Tilt Displays: Designing Display Surfaces with Multi-axis Tilting and Actuation

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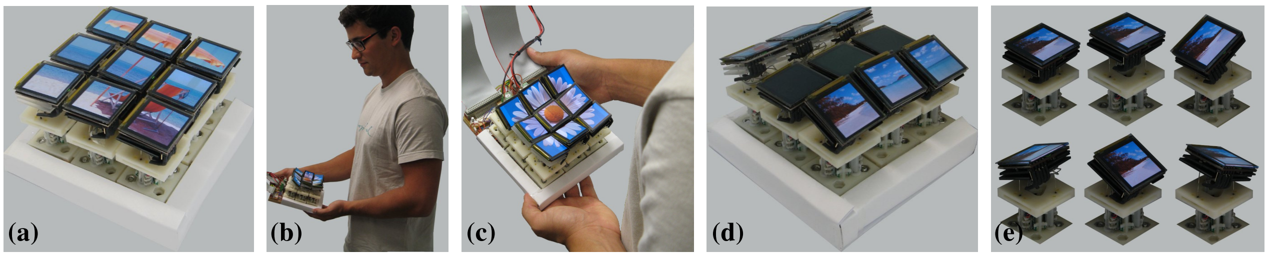

Figure 1. Tilt Displays. (a) Flat screen configuration; (b, c) User holding 12cm×12cm portable prototype; (d) Collaboration Mode; (e) Individual modules in (clockwise from top left) down, up, tilt left, tilt right, tilt forwards and tilt backwards configurations.

ABSTRACT

We present a new type of actuatable display, called Tilt Displays, that provide visual feedback combined with multi-axis tilting and vertical actuation. Their ability to physically mutate provides users with an additional information channel that facilitates a range of new applications including collaboration and tangible entertainment while enhancing familiar applications such as terrain modelling by allowing 3D scenes to be rendered in a physical-3D manner. Through a mobile 3×3 custom built prototype, we examine the design space around Tilt Displays, categorise output modalities and conduct two user studies. The first, an exploratory study examines users' initial impressions of Tilt Displays and probes potential interactions and uses. The second takes a quantitative approach to understand interaction possibilities with such displays, resulting in the production of two user-defined gesture sets: one for manipulating the surface of the Tilt Display, the second for conducting everyday interactions.

Author Keywords

Tilt Displays; actuated displays; physical actuation; non-planar surface interaction.

ACM Classification Keywords

H.5.2 **[Information interfaces and presentation]:** User Interfaces. - Graphical user interfaces.

INTRODUCTION

Innovations in sensors and actuators allow us to explore the design of mobile devices that extend beyond the static flat display surfaces with which we are currently familiar. The next generation mobile devices will instead include actuatable screens that physically mutate themselves to better represent their on-screen content.

Imagine for example, a mobile device that is visually displaying a street map and whose screen has physically mutated to show the hilly terrain and buildings. The device both visually and physically represents the 3D scene. This physical mutation facilitates effective consumption of multi-dimensional data by moving one information layer to another modality. As a step towards realising such a scenario, this paper builds on previous work on actuated surfaces [11, 20] and dynamic displays [9] by presenting Tilt Displays: a new form of display surface whose components not only actuate but also physically tilt.

A Tilt Display (Figure 1) is a display surface about half-the size of a standard tablet (e.g. an iPad). It consists of a collection of individual display components each of which can tilt along one or more axes and move vertically up and down (Figure 1e). This ability to tilt along multiple axes distinguishes them from previous actuatable displays.

Such screen versatility opens a range of opportunities for providing an additional integrated information channel to the user. These opportunities include: collaboration (Figure 1d), terrain modeling (Figure 3a and Figure 3b), 3D video that is beyond auto-stereoscopic 3D and tangible gaming. We can imagine many scenarios that would benefit from the physicality afforded by Tilt Displays; however, we first need to establish whether users can relate to the new experiences and advantages of using such a device. This type of display also raises a number of unique interaction issues, such as the difficulties around applying commonly used multi-touch input techniques.

The primary goal of this paper is to explore the design space around Tilt Displays to understand users' initial impressions and to examine how users may interact with these surfaces. We are especially interested in the use of these displays in mobile contexts, as this domain presents a range of opportunities for exploitation. To do this, we start with a more detailed description of Tilt Displays and situate them within existing literature. We describe our prototype display giving details of our design rationale, identifying factors that influence the design of Tilt Displays and outline example scenarios where they would be beneficial. We then describe our first exploratory user study that gathered initial user impressions of the concept, and possibilities for interaction. A second user study then investigates interactions with Tilt Displays. We finally discuss this concept and its future for construction and deployment.

The contributions of this paper are: 1) The design and implementation of a Tilt Display; 2) A taxonomy of Tilt Display output modalities, with example applications; 3) An exploratory user study probing initial user reactions to applications and interaction possibilities; 4) A study examining user perceptions of interactions with such a display resulting in two user-defined gestures sets for interaction: one for manipulating the display's tilt angle, the second for performing low-level tasks with such a display.

RELATED WORK

Tilt Displays draw their inspiration from actuatable displays, shape displays and deformable displays. They are also an instantiation of a multi-display environment. We summarise previous work in these areas in this section.

