amplitude level, modality condition, response time and accuracy. The mean accuracy rates for each amplitude level in each condition are shown in Figure 5.

A repeated measures analysis of variance (ANOVA) of amplitude accuracy rates showed a significant main effect

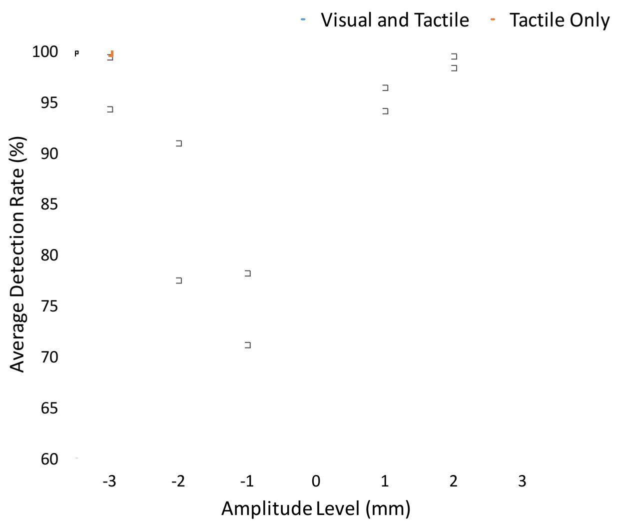

Figure 5: Mean accuracy rates for each amplitude level and modality condition.

for *Amplitude Level* ($F(1.93, 108) = 44.9$, $p<0.05$) with Greenhouse-Geisser correction. There was also a significant interaction between *Amplitude Level* and *Modality Condition* ($F(1.7, 96.5) = 26$, $p<0.05$) with Greenhouse-Geisser correction.

Bonferroni adjusted post hoc tests of *Amplitude Level* showed that the largest change of 0mm to 3mm or 0mm to -3mm (and vice versa) produced significantly higher accuracy rates than all other levels ($p<0.05$).

In terms of the interaction between *Amplitude Level* and *Modality Condition*., concave levels of -3mm, -2mm, and -1mm produced higher accuracy rates in the tactile only condition than the visual and tactile condition ($p<0.05$). Also, for the 1mm and 2mm convex levels, the accuracy rate in the visual and tactile condition is significantly higher than the tactile only condition ($p<0.05$).

The lower accuracy rates for the concave amplitudes reflects findings in previous research. For example, Kappers *et al.* [9] found that concave shapes yield significantly higher standard deviations than convex ones in identification tasks. Human beings are much more often confronted with elliptic than with hyperbolic shapes in the real world and similar results are found in vision research, with hyperbolic shapes classified less accurately than elliptical shapes. That being said, the perception levels for concave ridges were still promising and indicate that they may be used to transmit information.

The reason why the concave amplitude levels tend to be detected better through the sense of touch could be because the visual feedback from such a movement is limited. Whereas, when the convex features rise out of the shell, the visual feedback is much more noticeable. We asked the participants about this issue in the post-experiment questionnaire. 83% of the participants said that they relied

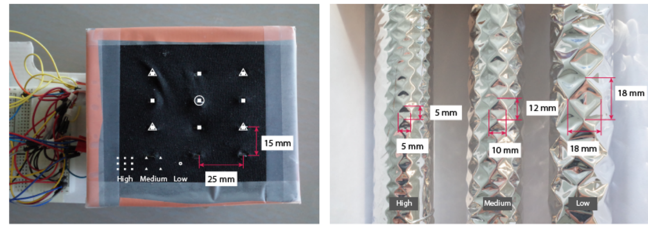

Figure 6: Granularity levels for the Pin Array (left) and Mylar (right).

mainly on their sense of touch as opposed to their vision. Several participants said that, even though some of amplitude changes were very easy to detect through sight, they preferred to use touch. They also noted that smaller amplitude changes required exploration through touch.

EXPERIMENT 2 – GRANULARITY

A second user experiment was conducted to investigate the perception of the Pin Array and Mylar UnCovers' granularity changes (as shown in Figure 6).

