MagicScroll: A Rollable Display Device with Flexible Screen Real Estate and Gestural Input

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ABSTRACT

We present MagicScroll, a rollable tablet with 2 concatenated flexible multitouch displays, actuated scrollwheels and gestural input. When rolled up, MagicScroll can be used as a rolodex, smartphone, expressive messaging interface or gestural controller. When extended, it provides full access to its 7.5" high-resolution multitouch display, providing the display functionality of a tablet device. We believe that the cylindrical shape in the rolled-up configuration facilitates gestural interaction, while its shape changing and input capabilities allow the navigation of continuous information streams and provide focus plus context functionality. We investigated the gestural affordances of MagicScroll in its rolled-up configuration by means of an elicitation study.

Author Keywords

Organic User Interface; DisplayObject; Rollable Display; Flexible Display Interface; Tablet; Scroll.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous;

INTRODUCTION

The use of scrolls dates back to ancient Egypt, where they served as the main medium for information storage. Scrolls were a logical solution for recording long texts, as they supported the continuous nature of the written discourse while allowing for compact storage [40]. Artists in ancient China used scrolls for paintings, as their works were intended to be experienced temporarily rather than permanently exhibited on walls. These artists made use of a physical narrative structure that one could liken to filmmaking: the content of a scroll was gradually revealed as it was unrolled, creating a unique experience imbued with tension between expectation and reveal [7].

Figure 1. Unfolded MagicScroll prototype showing Street View navigation.

Scrolls were replaced around the 1st century AD by the codex, the precursor to the modern book. Books made random access more convenient via bound pages, but pagination introduced an unnatural periodic interruption in the flow of discourse. Dissatisfied by this, American writer Jack Kerouac decided to type his celebrated novel "On the road" on a continuous, 120-feet long piece of paper [17]. This seamless canvas spared him the trouble of having to switch paper sheets, providing a more adequate medium for his uninterrupted spontaneous prose. Modern artifacts based on the scroll form factor—such as the typewriter, Rolodex [50] and the architectural blueprint—were successful because they combined continuous screen real estate with tangible navigation mechanisms in a compact form factor. In modern GUIs, software applications implement scroll functionality, mimicking some of the affordances associated with the aforementioned artifacts. While researchers have envisioned the form and function of scroll-like properties in computing devices [11,19,27], they have been impeded by limitations in rigid display technologies. The introduction of

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Flexible Organic LED (FOLED) displays has only recently made possible the molding of high-resolution, full-color displays around cylindrical shapes [28].

Contribution

We present MagicScroll, a digital scroll whose dual shape configuration naturally allows gestural interaction as well as navigation through continuous information streams (Figure 1). Our prototype features a high-resolution flexible display that can be rolled or unrolled around a 3D-printed cylindrical body. Two wheels with magnetic rotary encoders at both ends of the cylinder provide tangible control for scrolling through the information presented on the display, making it easier to scroll information in rolled up conditions. Furthermore, the ergonomics of a cylindrical body affords one-hand grasping and gestural interaction, like a wand or baton. We evaluated gestural interactions of the rolled up state by comparing MagicScroll with a typical flat mobile device through an elicitation study. Drawing inspiration from ancient paper scrolls, MagicScroll's flexible screen can be unrolled to effectively extend the display real estate. We present interaction scenarios to illustrate how physical resizing of the display can be used as an input technique for interacting with digital information, allowing for focus+context-like action. MagicScroll is powered by two Android 5.1 boards, and can detect its current configuration by means of a bend sensor. Next, we will discuss background literature, followed by MagicScroll's implementation, the user study, interaction techniques, and application scenarios.

RELATED WORK

Over the past years, the scroll has served as inspiration for interaction techniques with digital simulations. Small et al. [35] proposed the use of two cylindrical controls to scroll information presented on a rigid flat display. Xpaaand [19] used projection mapping on a resizable screen held between two handles. Their findings suggest that physical resizing of screen real estate can effectively improve interaction with handheld devices. Pillias et al. [27] evaluated a digital roll using a 3D model and an external input device. Preliminary results indicated that reading on a digital roll can be as fast as reading on paper. Similarly, Häkkinen et al. [11] attached a plastic sheet with printed text to a cylindrical surface to evaluate its reading experience. It is important to note that none of the above prototypes used real rollable displays, which are much more limited in shape functionality, and size. The first scroll-like form factor with a real flexible screen was MagicWand [28], a prototype featuring two FOLED displays. MagicWand was used as a cylindrical mobile gaming display with gestural input. We were inspired by the above explorations in designing a real high-resolution rollable display device whose screen size can be modulated by dynamically changing between rolled up and expanded form factors. Within Rasmussen et all's framework [29], by switching between a wand-like shape and a tablet shape, MagicScroll uses changes of *Form* and *Orientation* as *Input* with a *Functional Aim*, revealing different possibilities for action.