Actuatable Displays

Actuatable or 'shape' displays vertically move display surface components. Lumen [20, 21] is a low resolution display where each pixel has a colour value and can vertically actuate. Projection-based systems are used to increase the resolution of the display. Feelex [11] used an actuator array, covered with a flexible screen, to present a physically reconfigurable surface that was augmented with graphics. Force sensors on each actuation rod conveyed presses to the system. Leithinger and Ishii's Relief display [14] used 120 motorised pins (electric slide potentiometers from audio mixing boards), allowing users to push and pull individual rods. A Lycra cover was added to provide a smooth surface when modelling terrain. Top projection provided visual cues. Blackshaw et al. [5] and Leithinger et al. [15] continue this work by conceptually examining the design-space for input control with shape-changing displays, describing touch input, external controller input and mid-air gestural control. Our studies examine user perception of such input methodologies for Tilt Displays.

Implementing Actuation

Researchers have employed a variety of tactics to create vertically actuating visual displays. Pneumatic actuation employs a gas, usually air, to flood or evacuate chambers. Harrison and Hudson [9] used a chamber-based button system to make shapes protrude, lie flat or sink into the display. A latex cover is used to seal over pre-defined cutouts and rear projection provides the display, with diffused illumination used to detect touches and pressure-sensing used for continuously variable parameters.

Mechanical and electromechanical systems actuate by moving rods using either solenoid or motor-based actuation. Pin arrays consist of small cylinders (a few millimetres in diameter) that protrude a few millimetres out of a surface. Actuating these 'pin' sized tubes creates patterns the finger can detect. Pin arrays are most commonly actuated using solenoids [8] or servo motors [25].

Shape Memory Alloys (SMA) are composite materials that maintain their shape until heated. At a critical temperature the alloy flexes in a particular direction. This 'on-demand' flexing is used in devices such as Surflex [6], a foam sheet with embedded SMAs that bends according to the user's input, and Sprout I/O [7] that programmatically represents patterns in a similar manner to when a foot leaves an imprint on carpet. Lumen [20, 21] uses SMA actuation to raise and lower a series of wave guides to provide a height and colour controlled display. SMAs are also being employed in pin-rod actuators to provide increased range of motion and reduced pin intervals [19].

Deformable Displays – Flexing, Bending and Stiffening

An alternative to vertical actuation is to manipulate the properties of a surface to emulate the feel of virtual objects. The viscosity of fluids contained in pouches can be altered by changing the surrounding magnetic field. Particles suspended in the fluid form chains along the flux lines altering the fluid's viscosity. Jansen [12] used magneto-rheological fluid to change the viscosity of their multi-touch display, while Taylor et al. [23] employed electro-rheological fluid under a rubber skin to stiffen a surface.

Adjusting the tension bias of a flexible sheet allows the user to feel the different 'hardness' of virtual objects proportional to the sheet's tension [24]. Placing an LCD below a tension sheet allows the haptic and visual channels to be combined in the same space. Usually, the deformation in these environments cannot be visually inspected.

Flexible displays provide an opportunity for presenting the visual data in an actuatable display. Unfortunately, while flexible displays are capable of bending, they do not stretch. This prevents their use as the display surface on top of vertical actuators as upwards pressure will simply result in a curved surface, rather than one that can display, for example, map relief. However, bend gestures using a flexible display offers insights into alternative methods of input appropriate to Tilt Displays. Schwesig et al's Gummi

[22] suggested a range of non-WIMP interactions using bending, while Lahey et al. [13] produced a bend gesture set for a display tied at two corners.

Multi-Display Environments (MDEs)

Tilt Displays are a type of MDE, with each component a separate display. The MDE literature describes solutions to the ‘displayless space’ problem: stitching is commonly employed in desktop computing (where the cursor ‘jumps’ from one monitor to the next), other proposed techniques include mouse ether [3], where the pointer must move the equivalent physical distance between two displays, cursor warping [4] and display selection using head tracking [1]. Studies also show that tilting a secondary display can aid in minimizing the effects of visual separation [27].

Desktop-centric MDEs are generally too cumbersome for spontaneous physical reconfiguration. However, providing the user with the flexibility of reconfiguration has proven beneficial. Siftables [18] allow the user to rearrange small screens into user-defined configurations. They allow direct interaction with digital media, with piling and gathering gestures having a direct connection to the Siftable’s content. Although we envisage Tilt Displays to always be attached, their ability to flexibly reconfigure themselves will allow a range of contexts of use.

TILT DISPLAYS

What are Tilt Displays?

Tilt Displays are a new class of physically mutatable visual feedback devices whose display components support multi-axis tilting and vertical actuation. The distinguishing feature of Tilt Displays over previous actuatable systems is their ability to tilt visual components along multiple axes, as illustrated in Figure 1e.

Design Decisions

We made a series of conscious design decisions during development of our prototype Tilt Display. These are described below.

