FlexCase: Enhancing Mobile Interaction with a Flexible Sensing and Display Cover

Christian Rendl[1], David Kim[2], Patrick Parzer[1], Sean Fanello[2], Martin Zirkl[3], Gregor Scheipl[3], Michael Haller[1], Shahram Izadi[2]

[1]Media Interaction Lab, University of Applied Sciences Upper Austria
[2]Microsoft Research, Redmond, WA, USA
[3]Institute of Surface Technologies and Photonics, Joanneum Research

Figure 1. FlexCase is a novel flip cover for smartphones, which combines a flexible sensor and e-paper display to enhance interaction with existing mobile phones. The cover can be used in a variety of configurations and it augments phone's existing input and output capabilities with a variety of new interaction techniques, such as bimanual and back-of-device interaction or the incorporation of different grips for mode-switching.

ABSTRACT
FlexCase is a novel flip cover for smartphones, which brings flexible input and output capabilities to existing mobile phones. It combines an e-paper display with a pressure- and bend-sensitive input sensor to augment the capabilities of a phone. Due to the form factor, FlexCase can be easily transformed into several different configurations, each with different interaction possibilities. We can use FlexCase to perform a variety of touch, pressure, grip and bend gestures in a natural manner, much like interacting with a sheet of paper. The secondary e-paper display can act as a mechanism for providing user feedback and persisting content from the main display. In this paper, we explore the rich design space of FlexCase and present a number of different interaction techniques. Beyond, we highlight how touch and flex sensing can be combined to support a novel type of gestures, which we call *Grip & Bend*. We also describe the underlying technology and gesture sensing algorithms. Numerous applications apply the interaction techniques in real-world examples, including enhanced e-paper reading and interaction, a new copy-and-paste metaphor, high degree of freedom 3D and 2D manipulation, and the ability to transfer content and support input between displays in a natural and flexible manner.

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Flexible, input, output, sensor, deformation, grip detection

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INTRODUCTION
The smartphone has revolutionized computing, making interacting with digital information as simple as reaching into your pocket. Although the hardware continually improves, many of the interactions are still reduced to touching and sliding our fingers on a rigid piece of glass.

To remove these bounds on 2D input on the front of the display and to avoid occluding (often valuable) pixels on screen, researchers have explored interaction on the back [6, 53], above [29], or around the device [9]. Further, researchers have looked at using flexible sensors [41] or even the combination of flexible display and input [15, 19, 22, 27, 28, 47, 48] to bring more paper-like physical interactions to mobile devices.

Another trend extends the output space of smartphones by using electronic paper (e-paper) displays in conjunction with the phone's regular screen [5, 35, 38, 55]. These e-paper displays are very power-efficient as they only need to be powered while the screen content is being updated, and exhibit a paper-like reading experience, which can remove aspects of eye strain. However, none of the aforementioned systems support rich flexible and gestural interactions between the two screens or make use of the combined extended screen space.

In this paper, we present FlexCase, a flexible interactive flip cover that augments the input and output capabilities of smartphones with novel paper-like and gestural interactions. As shown in Figure 1, a cover housing both our novel sensor and e-paper display is attached to the phone without compromising the form factor. We utilize a custom-made flexible touch, pressure and bend sensor, combined with a flexible e-paper display that turns the phone cover into a versatile input and output device. The cover provides interactive mechanisms to move content between displays. It allows the secondary display to be used as a peripheral surface for input and output. It also enables rich physical paper-like interactions with the cover using touch, pressure and various flex gestures. The ability to simultaneously detect touch and complex deformation of the surface allows for gestures, which we call *Grip & Bend*, that provide a variety of novel paper-like interactions. We explore the design space for FlexCase in detail, demonstrating a variety of new applications.

While we consider the novel form factor and the resulting interaction techniques as the main contributions of this paper, we also present technical novelty with a sensor that combines multiple modes of input. The flexible input sensor is built on a touch and pressure-sensitive printed piezoelectric film [40, 56], which recently demonstrated its ability to sense complex deformations [41]. In contrast to this prior work that utilizes a sparse arrangement of sensors around the periphery, we use a matrix-like sensor layout to sense touch, pressure, and complex deformations with only a single sensor. Summarizing, the main contributions of this paper are:

- A concept of a novel flip cover form factor that augments existing mobile interaction with flexible output and input, including touch and bend input.
- Exploration of the design space for our system with its reconfigurable multi-display and multi-input form factor.
- Novel interaction techniques, which arise from the combination of touch, pressure, grip, and bend sensing.
- A custom input sensor, which enables bi-directional bending and touch on both sides; and a new-machine learning algorithm for leveraging grip sensing for richer bend input.
- A set of application scenarios demonstrating novel interaction possibilities with our proposed design.

We will firstly discuss the design rationales for the FlexCase form factor and its resulting design space. We will then introduce the hardware architecture, the sensing principles and the algorithms of our system. Further, we will present a compelling set of novel application scenarios arising from our proposed design and its input modalities. Finally, we will conclude with a discussion, limitations and future work.

RELATED WORK

Our work relates to many areas of HCI research, including work on flexible displays and mobile interaction. In this section, we will introduce the most important work for each field, starting with a review of devices combining traditional touchscreens and e-paper displays. Then we discuss work dealing with flexible display interaction and interactions with multiple displays. Finally, we discuss possibilities of extending input around and behind the device.

Combination of Touchscreen & E-Paper Display

Nook [5] was one of the first commercial E-Readers, which combined an electronic paper display with an additional smaller LCD touchscreen. The secondary display was mainly used for more dynamic interactions such as animated menus. More recent products, like Yotaphone [55], InkCase [35], or PopSlate [38], use e-paper displays as a secondary, more power-efficient ambient display. Although these products show compelling scenarios, the secondary display is not used as an additional input device nor as direct extension of the main display, thus both screens are mostly used in isolation. In contrast, Dementyev et al. [14] showed wirelessly powered display tags, which can serve as mobile phone companion displays. However, they were not attached to a smartphone.

