Emergeables: Deformable Displays for Continuous Eyes-Free Mobile Interaction

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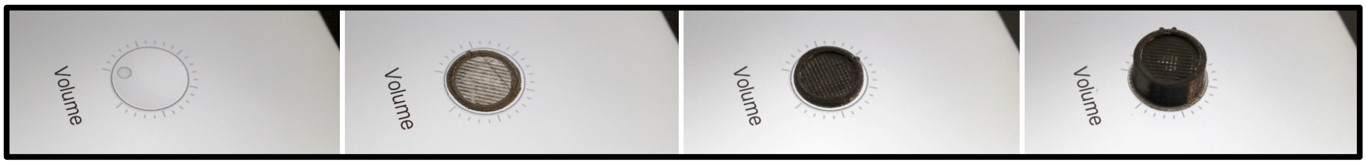

Figure 1. The *Emergeables* concept: instead of graphical widgets, tangible continuous controls emerge from the surface of the mobile device.

ABSTRACT
In this paper we present the concept of *Emergeables* – mobile surfaces that can deform or 'morph' to provide fully-actuated, tangible controls. Our goal in this work is to provide the flexibility of graphical touchscreens, coupled with the affordance and tactile benefits offered by physical widgets. In contrast to previous research in the area of deformable displays, our work focuses on continuous controls (e.g., dials or sliders), and strives for fully-dynamic positioning, providing versatile widgets that can change shape and location depending on the user's needs. We describe the design and implementation of two prototype emergeables built to demonstrate the concept, and present an in-depth evaluation that compares both with a touchscreen alternative. The results show the strong potential of emergeables for on-demand, eyes-free control of continuous parameters, particularly when comparing the accuracy and usability of a high-resolution emergeable to a standard GUI approach. We conclude with a discussion of the level of resolution that is necessary for future emergeables, and suggest how high-resolution versions might be achieved.

Author Keywords
Deformable devices; continuous control; mobiles; tangiblity; shape-changing.

ACM Classification Keywords
H.5.2 User Interfaces: Input devices and strategies.

INTRODUCTION
Mobile phone and tablet touchscreens are flat, lifeless surfaces. In contrast, the physical controls that touchscreens attempt to emulate (such as raised buttons and other widgets) support rich interactions that are directly afforded through their tangibility. The benefit of such tangible elements has long been accepted in the HCI community (e.g., [20]), but prior work has largely focused on display deformation to *render* information to users (or "physicalisation" – e.g., [10]). Our interest here is in direct, tangible, *hands-in* and *hands-on* interaction with mobile devices – that is, creating a physical surface which can be both a visual display, and present physical control widgets—buttons, dials, sliders and so on—that emerge from the screen to provide control when needed, disappearing back into the surface when not required. In this work, then, we present what we believe is the first exploration of hands-on continuous interaction with dynamically deformable mobile devices.

The basic advantages of tangibility for interaction are clear, ranging from ease of manipulation to the reduced need for visual attention in safety-critical situations (e.g., driving). These advantages are also evident in dynamic situations when, for instance, people still prefer to switch between multiple physical controls over combined digital versions [3]. Prior work has demonstrated the benefits of reconfigurable tangible controls via detachable widgets that can be used with a mobile touchscreen surface [21]. However, while these are beneficial for interaction performance for single tasks in isolation, carrying a collection of tangible elements at all times is clearly impractical in reality. The advantages of mobile deformable displays in these situations could, therefore, be highly significant, allowing a single device to take the form of the most appropriate control for the situation at hand.

In this work we are interested in displays that are able to deform to create and present these controls dynamically. Producing controls on-demand has previously been proven beneficial for static buttons [2, 14]. However, there is a significant gap around tangibility of *continuous* controls that we aim to address here. Secondly, it is clear that in order to create truly deformable mobile displays there is a large amount of research and development work still to be done. In order

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to support and direct this effort, then, in this research we also aim to quantify the gains that can be had by creating tangible controls on-demand.

In the process of investigating this question, we introduce *Emergeables* – a demonstration of how tangible controls could be dynamically created on mobiles. Emergeables depart from existing deformable research by endeavouring to provide truly direct interaction with affordances, controls and content integrated within a visual display (see Figs. 2 and 4). Our ultimate long-term aim is to create a mobile device where any control widget can appear anywhere on its surface – in essence, affording the same flexibility as a graphical interface, but with the affordance and tactile benefits of tangibles. Consider the following scenario, then, which illustrates the approach:

> *Alex is playing a role-playing game on his Xbox and is keen to use his new Emergeable mobile to enhance the experience. While focused on the television screen, Alex pulls out his mobile, which begins acting as a controller. At the start of a mission, his character needs to drive a car, so the controls on his touchscreen become a steering wheel, joystick gear lever and raised gas and brake pedals. When he arrives at his destination, there's a lock to pick, so the controls morph into two levers he has to gently manipulate to tease out the pins of the bolt. After opening the door, he notices some accessories on the table. His mobile shifts to reveal 3D representations of the objects so he can select which ones he wants to pick up by touch alone. As he moves towards the next room he hears voices: the touchscreen quickly changes shape to reveal the weapons Alex has in his possession, and he quietly arms himself ready for combat…*

The contribution of this work is to quantify the performance benefits of, and gain qualitative user experience insights into, the concept of emergeables. It may take many years of development to produce such a display at consumer level, but we believe that this paper provides a solid grounding for future work in this adventurous area.

Our first motivation in carrying out this work is to consider whether such an ambitious end-goal will provide enough benefits given the costs associated with its development. We are also interested in the value of intermediary articulations of the concepts – that is, devices that afford continuous inputs but at a lower level of resolution. We sought, then, to understand the relative performance of such displays—that may be more achievable in the short-term—compared to both a high-level prototype and the conventional, flat GUI.

To demonstrate and test the potential of this concept, we created two emergeable prototypes: one high-resolution, where controls appear on the surface on-demand, but in a set of fixed positions; and, a second that uses a pixel-based widget model to produce lower-resolution controls, but already provides flexibility in positioning. In the rest of this paper we discuss background work, present the design space of emergeables, describe the prototypes we developed, and present the results of a study conducted to measure the effect of dynamic tangibility with regards to accuracy, visual attention and user preference. We conclude by discussing design implications for the control widgets that we have studied, and suggesting potential future pathways to developing emergeable mobile devices.