Tilt Component Surface Profile: The surface profile of the actuated components, especially if they are larger than a few millimeters, will influence the raised or lowered shapes that can be conveyed when multiple components are actuated simultaneously. These components may either be identical (e.g. uniform triangles) or non-identical (e.g. circles with space-filling diamonds). Selection of the size and shape will be intertwined with the envisioned applications and the choice of display method. We believe the square 34mm×34mm surface profile of our displays provides an ideal platform for evaluation (sufficiently sized components to expose issues such as the size of bezels and gaps) while supporting our chosen display method (see below).

Display Method: There were three feasible choices for producing the visual output for our Tilt Display: top projection, rear projection and embedded displays. Single source top projection suffers from shadowing issues during user interaction, which can be resolved using multiple projectors [2], although this inhibits use in mobile contexts, and increases the system cost and complexity.

Rear projection does not suffer from shadowing, however, incorporating projection within actuation components is challenging, if mechanical mechanisms are employed. Both top and rear projection systems require pre-processing to reduce distortion when projected onto non-planar surfaces.

We chose to use embedded screens to prevent the issues associated with projection. We selected small (34 mm square) OLED screens—these were the smallest, readily available self-contained commercial display. The additional complexity of actuating a display surface (instead of a projection surface) was further outweighed by the constant non-deforming visual resolution and related experience.

Method of Tilt and Actuation: Having settled on the display method, we examined a number of actuation possibilities, as discussed in the related work section. For simplicity and cost, our prototype uses small actuators, typically used in model aeroplanes—these were inexpensive, robust and easy to control. This model of actuator provides 9.1 mm of stroke—sufficient to differentiate between raised and lowered components and provide approximately 30º of tilt along the x- and y- axes.

Display Surface: When the individual OLED displays tilt, the edges of adjacent screens move apart, exposing the edges of the screens and creating a variable sized gap between the displays (see Figure 1d and Figure 3c). One option is to cover the displays with a stretchable material (such as lycra) to remove the gaps and smooth the surface between displays. We chose not to add such a covering so that we could explore user perceptions and any required coping strategies with variable width gaps in the display.

Input: Tilt Displays, like their mobile device counterparts, can support external key/button input, touchscreen input/gestures and also potentially above-device gestures [15]. Touch/pressure input can be achieved by adding touch-overlays onto the display panels; physical manipulation of the displays can occur by replacing the servo motors with back-drivable models.

Our prototype Tilt Display does not explicitly support input. The literature reports several *possible* methods of input, but does not report user perception of these methods. To solicit uninhibited user suggestions (and to avoid any bias from the implementation), we chose against implementing all possible forms of input.

Prototype Construction

To validate the feasibility of Tilt Displays, to examine users’ perceptions and understand how people might interact with such a device, we implemented an initial prototype system. The system is in between the size of a typical mobile-device and a tablet, having a footprint of 120×120 mm. It is light enough to be picked up and held in a similar manner to a mobile phone (see Figures 1b and 1c). The prototype display is illustrated in Figure 1.

Our prototype consists of a 3×3 array of 34mm×34mm OLED screens (4D Systems µOLED-128-G1), with resolution 128×128px, each mounted on three actuators (Spektrum AS2000L) to provide both vertical actuation and tilting along the x- and y-axes (Figure 1e). A single module's construction is illustrated in Figure 2. The actuators have a stroke of 9.1mm. Each module is based around a small, interlocking 3D-printed block. Each of the displays and actuators are individually addressable and independently configurable.

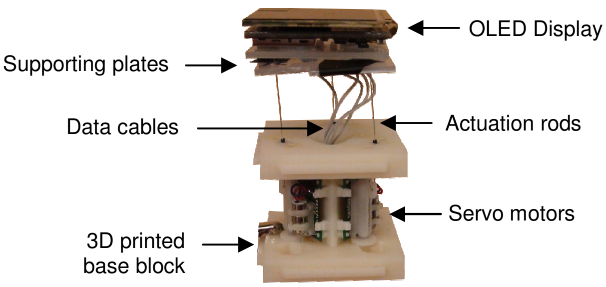

Figure 2: Prototype construction

The prototype Tilt Display is controlled using an XMOS XC-1A microcontroller (www.xmos.com/xc1a), with commands issued via serial control from a PC. The microcontroller continually sends PWM signals with an appropriate duty cycle to each of the 27 actuators. By varying the PWM duty cycle at different rates, the actuators can also move at different speeds, up to a maximum of 20mm/sec. The microcontroller also maintains the appropriate display by instructing each OLED to show images or videos from their on-board micro-SD card.

		Visual display	
		Static	*Dynamic*
Physical movement	*Static*	3D model	3D fixed mode
	Dynamic	3D movement	3D video

Table 1: Tilt Display output modalities

Output Modalities

Tilt displays offer four primary modalities of use, which we classify based on the coupling between the visual display and physical movement. This classification is shown in Table 1 and described, with example applications below.

3D Modelling: Static Physical State/Static Visual State

Once configured, the physical and visual states remain constant. 3D modelling allows physical three-dimensional data to be represented in a physical 3D manner.

3D Terrain modelling provides users with an additional information channel that is difficult to represent using a traditional 2D display. Contour lines are often excluded from electronic street maps to aid clarity and because users may not have sufficient technical understanding to correctly interpret their meaning. Tilt Displays are advantageous over vertical actuation in this scenario as they can easily and more accurately represent sloped surfaces, such as hills and mountains (Figure 3a and Figure 3b). Users can absorb this additional information by passing their hand over the Tilt Display or by visibly observing the peaks and troughs in the terrain. This type of route-finding is particularly useful for wheel-chair users, cyclists, and the elderly who wish to choose an appropriate route based on surface gradient.