Flexible Display Interaction

Bendable interfaces, such as ShapeTape [13], Gummi [42], PaperPhone [28], or MorePhone [18] demonstrate many novel interaction scenarios based on making a mobile device with flexible sensing or input and output capabilities.

ShapeTape is a thin long tape subdivided into a series of fiber-optic bend sensors, each detecting bend and twist. Balakrishnan et al. [3] demonstrated modeling 3D curves with this technology. PaperPhone [28] was one of the first prototypes that coupled flexible input and output into one self-contained device. PaperTab [49] is a self-contained electronic reader with a flexible touchscreen and two bi-directional bend sensors for input. In contrast, the Kinetic Phone [27] demonstrates a full-color bendable phone, providing both gentle twist and bend gestures. In a follow-up study Ahmaniemi et al. [1] demonstrated the utility of bidirectional continuous bend gestures. More recently, FlexView [8] augmented predominant touch input on flexible devices with a set of bending interaction techniques for navigation in 3D (along the Z-axis).

Researchers have also used external devices, generally in form of cameras and projectors to prototype flexible interactions. Examples include high-fidelity input [47], foldable [25, 30], and rollable displays [26]. These however are limited to a non-self-contained form-factor, requiring heavyweight input and output capabilities to be placed in the environment.

Multi-Display Interaction

Both Hinkley et al. [20] and Chen et al. [10] have shown multi-display interaction in the context of handheld tablet devices. However, none of them utilized bending as additional input metaphor. Recently, Duet [11] explored new interaction possibilities on mobile phones by coupling a mobile phone with a smartwatch. The watch acts as an active element in the interaction, where its orientation and acceleration are used to control the interaction on the mobile phone.

Several researchers explored paper-like interaction with flexible interactive displays. Holman et al. [22] presented a desktop-windowing environment, which projects desktop windows on flexible sheets of paper. By tracking their motions, simple paper sheets become fully interactive. DisplayStacks [16] allows the physical stacking of e-paper displays. These displays are tracked relative to each other, enabling cross-device interaction for moving content or displaying contextual information. More recently, Paperfold [19] presents a configurable multi-device concept based on e-paper displays. The detachable displays can be arranged to a wide variety of different device configurations. Although, Paperfold shows multi-display interaction for e-paper based mobile devices, our work explores the use of novel flexible input and output combined with a regular phone.

Input Around and Behind the Device

One common problem is that interactions on handheld devices are limited due to the small form factor. Researchers have systematically explored the space around and behind the device for further input possibilities.

SideSight [9], for example, uses optical sensors embedded into the side of a device to track multi-touch around the device. Besides interactions around the periphery of the device, our flip cover form factor also enables input behind the device. LucidTouch [53] introduced the idea of a tablet-sized see-through display, where some interactions are performed at the back of the device. A user study showed that many prefer this technique over touching on the front due to reduced occlusion and higher precision. Baudisch and Chu took this concept further and explored the possibility of back-of-device interaction on very small displays [6]. More recently, Löchtefeld et al. [32] explored the combination of front- and back-of-device interaction with one hand. An evaluation showed, that although it is slower compared to traditional front-of-device input, it allows for accurate input. Finally, [46] explore the 3D space behind the smartphone leveraging the existing camera. Unlike prior work, FlexCase allows for continuous flexible input behind the display, in combination with touch. This adds tangible and physical qualities to these types of back-of-device interactions.

Utilizing Grips and Bimanual Input on Mobile Devices

Another interesting approach for extending input is to utilize grips, e.g. for implicit mode switching. This idea was shown for mobile phones [12, 17, 54], multi-touch pens [45] and mice [51]. Recently, Ansara and Girouard [2] proposed the idea of overloading bend gestures with different modes by pressing pressure-sensitive keys with the non-dominant hand. In contrast, FlexCase extracts grip information from how a user is touching the device before bending and utilizes this information to assign different meanings to bend gestures.

Prior work has also shown that desktop-based bimanual interaction techniques increase both performance and accuracy [4, 24]. More recently, this idea was also applied to handheld devices [34, 52] and flexible devices [8]. Wagner et al. [52] used touches of the thumb or fingers of the grasping hand for implicit mode-switching while Burstyn et al. [8] used the thumb of the grasping hand for scrolling on flexible devices. FlexCase tries to take the idea of bimanual interaction further, and combines touch interaction with the one hand with continuous bend input with the other hand.

DESIGN RATIONALE

As highlighted, our work overlaps with many areas of interaction research, and this is because of the richness, flexibility, and diverse capabilities that our flip cover configuration affords. In this section, we give insights on the design process leading to this kind of form factor.

There is clearly compelling work in the area of flexible sensors and displays, with a large focus on mobile interaction. The

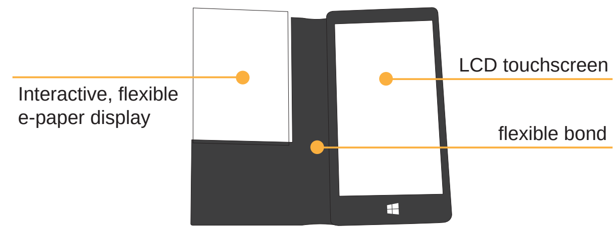

Figure 2. The FlexCase form factor. The usage of a flip cover-like form factor allows for different configurations with only one additional device.

majority of this work has, however, looked at replacing the smartphone with a flexible display or leveraging an e-paper display as a peripheral display with limited interaction. Our work preserves the interactive qualities of existing smartphones and augments their capabilities with additional input and output, in the form of a highly interactive, bendable flip cover.