BACKGROUND

Mobile eyes-free continuous interaction

Previous work has explored mobile eye-free continuous interaction, for instance through devices (e.g., smart watches [30], haptic feedback on mobiles [12], on-clothing control [23], or elastic control [25]). Another approach is to leverage the user's body, for instance through foot control [35], on-skin control [27] finger-based [45] or face-based [36] control. All of these works emphasise the need for *eyes-free*, *continuous* control. However, most of the proposed solutions require the user to learn new interaction techniques on surfaces that do not provide feedback specific to the interaction itself. For instance, touching your arm to control a slider will likely be convenient and effective, but will not give the tangible feedback of a real, physical slider. One exception to these previous approaches is the use of tangibles on a touchscreen, such as Jansen et al.'s *Tangible remote controllers* [21], or Born's *Modulares*[1], which leverage users' existing experience with physical controllers.

Tangible User Interfaces (TUIs) for eyes-free interaction

Harrison and Hudson [14], Tory and Kincaid [40] and Tuddenham et al. [42] showed that, when the item being controlled is adjacent to the controls used (e.g., the tangible is situated right next to the display screen), tangibles outperform touchscreens. The benefit for entirely eyes-free interaction (where the feedback area is completely separated from the control area – on a remote surface, for example) has also been demonstrated by Fitzmaurice and Buxton [8] and Jansen et al. [21]. In the latter, a tangible slider outperformed a tactile slider on a tablet. However, the solution Jansen et al. proposed was to attach tangible controls to a mobile surface. Clearly, carrying a collection of tangible controls at all times in order to switch between them according to the task at hand is not practical. This technique also requires an additional articulatory stage for each action to add the controls to the screen. In this paper we take at a different approach, where the system can dynamically provide the necessary tangible controls as and when needed.

Motor-spatial memory is considered a key factor in the success of TUIs ([9, 37]). With their dynamic and system-controlled actuation of controls, our prototypes reduce the ability of users to rely on this motor-spatial memory, so provide a challenge to previous results. From prior work, it is not possible to tell how important motor-spatial memory is in the combined factors that result in TUIs' benefits – a question we address here.

Organic User Interfaces (OUIs)

In arguing for OUIs, Holman and Vertegaal present the benefits of computing form factors that can physically adapt depending on the functionality available and on the context of use [17]. Their three principles for OUI design (input equals output; function equals form; form follows flow) have informed our

[1] See: florianborn.com/projects/modulares_interface

work, but while their vision accommodates a comprehensive range of novel deformations, we focus on OUIs that allow the presentation of well-known controls (e.g., dials and sliders). Previous work showed that learning very different controls is a possible source of difficulty and frustration for users [5].

Dynamic and shape-changing tangible interaction

Self-actuated tangible interfaces were originally introduced by Poupyrev et al. [32], who presented the concept of dynamically surfacing 3D controls, implementing buttons using the Lumen display [31]. The efficacy of such controls has been demonstrated for discrete tasks – for example, in the work of Harrison and Hudson [14], who showed that inflatable buttons were able to provide the tangibility benefits of physical buttons together with the flexibility of touchscreens. However, the prototype was limited to buttons alone, and so did not allow the control of continuous parameters. In addition, the inflatable membrane technique did not allow flexible placement of controls on the interface – a limitation that is also seen in the commercial version of the technology, which provides only a keyboard.[2]

More flexible approaches have been proposed through reconfigurable materials placed on top of a sensing surface. Ferromagnetic input [18], for example, allows for the physical form of a device to be defined using combinations of ferrous objects such as fluids or bearings. This allows users to construct new forms of tangible widgets, such as trackballs, sliders and buttons. However, when using separate magnetic objects the approach suffers from the same mobility problems as Jansen et al.'s approach (cf. [21]); and, when using a fluid-filled bladder, it is only able to detect input, rather than provide tangible controls. Another approach to reconfigurable tangibility is *MudPad* [22], which provides localised haptic feedback through an array of electromagnets combined with an overlay containing magnetorheological fluid. However, the haptic feedback that is generated is not strong enough to constrain the user's displacement of the widgets. *ForceForm* [41] is a similarly mouldable interactive surface that can create concave areas in order to guide touches on the surface. Users can, for instance, feel a finger guide for a touch slider, though cannot grasp objects to interact, unlike our design.

In contrast to these approaches, we aim to provide controls that present the same grasp and feel as their physical counterparts, in addition to offering the same manipulation flexibility. In order to do so, our technique uses a grid of 'sensels' ([33]; see design space, Fig. 3) that are able to rise or fall in any location depending on the interaction that is required. This class of approach has previously been demonstrated on tabletop interfaces – *inFORM* [10], for example, provides an impressive array of visualisations and dynamic affordances that are created by reconfiguring the tabletop surface in the Z dimension. However, input capability is limited to vertical displacement and touch on the shape display (detected by a depth camera). Rod displays have not yet provided manipulation beyond pull and push (e.g., [39]). In our work we go further by dynamically reproducing existing tangible controls through emergeable elements. Adding such capabilities to mimic current TUIs brings new challenges to maintain performance.

[2] See: tactustechnology.com and getphorm.com.

The *Haptic Chameleon* [26] was an early demonstration of shape-changeable tangible controls applied to video playback. For example, controlling video playback at a frame-by-frame level used a large dial; scene-by-scene level used a thin central wedge of the same dial. More recently, dynamic tangible controls with pneumatic actuation have been demonstrated, allowing programmatic manipulation of tactile responses to require different levels of actuation force from users [43]. The same technology was used in [44] to change the shape of tangible elements. Moving away from buttons and dials, recent work demonstrated how a single tangible slider could be deformed to adapt to users' needs [6]. Unlike these approaches—which each address a single tangible widget—we propose and demonstrate a broader view of this area, studying interfaces that can deform their entire surfaces to create various different tangible widgets at any position.

Shape-change for mobile interaction

Many approaches exist for changing the physical shape of mobile devices. One technique for example, is to allow the interface to be folded, expanded or contracted by the system or the user, such as *FoldMe* [24], PaperFold [11] or *Morphees* [34]. The *MimicTile* [28] used smart memory alloys to sense bending of a mobile interface and also provide feedback through the device's stiffness. Another approach is to expand the physical volume of a device (e.g., [7, 15]). The key difference between our work and these examples is that each of these prototypes deforms the whole interface at once, rather than bringing tangibility to the widgets it is composed from.

A second approach to mobile tangibility is to provide deformability to dedicated parts of the mobile interface with localised protrusions (e.g., [7, 16]). However, the placement of these is not flexible, as it is in our technique. In addition, existing research that takes this approach has primarily investigated shape-change for notifications (e.g., [29]), rather than for the control of continuous parameters.