Partially sighted persons can also make use of terrain modelling. For example, by illustrating steps and slopes, the physical output can help the user to find a suitable route. Tilt displays provide a mechanism for physically representing a scaled version of the environment, avoiding the need for users to translate crude tactile feedback from vibration motors into visualisations of the environment.

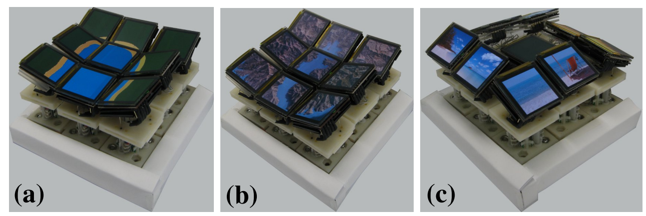

Figure 3: (a, b) Example of terrain modeling, with mountains raised around a lake (c) Four-way colllaboration

3D Fixed Mode: Static Physical State/Dynamic Visual State

This modality pre-sets the physical configuration of the display and then allows user interaction with the visual content. This is useful in collaborative situations.

In mobile contexts, users are often seen rotating or handing their mobile device to a peer to share on-screen content, such as photos or videos. Tilt Displays facilitate sharing by tilting a portion of the screen towards a second viewer (see Figure 1d). A primary user with a 'private' view could then only push selected images or content to the remainder of the display. Four people can also be accommodated by appropriate screen tilting (Figure 3c).

3D Movement: Dynamic Physical State/Static Visual State

Physical movement can play an important role in conveying information. For example, a 2D image of a flower can 'come to life' by a slowly animating the raising of the petals (Figure 1). A sensation of gradient can be created using the same effect: a photograph taken at street level looking up a hill can be animated with slowly tilting forward screens to give the impression of an up-hill slope.

This same physical movement also provides the opportunity to explore a new gaming dimension—that of tangible entertainment in mobile contexts. Tilt Displays would allow users to add simple tangible objects, such as a small foam ball, onto their display and then with careful manipulation of the actuation components the tangible objects will roll or slide across tilted screens.

3D Video: Dynamic Physical State/Dynamic Visual State

3D video couples a continually changing physical movement with dynamic on-screen visuals. The most striking example of this modality is a video stream that incorporates 3D height information. Gathering depth information is becoming more common with 3D cinematography and cheaply available depth cameras. One example is a low level fly-over of a route on a map. As the visual content passes by hills or buildings the physical surface protrudes from the display to show the height of passing objects (see accompanying video figure).

Support of this modality is also crucial for future interactive applications: if a map were panned or zoomed the user will see both the visual and physical representations change.

Concept and Prototype Evaluation

After the Tilt Displays' construction, we informally demonstrated the device to many groups of people, each time receiving comments and suggestions on possible applications and ideas for improvement. For the evolution of Tilt Displays we believe it is important to capture these first impressions and explore users' first reactions using each of the four output modalities described in the previous section. To do this we carried out a user study on initial impressions and applications of Tilt Displays.

EXPLORATORY STUDY 1: IMPRESSIONS AND APPLICATIONS

Following a user-centered design approach, we conducted a study to gather initial impressions and to explore potential uses of Tilt Displays. Participants experienced a range of applications in each of the device's output modalities. We wanted to assess the effect of independently tilting and actuating the screens, investigate how people would interact with Tilt Displays and how they perceived the variable gaps in between the screens, both visually and for interaction.

Participants

We recruited 11 participants who varied in gender (10 male, 1 female), age (25 to 39), and background (8 technical, 3 non-technical). Almost half of these participants (5/11) had previously participated in evaluations of the MindMap [17] or the *pass-them-around* [16] prototypes and had therefore witnessed and interacted with a system that allows people to tile displays together. This mixture of participants ensured we had feedback from early and late technology adopters and from people who had and had not previously encountered new and novel forms of displays.

Method

The study consisted of three parts: an introduction, the prototype's demonstration and a semi-structured interview. We first gathered the participants' background information and explained the primary goal of the study. We then demonstrated a range of applications with the Tilt Display (see Table 2). Finally, we conducted semi-structured interviews with the participants where we asked them a series of open-ended questions and encouraged open discussion regarding both the positive and negative aspects of the prototype display.

1. Flat screen, beach image (Figure 1a) *(3D Model)*
2. Collaboration for 2, 4 and 8 people (Figure 1d, 3c) *(3D Fixed Mode)*
3. Vertical actuation, terrain and buttons *(3D Fixed Mode)*
4. Map terrain (Figure 3a, b) *(3D Model)*
5. Uphill and downhill visualization *(3D Movement)*
6. Flower petals raising ('coming to life') (Figure 1b,c) *(3D Movement)*
7. Terrain flyover *(3D Video)*

Table 2: Tilt Display applications demonstrated

The session was conducted in an open meeting room, with the prototype set on a tall table in the middle of an open space. All 11 participants saw the demonstration at the same time. Each application was shown twice with all participants having the opportunity to experience the demonstration from the 'front on' position. The semi-structured interview was video-recorded. Each participant received a movie ticket to compensate them for their time.