We conducted a within subjects experiment to identify the distinguishability of different granularities when a user's hand is in contact with the UnCovers (with and without visual feedback).

Participants and Task

We recruited 12 participants (3 female, all right-handed, with an age range of 20 to 35) through the University and social networks. All of the participants wore headphones to mask any noise.

In each trial, two granularities were presented to the subjects in a counterbalanced order. After examining the stimuli, by touching them (with and without visual feedback), the participant was asked to identify the stimulus with the largest granularity. This comparison task was repeated for each UnCover (pin array and Mylar) four times, resulting in 24 samples for each condition.

Conditions and Variables

We used three different granularity levels for each of the UnCovers.

Pin Array:

- Small: 1 control point, raised area of $3mm^2$
- Medium: 2 x 2 control points, raised area of $15cm^2$
- Large: 3 x 3 control points, raised area of $15cm^2$.

Mylar:

- Small: 116 control points (diamonds), diamond surface area of $1.62cm^2$
- Medium: 314 control points, diamond surface area of $0.6cm^2$
- Large: 1450 control points, diamond surface area of $0.13cm^2$

The experiment was conducted under two counterbalanced conditions: tactile feedback only, and tactile plus visual feedback. In all conditions, the Uncover was placed on a table and participants were asked to touch the UnCover with their hand once the deformation was complete. In the haptic feedback only condition, a box was placed over the participants' hands and the UnCover. This was to ensure that the shape-change could not be identified visually.

Results

In this experiment, the system logged the granularity level, modality condition, response time and accuracy. The mean accuracy rates for each granularity level in each condition are shown in Figure 7.

A repeated measures analysis of variance (ANOVA) of granularity accuracy rates showed a significant main effect for *Granularity Level* ($F(1.4, 15) = 5.2$, $p=0.02$) with Greenhouse-Geisser correction. The ANOVA also showed a significant main effect for *Modality* ($F(1,11) = 22$, $p=0.001$), and for *Prototype* ($F(1,11)=14.7$, $p=0.003$). There were no significant interactions between the conditions.

Bonferroni adjusted post hoc tests of *Granularity Level* showed that the smallest granularity level produced significantly higher accuracy rates than the medium and large levels ($p<0.05$), and there was no significant difference between the medium and large levels ($p=0.61$).

As shown in Figure 8, as the difference in granularity levels increases, so do the accuracy rates. In terms of the main effects of *Modality* and *Prototype*, post hoc tests show that there are higher accuracy levels in the *Visual* and *Tactile* condition, compared to the *Tactile* condition (0.001), and that the *Pin Array* led to higher accuracy than the *Mylar* ($p=0.003$).

The results show that the detection rates with the Pin Array are generally higher than the Mylar. This may be due to the more rigid and defined structure of the Pin Array, compared to the flexible and organic structure on Mylar.

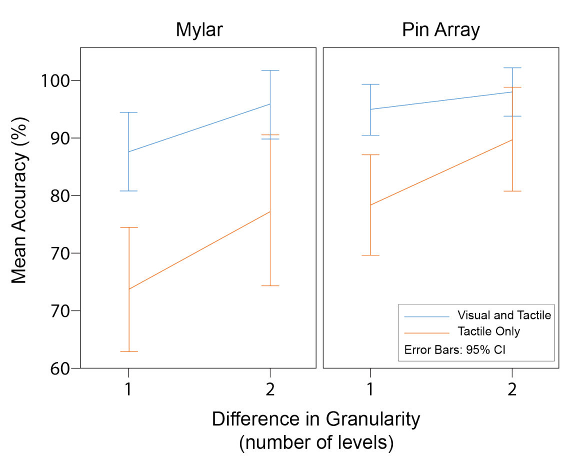

Figure 7: Mean accuracy rates for each granularity level, type of UnCover, and modality condition.