Another approach for deforming mobile UI is to raise tangible pixels from the surface – our work falls into this classification. One example of this approach is Horev's *TactoPhone* [19], a video concept scenario using a Pinscreen.[3] Horev envisioned deformation on the back of a mobile device to allow for a rich vocabulary of notifications through shape coding. In contrast, *ShapeClip* [13] uses linear motors on top of a regular capacitive touchscreen. Through control of the underlying screen's brightness and colour, deformation events can be communicated between the detachable widgets and the device underneath. However, *ShapeClip* focuses on deformation for *output* – with direct input capability limited to capacitive forwarding onto the screen below. While we use a similar approach, with micro linear stepper motors to raise and lower emergeable elements, our aim is to widen the direct tangible *input* possibilities for mobile devices.

EMERGEABLES: CONCEPT AND DESIGN SPACE

To provide a framework to guide our prototype development, informing options and choices, we first developed a design space, illustrated in Fig. 3. While display- and touch-screens

[3] See pinscreens.net (also known as Pinpression).

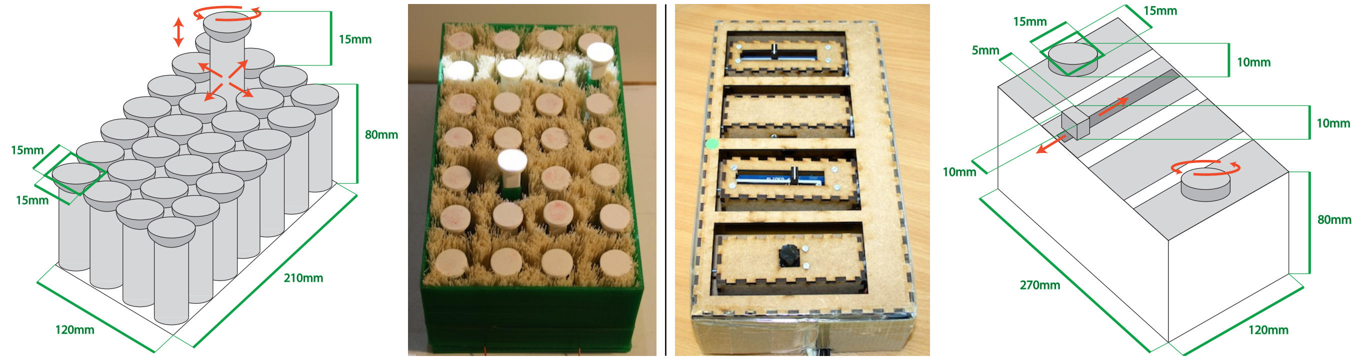

Figure 2. ***Far left:*** **the design of the low-resolution emergeable. Each circular 'sensel' of the device can be pushed vertically as a button, rotated as a dial, and tilted vertically or horizontally to form part of a slider.** ***Centre left:*** **the low-resolution emergeable prototype, with projection to highlight a raised slider (top) and dial (bottom). See Fig. 4 for an example of using the prototype.** ***Centre right:*** **the high-resolution emergeable prototype.** ***Far right:*** **the design of the high-resolution emergeable. The box contains four rotatable subsections, each capable of flipping between dial, slider or flat surface.**

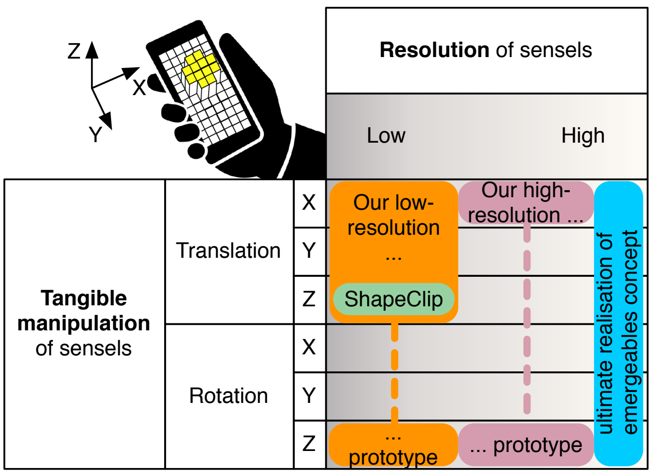

Figure 3. The core design space for emergeables describes devices that allow for both translation and rotation in three axes. Our low-resolution prototype fully supports translation, and partially supports rotation (Z-axis), while similar prior work (e.g., ShapeClip [13]) has supported only Z-axis translation. Our high resolution prototype, in contrast, supports X-axis translation and Z-axis rotation.

are constructed of pixels, emergeables' elementary unit is a *sensel* [33], with two key properties:

Manipulation: Sensels can be manipulated by the user. As a starting point to explore their potential, we consider two basic tangible manipulations from [4]: translation and rotation, each in three dimensions.

Size: The size of each sensel defines the resolution of the emergeable interface. Sensels' physical size is completely independent of the pixel resolution of the display surface.

As illustrated in Fig. 3, our ultimate aim is for emergeables to be created at very high resolutions, on the order of millions of sensels (just like today's visual displays have millions of pixels). Such a display would allow users to grab and manipulate groups of sensels to interact with as, for example:

- A slider, by translating the sensels in the Y-axis only;
- A dial or handle, where the central sensel rotates around the Z-axis, while other sensels translate in the X- and Y-axes;
- A mouse wheel, where the central sensel rotates around the X-axis, while other sensels translate in the Y- and Z-axes.

There is a richer design space to be explored that goes beyond *manipulation* and *resolution*. Alexander et al. [1]'s survey of more than 1500 household physical buttons led to a range of features of existing physical buttons (e.g., bigger buttons are pressed with less force) that can inform the design of emergeables. As explained in [1], controls could be physically modified to make critical actions harder to invoke. Moreover, controls could be provided with a range of *textures* and vary in *response*, some gliding smoothly, others providing more resistance. Adding such features to a prototype will certainly create a broad range of interaction experiences, including a method to address the eyes-free recognition of controls as they emerge. In this work, though, we have focused on the two key ones that describe the fundamental operation of the controls.