RESULTS

We adapted the standard affinity diagramming method [10] to analyse the data from the semi-structured interviews. We grouped together participants' main reactions to the Tilt Display into four categories. We interleave our discussion with participants' comments (italicised).

Tilt Displays as a New Form of 3D

In general, participants were very positive about the Tilt Display concept. Their first impression was to associate Tilt Displays to a new method of presenting and consuming 3D content: *"For me it's like watching a 3D movie without wearing 3D glasses"* [P7]. Participants immediately valued the advantages of Tilt Displays over other 3D content, *"This visual presentation is very important. (…) When you wear a 3D glass, it takes some time for your brain to (…) get a real feeling. But if you have this kind of display then it's very good"* [P2]. Participants envisioned wide application of the technology, for example in a travel agent: *"You don't need to go to Hawaii, just experience it"* [P8].

Participants immediately linked the Tilt Display to other forms of 3D displays, such as those used in cinemas. Participants liked and noted the reduction in cognitive load that the physical 3D representations required to interpret compared to glasses-based 3D displays. These initial comments confirmed our impressions that Tilt Displays are a viable method for physically presenting 3D information.

Movement Conveys Additional Information

The movement of display components played an important role in conveying an additional information layer. In some scenarios, observing the physical movement conveyed more information that the final rendered position. With reference to the dynamic movement of a flower 'coming to life', one participant said: *"For me, the movement itself conveys more information. (…) The movement itself is compelling for how our vision system works in our minds"* [P9].

For this same reason, participants were positive about the use of vertical actuation to display high priority positions of interest. For example, clickable areas of a map were highlighted by raised tiles. Participants also appreciated and understood the use of movement to inform navigation. One demonstration showed the view of a street looking uphill. Slowly tilting the displays towards the user had the immediate effect of conveying the street's gradient: *"It's a good way to direct yourself and where to go, what are the directions and things like that"* [P4].

Orienting Displays for Collaboration
Participants were positive about the usefulness of the collaboration mode and could easily foresee using it to share content on their device. They discussed several aspects of Tilt Displays that would impact their success for collaboration: size, distance, number of displays and the orientation. At the start of the conversation, participants reflected on the screen size required for effective collaboration, reaching a consensus that a tablet-sized device would be most appropriate: *"I think it's only good on tablets or maybe big screens, because if we have a smartphone with a small screen it's not suitable for [that]. At least 7 or 10-inch screens"* [P1], *"Using tablets for presentation while having 8 people there, that would be really good. It would be fantastic to do that."* [P11]

By the end of the session, participants had also mentioned the distance from the display and the number of Tilt components as important factors that would influence whether Tilt Displays would be suitable for collaboration:*"[The experience]would depend on how far you are looking from"* [P10], *"It depends on the application, but the greater the number of screens, the greater the experience"* [P7].

Participants also concluded that, regardless of the size of the Tilt Display (mobile phone or tablet), they would place the device on a horizontal surface to allow users to sit or stand around. In this way, individual displays (or groups of displays) can be tilted towards different locations.

Three Methods of Interaction with Tilt Displays
The physically dynamic nature of Tilt Displays means that traditional touch-screen interactions will not always be practical, such as when the display is in a convex configuration. Throughout the study we asked participants to consider how they would interact with such a device. Three types of interaction emerged: touch gestures, direct manipulation of the screens and gestures above the display.

Almost all the participants mentioned some kind of touch input, either by performing touch gestures on the screen (e.g. swipe) or by physically pushing the screens down. One participant described the physicality of interaction: *"(I would interact) by tilting the displays, by pushing with different strengths and really doing the tilt as it is now, but with my hands"* [P9].

Participants also discussed the trade-off between performing gestures across all screens, and using a single screen that would control all other screens: *"A swipe could go through several screens (…) sometimes you might just use one screen for swiping, but if you want to exchange pictures then you can do reverse swipes across different screens."* [P9]

The varying size bezels gaps between the screens also influenced opinions on interaction. Some participants foresaw the bezels hindering interaction: *"It's impossible, I think (to swipe uphill or downhill with the gaps)"* [P1]. Other participants saw the bezels as an opportunity for interaction—covering the gaps with a stretchable material (e.g. lycra) would create visual continuity between the screens and also create an interaction surface: *"The stretchable material could also be touch sensitive. For the visuals, the material would smooth the gaps, but it could (…) also become part of the interaction."* [P9]

We believe that the bezels play an important role in Tilt Displays. Participants did not mention the bezels as hindering their perception of the visual display. But, it appears that these gaps play an important role in the perception of movement and thus how we extract the additional (3D) information from Tilt Displays. Before filling the gaps with Lycra for smoother interaction, consideration should be given to the role these gaps play in the perception of movement and direction.

Summary
This user study found participants were positive about Tilt Displays and were enthusiastic about their practical applications. One aspect that induced much discussion was that of (input) interaction. The issue of 'how best to interact' was present from the design stages of our prototype Tilt Display. To examine this issue further we conducted a second user study to explore user perceptions on methods of interaction.

