FoldMe: Interacting with Double-sided Foldable Displays

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ABSTRACT
In this paper, we present a novel device concept that features double-sided displays which can be folded using predefined hinges. The device concept enables users to dynamically alter both size and shape of the display and also to access the backside using fold gestures. We explore the design of such devices by investigating different types and forms of folding. Furthermore, we propose a set of interaction principles and techniques. Following a user-centered design process, we evaluate our device concept in two sessions with low-fidelity and high-fidelity prototypes.

Author Keywords
Tangible interaction, mobile devices, dual-sided display, foldable display, flexible display, folding, input techniques.

ACM Classification Keywords
H5.2. User interfaces: Graphical user interfaces (GUI), Input devices and strategies, Interaction styles.

General Terms
Human Factors, Design, Experimentation.

INTRODUCTION

Given the rapid advances in thin-film display technology such as E Ink and Organic Light Emitting Diodes (OLED), we will witness a radical change in the design of handheld computing devices. These technologies provide thin, lightweight and even deformable displays which incorporate many of the physical properties that until now were unique to paper. Multitouch displays might ultimately become so thin that they can be arbitrarily folded and rolled while featuring high resolution display both on the front and the reverse sides. This does not only offer a high level of portability but also supports novel physical input techniques.

Recent work focused on investigating different input techniques that are based on bending [1, 8, 11, 18], rolling [10], and folding of displays [2, 9, 5]. We believe that in order to pave the way for effective user interfaces of future

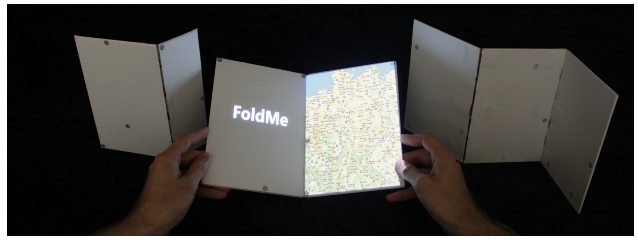

Figure 1: Double-sided foldable display prototypes

displays, each of these modalities need to be systematically investigated. In this work, we want to contribute to the understanding of fold gestures by exploring different types and forms of fold. Since folding enables access to the backside of the display, it is of interest to assess folding in combination with displays that feature screens on both their front and reverse sides (see Fig. 1). To our knowledge this has not been addressed before.

In this paper, we contribute a physical design space of folding gestures and a set of novel interaction techniques and examine how folding gestures can be used effectively to interact with digital content. While recent advances in display technology produce displays that are thinner, higher in resolution and can even be deformed to some extent, we still are a long way until the vision of the fully flexible displays becoming a reality. To inform the design of devices that can be deployed in the near future, we focus on folding interactions with rigid displays that have predefined hinges. This moreover provides the advantage that touch input is more efficient than on flexible displays [6]. In this paper, we also report on two studies in which we evaluated our low fidelity (i.e. paper mock-ups) and high fidelity (i.e. projection-based realization of interaction techniques) prototypes.

The remainder of this paper is organized as follows. First, a discussion on related work is given. Next, we present a physical design space of double-sided foldable displays followed by a report on our paper prototype study. Then, we introduce a set of interaction techniques followed by results of our second study.

RELATED WORK

Our work is situated in the fields of flexible display interfaces and dual-sided devices. We will discuss each of them in turn and finally present work that makes use of virtual document folding in GUIs.

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Flexible Display Interfaces

In recent years, a relatively large number of studies have focused on bend gestures as a deformation-based input modality for flexible displays. Schwesig et al. introduced Gummi [1], a concept of a deformable handheld computing device and a set of interaction techniques that leverage bending as an input technique to manipulate digital content. While their prototype has a rigid display, a slightly larger flexible substrate with integrated resistive bend sensors enables recognition of discrete and continuous input events. Twend [8] is a hardware prototype that can be bent and twisted to perform navigational tasks such as scrolling through the pages of an eBook. Similarly, Bookisheet [18] presented an interface for browsing digital information based on physical page turning metaphor. Lahey et al. presented PaperPhone [11] to examine user preferences for bend gestures with a thin E Ink. The results showed user selected gestures that were simple and less physically demanding.

Prior research has also investigated using multiple flexible displays simultaneously. PaperWindows [4] augments passive paper sheets with an in-place projection of digital contents. The authors introduced a set of interaction techniques for individual and multiple displays.