The following high level design goals underpinned the development of FlexCase:

- **Compactness:** Preserving the compact form factor of current mobile devices - while enhancing interaction.
- **Versatility:** Allow the device to adapt to various usage scenarios - through simple adjustment of the form factor.
- **Expressiveness:** Enable richer input - through touch and other direct physical manipulations.
- **Mobility and Portability:** The flip cover should be an unobtrusive companion of the smartphone, which should not significantly decrease battery life or increase weight.

In order to fulfill the specified design goals, we evaluated a number of different form factors. We experimented with fixed displays at the backside of the smartphone (as other e-paper products do) as well as displays, which were attachable to the side of the smartphone. Detachability is an interesting concept since it increases the ability to reuse the flexible display for different smartphones and it allows even more different form factors. However, early user tests revealed that this also raises a number of issues, particularly mounting and subsequent stability issues. We therefore chose to focus on integrating the flexible display into an existing phone accessory rather than requiring two separate devices. By integrating an additional, flexible device into a flip cover (see Figure 2), various physical configurations are possible while being folded and enable the smart cover to be used as a versatile input and output device for existing mobile phones (*cf. Compactness & Versatility*). By further embedding a thin-film sensor into the device, we can enable flexible and continuous input for existing phones.

In choosing our configuration, we developed a new iteration of a printed piezoelectric sensor film that combines shape deformation [41] with touch and pressure [40, 56]. A major advantage of this technology based on PyzoFlex sensors [23] is, that we are able to achieve both touch [40] and complex bend sensing [41] with one single sensor (*cf. Expressiveness*). In contrast to multiple sensor layers, the advantage of a single layer is that it greatly reduces the rigidity of the layer stack and therefore improves flexibility for bend interaction.

Figure 3. The final layout was evaluated with early mockups. For ergonomic reasons, given the hand position and hand mobility, we decided for arranging the display at the top left side of the flip cover (Right).

For output, we decided to focus on slower framerate, but ubiquitous e-paper displays rather than emerging OLED displays. Whilst work on flexible OLEDs is incredibly promising, it is still not broadly available due to ongoing research on improving durability and robustness [31, 36]. Furthermore, e-paper displays have already begun to appear on mainstream phone products, have demonstrated long lifetime and power efficiency, and also provide an interesting challenge of combining higher framerate input with slower output. For instance, the main phone display has the advantage of being able to render high-fidelity colors with a high framerate, but the secondary e-paper display offers good readability while preserving power and reducing eye strain (cf. *Mobility and Portability*). Instead of merely using the e-paper display for displaying 'offline' and ambient content, the flip cover form factor gives us the possibility to actively use the second screen in conjunction with the main display of the phone for interactive scenarios to combine the best of the two worlds. For example, the phone screen can be used to give instant visual feedback for continuous flex interactions, while the flexible e-paper output can actively guide and control the users' interactions.

Flexible displays suffer from inflexible parts, such as the lamination with the e-paper display's rigid driving electronics, which usually requires one edge to be rigid. In our case, it is the short display edge, as this affected the flexibility least. Furthermore, we decided to detach the long edge from the flip cover's bond to additionally increase flexibility and to allow rich deformations (otherwise only one corner would be available for flex interactions). The final form factor including some design considerations can be found in Figure 3.

DESIGN SPACE

In this section, we explore the different physical configurations and interactive modalities the flip cover form factor affords.

Configurations

FlexCase enables the following configurations (cf. Figure 4):

Book. This configuration provides extended screen space, allowing specific content to be offloaded to the second screen. Since the e-paper display has a lower resolution and a lower refresh-rate, it makes sense to offload static content to the secondary display, providing instant access to otherwise hidden menu items and reducing clutter on the main screen. The secondary display can be used for displaying persistent information without battery drain but can also act as a high-fidelity input device for continuous interaction.

Laptop. By rotating the display into a landscape configuration, the interactive display can be seen as a keyboard-like input

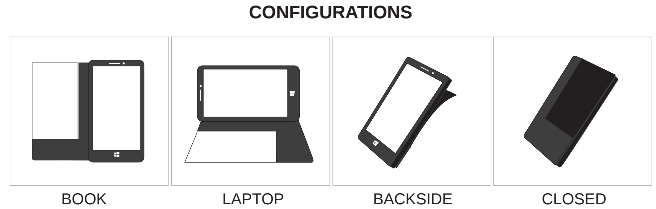

Figure 4. The design space derives from the combination of various different physical configurations and interactive modalities. The e-paper display can be used next to (*Book*), below (*Laptop*), behind (*Backside*), and above the smartphone (*Closed*).

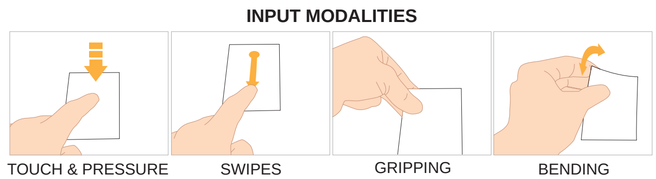

Figure 5. From an interaction point of view, the device allows for touch and pressure interaction, swipe gestures, recognition of grips, and high fidelity bending.

device. For specific input, we can also turn the secondary display into a versatile direct input device with dynamically changeable visual feedback.

Backside. By flipping the cover behind the main screen, we support a configuration that allows for tap and slide gestures behind the mobile phone's screen. Beyond this, the interactive display enables continuous bend input for the main display. The affordance of having a flexible, interactive display behind the device helps to reduce existing problems of today's mobile phones (e.g. fat-finger problem [44]) but also gives the possibility to interact with, for example, zoomable or browsable user interfaces in a more natural way.

Closed. When closed, the backside of the flip cover still provides interaction possibilities. From an interaction point of view, this configuration can be used for very explicit interactions, e.g. copying content between two screens or putting the phone into silent mode.

Input Modalities

The sensor foil within the FlexSense flip cover can detect *pressure* and *touch* location, allowing simple *tapping*, *sliding* or *rubbing* gestures, as well as detecting how the device is being *gripped*. This is combined with the ability to reconstruct continuous *bending* of the surface (cf. Figure 5).