INTERACTING WITH TILT DISPLAYS
There are two fundamental interaction issues that require evaluation before such displays could be deployed in real-world contexts. First, how would users manually manipulate the tilt of actuation components and second, how would users perform commonly required actions, such as panning and zooming on non-flat surfaces. These two issues do not arise in static, flat displays.

We wished to derive user impressions of how such interactions should take place on these types of devices. To do this, we chose a methodology similar to Wobbrock et al. [26] by providing users with a series of *initial* and *end* states and asking them to provide appropriate gestures to achieve the required transformations. This allowed participants to conduct their own interactions, without the restrictions of technical limitations, that they felt appropriate to achieve the goal. To summarise participants' input we derive two user-defined gesture sets. Our full methodology is outlined below.

Participants

We recruited 12 participants (four female), with a mean age 28.3 years. Ten had previous experience with touch-screen based gestures and ten had previous experience with mid-air gestures (e.g., those captured by an XBox Kinect).

Experimental Design and Methodology

We used the same methodology (and participants) to investigate both tilt manipulation and the interaction with tilted surfaces. All participants completed the tilt manipulation tasks first.

We used a series of cardboard mock-ups to allow users to pick-up, feel, push, pull and manipulate in any manner to avoid any limitations or preconceptions that accompanied our prototype. For each task, participants were first shown, using the cardboard mock-ups, the initial state of the screen, followed by the final state of the screen. They were then asked to hold a mock-up device in one hand and perform a single-handed gesture with their other hand. This was to simulate what would be possible in a mobile device context. Users were free to change the hand they held the device with during the study.

For each task we asked participants to perform a contact gesture and then a mid-air gesture. Contact gestures required one or more fingers to be in contact with any part of the device—either on or around any part of the screen. These two classes of gestures align with those expressed in user study one, with contact gestures encompassing both on-screen and screen manipulation gestures.

Participants were asked to consider their gestures independently from other tasks they had performed (i.e. participants did not have to concern themselves with gesture uniqueness). Users were also encouraged to not think about any technical limitations of implementing or detecting their actions. Finally, before moving to the next task, we asked participants to pick which of the two gestures they preferred. All sessions were video recorded.

We used two sets of initial and end states—one set for the tilt manipulations, the other for the tasks that required interaction with a tiltable surface. The following two sections describe these task sets.

#	Start	End	#	Start	End
1.	Flat	Tilt right	6.	Tilted right	Flat
2.	Flat	Tilt left	7.	Tilted left	Flat
3.	Flat	Tilt forward	8.	Tilted forward	Flat
4.	Flat	Tilt backward	9.	Tilted backward	Flat
5.	Flat	Raise	10.	Raised	Flat

Table 3: Physical state change tasks

Tilt Manipulation

This set of tasks required the participants to perform gestures to take the display from one physical state to another (e.g. for configuring a collaborative mode). These tasks assume that an appropriate region of the screen is already selected (selection is investigated in the following set of tasks). The state changes tested are shown in Table 3.

Interaction with Tiltable Surfaces

We also wished to investigate how users might perform common low-level interactions with tilted surfaces. We selected panning, scaling, rotating and area selection as gestures that may require re-designing on non-planar surfaces. We then provided participants with a series of non-flat screen configurations and asked them to perform an appropriate gesture to achieve each of the four required tasks. The screen configurations are described in Table 4.

#	Description	#	Description
1.	Flat screen	6.	Concave
2.	Tilt left	7.	Convex
3.	Tilt right	8.	Vertically raised section
4.	Tilt forward	9.	Vertically lowered section
5.	Tilt backward	10.	Steps

Table 4: Surface configurations for interaction tasks

Results

We analysed of our results by first calculating the between participant agreement of the gesture sets and from that extracting a user-defined gesture set for *tilt manipulations* and *interactions*. We then summarise the participants' subjective preferences.

Tilt Manipulations

Each participant provided a contact and a mid-air gesture for the 10 tilt manipulations, providing a total of 120 observed gestures (12 users × 10 manipulations). Based on the participants' interactions, we extracted a user-defined gesture set for the 10 manipulation tasks in Table 3. This set is depicted in Figure 4. All interactions are mid-air gestures except for tilting the screen backwards, where users preferred an on-screen swipe.

The selected interactions are those that had the greatest agreement between participants for that task—high agreement values indicate many participants selected the same gesture for a task, low agreement indicates a large diversity in the selected interactions. The agreement value, A, is calculated as [26]:

$$A = \frac{\sum_{t \in T} \sum_{P_i \subseteq P_r} \left(\frac{|P_i|}{|P_t|} \right)^2}{|T|}$$

Where t is a task in the set of all tasks, T, P_t is the set of all proposed interactions for task t, P_i is a subset of identical interactions from P_t. An agreement value of 1 indicates complete agreement between all participants.

Figure 5 shows the agreement values between the gestures that participants chose for each task. Many of the mid-air gestures showed strong agreement, while contact-based gestures showed greater diversity.