Wand-Like Input Devices

Cao et al. presented VisionWand, a passive wand tracked in 3D space for interacting with large displays [4]. XWand [44] was an electronic wand augmented with inertial sensors, used pointing gestures for controlling devices in interactive environments. Mathews' Radio Baton [23] offered early expressive gesture-based control for music performance through radio tracking. In Hapticast, Andrews et al. [1] used a Phantom Omni [37] to provide force-feedback to a virtual wand for a game environment. Nakagaki et al. introduced Linked-Stick [24], a shape-changing device that mirrors the shape of a homologous device. Commercial game controllers with a wand-like shape, such as the Nintendo's Wiimote and the Sony PlayStation Move, are based on motion sensing for gestural input. This type of game controllers is sometimes credited with introducing the use of physical activity in video games. These game controllers, however, do not feature high resolution displays.

Flexible Displays

Although a traditional display can represent a convincing 3D visual affordance of an object, its physical shape is still that of a flat and rigid surface [25,23]. This limitation has motivated research on Organic User Interfaces (OUIs) [41], computer interfaces with physically shaped, non-flat displays. A major source of inspiration for the development of OUIs has been the historical use of paper for information storage and access. As explained by Sellen et al. [33], paper documents have haptic qualities that facilitate physical interactions that digital documents do not provide. Researchers initially attempted to bridge the gap between digital and physical by using paper prototypes [21], and projection mapping on paper sheets. An example of these early explorations is PaperWindows [14]. The introduction of flexible electrophoretic display technology allowed further mimicry of physical paper-like qualities, providing interactions such as folding [10,18] and multi-document access [39]. E-Ink technology, however, suffers from low contrast and slow refresh rates. Recently, Strohmeier et al. introduced Reflex [38], the first fully flexible smartphone to feature a full-color, high refresh rate FOLED display as well as haptic feedback for providing convincing page-flipping navigation.

Resizable Displays

Researchers have proposed that displays should be able to change shape to reflect the dynamic nature of digital documents [32]. A logical application of this idea is in displays that resize in order to accommodate increased screen real estate while preserving a flexible and convenient form factor. One of the early examples is the dual-display e-book reader presented by Chen et al. [6]. Similarly, Hinckley et al.'s Codex [12] demonstrated the use of tablet PCs for spanning contiguous images across multiple display surfaces. Gomes et al. [10] proposed the use of multiple E-Ink display panels that can self-detect their configuration and adjust the information presentation accordingly. With FoldMe, Khalilbeigi et al. [18] used projection mapping to explore interaction techniques for double-sided foldable displays. Lee et al. [20] also used projection mapping and low-cost tracking to implement resizable displays with arbitrary shapes. In addition to the above explorations, researchers have also investigated wrist-worn systems comprising multiple-segment displays. TUISTER [48] proposed a cylindrical tangible user interface with embedded displays and sensors that relied on twisting gestures to differentiate between fine grained and coarse browsing in hierarchical structures. More recently, Lyons et al. [49] developed a multi-display wrist-worn system consisting of multiple display segments that spanned across the entire diameter of the wrist. Over the years, a number of commercial devices also explored resizable displays. The Readius [9] featured a 5” flexible eBook reader that could be folded into a compact form factor. Sony Tablet P [8] featured interoperating hinged displays. The above explorations and devices produced valuable guidelines for the design of non-planar interfaces. However, previous research prototypes have typically been implemented using either rigid and heavy display technologies or 3D projection mapping, which requires robust real-time tracking and multiple projectors. The above limitations introduce significant implementation challenges and may result in fatigue and discomfort while interacting with these devices [19]. Example features not easily supported by projection-based systems include multi-user applications (i.e. sharing of views), multitouch input on curved surfaces as well as mobile applications. We believe flexible display technology has the potential to drive the next generation of high-resolution, self-contained and shape-shifting displays.