PROTOTYPES

We built two prototypes with different levels of resolution to both demonstrate the emergeables concept and test its potential (see Fig. 2). The first is a low-resolution emergeable designed after the popular Pinscreen[3] desk toys, and existing research implementations, such as [10]. Each 15 mm sensel can emerge and be fully rotated, or translated up to 15 mm in any direction. The second, built to the predefined tasks of our experiment, raises real tangible controls on-demand. Using real controls allowed us to explore the benefits of high-resolution, fully manipulable future emergeables. The full dynamics of both systems are shown in the video accompanying this paper.[4]

Low-resolution emergeable

The low-resolution emergeable prototype (see Fig. 2 (left)) consists of an array of 4×7 circular sensels of 15 mm diameter. Each sensel moves independently (powered by a micro stepper motor), and can be raised and lowered up to 15 mm to create a three-dimensional relief. Each individual sensel can also be manipulated by the user in three ways: pushing (as a button); rotating (as a dial); and, tilting to simulate a limited translation (15 mm in any direction), which is used to create sliders in conjunction with adjacent sensels (see Fig. 4). Sensels are surrounded by a bristle mesh that fills gaps as they are moved during interaction (see Fig. 2 (centre left)). With these features, it is possible to emerge a dial or slider in any location on the prototype's surface, but remove it when not required.

[4]See ACM Digital Library resources or goo.gl/sPKtyu.

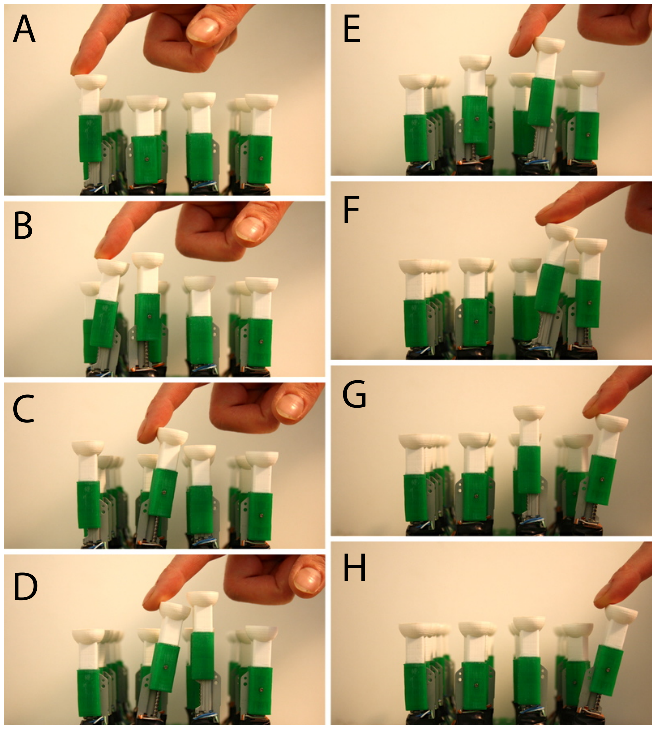

Figure 4. Slider interaction with the low-resolution prototype. First, a single sensel emerges at the slider thumb's current position (image A). The user can then tilt this and each adjacent sensel in succession to simulate movement along the slider's path (images B–H).

To create a dial, a single sensel is raised for the user to turn. To create a slider, one sensel is raised – when this sensel is tilted, the next sensel along the line of the slider is raised, and the movement continues. In this way, it is possible to simulate fluid interaction with a slider via tilting alone (see Fig. 4). While the current version has relatively large sensels, we believe this approach could in future be greatly miniaturised, allowing for richer interaction as illustrated in Fig. 3.

High-resolution emergeable

The high-resolution emergeable prototype (see Fig. 2 (right)) is far simpler, and is made of actual dials and sliders that can be revealed when needed by rotating a panel on its surface. The prototype consists of four of these rotatable panels, each of which is controlled by a separate motor, allowing it to display either a slider, dial or flat surface (mimicking the 'un-emerged' display) in each position (see Fig. 2 (centre right)).

Construction of the prototypes

The prototypes were custom-made to provide manipulation as specified in the design space. The high-resolution prototype was made of laser-cut MDF panels, with four compartments, each containing actuators that rotate the sensor panel to display the correct combination of dial, slider or blank space. The low-resolution prototype consists of 28 micro stepper motors repurposed from laptop DVD drives. These are vertically mounted on navigation switches with inbuilt rotary encoders, which provide both X- and Y-axis translation, and Z-axis rotation. Each sensel has a 3D-printed gearing shaft that allows Z-axis translation, and also functions as the interaction point.

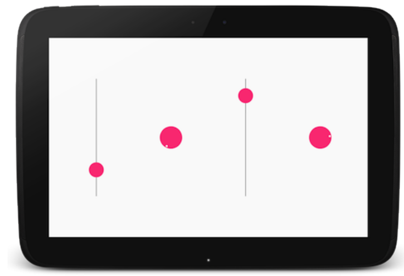

Figure 5. The graphical interface used for comparison in the study. A widget is shown in each of the four positions used (where the leftmost is a slider and the rightmost is a dial. Note that at most only two of these positions were used at any one time in the study.

The high-resolution prototype uses dials and sliders that are of comparable resolution to those used in everyday objects. The operation of the low-resolution dial is less smooth and continuous relative to the high-resolution one (having only 30 steps per revolution). The low-resolution slider provides three steps per sensel in either of the X- or Y-axes.

EXPERIMENT

We conducted an experiment in order to evaluate the impact of resolution on performance with continuous, mobile deformable controls. With this in mind, we chose to focus on dials and sliders, as they provide continuous adjustment of a parameter; and, the benefits of tangibility for buttons have been well demonstrated previously (e.g., [14]).

In addition to the two emergeable prototypes, we also created a non-emergeable touchscreen interface for comparison (developed on an Android tablet), which displayed standard platform dials and sliders in the same positions and at the same sizes as the two physical prototypes (see Fig. 5). The size, input resolution, location and latency of each widget was the same between all three designs. That is, sliders were 80 mm in length, and consisted of four sensels on the low-resolution prototype; dials were all 15 mm in diameter.

Method

The experiment followed a within-subjects design with three independent variables:

Resolution: GUI, low-res emergeable or hi-res emergeable;
Complexity: 1 or 2 widgets (controlled simultaneously);
Widget: Dial or slider.

The order of presentation of *Resolution* conditions was counterbalanced across participants using a Latin square design. The *Complexity* variable was presented in increasing order. Finally the order of presentation of *Widgets* was randomised. For instance, participant 1 was presented with the following sequence: single dial, single slider, two dials, two sliders, dial+slider; and, used each widget first with the GUI, followed by the low-resolution and then the high-resolution prototypes. In all cases, the physical location of the widgets was randomised between one of four positions (see Figs. 2, 5 and 7).