The gestures that emerged for several of the tasks were identical. For example, a mid-air downward push was the accepted gesture for lowering a raised screen, flattening the screen from a forward tilt and flattening the screen from a backward tilt. Because all of these tasks require the screen to end in a flat state, there is no conflict or ambiguity in using the same gesture for multiple tasks.

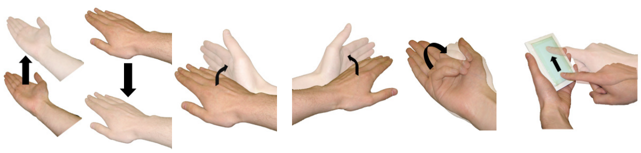

Figure 4: User-defined gesture set for tilt manipulations. Left to right: raise screen; lower screen & flatten from backward or forward tilts; tilt right (right hand) & flatten from left tilt (left hand); tilt left (left hand) & flatten from right tilt (right hand); tilt forward; tilt backwards.

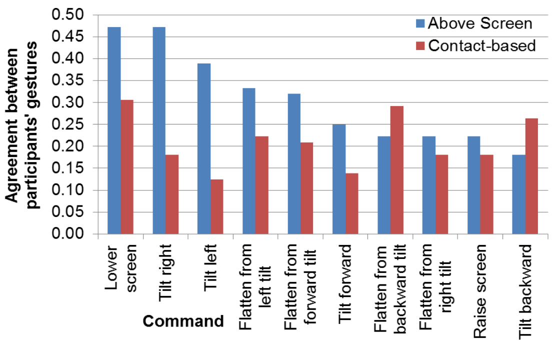

Figure 5: Agreement between participants' gestures for tilt manipulation

	Panning		Scaling		Rotating		Selection	
	CB	Abv.	CB	Abv.	CB	Abv.	CB	Abv.
1. Flat Screen	**FS**	FS	**P**	P	T	**T**	TP	TP
2. Tilted left	**FS**	FS	**P**	P	T	**T**	TP	TP
3. Tilted right	**FS**	FS	**P**	P	**T**	T	**TP**	TP
4. Tilted forward	**FS**	FS	P	P	**T**	T	**TP**	TP
5. Tilted backward	**FS**	FS	**P**	P	**T**	T	**TP**	TP
6. Concave	FS	**FS**	P	**P**	FR	**T**	TP	**TP**
7. Convex	FS	FS	**P**	P	FR	**T**	TP	**TP**
8. Vertically raised section	FS	**FS**	P	**P**	T	**T**	**TP**	TP
9. Vertically lowered section	FS	**FS**	P	P	T	**T**	**TP**	TP
10. Steps	TS	**FS**	P	**P**	VFS	**T**	TP	**TP**

Key: FS=1-Finger Swipe, P=Pinch, T=2-Finger Twist, TP=Trace Path, FR=1-Finger Rotate by dragging corner, TSE=Touch Start, Touch End, VFS=Vertical Finger Swipe.

Table 5: User-defined gestures (CB = Contact Based gesture, Abv = Above screen gesture)

Interactions

Each participant provided a contact-based and a mid-air gesture for the four tasks on 10 different surfaces, giving a total of 960 observed interaction gestures. Gestures took a variety of forms, but were heavily biased towards those that physically acted on the required objects.

For each surface/task pair, we grouped identical interactions and listed the most common in Table 5. We also calculated agreement values between the user-provided interactions for each task on each surface. The interactions with the highest agreement for each surface/task pair are shaded in the table (those pairs without shading had equal agreement values). The interactions in bold show those which had the greater overall user preference (no bolded value indicates preferences were evenly split).

Figure 6 depicts the user-defined gesture set. It contains no overlap in interactions for different tasks; the majority of gestures selected by participants are identical for the same task across different surfaces. The interactions were often identical for both the contact-based and mid-air scenarios.

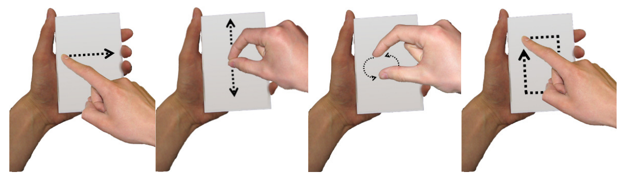

Figure 6: User-defined interaction set. From left, panning, scaling, rotating and selection. Contact-based gestures were used for planar displays, mid-air gestures of the same nature were used for non-planar surfaces.

Regardless of the tilt angle, an identical gesture set emerges for each of the planar surfaces (lines 1–5). On-screen swipe and pinch gestures are preferred and show greatest agreement for panning and scaling respectively, while rotation is performed using two-finger twists and path tracing used for selection (again with preferences and agreement towards contact-based gestures). Participants noted that when either gesture was practical, they tended to prefer on-screen gestures due to the inherent tactile feedback that is present.

When using uneven or non-planar surfaces, participants in general had a greater preference for mid-air gestures (lines 6–10). For panning and scaling, swipe and pinch gestures again showed the greatest agreement, with preferences this time for *above* the screen versions. Participants employed a wide range of contact-based rotation gestures for non-planar surfaces. However, they showed a unanimous preference for an above-screen twist gesture. Path tracing was preferred for non-planar selection, with the particular surface influenced preference of on- or above-screen.