Touch & Pressure. Users can perform taps on the interactive display. Furthermore, the piezoelectric input sensor gives the possibility to detect the strength of a certain tap, both continuously or for distinguishing different pressure levels. Beyond this, the input sensor can detect whether the user is tapping on the display or on the back of the display. Users can also perform basic *swipe* gestures in four directions.

Gripping. Given the matrix-like layout of the input sensor, the sensor can detect where, how and how strong a user is gripping the device. This becomes an important modality for input and is described later.

Bending. Users are able to perform complex deformations in both directions. The strength of bending gestures can be used for continuous operations (e.g. zooming) but also for triggering specific actions (e.g. corner bend for page turning).

Output Modality

The interactive e-paper display provides also a possibility to enhance interactions with appropriate feedback. This can be used to either show persistent information without battery drain, or can accompany input with changeable output to guide the users' interactions (e.g. changeable soft keyboard layout).

Compatibility of configurations and modalities

Although the form factor offers a wide variety of different configurations and modalities, not every modality is compatible and useful in each configuration. Table 1 shows a detailed correlation of configurations and modalities.

	Front Touch	Back Touch	Pressure	Swipes	Gripping	Bending	Output
Closed	-	+	+	+	o	o	-
Backside	+	-	o	+	+	+	+
Laptop	+	-	+	+	-	o	+
Book	+	o	o	o	+	+	+

Table 1. Designers should bare in mind that not every combination of configurations and modalities is compatible and useful.

For instance, it is inconvenient to use different grip gestures when the interactive e-paper display rests on a table in laptop mode, as it lacks the affordance of grasping in this configuration. In contrast, given the flexible cover, it is also important to consider that interaction in mid-air would make some interactions, such as accurate pressure input, impractical. When creating and designing new interactions, it is important to keep this compatibility of configurations and modalities in mind.

INTERACTION TECHNIQUES

In the previous section, we described various device configurations that FlexCase can be used in and we also described a number of different interaction modalities, such as swiping, gripping, bending and touch. As it can be seen in Table 1, each device configuration affords a certain set of interaction modalities better than other device configurations. There is no one form factor that could serve all usage scenarios equally well. However, a unique feature of FlexCase is that it allows the user to quickly combine and switch between a number of different configurations and modalities. In this section, we will describe the interactive modalities in more detail. Later in the paper, these will be showcased in the context of fully working application scenarios.

Force-sensitive & Dual-sided Touch

The sensor capabilities can be utilized to enrich traditional touch interaction. The addition of pressure information alongside touch can be used for quick actions, e.g. for switching between upper- and lowercase typing [33]. The touch sensitivity on the backside can be further utilized for indirect manipulations, e.g. *Rubbing* by sliding over the backside of the cover for pinning content.

Continuous Bend Input

Given the flexibility of the input sensor, the flip cover can act as a novel input device for existing smartphones. Existing smartphones can be enhanced with continuous bend input, which could be used for all sorts of linear navigational tasks in existing phone applications, e.g. zooming a map [1]. The smartphone display provides instant feedback, which is necessary to ensure smooth user interactions.

These types of bend gestures can naturally map to 3D navigation tasks [8], bringing these capabilities to existing (rigid) smartphones. Beyond this, FlexCase can map paper-like actions to the digital world, e.g. making a *Dog Ear* by bending the top right corner to memorize a page.

Back-of-device & Background Interaction

When the interactive and flexible display is folded back to the rear of the smartphone, it allows for back-of-device [6, 53] interactions, all without requiring any other modifications to the phone or additional sensors. This can be used for one-dimensional navigation tasks, such as list scrolling, with the benefit of not occluding the screen while browsing. Another possibility is to use discrete gestures at the backside to perform background tasks without needing to change the foreground app (e.g. performing swipes to switch music). The combination of bend gestures with back-of-device interaction can enable the user to change or manipulate UI layers or enable zoomable user interfaces [37], just by bending the cover.

Bi-manual Interaction

The possibility to have two screens next to each other also enables bi-manual interaction using the dominant and non-dominant hand simultaneously. Researchers have shown the usefulness of such an interaction both for speed and accuracy [4, 24]. For instance, users can use the thumb of the grasping hand to pan on the smartphone while performing continuous bend gestures with the other hand. Bending affords an easy way for changing a linear parameter [8] and greatly reduces the clutching issue [43] and screen occlusions due to pinching.

Interaction Across Screens

The output capability of FlexCase creates the possibility of sharing interactions, UI, and content between displays. This can be, for example, utilized to transfer static or temporary content from the main screen to the e-paper display and vice versa. One example is a clipboard, where the secondary display can reduce the clutter on the main screen while keeping the user informed about what is stored on the clipboard.

Grip & Bend

The touch and bending fidelity of our input sensor allows for a novel gesture where the user first *grips* the flexible display in different ways prior to bending in order to perform different actions. The e-paper display can act as a mechanism to preview the gesture or provide feedback to the user prior to when bending begins. This type of gesture is only feasible given the touch and bending fidelity of our sensor, where different grips can be detected robustly and combined with different types of bending deformations. This allows for a single edge of the display to be used for different gestures simply by adjusting

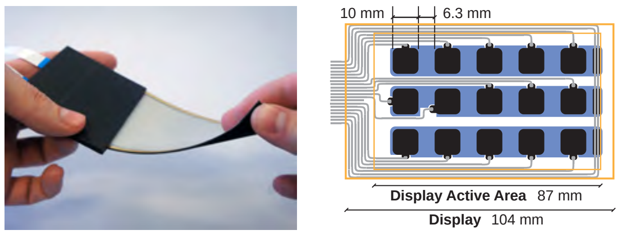

Figure 6. The layer stack of FlexCase consists of (I) an electrophoretic display on top, (II) a piezoelectric input sensor and (III) a self-adhesive protection layer behind (left). The input sensor layout consists of a 3×5 matrix of piezoelectric sensors, which is capable of sensing high-fidelity bending, pressure-sensitive touch and grip detection (right).

the user's grasp. Researchers have shown the usefulness of incorporating grasping for input on styluses and tablets [17, 21, 45], which is also enabled in FlexCase by combining grip detection with *bend* gestures to support rich mobile interactive possibilities.