Lee et al. [3] demonstrated four different types of foldable and resizable displays by using a low-cost tracking system and a projector. They proposed that devices which can be resized and reshaped offer advantages for mobile contexts. Foldable User Interfaces (FUI) [7] leverage a paper cardboard that can be bent and folded in order to manipulate a 3D GUI. Xpaaand [10] is a handheld device that features a rollable display. The authors explore how dynamic resizing of the display can be used as an input technique for interacting with digital contents. None of this prior work investigated fold techniques with double-sided displays.

Our design concept is inspired by the empirical findings of Lee et al. [5]. Their study elicited gestures for a set of basic commands performed with imaginary flexible displays made of plastic, paper and cloth.

Dual-sided and Double-sided Devices

Chen et al. [2] introduced an e-book reader which features two displays mounted on two separate slates that are connected by a hinge. The device allows back-to-back and side-by-side configurations of the displays as well as detaching the slates while reading. A set of embodied interaction techniques based on folding, flipping, and fanning of the displays supports navigation in e-books. Hinckley et al. [9] introduced a similar device. Codex is a tablet computer which features two displays. Embedded sensors can measure the angle between both displays and the orientation of the device. This provides for a richer design space of different device postures that afford individual, ambient and collaborative use scenarios. However, while both these devices provide two displays, each of these displays is single-sided: it cannot display information on its reverse side. In contrast our design concept leverages displays that can display information both on their front and their reverse side. This enables an even larger set of device configuration and folding interactions. Moreover, we do not only consider single, but also multiple folds.

Despite the large body of research on using the backside of a device for touch input, only little research investigated double-sided displays. Nakamura [13] introduced a set of flipping gestures for navigating through information displayed on a reversible display. Folding is conceptually different from flipping in that it allows for more than only two different physical configurations.

DESIGN SPACE

In this section, we systematically investigate the design space of double-sided foldable displays that are interconnected by hinges so that they can be folded and unfolded. While in the farther future, displays might ultimately become so flexible that they can be arbitrarily folded along any axis, thin-film display technology is still quite far from this point. This is why, as a first step, we opted for predefined hinges with rigid displays. Although the device configuration provides folding with limited degrees of freedom we believe that most of our techniques can be equally applied to arbitrary user-defined folds. Our design space is primarily organized by different types as well as some physical properties of folds. Moreover, we investigated possible combinations of fold and touch. An overview is presented in Fig. 2.

Types of Folding

Fold-to-front and Fold-to-back

We consider the general case in which the hinge allows for fully rotating the flaps, i.e. they can define any angle from 0 to 360 degrees. In this case, each of the flaps can be folded towards or away from the user. In origami art, based on the form of crease, these are named as valley and mountain folds. These terms are well-suited for describing the actual state of the fold, but they do not account for the different directions involved in the folding process (fold or unfold). This is why we introduce the following terminology: *fold-to-front* and *front-unfold* for the valley fold; and *fold-to-back* and *back-unfold* for the mountain fold. These are depicted in Fig. 2d-g. Both fold gestures change the size of the available screen space. Yet, fold-to-front brings a portion of the reverse side to the front. In fold-to-back, it is vice versa, i.e. a portion of the front display is brought to the reverse side. These two types of folding are similar to the way we might handle a book or magazine. Folding over and front-unfold are used to open and close the book. Fold away allows for more convenient holding of the book while reading.