Mobile Gestural Interaction

Rekimoto [30] presented one of the earliest studies on gestural input for mobile devices, using a combination of button clicks and tilt sensing for single hand interaction. Researchers subsequently explored the use of tilt as input [3,12,35], and display orientation change [14] eventually became a universal feature in handheld mobile devices. Gestural interaction is more prevalent today, since most modern smartphones have inertial sensors. However, the unconstrained nature of gestures can make it difficult to develop gesture sets that minimize the user’s cognitive load when using a system. Wobbrock et al. [46] proposed a methodology for improving *guessability* of symbolic input that has been successfully applied in gesture elicitation studies. In this type of studies, participants are asked to perform gestures with the intention to trigger a set of actions. By finding the gestures with highest agreement in the resulting set, a common vocabulary can be constructed. Ruiz et al. [33] used this methodology to propose a taxonomy of motion gestures for smartphone applications. They mapped gestures to both *actions* and *navigation-based* tasks. A similar methodology has been used for finding natural gesture sets for interactions with tabletops [47], drones [5] and TVs [32]. In this paper, we present an user elicitation study to investigate what gestures are naturally afforded by MagicScroll in its rolled up configuration. We specifically focused on what user-generated gestures map to commonly used mobile OS actions.

DESIGN RATIONALE

Inspired by existing literature, the following design considerations informed the development of MagicScroll:

a) Dynamic Affordance

In previous related explorations, displays were usable only in either rolled [27] or unrolled [19] states. We designed MagicScroll to function while rolled into a cylinder, as well as when extended into a multitouch tablet. By morphing between these shapes, MagicScroll naturally provides dynamic affordances [29]: the ergonomics of the rolled up configuration affords better grasping and thus improved gestural input, while the extended configuration provides a larger screen real estate.

b) Continuous Stream of Information

Scrolls have historically been used in scenarios where information consumption requires a continuous and uninterrupted stream. Examples include the paper feeding mechanism of a typewriter, player piano rolls, and the Rolodex. Many popular websites, including most social networks, provide activity streams that are suitable for continuous browsing. Similarly, email and contact management apps present information as long lists of information, which can be difficult to browse through iterative swipes. To facilitate tangible and infinite scrolling navigation of such streams of information, we designed our prototype with two infinite rotary encoders at the extremities of its body.

c) Focus+Context Display

MagicScroll can sense its configuration, allowing shape changes to be used as a contextual form of input. We used this feature to develop applications inspired by focus+context displays [2]. In this type of display, screens of different resolutions interact to provide focused information while preserving a contextual overview. E.g., when MagicScroll is rolled, its scrollwheels can be used to browse a long list of thumbnail items. Once the desired item from the thumbnail list is selected, the display can be unrolled to automatically present expanded information about that item.

e) Haptic Feedback

We designed the scrollwheels to be actuated, allowing MagicScroll to provide haptic feedback to the user, drawing inspiration from the affordances of physical paper documents. For example, physical documents provide tactile-kinesthetic feedback when organizing and navigating information that is not available in GUI-based documents, facilitating spatial memorization skills [34]. Using the actuated wheels to introduce sensations such as friction allows MagicScroll to modulate the kind of passive feedback experienced when, e.g., flipping through cards, potentially easing selection.

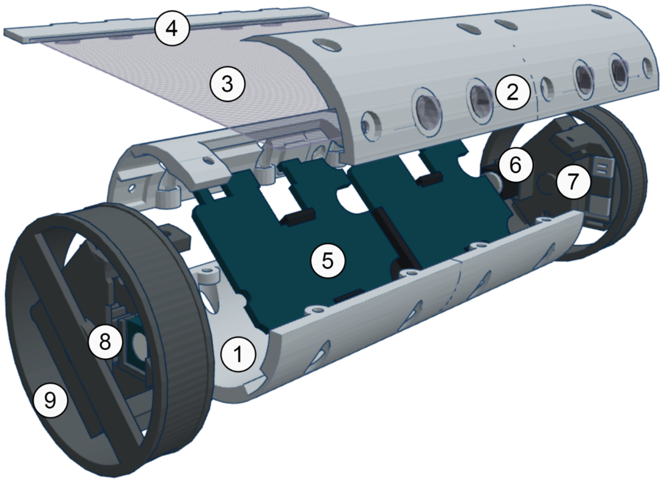

Figure 2. Exploded View of MagicScroll. (1) 3D Printed Body; (2) Magnet Inserts; (3) Flexible OLED Displays; (4) Magnetic Locking Mechanism; (5) Android Boards; (6) Gearmotor and Magnetic Encoder; (7) External Connectors and Power Buttons; (8) 3D printed gear box; (9) Scrollwheel.

IMPLEMENTATION

MagicScroll is a rollable display device with malleable screen real estate, consisting of 4 parts: A 3D printed cylindrical body that houses 2 concatenated flexible displays; all logic circuits that drive the displays, sensors and actuators present in the device; 3 lithium-ion batteries that power all the electronic components present in our system; and a pair of rotary encoders that double up as actuated wheels.