The initial grip (comprising touch and pressure information) can be used to overload bend gestures with different meanings, such as mode switching, depending on which initial grip gesture was used. This concept is particularly interesting for flexible devices with a smaller form factor, where the variety of possible bend gestures is limited due to physical constraints.

IMPLEMENTATION DETAILS

The hardware implementation of the FlexCase prototype consists of a flexible, electrophoretic display and a piezoelectric input sensor on its backside (cf. Figure 6).

Display

We use an electrophoretic ink display (EPD) in our FlexCase prototype. These displays suffer from slow screen update rates, however, their power consumption is low since only refreshing the displayed content consumes energy. For FlexCase, we chose a flexible, monochrome 4 inch electrophoretic display manufactured by FlexEnable. The active area of the display is 87×54 mm and it provides a resolution of 400×240 pixel, which corresponds to a pixel density of 85 ppi. The display features 16 gray levels and performs a complete full-screen refresh in < 900 ms.

Sensor

For input, we used a low-resolution 3×5 matrix of printed piezoelectric sensors (cf. Figure 6). When deformed, a piezoelectric sensor creates a surface charge, which correlates with the applied mechanical deformation. This sensing principle has been used for touch and pressure input [40] as well as complex bi-directional bend [41]. FlexCase brings these capabilities together, in one single sensor. In contrast to multiple sensor layers or technologies, this is particularly beneficial for reducing the rigidity of the layer stack.

During our experiments with deformation of piezoelectric sensors, we found pressure induced by touch creates small, local deformations triggering one or a few adjacent sensors (cf. Figurin 7, left). In contrast, bending the sensor usually results in global deformations, triggering a greater number of sensors across a larger surface area (cf. Figure 7, right). Given this fact

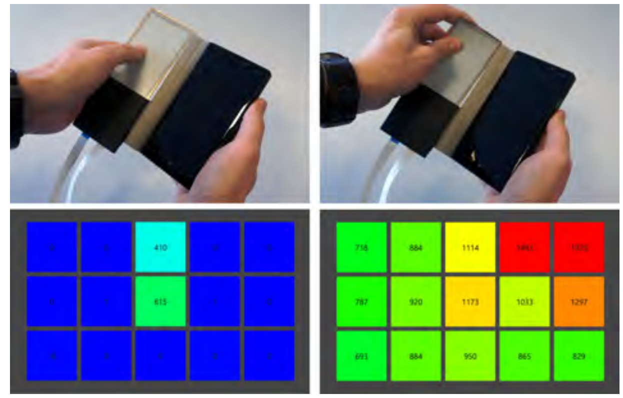

Figure 7. FlexCase utilizes one single sensor for both touch (left) & bend (right) sensing. The distinction is based upon a simple function incorporating the number of active sensors and the standard deviation across all readings.

and in contrast to prior work [41], we were able to use a sensor matrix for both touch & bend sensing without any additional optimization of the layout. A distinction between touch and bend can be easily identified based on a simple function that incorporates the number of active sensors and the standard deviation across all readings:

$$\theta = N \cdot \sqrt{\frac{\sum_{k=1}^{n} (s_k - \mu)^2}{n}} \tag{1}$$

where N is the number of activated sensors, s the set of all integrated sensor signals, n the total number of sensors, and μ the population mean. The smaller the value of θ, the less variance and active sensors, indicating a touch. A high value indicates a large variance with a high number of activated sensors, which corresponds to a bend gesture. The threshold for robust distinction between touch and bend can be then empirically defined.

Grip Detection

In the interaction techniques section we introduced a new concept called *Grip & Bend*. In the following, we will explain the learning-based algorithm we used for detecting different grips in detail, to aid reproducibility.

Figure 8 shows the temporal signature for grip and bend. Note a strong peak when performing bending across all sensors. At a high-level our algorithm detects that a bending gesture has started by identifying these peaks, and then backtracks to recognize the grip, by analyzing a sliding window across previous sensor readings. Given the range of different gestures we wished to support, and to better deal with changes in the temporal sequence due to different execution speed of users, we decided to use a learning-based algorithm to achieve high recognition accuracy (as opposed to heuristic-based approaches). Note that our algorithm incorporates both location of the grip as well as polarity (touched side).

We can assume that we have to infer the grip label y from a small sequence $\mathbf{X} \in \mathbb{R}^{15 \times T}$, where $T = 50$, which is the number of observations (in ms) used for the grip classification.

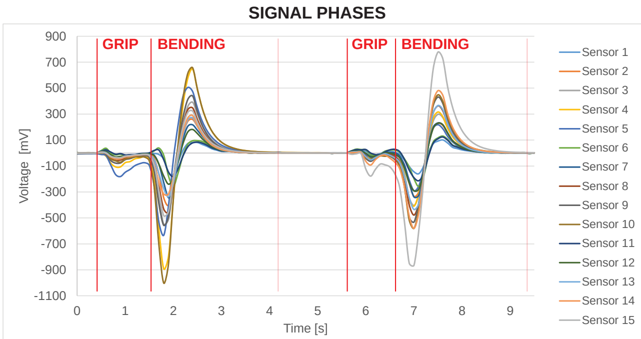

Figure 8. The chart highlights the two signal phases of Grip & Bend. If a bend gesture is recognized the grip gets evaluated based on the last set of observed sensor signals. Colors denote each of the sensors.