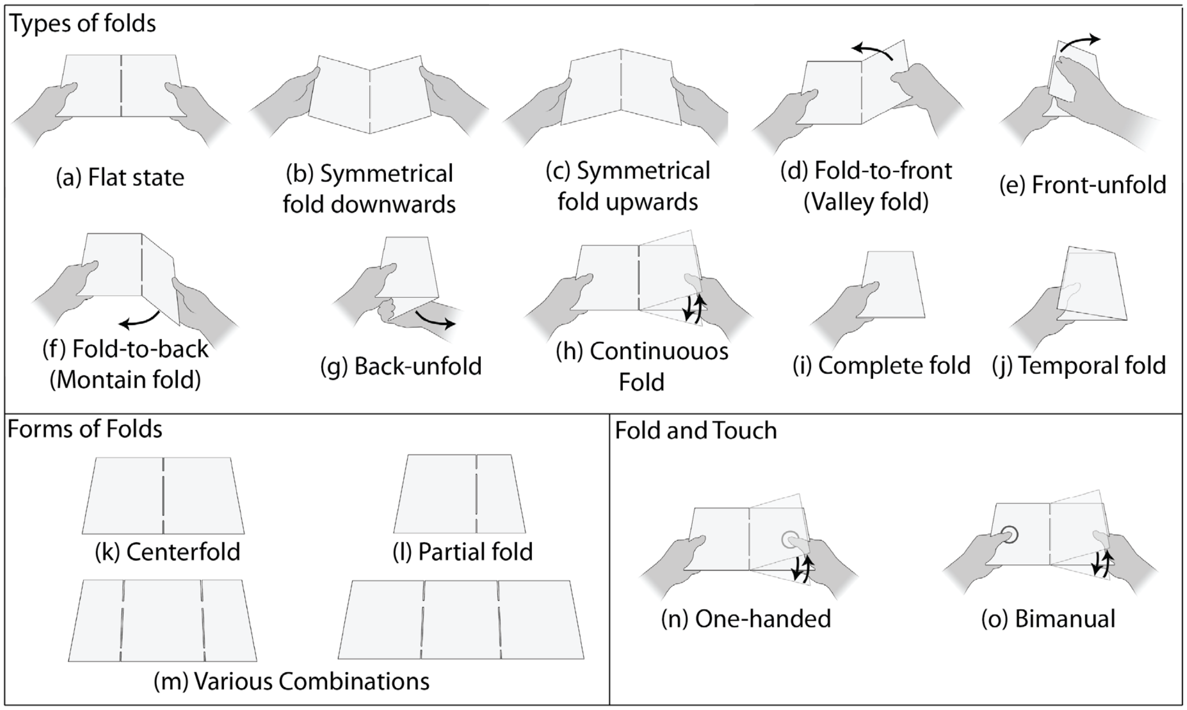

Figure 2: Physical design space of double-sided foldable displays

Continuous fold

Folding can be interpreted as a continuous rather than discrete action. In this way, starting from neutral state (flat state), turning the flap either towards to or away from the user results in a continuous input with positive or negative values (Fig. 2 h).

Temporal fold

With physical books it is a common practice to temporarily index a page by putting the forefinger or thumb at that page. This enables a quick and convenient way for referring to a specific page while flipping through the pages of the book. Inspired by this practice, we define the temporal fold as a type of folding in which one finger is put in-between the flaps as illustrated in Fig. 2 j. In contrast, a complete fold requires that the flaps be placed directly on top of each other (see Fig. 2 i).

Physical Properties of Folds

The method of folding, yet simple, offers a rich set of alternatives. We consider folds that are oriented along a single axis (longer edge) with two different sizes:

Centerfold: folding the display along its center axis to create two equally large flaps (see Fig. 2 k). This resembles physical books.

Partial fold: folding the display along an asymmetric axis. In this case, folding-over the flap does not cover the entire screen (see Fig. 2 l).

Different configurations can also be achieved by combining different types of flaps (n) with hinges ($n - 1$) in one dimension (see Fig. 2 m).

We believe that study of these basic forms of folding, yet simple and restricted to one dimension, provides the foundation which is necessary for the design of future, more faceted foldable devices. Moreover, these basic fold gestures maintain common rectangular form factors of today's handheld devices that we are already accustomed to use. We leave more complex, diagonal and origami-style folding interactions for future work.

Fold and Touch

Although we have shown that one single hinge allows for a number of different folding interactions, their overall number is limited. So only a limited number of commands can be triggered using folding on its own. Direct touch input on the display has the potential to distinguish between different commands that are all associated to one folding gesture.

We looked for plausible combinations of folding and touch input. We base our design on whether folding and touching are both performed with the same hand or whether they are delegated to different hands. In the one-handed case, the user holds the device with one hand while the other hand touches while folding. In the bimanual case, one hand touches while the other hand folds (see Fig. 2 h-i). There are some cases in which it is difficult to touch while folding (e.g. touching on the front page of the book device while doing a front-unfold). In these cases both activities are performed in a sequential order: first touch, then fold.

One apparent issue in integration of touch interface is that users might trigger false touch events by simply holding the device. We propose two solutions for this issue. First, a bezel can assist users in preventing triggering unwanted touch events, pretty similar to the bezel of current rigid handheld devices. In our device concept, however, this would require that each of the flaps is entirely surrounded by bezel, resulting in a very large bezel in the middle of the display when it is in an unfolded state. Hence, this approach on its own might not be a practical solution. Another solution is by automatically distinguishing between contact points that are created by the grip and actual touch events [14]. We believe that a combination of both approaches will allow users to hold the device comfortably while folding and touching.