Tasks

To simulate mobility and users switching between continuous control tasks, the main part of the study involved participants using the prototypes to control a graphical display projected on

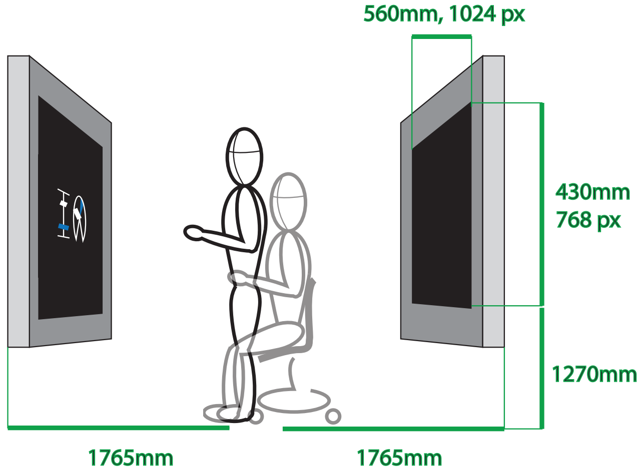

Figure 6. Experimental setting. Participants were positioned between two projected screens, and used each of the prototypes in turn to perform a pursuit task with dials and sliders (see Fig. 7). The task switched between the two screens every 15 s, and participants performed the task for 60 s at a time. When using a single control, participants stood; for two controls participants were seated.

two separate screens either side of their location (see Fig. 6). Participants used each prototype in turn for pursuit tasks.

As in previous work on continuous parameter adjustments (e.g., [8, 21]), the tasks required participants to follow a target cursor along either a linear or circular control. We chose this type of task for the trials as many higher-level human actions depend on this one-dimensional pursuit method (cf. [21]). Figure 7 shows the graphical representation of both the slider and dial pursuit tasks. In each case, the current position of the cursor is shown as a thick white line, and the target region is in blue. Participants were instructed to keep the white line within the blue target area at all times.

Following [21], the target moved at constant speed and darted off at pseudo-random intervals (2 s to 4 s). The full projected size of each control was 20 cm. The movement speed was $0.15 \times$ the control's range (R), and the dart-off distance was $0.25 \times R$. Every 15 s, the projected control moved to the other screen, and participants were prompted by on-screen instructions to turn around, simulating a change in focus or application. This was repeated four times (i.e., 60 s total), after which participants were able to take a short break if they wished. With one-widget Complexity, participants performed a second iteration of 4×15 s tasks. With two-widget Complexity only a single iteration was performed.

When the task changed between screens, the location of the widget(s) used changed randomly (consistently on both the projected screen and the prototype). As a consequence, participants needed to reacquire the control(s), but could not use their spatial memory for this. This task design allowed us to take the change of focus or application into account in our evaluation (as happens in ecological, uncontrolled settings), and measure the impact of this change on the interaction. In the case of the two-widget Complexity, each target moved independently, and participants were required to control both widgets simultaneously. Participants stood between the two

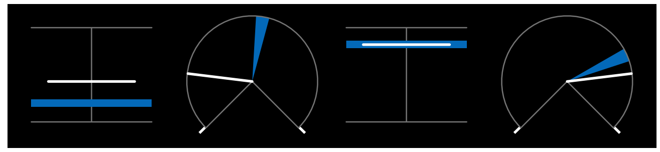

Figure 7. An example of the displays the user saw on the projected screen while carrying out the pursuit task. Widgets on the emergeable are used to control the sliders (far left and centre right) or dials (far right and centre left). There are four positions that controls could be displayed, as illustrated in the image. Each position can display a slider or a dial. Only one (single widget task) or two (dual widget task) widgets were visible at any one time. The widgets on each prototype were rendered in the same positions relative to the large screen. Solid white lines are the user's controller in each case; blue shaded areas are their target.

display screens for the single widget task; for two widgets they sat (to allow both hands to be used at the same time).

Procedure

We recruited 18 participants (9M, 9F, aged 18–66) to take part in the experiments. All except one of the participants had at least two years' experience with touchscreens (the remaining participant had no experience), and four were left-handed. Sessions lasted around 50 min on average.

After a discussion of the experiment and obtaining informed consent, each experiment began with a short demographic questionnaire, including questions regarding the participant's preference for physical or digital interaction with buttons, dials and sliders. Following this, we showed the participant a short video of concept designs illustrating our intended use of the system. The participants were then given training on each of the prototypes, first using a dial on each (GUI, low-res, hi-res), then a slider in the same order.

Participants then performed the series of tasks according to the experimental design described above. In cases where there was only one widget to control, participants were asked to stand up holding the prototype with one hand while controlling the widget with the other. In cases where there were two widgets to control, we allowed the participant to sit in a swivel-chair with the prototype on their lap (to free up both hands for controlling widgets). In both cases, participants were free to move their entire body (or body+chair) to face the appropriate screen.

Participants' accuracy for each task was captured in software, and all tasks were recorded on video to allow analysis of participants' head direction as a proxy for visual attention. The study ended with a short structured interview probing participants' views on each interface. Participants were given a £10 gift voucher in return for their time.

Measures

Our main objective in this study was to determine the effect of Resolution on performance. To this end, we recorded—via logs—the accuracy of each participant's tasks – that is, how well they were able to follow the blue target region using the controls given. The accuracy was computed for each frame as the distance between the centre of the cursor and the centre of the blue target region. The accuracy was then aggregated for each participant using the geometric mean (giving a better indicator of location than the arithmetic mean, as the distribution of the error is skewed). In the case of two widgets, the accuracy was then computed as the geometric mean of the accuracy of both widgets.

In addition to this measure, we also wanted to determine the level of visual attention required to operate each prototype – that is, how often the user needed to look down at the device while controlling the projected widget(s). To capture this information, we analysed each study's video footage using ELAN [38], recording points where the user's head direction moved from the projected screen to the physical device, and the time spent looking at the controls.

Finally, as an indication of participants' perceived usability of the devices, we asked them to rate each prototype out of 10 for how easy they found it to use (10 easiest). They were also asked to rank the prototypes in order by the amount of perceived visual attention required to use each one.

RESULTS

Pre-study questionnaire

The results from the pre-study questionnaire mirror previous work in this area (e.g., [14]), showing that the majority of participants favour physical widgets over touchscreen interactions. Of the 17 participants that could answer this question,[5] 13 preferred physical buttons, 9 of 17 preferred physical sliders, and 15 of 17 preferred physical dials. The reasons for this preference as stated by the participants included the tangibility and "feel" given by physical controls; but, more commonly, the precision that is afforded by these widgets. One even went as far as describing the poor migration of physical widgets to digital representations, stating *"[. . .] touchscreen widgets are only attempts to imitate the real thing – they try and give the same experience but in a format that fits in your pocket"*.