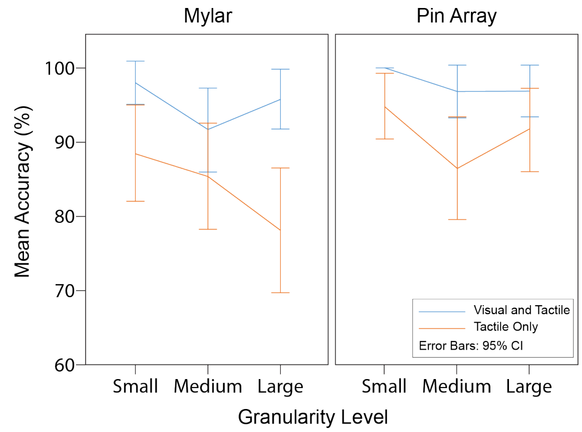

Figure 8: Mean accuracy rates for distinguishability across differences in granularity levels.

However, the Mylar detection rates increase greatly when visual feedback is provided. This is most likely because Mylar is a highly reflective material, and the enhanced contrast highlights the difference in granularities. The medium and large granularities are confused more often than the small granularity. This indicates that, even though it is theoretically possible to count the number of control points, the larger granularities may be perceived in a relative manner as it becomes more difficult to count the number of control points.

Post-Study Questionnaire

After the experiments, the participants were asked about their experiences with the UnCover amplitude and granularity changes. Several participants suggested some potential applications for this type of haptic feedback. For example, 24 of the participants said that they would use the feedback as a form of mobile alert or device state notification. Seven of the participants also said that they would like to use the Pin Array as a representation of a clock so they can check the time by touching their pocket. Lastly, another intriguing application, suggested by many of the participants, is remote interpersonal communication. Users could send textural deformations to other users' UnCovers. As stated in [8], human to human communication is a natural application of OUIs. Participants were shown all possible texture deformations, one at a time, and asked to rate how strongly [they] agree or disagree with various different interpretations of the message. The message types were based on those used in [4][7][15] and were rated on a 7-point Likert scale.

A principle components factor analysis of the 18 message types, using varimax rotations, was conducted with 3 factors explaining 78% of the variance. We chose three labels for the factors: *Caring and Supportive*, *Provocative* (negative and positive), and *Attention-Grabbing*. The factor loading matrix for this final solution is presented in Table 1. Composite scores were created for each of the three factors, based on the mean rating of the items which had their primary loadings on each factor.

	Caring & Supportive	Provocative	Attention-Grabbing
Alert	-.169	.588	.665
Anger	-.048	.887	.262
Annoyance	.437	.649	.177
Appreciation	.920	.069	.081
Attention	-.001	.419	.776
Comfort	.884	.064	-.047
Congratulations	.845	.245	.313
Emphasis	.297	.382	.657
Encouragement	.757	.290	.084
Friendship	.895	.182	.083
Frustration	.228	.883	.194
Greeting	.487	.080	.767
Intimacy	.750	.345	-.155
Joke	.385	.804	.061
Laughter	.436	.704	.211
Love	.921	.208	.091
Playful	.623	.716	-.009
Question	.491	.496	.381
Reassurance	.792	.089	.322

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Table 1: Factor loading matrix.

Attention-Grabbing was the message type that participants rated the most appropriate across all prototypes, in particular for the *Pin Array UnCover* with the highest amplitude and granularity.

Caring and Supportive messages were rated most appropriate for the highest magnitudes of shape-change for the *Pin Array UnCover*, whereas in the *Mylar UnCover*, the lower magnitudes of granularity were more appropriate.

Lastly, *Provocative* messages were associated with granularity changes in the *Pin Array* and *Mylar UnCovers*, at the highest granularity levels but were not so appropriate for the *Pin Array* amplitude changes, as shown in Figure 9.