PAPER PROTOTYPE STUDY

To further investigate different types of folds and their use cases, we constructed several paper prototypes. These incorporate the main physical properties of our display concept: lightweight, rigid and easily foldable in both directions. Furthermore they become stiff when in an unfolded flat state. This provides for a single unified display space that can be easily held from one side.

We used foamboard that is made up of a sheet of foam sandwiched between two sheets of cardstock paper. To connect two sheets of the foamboard, we embed a number of relatively strong magnets into the long edge of each sheet, which realize a snap-in effect when the display is in an unfolded flat state. In order to ensure that sheets cannot be detached and hinges remain stable and well-aligned during manipulation, we moreover integrated three straps connected to both sheets (see side view in Fig. 3). A schematic view of prototype design is depicted in Fig. 3 a. In this way, no gap is visible at the hinges. Users perceive only a slightly visible crease at the possible fold location. We constructed three different prototypes namely *book*, *partial-fold* and *dual-fold* devices (Fig. 3 b). They allowed us to examine different types and sizes as well as more-than-one-fold variations.

In this paper prototype study, we were particularly interested in looking for various functional roles that can be assigned to each folding type and form. We recruited 10 volunteer participants (9 male, 1 female) for single-user sessions. Three of them were left-handed. All were professional computer scientists. Each participant owned a smart phone that they used on a daily basis. Five participants owned a general-purposed tablet for longer activities such as reading and surfing. E-book reading devices were used by two participants.

We first asked participants about the mobile devices they use and requested a brief description of their usage. Next we presented the paper prototypes and invited the users to think aloud of different scenarios in which they could imagine using the prototypes. No information was displayed on the device. However, we utilized some printouts of screen captures of some common mobile applications to foster brainstorming. Sessions were video recorded for analysis.

Results

All participants appreciated the concept of double-sided display and the possibility of folding and unfolding to alter the screen. They found folding very natural (particularly the fold-to-front) and useful in terms of having a compact form factor for mobility and enlarging the screen when the context permits. One participant commented *"folding [over] is kind of a shortcut to access the backside compared to flipping the whole page"*. All participants appreciated the strong sense of going back and forth which is suggested by folding. Folding was also found to be very appropriate for temporarily referring to something on the backside and then returning back to the main task.

Book device: All participants commented that the book device is suitable for active reading. Fold-to-front and front-unfold were found to resemble close and open actions. We observed that since all four displays have the same physical appearance in size and shape, users did not map different roles to the displays, but treated all of them as having the same role. A participant mentioned that *"having multiple displays on one side is useful for dividing your coupled task [like reading and writing] and the backside can be used for background applications that you need to refer to from time to time"*. 4 participants explicitly mentioned that it might be suitable for occasionally referring to the backside.

Partial-fold prototype: Users reported that the smaller flap of the partial-fold prototype is *"an add-on to the main screen"* and offers additional functionality, similar to a tool palette. *"It [the flap of the partial-fold device] is very quickly accessible and easily foldable; it is more convenient than folding using the book prototype"*. Another participant commented: *"out of sight, out of mind but still quickly accessible"*. Six participants stated that the flap of the partial-fold prototype is suitable for having a list (or an overview) while the main screen displays the detail.

Dual-fold prototype: Seven participants perceived the dual-fold device as an extension of the book device. In general, participants had difficulties in imagining an appropriate application of the dual-fold device. However, they could envisage using the device for specific purposes such as a graphics editing program or a map application.

Almost all participants expressed privacy concerns of having contents displayed on the backside. They mentioned that it has to be inactive while working on the front side.

INTERACTION TECHNIQUES

Several interaction principles form the foundation of our interaction techniques. We start by presenting the principles before discussing the more concrete techniques.