Cylindrical body

Figure 2 shows the cylindrical body, which was 3D printed in ABS plastic and consists of 3 segments. The first two segments create the container for the logic boards, circuits, and batteries. The third segment is used as a clamp to lock down the flexible displays at the end, where they connect to the logic boards. This relieves forces applied to the connecting circuitry when the flexible displays are bent around the cylinder. Without a clamp, display connectors would peel off, causing the displays to malfunction. Inside the cylinder are 3D printed mounts for two Android boards. The boards run Android OS 5.1 and are powered by two 3.7V 600 mAh batteries. A third 300 mAh battery powers the actuated wheels. Logic control for the actuators and additional electronics is provided by a Teensy 3.1. One button on the extremity of the cylinder switches both Android boards on or off. In its rolled up state, the device measures approximately 7.5” x 2”.

Flexible Displays

Connected to the Android boards are two 5.5” multitouch Flexible OLEDs harvested from LG G Flex 2 smartphones. Upon tearing down the smartphones, each screen assembly is placed on a hot plate at 90° Celsius for 4 minutes to soften the LOCA glue that attaches the display to the glass. A thin enamel wire is gently dragged in a side to side and top to bottom motion to separate the screen and digitizer from the glass (see Figure 3). The glue residue is subsequently by removed using acetone. Once extracted, the displays are seamlessly laminated together to create a single 7.5” diagonal display surface with a very minimal bezel of 0.5 mm between screens. The resulting display has a total resolution of 2160 x 1920 pixels—higher than 2K.

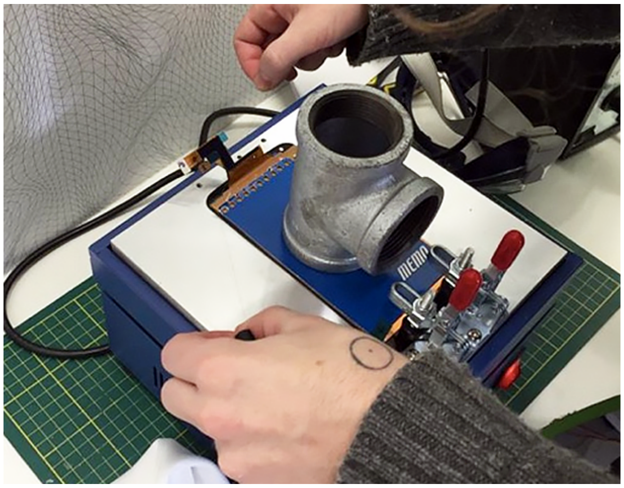

Figure 3. Extraction of a Flexible OLED Display

Dual-Display Applications

Applications are extended to the dual display mode through a full-screen client-server Android application that replaces both home screens. The server application running on the first Android board computes and generates all the graphics. The first half of the rendered image is displayed locally while the second half is sent over a Wi-Fi connection to the client application running on the second board. Touch events are detected by both boards, but only processed on the server. For this purpose, touch events on the client are transmitted back to the server for processing.

Scrollwheels with Rotary Encoders

Each end of the device is attached to a wheel with a micro gearmotor controlled by the Teensy (Figure 2, (9)). Rotary encoders allow the wheels to operate as both input and output devices. Gearmotors are mounted off-axis with respect to the device body to give room to the Android boards. Two 3D-printed gear boxes connect the motors to the wheels to allow the wheel axes to be aligned with the body axis. When the user rotates a wheel, scroll events are reported. These are typically used to scroll graphic content. The motor action can then be used to provide haptic feedback synchronized with the graphic content. Additionally, robotic activation of the scrollwheels allows the device to move on a flat surface. The main purpose of this is to allow real-time remote tangible interaction as well as motion emoticons: emotive expressions through the recording and remote playback of rolling gestures.

Bend Sensor

A 4” Flexpoint bend sensor affixed behind the seam of the two displays allows the measurement of bend gestures for input purposes. Currently, the only function of this sensor is to detect whether the MagicScroll is rolled or unrolled. This shape detection mechanism is useful for preventing spurious input caused by deformation of the touch circuit and by hand holding in the rolled up state. In the rolled up state, touch input is filtered to allow touch on active buttons only.

Magnetic Locking Mechanism

We designed a locking strip (Figure 2, (4)) with 4 magnets that attach to another set of magnets embedded within the 3D printed housing. The locking strip slides over the two displays, allowing the forces on the displays to be equally distributed to prevent breakage in the flexible circuits. The locking strip is further held in place by 4 extrusions that interlock with holes in the cylinder, allowing no lateral movement to occur.