Pursuit accuracy

Figure 8 shows the mean pursuit error (as a percentage of the whole widget's range), for each combination of Resolution, Widget and Complexity, aggregated over all tasks. Overall (Fig. 8 (A)), the high-resolution prototype led to 6.7 % of pursuit error, and the low-resolution and GUI prototypes to 11.6 % and 12.0 % of pursuit error, respectively (all 95 % CI). The high-resolution prototype was the most accurate, while the low-resolution and GUI designs were broadly similar, overall. In order to further unpack the differences between the prototypes, and understand the performance of the low-resolution emergeable prototype, we analysed the results for one and two widgets separately (see Fig. 8, (B) and (C)).

Single widget task

A two-way ANOVA shows a significant main effect of Resolution ($F(2,102) = 27.671, p < 0.001$) and Widget ($F(1,102) = 72.308, p < 0.001$) on the pursuit error. We also found a significant interaction between Resolution and Widget ($F(2,102) = 18.674, p < 0.001$).

For the single dial task, comparisons using paired t-tests with Bonferroni corrections revealed significant differences between the low-res and GUI, hi-res and GUI, and between

[5]The participant with no touchscreen experience did not respond.

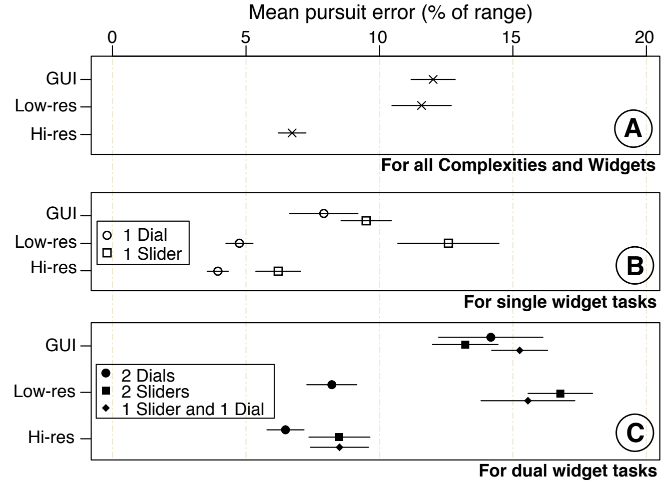

Figure 8. Mean pursuit error as a percentage of control range. Error bars show 95 % confidence intervals.

low-res and hi-res prototypes (all $p < 0.001$). The low-res and hi-res prototypes' dials led to 4.8 % and 4.0 % of pursuit error, respectively, whereas the GUI dial led to 7.9 % of the error. For the single slider task, the same comparison method revealed significant differences between the low-res and GUI ($p < 0.01$), and between hi-res and GUI, and low-res and hi-res prototypes (both $p < 0.001$). The low-res prototype's slider led to 12.6 % of pursuit error; whereas the hi-res slider led to 6.2 %, and the GUI slider to 9.5 %.

Two-widget tasks

A two-way ANOVA shows a significant main effect of Resolution ($F(2,153) = 85.954, p < 0.001$) and Widget ($F(2,153) = 26.270, p < 0.001$) on the pursuit error. We also found a significant interaction of Resolution and Widget ($F(4,153) = 14.716, p < 0.001$).

For the dual dial task, comparisons using paired t-tests with Bonferroni corrections revealed significant differences between the low-res and GUI, hi-res and GUI, and between low-res and hi-res prototypes (all $p < 0.001$). The low-res and hi-res prototypes' dual dials led to 8.2 % and 6.5 % of the pursuit error, respectively, whereas the GUI dual dial led to 14.2 % of the error. For the dual slider task, the same comparison method revealed significant differences between the low-res and GUI ($p < 0.01$), and between hi-res and GUI, and low-res and hi-res prototypes (both $p < 0.001$). The low-res dual slider prototype led to 16.8 % of the pursuit error; whereas the hi-res sliders led to 8.5 %, and the GUI sliders to 13.2 %. For the dial+slider task, the same comparison method revealed significant differences between the hi-res and GUI, and between the low-res and hi-res prototypes (both $p < 0.001$). However, no significant difference was found between the low-res and GUI prototypes. The low-res and GUI prototypes' dial+slider controls led to 15.6 % and 15.3 % of the pursuit error, respectively, whereas the hi-res dial+slider led to 8.5 % of the error.

Reacquiring controls after a change of focus

After switching targets, there is naturally a period of time at the beginning of each task where the participant needs to reacquire the control, due to it moving to a different position on the device and display – a novelty of our experiment. Overall, the GUI and low-res sliders take the most time for users to catch up with the target, causing an impact on the respective mean pursuit error. With one widget, it took 4.7 s on average to reacquire a low-res or hi-res dial, or a hi-res slider, whereas it took 5.9 s on average with a low-res slider or either of the GUI widgets. With two widgets, it took 5.9 s on average to reacquire a low-res or hi-res dial, or a hi-res slider, whereas it took 6.9 s on average with a low-res slider or either of the GUI widgets.

Glance rate

One of the metrics we feel is vital to the use of mobile devices for eyes-free interaction is the visual attention required to use the controller. To measure this, we systematically analysed the video footage from each participant's tasks, annotating every time their gaze switched from one of the projected screens to the controlling device (see Fig. 9 (top, N1 and N2)). We also recorded the time spent looking down, as shown in Fig. 9 (bottom, T1 and T2). Although the overall time spent looking down is an interesting metric, we chose in our analysis to focus primarily on the number of times the user glanced down. As participants tend to look down to reacquire a control, we believe this provides a more accurate measure of how often the user loses control of a particular widget—particularly important for deformable devices—as opposed to how long it takes to reacquire it.

Single widget task

A two-way ANOVA on the glance data shows a significant main effect of Resolution ($F(2,102) = 106, p < 0.0001$), indicating that the hi-res prototype requires the least amount of visual attention, while the GUI requires the most. The main effect of the type of Widget was also significant on the glance rate ($F(1,102) = 8.34, p < 0.05$), as was the interaction of Widget and Resolution ($F(2,102) = 4.7, p < 0.05$). Paired t-tests with Bonferroni corrections found no significant differences between dials and sliders on the hi-res or GUI prototypes. A significant difference was found between sliders and dials on the low-res prototype ($p < 0.0001, t = 6.29, df = 17$) which shows that sliders on the low-res prototype require more visual attention than dials when performing a single widget task.