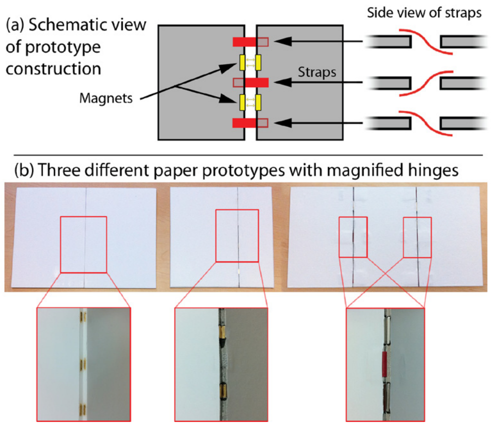

Figure 3: Schematic view and paper prototypes

General Interaction Principles

Fold-to-front

It was found from the literature overview and from our study that apart from changing the screen size, folding quite naturally maps to triggering a command. In previous work it has been mapped to the *close* and *open* commands [5]. In our design concept fold-to-front provide access to the back of display. The combination of fold-to-front and the screen space on the backside opens up a set of novel actions:

• *Level-up:* the user can have access to one level higher in a hierarchy using fold-over. For example, in a photo browsing application, the user can fold over and expose the view of albums.

• *Overlay:* naturally, fold-to-front cover the front side of the display with a display layer coming from the backside. This can be interpreted as an overlay or an augmentation to the current view.

• *Accessing backside content*: in our design we also assign fold-to-front to access content or functionality on the backside of display.

A front-unfold gesture triggers the respective reverse action.

Fold-to-back

Unlike fold-to-front, which replaces the topmost display by an additional layer, fold-to-back maintains the current display partially, but reduces the visible screen real estate. This is somewhat similar to resizing of rollable displays [10]. However, in contrast to continuous rolling out or in, fold-to-back provides for discrete changes in size. We use this type of resizing for the following purposes:

• *Displaying more contents*: back-unfold expands the screen contents to a display real estate twice as large as before. The larger size can be used to display more contents, facilitates comparison of several items, and improves the display of contents that are better suited for landscape mode. Fold-to-back turns the display again in compact (portrait) mode for comfortable mobility.

• *Displaying more detailed content*: back-unfold can be also used to display either more detailed content or overview content. Doubling the screen size in the book device naturally maps to showing more detailed contents whereas unfolding in partial-fold device serves as a place to display overview.

• *Exposing different application mode:* dynamic increasing of screen size with fold-to-back and back-unfold can be used to expose additional functionality within and between application. As an example, these types of fold can result in exposing or hiding different functions of an application.

Interactions

In the following we apply the general interaction principles with different fold sizes and their corresponding roles to generate a set of more advanced interaction techniques. Moreover, we present some interactions that make use of direct touch input while folding.

Foldable multitasking

One of the key features of today's handheld devices is multitasking: allowing users to quickly switch between a foreground application and other applications, which continue to run in the background. With the iPhone or iPad for instance, a common way of switching between applications is to double click the home button which opens up a tray containing icons of all running applications. By clicking on an icon, the user can switch to an application. This approach, although simple, can become awkward in cases in which the user needs a quick means for frequently switching between several applications; for instance when doing a text chat parallel to reading an e-book or when using Wikipedia for looking up definitions of terms that are used in an e-book.

One key affordance of double-sided foldable displays is to be folded for accessing content which is located on the backside. This feature is particularly useful for an effective, embodied multitasking. Having one or several applications assigned to the backside, the user can quickly refer to them and then get back again to her context. Since each application is assigned to one unique page of the foldable device, rich spatial cues guide the user and, in combination with folding, generate a more direct and physical experience of multitasking. In this technique a complete fold results in closing the foreground application. In contrast, finger bookmarking keeps the application running in the background while the user is working with another application.

We implemented the foldable multitasking technique using the example of an e-book reading application on the book device. Two other applications, a music player and a text messenger, run on the backside. If the user receives a new text message while reading the book, a notification is displayed. The user can touch the notification and fold to interact with the background application on the backside.

Figure 4: Interaction techniques: a) Foldable multitasking, b) Foldable tool palette, c) Foldable layers d) Foldable spin control

Of course, the user can switch at any time to any of the two applications by folding the device in either direction. Performing a complete fold will close the e-book application. Fig. 4 a illustrates how the user can access the messenger application.

Foldable tool palette

The screen of today's mobile and handheld devices is limited in size. In contrast to GUI applications, tool palettes are most often realized as pop-up windows, which overlay and occlude existing screen content. Based on user comments from the first user study, we developed a tool palette technique that separates controls and widgets from the main screen content. The flap of the partial-fold device acts as a tool palette while the bigger screen (primary screen) displays first-class contents. The user can remain focused to the contents. When needed, using back-unfold the user can access the controls and once the interaction is completed, the user is able to fold away the flap to the back of the primary screen. This enables a quick and intuitive accessing of controls and widgets while keeping the primary screen free from any widgets and other distracting elements.