Single frames $\mathbf{x}_t \in \mathbb{R}^{15}$ were too noisy to be used directly as a feature descriptor: instead, we use an average pooling operator to aggregate frames of P descriptors. Consequently, our feature vector $\mathbf{f}_t \in \mathbb{R}^{15}$ for the frame t becomes:

$$\mathbf{f}_t = \frac{1}{P} \sum_{p=t-P}^{t} \mathbf{x}_p. \tag{2}$$

Given the set of tuples $\{(\mathbf{f}_t, \mathbf{y}_t)\}_{t=1}^{N}$ we want to learn the class model $\mathbf{W} \in \mathbb{R}^{15 \times n}$ minimizing the following objective function:

$$E = \frac{1}{N} \sum_{t=1}^{N} \mathcal{L}(\mathbf{W}, \mathbf{f}_t, y_t) + \mathcal{R}(\mathbf{W}), \tag{3}$$

which represents the sum of a loss function $\mathcal{L}(\circ)$ and a regularization term $\mathcal{R}(\circ)$ that gives a tradeoff between the accuracy and the complexity of the model. Since we want to detect grip gestures with a certain probability, our loss function and regularizer are defined using a standard softmax model [7] and the optimization is carried out using Stochastic Gradient Descent (SGD), which could be also employed for online learning of new grip gestures.

The learned model $\mathbf{W}$ is only able to describe linear dependencies in the data, however grip gestures can share non-linear relations and a better classifier must be used. Non-linear classifiers are usually expensive from the computational viewpoint, thus we use *Random Features* to approximate a non-linear kernel [50, 39]. The idea of random features consists of using a non-linear mapping $\Phi(\mathbf{\Omega}, \mathbf{f})$ to transform a non-linear separable problem into a linear separable one. After this mapping is computed, simple linear classifiers can solve the problem efficiently. Following [39] we define:

$$\Phi(\mathbf{\Omega}, \mathbf{f}) = \frac{1}{\sqrt{F}}[\exp(-i\omega_1 \mathbf{f}), \ldots, \exp(-i\omega_F \mathbf{f})], \tag{4}$$

where the parameters $\mathbf{\Omega} \in \mathbb{R}^{F \times 15}$ ($F = 128$ total number of random features) are sampled from a random distribution. Finally, the objective function $E = \frac{1}{N} \sum_{t=1}^{N} \mathcal{L}(\mathbf{W}, \Phi(\mathbf{\Omega}, \mathbf{f}_t), y_t) + \lambda \|\mathbf{W}\|^2$ is optimized using SGD.

Given the current observations $\mathbf{X} \in \mathbb{R}^{15 \times T}$, to recognize the grip y we first compute the descriptors $\mathbf{f}_t$ with $t = P, \ldots, T$. These $T - P$ descriptors are then mapped into a non-linear space using the random features $\mathbf{\Omega}$ as described before. Finally, we compute the label $\hat{y}$ using the probability scores as follow:

$$\hat{y} = \arg\max_i \frac{\sum_t \exp(\Phi(\mathbf{f}_t, \Omega)\mathbf{w}_i)}{C_t}, \tag{5}$$

where $C_t = \sum_i \exp(\Phi(\mathbf{f}_t, \Omega)\mathbf{w}_i)$ is a normalization constant.

Technical Evaluation

To be able to evaluate the precision of our grip detection, we performed an elicitation study with the primary goal to extract common grip gestures that are both ergonomically feasible and comfortable to users. The goal of the study was not to find the most natural grips without any constraints, but a distinctive set of common grips, which can be used to train and test our learning-based algorithm.

We asked eight unpaid participants aged between 25-36 years ($M = 27.5$) from a local academic research lab (two female; all right-handed) to grip several regions of the device as naturally as possible. The task was performed in two different configurations, namely *Book* and *Backside* configurations, for four obvious regions of interest (*top left corner*, *top right corner*, *side edge* and *whole display*), resulting from the physical limitations of the flip cover. The grips were video-taped from two perspectives and later transcribed for analysis.

Results revealed that although the available area for gripping is limited, participants found a large variety of different gestures (on average 10.1 different grips per condition, $SD = 3.79$). To extract a distinctive set of grips from this large number of candidates, we decided to nominate the two grips with the highest number of occurrences and diversity for each condition (see Figure 9).

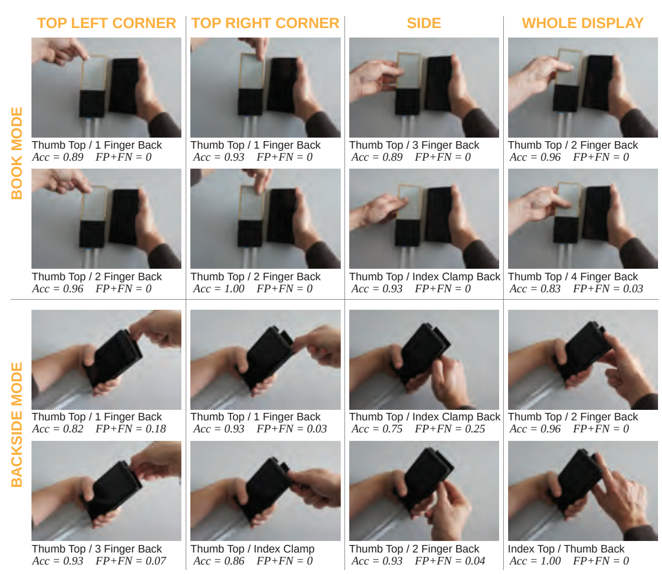

Figure 9. The resulting subset of grip gestures of the elicitation study was used to evaluate our learning-based grip detection algorithm. The *Acc* **values indicate accuracy and** $FN + FP$ **the miss classifications and false positives per class with non-linear feature mapping.**

The extracted set of grips was then used for evaluating our learning-based algorithm. The $n = 8$ grip gestures for each configuration were performed by different participants, resulting in an overall of 50 examples per condition. We evaluated the algorithm on 10 new sequences of 25 gestures. For the *Book* set of grips, the linear method achieved 70% accuracy on the test set, while the non-linear feature mapping approach reached 92.5% accuracy on the same test set. For the *Backside* grips we reached 69% with the linear classifier, whereas the random feature method achieved 89% of accuracy. Figure 9 shows the accuracy and false positives/negatives for each condition in detail. These results clearly confirm the benefit of using non-linear classifiers and in particular a random features approach as used in our approach.