Gesture Recognition

An on-board an inertial measurement unit (IMU) provides the acceleration and rotation data necessary for gesture recognition. The current prototype relies on Wekinator[1], a real-time interactive machine learning engine, to train and recognize IMU data into interactive gestures. MagicScroll sends IMU data wirelessly to a host computer running the Wekinator engine. Once the machine learning engine is trained with gesture data examples, it can be used to identify gestures in real-time. Future implementation would run the gesture recognition algorithms on the device itself.

GESTURE ELICITATION STUDY

Our dual flexible display prototype was considered prone to breakage when recording *hundreds* of repetitive roll/unroll events, making it difficult perform a design elicitation study with this part of MagicScoll's functionality. We also anticipated that in its unrolled state, the basic functionality of MagicScroll would be identical to that of a Tablet PC. We therefore focused on examining user behavior in its rolled-up state, which appears to favour gesture-based, Wiimote style, interactions. We wanted to elicit participatory design input from users on what type of gestures they would prefer when interacting with the rolled-up scroll.

Display Devices

We used the MagicScroll prototype in its rolled-up *Cylindrical* configuration. For the sake of simplicity, we used a prototype with no scroll wheels, as they were not essential for the goal of this study. We implemented a Unity application that presented simple Graphical User Interface actions on the device.

Tasks

We first created a list of actions covering common tasks users perform on mobile platforms, and based on prior studies [33,47]. Then we classified the tasks into two main categories: *actions* and *navigation-based* tasks. The list of tasks was further classified into two sub categories: *system-level* or *application-specific* tasks. We removed duplicate tasks and tasks that are usually unavailable in mobile operating systems (e.g., *minimize*). The final list is shown in Table 1 and contains 29 tasks. Note that the tasks that result in different possible actions are grouped together. For example, the actions *Move Up, Move Down, Move Left, Move Right* were grouped within the *Move* task.

Figure 4. Participant creating gesture for "Menu" in the first experiment.

Participants

20 paid participants volunteered in this experiment (9 females). Mean age of participants was 24.6 years. 17 participants were right-handed. It was imperative for our experiment that our participants understood the tasks and grasped the concept of creating motion gestures that triggered computer actions. We therefore recruited participants with prior experience with gesture-based controllers, such as the Nintendo Wiimote, Microsoft Kinect or Sony PlayStation Move.

Measurements

An Android application on the MagicScroll streamed IMU data to a logging application running on the experiment computer that recorded motion data for each gesture. In addition, all the sessions were video recorded.

Procedure and Task

First, participants were handed a MagicScroll and presented with a task from the list, followed by a verbal explanation. Participants were then shown an animation of the task result on the device. For example: "Show a menu" resulted in a menu depicted on the device (see Figure 4). Next, participants were asked to create a gesture that they thought was the most appropriate for this task. Task order was determined using a Latin square. We asked participants to hold the device with their dominant hand and use only one hand when performing the gestures. Participants were encouraged to invent and perform various motion gestures by moving the device freely in the air making wrist and arm movements. We instructed the participants to only perform motion gestures. Subjects were instructed to perform gestures for all 29 tasks per device condition, including all possible actions when applicable (e.g. *Rotate CW* and Rotate *CCW*). Participants were asked to perform one-handed

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[1] http://www.wekinator.org/

Category	Sub-Category	Task Name
Action	System Level	1. Answer Call 2. Hang-up Call 3. Ignore Call 4. Place Call 5. Voice Search
	Application Specific	6. Act on Selection 7. Hold Selection 8. Menu (Show, Hide) 9. Okay 10. Cancel 11. Undo 12. Redo 13. Cut 14. Paste 15. Delete 16. Duplicate
Navigation Based	System Level	17. Home 18. Next Application 19. Previous Application 20. Open 21. Close
	Application Specific	22. Move (Up, Down, Left, Right) 23. Next 24. Previous 25. Zoom In 26. Zoom Out 27. Rotate (CW, CCW) 28. Pan* (Up, Down, Left, Right) 29. Navigate List (Up, Down)

*E.g. panning a map.

Table 1. List of tasks used in the participatory design study, grouped by category.

gestures. We encouraged the participants to invent unique gestures for each task, but they were allowed to repeat gestures if they considered it appropriate. Participants were allowed to try more than one gesture and then use the preferred one as their final choice. Following Wobbrock's study [47], immediately after performing each gesture, participants were asked to answer how good they thought the gesture matched the task (*Goodness*) and how easy it was to perform the gesture (*Ease*). They answered these questions using a 7-point Likert scale. The experiment concluded with the experimenter asking the participants for comments, feedback and suggestions on their experience.