The tool palette technique is implemented in a photo viewing application scenario. Users can interact with photos using common touch gestures: swiping to go to the next or previous images in an album. Unfolding the flap displays several controls of the photo application, such as different buttons for sharing a photo and a set of foldable spin controls (see the next technique). The user can also use the flap to view an overview of the images in a collection. In order to select another collection, the user can fold-to-front the flap on the primary screen. This displays an overview of different albums on the flap and a thumbnail view of images of the selected album on the visible half of the primary screen. In this way, the technique offers two advantages. First, it provides a consistent mapping of the fold-to-front to going one level higher in hierarchy. Second, it provides a consistent preview of images on one single physical display i.e. the primary screen either as individual full screen in the flat state or thumbnail view once the flap is folded over the primary screen (Fig. 4 b).

Foldable spin control

This technique leverages the continuous nature of folding for fine adjustment of values. It can be imagined as a tangible spin control that increments or decrements a value when the flap is partially folded to the back or to the front. In this technique the main focus of the user, the primary screen, remains stable and well visible while the value is adjusted. It also provides a natural mapping based on the folding angle: an angle of zero degree corresponds to a neutral state; positive or negative angles result in increments or decrements.

This feature is implemented in the photo viewing application. Spin controls allow for adjusting brightness, contrast and blur level of photos. Our implementation uses an absolute mapping between the folding angle and the amount of increment repeater. For each function, a button is displayed on the flap. The user can touch on one of the buttons and fold to adjust the corresponding value. Visual feedback about the current state is given by a simple slider on the right side of the spin control. This technique is illustrated in Fig. 4 d.

Foldable layers

Based on the fold-to-front interaction principles we designed a technique that supports overlaying the information displayed on the front screen with the backside display. This is slightly different to the other techniques in the sense that fold-to-front does not result in a different view but rather *augments* the contents of the front display. This is similar to applying a lens or placing a display with a transparent background on it. Having a device with more than one hinge allows the user to combine or merge different layers on top of the front display.

This technique is implemented in a map scenario in which the middle screen of the triple prototype displays the Google map view as the primary view. Two adjacent screens represent textual explanation of a route (left screen) and a set of point of interests (POI) such as gas stations, hotels and parkings (right screen). To graphically show the route on the map, the user can fold the left screen with the root information over the map view. Similarly, the user can fold the right screen over the map view to augment the map with icons showing the location of POIs. In order to merge the two views, the user can fold both screens over the map. This results in a map view with integrated route and POIs (see Fig. 4c).

IMPLEMENTATION

Despite recent advances in thin-film displays, currently available technology does not yet allow us to produce a device with very thin double-sided and foldable displays that is untethered (which is crucial to free folding in all directions). Similar to [4, 3, 10, 20], we therefore simulate double-sided foldable displays using a passive display approach. Our simulation environment consists of an Optitrack motion capture system [19] with 6 infrared cameras, a full HD projector mounted on the ceiling and several foldable prototypes augmented with infrared retro-reflective markers. The information provided by the tracker system (position, orientation, folding state of the prototype) is used to warp the projected image onto the prototype in real-time.

In our software toolkit, we simulate the environment by constructing a Direct3D world model. In an initial calibration step, the Direct3D camera is set to the position and orientation of the projector, thus the camera "sees" the foldable display and its contents from the correct perspective. The camera view which is generated by Direct3D is displayed by the projector while the world model is continuously updated by the tracker data. In order to recognize different folding gestures, we implemented a gesture recognizer that analyses positional information of the foldable display. The Direct3D model receives real-time screen captures of Windows Presentation Foundation applications and renders them as textures onto the display.

In order to enable touch input, we attach an infrared reflective marker to one finger of each of the user's hands. Once the finger marker is sufficiently near to the display surface, we calculate the projection of the finger point onto the display plane using planar geometry. As this approach would fail when a touch occurs very close to one of the markers that are used for identifying the display, we took special care of positioning markers on the display surface in a way to ensure that the main screen area remains marker-free. Different approaches, e.g. by using pressure sensitive or capacitive touch foils [17], were not possible since these either require tethering or too bulky electronic components.