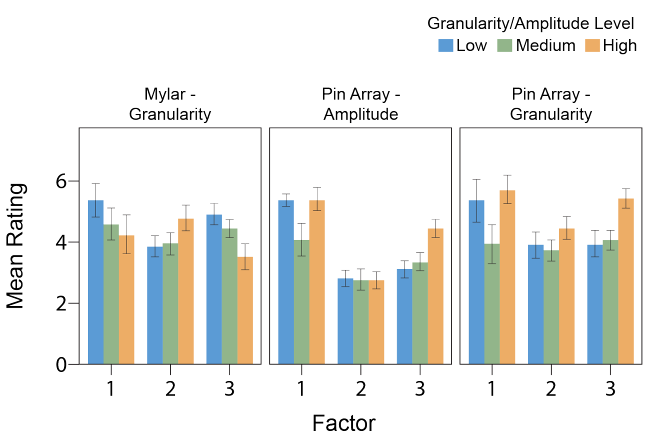

Figure 9: Mean appropriateness rating for each Factor (1: Caring & Supportive, 2: Provocative, 3: Attention-Grabbing) for each UnCover, and stimulus level. Error bars = 95% CI.

MOBILE PROTOTYPES

It is challenging to implement shape changing interfaces on mobile devices, since both the device and the interface mechanism need to share two of the device's most important resources: space and power. However, given the promising results from our experiment, it seems like mobile versions are not out of the question since very small shape-changes are perceivable, thus reducing demands on space.

We explored two types of actuators for driving the shape change. For the Pin Array Uncover we used a servomotor-based mechanism, which requires more space but can be power-efficient. In the case of Mylar Uncover, we chose to use muscle wires that are very compact in size but consume more power. Both actuators are common in shape-changing interfaces. In this section we present the practical implementation details, and discuss the compromises we made to ensure a small mobile form factor.

Mobile Pin Array Uncover

The mobile version of the Pin Array UnCover has four sinusoidal ridges that can be pushed and pulled using a single small servomotor with low power requirements (Figure 10). The ridges are 3D printed with polylactide (PLA), which means that they are robust and can withstand pressure. The shape-change mechanism makes use of a plate and lever system that is extremely compact, meaning that it can fit in a handheld device. The overall depth of the Pin Array UnCover plus mobile device is 2cm. The shape-change parameter values are:

- Area: 15.2cm^2;
- Granularity: 3x4 control points;
- Amplitude: 0.3cm;
- Porosity: 100% or 0%
- Speed: By using a servomotor, we can vary the speed of deformation (the default setting is 0.5 seconds).

Shape-Change Mechanism

A movable plate is built in to the underside of the cover. The ridges can be pushed and pulled through the cover using a servomotor, which is attached to two levers at either side of the plate (Figure 11). The servomotor is driven by an Arduino board, which also fits inside the cover.

Figure 10: The Mobile Pin Array UnCover.

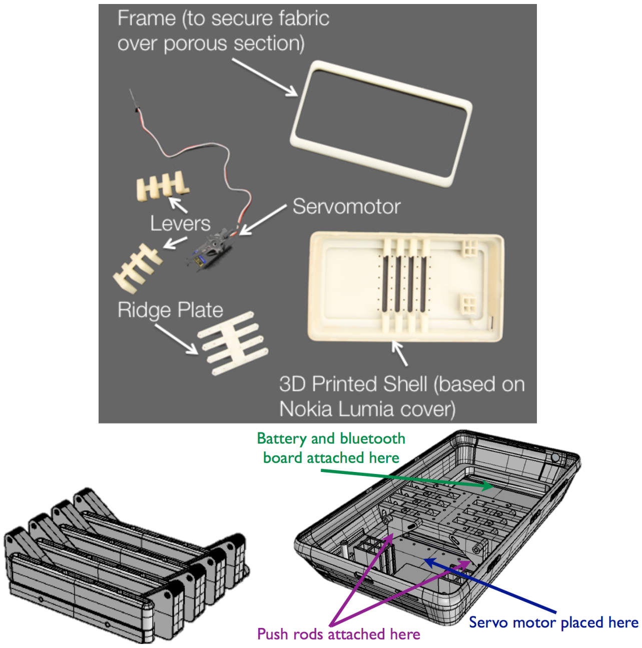

Figure 11: The mobile Pin Array UnCover components, movable plate with levers attached, and positions inside cover.

When the servo motor rotates clockwise, the plate is raised up and the ridges are pushed through the surface. When the servo motor rotates anti-clockwise, the plate is lowered so that the ridges are beneath the surface. The ridges pull the thin covering layer of material with them, creating dimples or concave features. The degree of motor rotation determines the amplitude of the texture. These shape changes are illustrated in Figure 12.