Results

We collected 38 elicited gestures[2] for each of the 20 participants, resulting in a total of 760 gestures. To identify and label the unique gestures, two researchers browsed the video recordings of all gestures and agreed on a coding scheme. A sample consisting of 100 randomly chosen gestures were then coded by both researchers. The inter-rater agreement was calculated using the Cohen's Kappa test, obtaining an agreement of 0.83. The remaining gestures were then coded by one of the researchers.

	Agreement	Goodness	Ease
Rotate CCW	0.73	5.79	6.00
Rotate CW	0.73	5.79	6.00
Answer Call	0.51	5.95	6.16
Move Down	0.41	5.74	6.21
Move Up	0.41	5.74	6.21
Move Left	0.37	5.74	6.21
Move Right	0.37	5.74	6.21
Place Call	0.33	5.79	6.16
Next	0.31	6.05	6.42
Previous	0.29	5.95	6.47
Navigate List Down	0.26	6.05	6.21
Navigate List Up	0.26	6.05	6.21
Ignore Call	0.24	5.58	6.21
Pan Down	0.23	5.53	5.95
Pan Up	0.22	5.53	5.95
Act on Selection	0.22	5.42	6.05
Zoom In	0.21	5.63	6.00
Zoom Out	0.21	5.63	6.00
Pan Left	0.21	5.53	5.95
Pan Right	0.21	5.53	5.95
Hang Up Call	0.19	6.32	6.26
Voice Search	0.16	5.16	5.95
Okay	0.15	5.68	6.11

Table 2. Agreement, Goodness and Ease for the gestures with highest agreement, obtained with the procedure introduced by Wobbrock et al.[47].

A total of 122 unique gestures were identified. On average, a participant invented 19 unique gestures. *Tilt* gestures were most frequently used, at 51% (386 out of 760 individual gestures). As we expected, a high percentage of gestures involved rotational motions. 12.1% of the gestures performed included a rotational motion around the y-axis of the device and 6.2% were *swirl* motions—a rotation around an axis parallel to the y axis but external to the device.

Agreement

We followed the procedure indicated by Wobbrock et al. [47] to calculate the *agreement score* for each task. This score determines the degree of consensus in the creation of gestures among participants. An agreement score of 1 indicates that all participants performed the same motion gesture for a given task. In contrast, an agreement score of 0 indicates that all participants performed different gestures for that task. Table 2 shows the Agreement, Goodness and Ease scores for tasks with top agreement (A >= 0.15). The top two agreement scores were for *Answer Call* and *Rotate*. All phone-related tasks made it to the top list in Table 2. The gestures for Navigation-Based tasks had higher agreement overall than those for Action tasks. The median agreement for Navigation-Based tasks was 0.225, and for Action, 0.125. This difference was significant, as determined by a comparison using a Mann-Whitney test[3] (U = 286.5, Z = 3.18, $p < 0.01$, r = 0.52). The majority (around 88%) of gestures used for Navigation-Based tasks involved tilting, rotation (around the y-axis) or translation. Figure 5 shows the most frequent gestures for the tasks with highest agreement.

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[2] Corresponding to the total number of actions, including those grouped together as a single task.

[3] We used nonparametric analysis as agreement data was found to be non-normal after a Shapiro-Wilk test.

Rotate CCW, Move Left
Gesture: Device is tilted left.

Rotate CW, Move Right
Gesture: Device is tilted right.

Answer Call, Place Call
Gesture: Device is moved towards ear.

Ignore Call, Hang Up Call
Gesture: Device is moved away from face.

Move Down, Navigate List Down
Gesture: Device is tilted towards body.

Move Up, Navigate List Up
Gesture: Device is tilted away from body.

Move Left, Next, Pan Left
Gesture: Device is rotated CCW around y-axis.

Move Right, Previous, Pan Right
Gesture: Device is rotated CW around y-axis.

Pan Up
Gesture: Device is moved downwards

Pan Down
Gesture: Device is moved upwards

Act on Selection
Gesture: Device is tilted away from body twice.

Figure 5. Most frequent gestures for the tasks with highest agreement.

DISCUSSION

Directionality

The study results showed that tasks that can be considered in pairs always resulted in a similar gesture that differentiated only in directionality. For example, tilting away from body was the most frequently used gesture for *Open*, and participants most frequently used tilting towards body for *Close*.

Navigating

The higher agreement for Navigation tasks suggests MagicScroll is suitable for gesture-based navigation when in rolled-up configuration. The top gestures for navigation involved both translational and rotational motions (move the device up, down along the y-axis and rotate left, right around the y-axis). We also observed that some users preferred to move the device relative to an external viewport, while others preferred to scroll the viewport inside the device. Most frequently (but not exclusively) participants moved the device relative to an external viewport only along the y-axis. Users preferred to scroll the viewport (i.e., rotating the device to the right around the y-axis to scroll to the left) when panning a map along the x-axis. We believe that this behavior was due to asymmetry between the x and y axes of a cylindrical shape. A similar behavior was observed in the top gestures for *Next* and *Previous* tasks.