EARLY USER FEEDBACK

In order to get initial user feedback on our interaction techniques, we conducted an explorative study with 5 participants (all male and right handed). None of them had participated in our first study. We were interested in observing how participants used our interaction techniques for identifying strengths and weaknesses, and also to see how easily users understood the novel interaction style of double-sided foldable displays. After a brief introduction to the prototypes and the applications, the participants explored the interaction techniques while thinking aloud. The session was followed by a semi-structured interview. In this study, we examine our concept and interaction techniques with high-fidelity prototypes, i.e. augmenting our paper prototypes with interactive projections as described above and shown in the video figure.

Results

Participants found the concept of dual-sided displays appealing and were able to quickly understand the interaction principle of fold-to-front and fold-to-back in combination with the reverse side of the display.

Three participants found fold-to-front to be more intuitive and practical than fold-to-back, particularly when using the book device. One participant commented that "*fold-to-front [from right to left] is like clicking the right mouse button to access the context menu, which is missing in touch interfaces*" and is like "*a special function*". Another commented that "*fold-to-front to access the backside to see more information or invoke other applications is very intuitive*". Tangible multitasking was very well received by all participants, particularly the combination with finger bookmarking that allows for "*haptic feeling of pausing your context*" and then unfolding to resume. They appreciated using the backside display for accessing the background application, and the front display for the foreground application. Three participants emphasized on the fact that it is suitable for less frequent and temporal application switching. Echoing the findings of [2] and [9], in cases where tasks are highly interwoven (such as reading and simultaneous note taking), participants preferred to have both applications on the foreground display divided on two adjacent screens to avoid the need for highly repetitive folding.

Although the technique for changing levels in a hierarchy with the fold-to-front gesture was limited to two levels, it was well received by 4 participants in the partial-fold device. The technique provides a rich physical experience of going up or down in the hierarchy. However, in cases that the levels of hierarchy were more than two, participants preferred alternative ways of changing levels, e.g. direct touch input, and using folding only as a shortcut for switching between two frequently used levels.

The tangible spin control received positive feedback for several reasons. Participants commented that it supports interacting with digital content while both hands are holding the device and avoids hand occlusion on the primary screen while manipulating the content. However, three participants were unsure about the effectiveness of this technique in terms of efficiency and accuracy in comparison to direct touch interaction with a slider control. One reason for this might be the fact that our implementation required participants to interact with the spin control using their non-dominant hand. Another possible shortcoming might be the direct mapping of the degree of folding to increment of value. Future work should examine various configurations of the flap and main displays based on the desired handedness of users, and quantitatively evaluate accuracy and speed of this technique.

Initially, the tangible layer (or overlay) technique on the dual-fold prototype was found to be difficult to understand by most of the participants, since it is conceptually very different from existing mobile devices. However, after a short while they could figure out the idea behind it. Two participants saw a natural mapping to 'do' and 'undo' actions: "*When I perform [fold and unfold] gestures to quickly check if a filter is appropriate or not, it resembles [do and] undo actions*". All participants appreciated having the middle screen as the main preview of the application (in this case the map) while folding the left or right sides over preserves and only augments the main view, even though the physical screen size is changed. The discussion with participants revealed that having the primary preview on one physical display and the filtered preview on the backside of another display gives them a safe feeling that the original content remains unchanged. Therefore participants frequently folded and unfolded the device repetitively, switching back and forth between different views. In contrast, results of the foldable multitasking technique showed that where the fold-to-front gesture entirely changes the current view, users tend to perform the fold gesture more selectively and infrequently.

LIMITATIONS

The main limitation of this work resides in the restriction to predefined hinges of rigid display surfaces and one (horizontal) dimension of folding. While this prevents us to investigate free-form folding variations, we believe that the techniques and results of the studies can be extended to fully flexible displays. Fully flexible displays will allow the user to select the position and the extent to which the display gets folded. This will render possible more flexible sizes of folded application windows, tool palettes and lenses. The results of our studies are limited to qualitative observations and subjective feedback from users. Due to the technical setup, use of the display prototypes is not possible in mobile settings, but restricted to a fixed location.

CONCLUSION AND FUTURE WORK

We presented FoldMe, a device concept and prototype that has thin-film displays both on its front as well as its reverse sides and can be folded along predefined hinges. We systematically explored the design space and discussed the design of several novel interaction techniques for manipulating digital content. Two user studies were promising and suggested that such devices have great potential to improve the way we manipulate information on mobile handheld devices. Future work should investigate more complex forms of folding, in particular folding along different axes, diagonal folding, folding at any arbitrary position, and compare foldable devices with existing fixed-size mobile devices.

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