Mobile Mylar UnCover

The mobile version of *Mylar UnCover* consists of a small flexible cylinder, wrapped in a Mylar sheet, attached to the side of the phone case. Instead of implementing a movable Mylar holder at one end of the cylinder for axial compression, the compression can be triggered by bending the cylinder. The curved cylinder creates a gap in between the Mylar sheet and the cylinder, which compresses the Mylar from both ends of the cylinder. It must be noted that the diamond-like shapes are only formed on the concave side of the cylinder.

Figure 12: Illustration of potential amplitude changes in Mobile Pin Array UnCover.

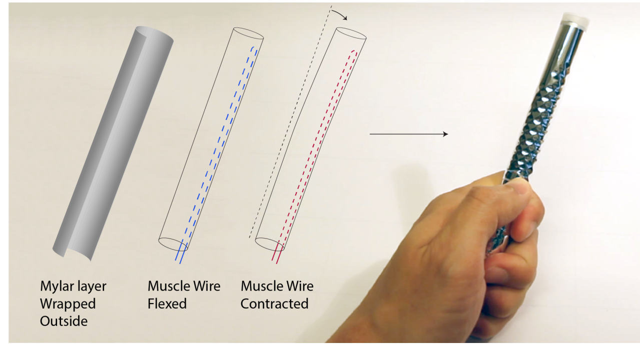

Figure 13: Mobile Mylar UnCover. A Mylar sheet is wrapped around a flexible tube with muscle wire attached inside of the tube. When the wire contracts, the tube bends toward one side and shape the Mylar.

The shape change parameter values are:

- Area: $20cm^2$ effective lateral surface (width 4cm, length 8cm);
- Granularity: 160 control points, diamond surface area of c. $0.125cm^2$;
- Amplitude: 1mm;
- Porosity: 0%;
- Speed: 2 seconds (The speed may vary according to the properties of the muscle wire and applied current).

Shape-Change Mechanism

Using muscle wires as an actuation mechanism is common in modern shape changing interfaces and robotics, such as the longitudinal tensile actuation in [18]. In our case, the muscle wire is attached to one side of the inner wall of the tube. The wire contracts when there is a current running through it, resulting in a bent tube (Figure 13). When the current stops, the flexible tube returns to its original shape.

DISCUSSION AND CONCLUSIONS

Building on previous explorations of shape-changing techniques and parameters, the experiments reported in this paper established that low frequency texture changes using amplitude and granularity can be easily distinguished. The results indicate that:

- Convex and concave amplitude changes in the Pin Array can be distinguished with 68% to 100% accuracy;
- Convex amplitude changes are distinguished more accurately when using tactile and visual feedback, whereas concave changes are distinguished more accurately through tactile feedback alone;
- Granularity changes can be distinguished with an average accuracy rate of 94% with the Pin Array and 89% with Mylar.
- The distinguishability of granularity changes in the Pin Array and Mylar UnCovers improves when using

tactile and visual feedback, as opposed to tactile feedback alone;

- Participants rated *Attention-Grabbing* messages as the most appropriate for both prototypes, *Caring and Supportive* messages were rated most appropriate for the highest magnitudes of shape-change for the Pin Array, and the lowest magnitudes of granularity in Mylar. *Provocative* messages were associated with the highest granularity levels in the Pin Array and Mylar.

There are still many challenges in this area of research. Firstly, it will be necessary to conduct longitudinal in-the-wild studies of shape-change perception to ensure that such stimuli can be successfully used as a method of information transmission regardless of the user's environment.

Furthermore, since the aim of this research is to use shape-change parameters as a form of static haptic feedback, the number of distinguishable levels of each shape-change parameter should be as high as possible. This can be difficult [10, 16], because parameters may interact with each other. If the granularity of control points decreases, it may be difficult for users to detect different amplitude levels. This is the case with the Mylar UnCover, as the granularity increases, the amplitude decreases.

It is our hope that this work will inspire other researchers to consider using texture-based shape-changing displays as a form of haptic feedback for mobile communication.

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