Interoperability

Both the input sensor as well as the display are connected to external driver electronics, which both offer a custom-made communication API via TCP/IP for smartphone applications. On the input side, an application receives raw input sensor data as well as pre-processed gesture information such as tap, grip, and bend gestures. For displaying content onto the secondary display, an application can use the display API to either render parts of the phone UI or upload images to the e-paper display.

Power consumption

In the current configuration, our sensor electronics consumes 81.3 mW with a refresh rate of 100 Hz. The typical update energy for refreshing the EPD display is 206 mJ (power consumption for microprocessor excluded).

APPLICATIONS

In this section and supplementary video, we present a number of novel application scenarios that show the benefits of our interactive flip cover for enhancing interaction with traditional mobile phones. The demonstrated applications try to combine the high-level interaction techniques, which were presented in this paper, in convincing real-world scenarios. Beyond scenarios where each of the two screens is used in isolation (e.g. the e-paper display for displaying persistent data such as a boarding pass), we were more interested in applications where the two screens actively support and enrich each other. Further, the system is shown in different physical configurations.

Document Reading

While e-paper displays are optimized for reading with low eye-strain and outdoor conditions, LCDs are well-suited for displaying dynamic media. For document readers, the benefits of the two worlds can be combined by using the secondary display for text and the smartphone screen for media content such as videos or animations (cf. Figure 10).

Grip & Bend. In order to switch to the next or previous page, the user can bend the top left corner forward or backward. To quickly browse through a greater number of pages, the user can - like with a book - bend the entire left edge of the cover. The LCD shows a live preview to overcome the slow update rate of e-paper displays and thus ensure a fluid interaction.

Bi-Manual Interaction. While flipping through the virtual pages, the user can tap onto the desired page on the LCD to select and to display it on the e-paper display.

Interaction Across Screens. If rich media is linked to the displayed page on the e-paper display, the resolution and color fidelity of the LCD display can be utilized to display it directly on the smartphone screen instead. For videos, another *Grip & Bend* gesture can be used to continuously navigate within a video figure, avoiding the use of small touch-based widgets on the main screen.

Figure 10. Document Reader. Left: The user can flip through the pages of a document on the LCD by bending the flexible display. Middle: A page gets selected by touch on the LCD and gets pushed over to the secondary e-paper display. Right: The fidelity of the LCD screen can be utilized to show rich media linked in text pages on the e-paper display.

Content Transfer

We also see a lot of potential in simplifying tasks on the main screen by using the two screens in unison, for instance for copy & paste tasks.

Interactions Across Screens. The secondary screen can be used as a *visual* clipboard where snapshots and texts can be easily copied and pasted (cf. Figure 11).

Bi-Manual Interaction. The clipboard is rendered on the e-paper display and contains several slots where information can be stored. By simultaneously tapping an information asset on the main screen and a clipboard slot a user can copy the information to the clipboard. To paste data, a user first double taps a clipboard item and then taps on the target location on the main screen. This not only provides visual feedback, it also allows for multiple clipboard entries to be stored unlike standard copy and paste mechanisms.

Figure 11. Clipboard. Left: A recommender app is temporarily opened. Middle: Content in the recommender app is copied onto the secondary screen by simultaneously tapping the content and the secondary screen. Right: Text and image are pasted into an e-mail app.

Maps

Another possible application area are maps (cf. Figure 12).

Continuous Bend Input. Here, we utilize the possibility to vary the amount of bending in both directions for smooth and natural manipulation of linear parameters, such as zoom factor, rotation angle and tilt angles. This type of high degree-of-freedom 3D navigation is often challenging to perform on a touchscreen without numerous overloaded gestures. With our proposed method, these interactions can be performed using different *Grip & Bend* gestures.

Grip & Bend. The user can zoom the map in and out by gripping and bending the whole display backward or forward, or can change the rotation angle by bending the left corner, or changing the tilt of the map by bending the right corner.

Interaction Across Screens. Additionally, the map allows for easy transfer of information to the secondary display, which is used as an extended visual clipboard. In our example, the user is able to store routes from the map onto the secondary display for quick previews of the stored routes.

Dual-Sided Touch. To store a route, the user can close the flip cover to put the two displays above each other and can, like with traditional blueprint paper, perform a rubbing gesture on the backside of the secondary display to transfer the content between the displays.

Figure 12. Maps. Different Grip & Bend gestures can be used to continuously control zoom (Left), tilt (Middle) and rotation (Right) in a map.

Photos
Another mode of operation is to use the secondary screen mainly for visualizing icons and widgets, which provides extended space on the primary display. This allows users to have faster access to the phone functions by not having to navigate through clutter. This can be applied for instance to media players or camera applications, where the user often wants to see the full image of the phone display (cf. Figure 13).

Continuous Bend Input. Various camera parameters can be selected, and the bending angle is used to input linear settings (e.g. zoom, aperture, exposure).

Figure 13. Camera. Capture settings are visualized on the secondary screen, leaving the primary display free of clutter. Functions, such as flash settings (Left), can be activated via touch or linear parameters, such as aperture (Middle) or exposure (Right), can be selected and controlled with different grips.

Grip & Bend. Grip & Bend gestures can be used, for example, to control different functions. By bending the corner of the display with a single finger, the user can control the zoom level, while different grips for the corners can accordingly adjust aperture or brightness settings. Speed can be controlled by varying the amount of bending.

Pressure Input & Gaming
In Laptop mode, the secondary display can also be used as a customizable, pressure-sensitive keyboard or gamepad.