The close correlation between contact-based and above-screen gestures demonstrates users' preferences to extrapolate their knowledge of current on-screen gestures to the mid-air realm. This reduces the users learning and memory requirements and is important for developers of gesture sets for these types of devices.

DISCUSSION

Device Size and Size of Tilt Components

This work focussed on our prototype Tilt Display that is sized between a mobile device and a tablet. We envision this footprint to approximate the ideal size for Tilt Displays.

However, there remains the question of device scalability and the impact that has on the size of tilt components.

Larger, table-scale implementations of these displays might be desirable for some of the applications outlined earlier. This then poses questions about the size of actuatable components (should they also scale in size?) and whether the stroke of the actuators must scale with an enlarged surface. To achieve the same flower effect on a larger surface would require the outside petals to move further away from the originating surface.

All Tilt Displays also lie on a continuum that describes the area of each actuation component. The extreme cases range from each individual pixel tilting and actuating to a single, whole device tilt. Single pixel tilt and actuation would provide high precision and likely come at very high cost. Whole device tilt and actuation opens a range of opportunities for multi-device collaboration: one such example might be for users to place their mobile devices together to form a large Tilt Display.

User Studies

Influence of Prior Knowledge and Familiarity

All but two participants indicated that they had prior experience with multi-touch input and 3D input devices. In the exploration of tilt control, we observed a diverse range of gestures for the required input. In the interaction study, users reverted back to more familiar, already known, gestures. Although we encouraged users to experiment with and employ any kind of gesture participants may have struggled to remove themselves from what they might class as 'common knowledge'. However, we can also interpret these results as the participants believing that these gestures are the most appropriate for the required actions.

Gesture Sets and Compound Gestures

In User Study 2, all gestures were provided using a single hand, based on the assumption that the remaining hand would be used for gripping the device. While all gestures in the interaction set can be performed with either hand, the tilt manipulation set contains two gestures that are most comfortably performed with a particular hand (the tilt right and tilt left gestures using the right and left hands respectively). While in isolation there is little issue with this, when users are performing compound gestures (multiple gestures one after another) then continually swapping the interaction and gripping hands will be tiresome. Further work is needed to address compound gestures and how users perform such actions.

Design Implications

Tilt Displays for 3D Content: Based on the results of the first user study, participants easily related to the Tilt Display concept. Users felt that the actuatable screens created a new form of 3D that was much more evocative than existing 3D displays. A clear advantage that was often mentioned by the participants was that of visualising 3D information without the need to wear 3D glasses. Participants of the first study mentioned that they could see Tilt Displays being used to display 3D images on a mobile phone or to enhance the experience of watching a 3D movie at home using larger and more screens.

Tablet-Sized Tilt Displays: Our first user study also indicates that while mobile phone sized Tilt Displays are suitable to present information to individual users, a larger tablet sized device would be better positioned to support all the interaction modes we created, especially for collaboration. Participants felt that a tablet size Tilt Display would allow subdividing the screen so that four users could comfortably gather around the device and start collaborating and sharing information. By placing the Tilt Display on a horizontal surface, its individual screens would transition between a flat mode where everybody would look at the same tiled display and a collaborative mode with separate views for each user.

Bezels Convey Information: Participants disliked bezels when performing continuous touch gestures (as expected), but surprisingly they did not complain about the bezels visually breaking an image. Instead, they commented on the importance that the gaps and bezels play in the perception of elevation and movement. Participants also suggested that Tilt Displays could be used for navigation as the gaps and the movement could more clearly show which direction you have to go to by taking a quick glance at the display.

Manual Tilt Manipulation: Participants showed a clear preference for 'copy me' style interactions when manually manipulating the display's tilt. Their 3D hand position indicated how the screen should mutate. This interaction style is simple and easy for new users to learn.

Interaction on Non-planar Surfaces: Participants showed a strong preference for alternate interaction for low-level tasks on non-planar surfaces. We derived a user-defined set of mid-air gestures that translated common on-screen interactions to their above-device equivalents. Participants were keen for the same touch actions they applied on planar surfaces to scale to mid-air gestures above non-planar surfaces. Mobile devices will soon contain depth cameras, mean recognition of such gestures will not be a problem.

CONCLUSION

This paper has introduced Tilt Displays, a new type of actuatable display that combines visual feedback with both multi-axis tilting and vertical actuation. We presented an exploration of the design space around Tilt Displays through two user studies. The first found positive user attitudes towards this new type of display, with participants immediately seeing the benefits in the physical 3D output.

The second user study examined interaction possibilities with such a display. It resulted in the generation of two user-defined gesture sets: the first to manipulate the tilt of the display, the second to interact with display. A set of six gestures were employed to control all facets of tilt and actuation. The second set, for the low-level interactions of panning, scaling, rotating and selection, found that users prefer on-screen gestures for planar surfaces, but mid-air versions of the same gestures for non-planar configurations. This demonstrates users' ability to 'scale up' their knowledge of gestures to the domain of Tilt Displays.

ACKNOWLEDGEMENTS

The authors would like to thank all of the study participants for their time and valuable feedback. This work was partially funded by EPSRC (EP/G058334/1) and MobileVCE (www.mobilevce.com) as part of the User Interactions for Breakthrough Services research program.

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