Targeting

Tasks related to targeting specific objects (such as an item in a list or within an ordered sequence) also presented high agreement. In most of these cases, we observed that participants approached the task by means of the *air bubble* metaphor [42], by rotating the device while trying to keep the target at the point closest to the “surface”. Although we do not have conclusive evidence, it is possible that users found that the rotation action around the y-axis afforded by the cylindrical object intuitively maps to certain navigation tasks. We plan to follow up on this in future user studies. In a similar fashion, MagicScroll’s scrollwheel input could be used for targeting items within lists by means of analogous rotation gestures. This has the downside of requiring the use of both hands, but also offers the advantage of reducing screen occlusion. We also plan to include this input modality in future research.

Phone Tasks

We did not instruct the participants to consider MagicScroll as a phone and did not mention the existence of a microphone or a speaker. However, participants performed gestures on an imaginary microphone and speaker on the device when performing *Answer Call*, *Place Call* and *Voice Search* tasks. Further, participants mentioned that it felt natural to perform those tasks as the cylindrical shape closely resembled a handset of an old-fashioned wired telephone: *"Phone calling feels a lot like a phone handle on older home phones and movements felt more natural" (P19).* A design implication from this behavior is that a cylindrical phone device should feature microphone and speaker arrays that would guarantee audio quality in any direction, but it should also be able to detect the position of the user to minimize ambient noise and maintain privacy.

Grasping

User comments suggested it was easy to perform gestures with MagicScroll. Participants often mentioned that it was "natural" to hold, that it offered a firmer grip, and that it facilitated better gestural interaction than a smartphone. Most participants commented that they felt a smartphone could be "dropped more easily" when performing gestures: *"It is more natural to hold the cylinder because you can firmly grasp it and move gestures, whereas with a [smartphone], it could fly out of your hand because you only touch it on two points" (P9). "[A] smartphone feels awkward in my hand, that it could fall out and break when making gestures. [A] Cylindrical device felt comfortable" (P13).*

Additional Participant Comments

Users suggested that a cylindrical shape was well suited for scrolling tasks, navigation tasks, reading documents, music applications, and gaming applications. We observed that *Move* actions (*up, down, right, left*) displayed high agreement, which suggests that the rolled up MagicScroll might do a good job at controlling on-screen objects. In line with our previous discussion, participants also noted that an unrolled tablet form factor is better for applications where the entire display should be visible at one glance, while the rolled up device would be better for scrolling actions.

INTERACTION TECHNIQUES

Based on our user study and other considerations, we designed several interaction techniques that take advantage of the MagicScroll's form factor.

Touch Input (Unrolled Form Factor)

Touch input in the unrolled state is identical to that on a normal tablet PC. Touch input was limited in the cylindrical form factor to the detection of button presses to avoid accidental triggering of content.

Gestural Input (Rolled-up Form Factor)

Since the rolled up form factor appeared to successfully afford gestural input, we focused our interaction design on the use of gestural techniques elicited in our study. Rotation, tilt and movement gestures intuitively map to spatial navigation actions on elements in the GUI. Quickly double tilting can be used to act on a selected item (e.g. when navigation though lists), a gesture analogous to a mouse double-click. One-handed rotation around the y axis (using the air bubble metaphor) can be used for navigating continuous list of elements in the screen.

Rolling-Unrolling

Rolling and unrolling of the display is an interaction technique unique to MagicScroll (Fig. 5). Since this is performed with arm movement, it is *not* envisioned as an efficient input technique, e.g., to activate or dismiss user interface elements, as arm movement is much slower than, e.g., finger swipes, which is why it was not included in the user study. Instead, we applied rolling and unrolling to switch between focus and context information, naturally following the provision of more screen real estate by this action, as will be elaborated in the application scenarios section. Since the displays stay upright, naturally providing a somewhat rigid surface in their unrolled state, flexibility does not appear to significantly affect touch input when unrolled. Note that while Figure 6 (right) shows the unrolled state held with two hands in landscape, it is not actually necessary to support the unrolled extremity of the display for touch input to function. Also note that the more ergonomic way to hold the unrolled form factor is in portrait, with the cylinder held vertically in one hand. When rolled-up, we expect that the device would provide rich gestural interaction possibilities, as studied in the previous section.