Dual widget task

A two-way ANOVA showed significant results for the main effects of Resolution ($F(2,153) = 383, p < 0.0001$) and Widgets ($F(2,153) = 4.8, p = 0.01$) on visual attention. Furthermore, the interaction between Resolution and Widgets was also significant ($F(4,153) = 8.16, p < 0.0001$). This shows that, as with the single widget Complexity, the hi-res prototype requires the least visual attention, followed by the low-res prototype, and finally the GUI prototype. Further post-hoc tests indicated significant differences between sliders, dials and slider+dial, indicating that, on the whole, the slider+dial task required greater visual attention than other dual-widget tasks. For the low-res prototype, dual dials required less visual attention than dual sliders; conversely, dual sliders required less visual attention than dual dials on the GUI prototype.

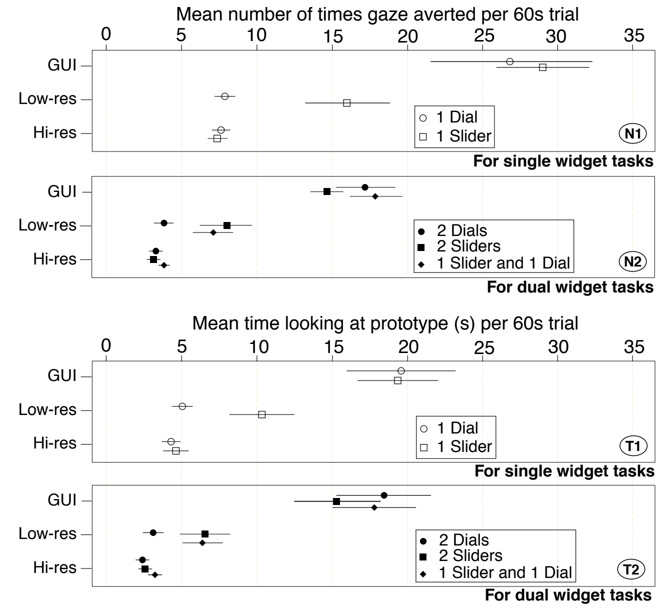

Figure 9. Glance rates. Top: mean number of times participants' gaze was averted from the projected screen. Bottom: the mean time participants spent looking at the prototype (rather than the display) per trial.

Subjective results and observations

The ratings given for the ease of use of each prototype (1–10; 10 easiest) resulted in average scores of 8.8, 4.8 and 3.4 for the hi-res, low-res and GUI prototypes respectively. A Friedman test of these results shows the difference to be statistically significant ($p < 0.0001, df = 2$). These results confirm that participants found the hi-res prototype the easiest to use, the touchscreen GUI the most difficult, and the low-res sensel-based approach somewhere between the two.

These results coincide with participants' opinions around tangible versus touch-screen controls. Many comments we recorded from participants after the trials discussed the benefit of tangible control: *"It's more precise. I find doing games on my iPad difficult – I'd much prefer using something tactile to have the feedback"*; *"It's more responsive – if you're touching it, you know [. . .] if you are using the touchscreen you have to look, but if something is protruding you can feel for it"*; and, *"In gaming situations it's more satisfying. I've played games on a touchscreen and its really not the same as having a controller because you need to be spatially aware of where they are [. . .] as opposed to having something you can physically manipulate. It would give a higher sense of control than just a flat surface."*

In addition to their perceived ease of use, we also asked participants to rank the interfaces in order for how much visual attention they felt each one required to use. One participant thought the low-res design required the most visual attention. The remaining participants (17 of 18) ranked them as: GUI (most visual attention), low-res, hi-res (least visual attention).

As part of our post-study analysis, we studied the video footage from each of our participants' tasks to determine any interesting or unusual behaviours. One discovery we made during this analysis was that even though all participants were instructed to keep the pursuit error as little as possible at all times, two distinct behaviours were apparent. Some users clearly chased the blue target region when it darted away. Other participants, however, simply waited for the blue target to come closer to their cursor before they began following it with the physical controls. How this differing behaviour affected the accuracy of each participant is not clear. Controlling or correcting this subjective accuracy requirement *a posteriori* is not straightforward, and needs further research. As a comparison, controlling or correcting the subjective speed-accuracy tradeoff for Fitts' law pointing tasks is a research area in itself [46].

While analysing the video footage, we classified the interaction methods participants used for each of the prototypes. From this, we hoped to gain some insight into how our new emergeable methods of interaction were approached by users. As expected, users had little difficulty using the well-known interaction methods of GUI and hi-res controls. In these cases, all participants used the same action to operate the widgets: a thumb-index grip on the hi-res widgets and a one-digit touch on the GUI. Similar interaction was seen during the low-res dial tasks. We attributed this behaviour to the experience users already have in operating touch-screens and physical widgets.

The low-res slider interaction, however, is one in which none of our participants had any prior expertise in how to manipulate. From analysis of the video data, we observed that participants had several ways of interacting with this new control. Specifically, we identified three interaction styles: pushing, sliding and gripping. Sixteen participants pushed the sensels using one, two or three fingers; seven slid their fingers on top of the sensels to interact with them, and just one participant tried to grip each sensel to operate it. Participants used different strategies to control the slider – some used just one finger (thumb, index, middle or ring); others used two or three fingers at the same time, while some mixed the number of fingers used to control the sensels for each interaction style. This gives an insight into how users might interact with sensels; and, into how the low-res prototype could be redesigned to better facilitate the slider interaction.

Overall, despite the difficulties some users had in using the low-res slider, the majority of participants saw the potential in the emergeable concept. Comments made included: *"[It's] easier to use a tangible object but if it could go back into the screen you keep the flexibility of having the flat screen device"*; and, *"dynamic changing into anything would be very interesting especially for things you need more precision on."*

Sixteen participants stated that they would use emergeables in the future if they became available in a commercial product, citing the ease of tangible controls as a major factor. For example, *"Yes, I'm likely to use touchscreens more if they have buttons. Im using this old [featurephone] for a reason"*; and, *"Yes, I've grown up with normal buttons, I now struggle with touchscreens – I'd give it a go to see what it feels like."*

DISCUSSION

This paper has introduced the concept of *Emergeables*, exploring and analysing the design space around continuous, eyes-free controls for tangible mobile interaction. Our vision for this research is to combine the flexible, mobile versatility of touchscreen displays with the affordability and precision of tangible controls. In doing this we hope to facilitate rich interactions with continuous parameters for situations such as safety-critical, remote, or even game-play scenarios. In this section, we present the main insights from our evaluation, discuss the levels of resolution necessary for future emergeable controls, and suggest how higher-resolution versions of our prototypes may be achieved.