Force-sensitive Touch. In our example, we use this configuration for PIN number input, where the user uses a combination of touch and pressure to enter a PIN (cf. Figure 14, left). This could also be extended to support pressure sensitive keyboard input for text entry [33].

Continuous Bend Input. This configuration is also useful in gaming scenarios, where the secondary display can be used as a novel input controller. Besides the possibility to show gamepad-like touch controls on the display, bending could be used as an additional input modality to enable more degrees of freedom (cf. Figure 14, right). In Jump&Run games, bending could be mapped to the jump of the character, while the magnitude of bending defines the height of a jump, allowing other buttons to be used for shooting or other actions.

Figure 14. Left: Input of a combination of digits and pressure information for increasing security in public areas. Right: Showing a flexible gamepad layout with touch-enabled buttons and bend sensing.

Background Interaction
Backside mode is particularly interesting for performing background tasks, which are not related to the foreground application (e.g. controlling a music player). For example, a user can use swipe gestures on the back of the device for changing to the previous or next song, while bending the corners either decrease or increase the music player's volume. This allows these settings to be set without even switching the application or interacting with the phone screen (cf. Figure 15).

Figure 15. Left: A swipe gesture on the back of the device plays the next song in a music player running in the background. Right: The volume is adjusted with a corner Grip & Bend gesture.

Navigation
Another possibility of the Backside mode is adding a richer, more physical way for navigating through content on rigid displays or zoomable user interfaces [37].

Back-of-device Interaction & Continuous Bend Input. The backside configuration allows the user to literally push back the user interface to gain an overview of running applications (cf. Figure 16, left). A similar approach uses bending for enhancing digital interaction with metaphors known from the real world, such as digital flip-book animations. Although the main display is completely rigid and provides only touch input, FlexCase adds a physical interaction layer which is very similar to an analog flip-book (cf. Figure 16, right).

Figure 16. Left: Zooming out of the user interface by bending the cover. Left: Flipbook animation on the LCD with back-of-device bend input.

DISCUSSION & LIMITATIONS

In this paper, we have focused on a new mobile interaction concept called FlexCase. Although we gained promising feedback from informal evaluation sessions with FlexCase, a quantitative comparison is clearly needed in the future, but was simply out of scope for this paper, where we focus on the interactive capabilities of our system. However, this is an important area to address in future work.

From an interaction point of view, we see novelty in incorporating grips for overloading continuous bend gestures and see this concept as a good avenue to further extend the interaction space when bend gestures are physically limited due to the compact mobile form factor. However, one issue of the *Grip & Bend* technique is that the mapping of different grips to their related digital task can be unintuitive. Ideally, the grips would show a strong physical correlation to their related digital task, but would also allow more abstract mappings to be memorized by the users, especially if different regions are incorporated (e.g. zoom, tilt, rotate in the map scenario). Moreover, the e-paper output gives the possibility to guide those interactions, e.g. by displaying mappings. However, we acknowledge that this requires the user to learn mappings. One possible improvement of the technique could be to let the user assign grips to different actions to improve memorability.

If the cover is interactive at all times, one problem could be false activations. An additional protective cover for the flexible display could decrease unwanted interactions, but may also decrease the flexibility of the display. Another solution could involve optimizing and activating touch & bend sensing for specific use cases. For example, if an application supports slide gestures on the backside, the cover should refuse all other input such as taps, grips, or bends. While false activations were not a big issue in our preliminary user studies, it is worth to explore this topic more systematically in future work.

The current prototype was wired to an external driver box for rapid prototyping and evaluation of the different interaction concepts. While this was sufficient for this paper, mobility is till a crucial part of this interaction concept. Further, the mechanical mounting of the e-paper driver electronics limits the use of one side of the flip cover. This could be addressed in the future by embedding the electronics directly between the FlexCase cover and phone (much like a spine of a book). One shortcoming of the FlexCase form factor is the flexible bond, which requires some fixation with the hand to hold the device in a certain configuration. This could be solved by using a shape-retaining material in the bond, which is easily bendable but keeps the device in the intended form.

Our e-paper display clearly suffers from a low refresh rate. However, as demonstrated in our application scenarios, we see how the combination of LCD and e-paper display can be used to exploit the best of both worlds. Therefore, while flexible OLED displays, of course, will provide additional value and different possibilities for FlexCase, we already see a great deal of potential in the inclusion of the e-paper display, which makes this not just an interim solution until fast full-color flexible displays are bistable, robust and lower-power.

In the previous section and accompanying video, we have hopefully demonstrated numerous compelling applications and interaction techniques for FlexCase. The richness of the design space is illustrated by the large body of application and interactive scenarios, and we feel this is just the beginning, and our hope is that practitioners and researchers will develop these scenarios further.

CONCLUSIONS AND FUTURE WORK

In this paper, we presented a novel flip cover concept for smartphones, which combines a purpose-built touch, pressure and flex sensor with an e-paper display. It is designed specifically to enable a range of reconfigurable uses and modalities, where our novel input and output surface augments the standard touch and display capabilities on the phone. Users can use our system to perform a variety of touch, pressure, grip and bend gestures in a natural manner, much like interacting with a sheet of paper, without occluding the main screen.

The secondary e-paper display can act as a mechanism for providing user feedback and persisting content from the main display. We provided insights about the design process for the form factor as well as the interaction techniques and systematically explored the design space, resulting from the different configurations and modalities. We have demonstrated many interactive and application capabilities, and highlighted how touch and flex sensing can be combined in a novel way, e.g. the Grip & Bend technique. We feel this ability to combine touch and bend interaction in one single interaction is compelling and novel. The range of applications already shown suggests a rich design space for researchers and practitioners to explore in the future.

For future work, we currently work on a fully mobile version and plan to experiment with different materials in order to further improve the form factor, e.g. a shape-retaining bond. On interaction side, we plan to conduct quantitative and qualitative evaluations to highlight the performance and benefit of our system compared to more traditional forms of interaction.

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