Scrollwheel Input

Actuated scrollwheels allow users to scroll through information in both rolled and unrolled states by means of rotational gestures. They are meant to provide input for navigating through long lists when the device is rolled up, in a way that is more adequate than swiping on or around the small surface of the rolled up form. Furthermore, by introducing sensations of friction or resistance, MagicScroll can provide users with haptic cues pertaining to the location of pertinent information within the document, as demonstrated by Strohmeier et al [38]. In our user study, we found evidence that the rolled form factor might be appropriate for certain navigation tasks. Future work should address the potential of MagicScroll for targeting within long lists [14] and similar tasks using rotation gestures and MagicScroll' scrollwheels.

APPLICATION SCENARIOS

We now discuss a some application scenarios to explore and demonstrate the combined interaction techniques.

Focus+Context Scroll

Our first application scenario depicts browsing through a long list of LinkedIn contacts using absolute rotary

Figure 6: LinkedIn Rolodex app running on MagicScroll. Left: MagicScroll rolled showing the profile photo and summary. Right: MagicScroll expanded displaying the full LinkedIn information.

scrollwheels (Figure 6). This example is inspired by the original Rolodex, a contact organizer that is browsed through a twist of the wrist. This may facilitate spatial memorization and kinesthetic memory, as every contact card is always at a fixed location on the cylindrical surface. MagicScroll naturally provides a 360-degree view, with the sides and back of the display supplying context about the location of contacts, e.g., via alphabetic tabs. This means contact lists are naturally zoomed in and out of view as the cards move to the front of the display and back, allowing for a natural fisheye effect (Figure 6, left). When the user finds a LinkedIn card, it can be further explored by unrolling the display. This increases screen real estate for the user's full LinkedIn page (see Figure 6, right). As such, the rolled up form factor provides contextual interactions through a set of thumbnail cards providing overview, while the unrolled form factor provides focused interactions with full, detailed, content views. Note that scrollwheels can also function as an infinite relative dial, or an alphanumeric dial, when scrolling through very long lists.

Dynamic Form Factor

Our second application scenario combines phone ergonomics with tablet multitasking by moving fluidly between compact and elongated form factors. Here, a user can modulate the screen real estate of the device between rolled and unrolled shapes, to suit the context of use. Users can make a phone call by scrolling through a list of contacts in rolled up form, and pressing the call button. During the call, they hold MagicScroll to the side of their face in rolled up form facilitating a traditional elongated phone form factor that better suits the ergonomics of the task while providing privacy. However, users can also unroll the display during a call, for example, to launch a mapping application showing where an appointment will be, a calendar app providing details about their appointments or to access other contextual information pertinent to the call without interrupting the conversation. The phone automatically switches to public speaker phone when unrolled, providing an example of auditory focus+context action. By allowing users to easily switch between form factors, MagicScroll allows for improved ergonomics, and better supporting for multitasking scenarios.

LIMITATIONS AND FUTURE WORK

Initial user observations show that MagicScroll, in its current implementation, suffers from being slightly oversized. The reason for this is that we needed to fit existing commercially available phone motherboards with a given size inside a cylinder. Another issue is that due to the binary unrolling state we have not been able to explore combining touch with rolling/unrolling action. Bend input can be successfully combined with touch input, but this has not been fully implemented. While the rigidity of the current FOLEDs makes it easier to provide multitouch input in the unrolled state, significant force is required to roll up the screen. Future FOLEDs would likely be more flexible, at a cost of having to engineer a method for modulating stiffness for touch input. One limitation of MagicScroll's implementation with current technology is the fragile nature of the FOLED display connectors, which can deteriorate after repeated rolling and unrolling of the display. This is one of the reasons we focused our study on the rolled-up configuration. We believe that despite these limitations, MagicScroll will motivate researchers to further investigate the design space of rollable display devices, and we see this prototype very much as an inspirational work that demonstrates feasibility.

CONCLUSIONS

We presented MagicScroll, a rollable device with a flexible display and actuated scrollwheels. When rolled up, MagicScroll can be used as a rolodex, phone, or gestural control interface. When unrolled, it provides full access to its 7.5" diagonal 2K+ resolution display. We studied and discussed how MagicScroll's rollable form factor allows a tablet to be rolled up into a portable mobile device that provides gesture-based interaction. We conducted a gesture elicitation user study on MagicScroll in its rolled-up configuration. We found evidence that it allows the intuitive execution of navigational UI tasks such as targeting and moving on-screen objects. Participant feedback also indicated the MagicScroll might afford a better grasp than a mobile phone when performing motion gestures. Finally, we presented several application scenarios demonstrating how MagicScroll may facilitate navigation of continuous information streams and provide functionality analogous to focus+context.

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