Turning first to the accuracy of each approach. The results of our experiment show that when controlling eyes-free, continuous tasks, the high-resolution emergeable user interface was the most accurate. Overall, this prototype was found to be almost twice as accurate as the GUI, and even higher when controlling two parameters simultaneously. This result illustrates the strong potential of high-resolution emergeable controls, showing their improvement over GUI displays – the current interaction style of state-of-the art mobile devices.

Our next step, then, is to focus on the accuracy of the low-resolution emergeable design. In the case of a single dial, the low-resolution prototype can provide almost the same level of accuracy as the high-resolution prototype – a result we anticipated based on the current similarities between the two designs. The GUI dial, however, is almost twice as inaccurate compared with our tangible prototypes. This is a promising outcome for our sensel-based approach, but clearly more work can be done to refine our prototype and improve the accuracy of its sliders. Indeed, in the case of a single slider, while the hi-res emergeable provided a gain in accuracy over the GUI, the low-res slider performed worse. The resolution provided in our prototype was created using four sensels, each of a size comparable to previous work (e.g., [10, 13]). This experiment suggests that this resolution is not yet sufficient to provide a comparable accuracy to either high-resolution tangibles or GUI touchscreens.

For both single and dual dial tasks, the low-res prototype offers almost the same level of accuracy as the hi-res prototype. In the case of two sliders, as with a single slider, the low-res prototype did not provide better accuracy to users. This makes the need for future improvements in emergeable technology (for example, in the size of the moveable sensels) even more important for complex tasks. In the case of slider+dial, the accuracy benefit of the low-res dial was able to compensate for the loss in accuracy of the low-res slider.

Beyond performance, users' safety can be at stake in situations where visual attention is critical – for example, controlling a car stereo while driving. The results of our video analysis show that emergeables require significantly less visual attention than the GUI approach. Since the pursuit tasks in the study required as much of the users' focused attention as possible, we can deduce from this that the best interface for such activities is the high-resolution approach – requiring around 74 % less visual attention than the GUI on the single widget task and 78 % less on the dual widget task. Even the low-resolution, sensel-based emergeable prototype performed better than the touchscreen for the amount of visual attention required – requiring around 57 % less visual attention than the touchscreen on the single widget task, and 61 % on the dual widget task. As a consequence, emergeables are a promising direction for mobile user safety, and, indeed, other scenarios where eyes-free interaction would be beneficial.

In terms of specific widgets, when using a single widget there was little difference between the loss of control for high-resolution sliders and dials – that is, there was no significant difference in the visual attention demanded by them. However, when controlling two widgets at once, it requires more visual attention to control one of each type of high-resolution widget (i.e., one slider and one dial) than two of the same (i.e., two sliders or two dials).

In general, sliders were less accurate and required more visual attention than dials. We anticipated that the sliders on the low-res prototype would be harder to use than its dials as not only are they an entirely new way of interacting which participants would not be used to, but are also an early prototype design with interaction limitations. Despite being able to control sliders to a certain extent, this effect was seen in the accuracy results (low-res sliders were more inaccurate than low-res dials) and in the glance rate results (low-res sliders required more attention than low-res dials), but only partially in the subjective scoring (low-res controls were rated higher overall than GUI controls). Our prediction is that as sensel-based emergeables get higher in resolution and users accrue increased exposure to the type of interaction, this gap in accuracy and loss of control between the high- and low-resolution approaches will reduce.

When we consider subjective preference, users preferred using the emergeables rather than the touchscreen GUI. Results from the pre-study questionnaire revealed that 73 % of participants preferred tangibles over touchscreens, especially for dials (88 %). After participation in the study, 100 % of participants found the high-resolution emergeable easier to use than the GUI, and 72 % found the low-resolution prototype easier to use than the GUI. They also rated the touchscreen approach significantly lower on average than both the emergeable alternatives (3.4/10 for the GUI, versus 4.8/10 and 8.8/10 for low-res and hi-res prototypes).

In summary, this evidence suggests that emergeables are easier to use, require less visual attention, are largely preferred by users, and are more often more accurate than the GUI alternative. Our results suggest that the high-resolution emergeable is the optimum prototype for controlling continuous parameters – an encouraging result which we believe justifies the continuation of this work. In addition to this, however, we have also identified the sensel approach as a promising candidate for further development.

While we strive for a fully-emergeable, high-resolution surface, we understand that this will not simply happen overnight, and are aware that there will be many iterations and refinements along the way. The sensel-based approach, which is currently at a relatively low-resolution (28 sensels) state, was our first step in this process. With additional work, however, this prototype can be miniaturised and increased in resolution, thus improving the usability and accuracy of its controls. We are pleased that even in this state our sensel-based approach performed well compared to its touchscreen counterpart, proving to be easier to use, more accurate for the use of dials and more preferred by users.

Our future work in this area will focus initially on increasing the resolution and decreasing the size of the sensel-based display. The current prototype uses stepper motors harvested from laptop DVD drives to facilitate the Z-axis motion of the sensels. The size of these motors, coupled with the additional wiring required for the joystick and rotation controllers, has resulted in the display being relatively large and adjacent sensels having small gaps between them. The next generation prototype could include smaller actuation motors or even nano-level Janus particles to create smaller sensels and allow a higher-resolution display in the same physical space.

Based on the results of our experiment, further study into how best to improve the sensel-based slider interaction is now on our research agenda. Before conducting trials on a new prototype—that will likely have smaller sensels that can be placed closer together—we would like to test slider controls on our current design using additional adjacent sensels (e.g., up to seven, as opposed to the four used in the study). This will allow us to investigate any differences in task outcomes when using different numbers of sensels in each widget. After this work has been carried out, our next step will be to create dials made up of multiple sensels, allowing rotational controls of different sizes to be created anywhere on the display.

CONCLUSION

In this paper we have presented emergeable surfaces for eyes-free control of continuous widgets. We have explored the design space around the area by building two prototype devices to test the viability of tangible, continuous controls that 'morph' out of a flat screen. Our first prototype—a high-resolution deformable UI—uses static dials and sliders that rotate on blocks to 'change' the device's shape. This design gave us insight into the use of fully working widgets, but as a trade-off only allowed them to be placed in four specific locations on the display. Our second prototype—a lower-resolution sensel-based approach—is an initial demonstration implementation providing dials and sliders that can be placed anywhere on its display, and which could be refined over time to become smaller and of higher-resolution.

Our results show the value and benefits of emergeable, high-resolution, tangible controls in terms of accuracy, visual attention and user preference. While clearly still in its early stages, we have also shown the potential of our low-resolution sensel-based approach, which we hope will be the start of a series of future iterations of a fully-emergeable, dynamic interactive control surface.

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