Bending the Rules: Bend Gesture Classification for Flexible Displays

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ABSTRACT
Bend gestures have a large number of degrees of freedom and therefore offer a rich interaction language. We propose a classification scheme for bend gestures, and explore how users perform these bend gestures along four classification criterion: location, direction, size, and angle. We collected 36 unique bend gestures performed three times by each participant. The results suggest a strong agreement among participants for preferences of location and direction. Size and angle were difficult for users to differentiate. Finally, users performed and perceived two distinct levels of magnitude. We propose recommendations for designing bend gestures with flexible displays.

Author Keywords
Deformable User Interface; Flexible Display; Affordance; Bend Gesture; Organic User Interface

Classification Keywords
H.5.2 User Interfaces - Evaluation/Methodology, Haptic I/O, Interaction Styles, Prototyping

INTRODUCTION
With the emergence of flexible displays, researchers are increasingly exploring the use of bend gestures as an input technique [2,4,5,6,8]. Bend gestures have their roots in paper documents, where one may flip the corner of a page to turn it [7], and their success is largely due to the inherent tactile feedback. Bend gestures are most successful in the context of e-book readers or maps [4,6,8].

One of the main features of bend gestures is their large number of degrees of freedom: location, direction, size, angle, and speed, to name a few. Such variety offers a rich interaction language, yet can be overwhelming to users. When using PaperPhone, a flexible smartphone prototype, some users had trouble precisely repeating the same gesture, even given the use of limited bend classifications [4]. Bend gestures can be difficult to execute precisely, especially if users are required to distinguish between collocated gestures (Figure 1). Therefore, it is paramount to determine how users perform bends to create and implement appropriate bend gestures.

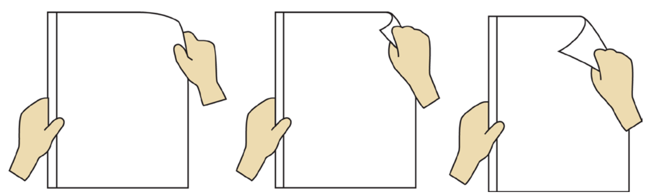

Figure 1. Collocated gestures, e.g. a small, medium and large angle bend, may be difficult to distinguish in practice.

In this paper, we propose an extended bend gesture classification scheme and we evaluate how users naturally perform bend gestures with minimal instruction. By observing gestures classified using location, direction, size and angle, we determine which degrees of freedom can be differentiated by users. We identify strong user preferences for bend gestures and offer design recommendations for future flexible displays.

RELATED WORK
This prior work section is focused on prototypes that introduced different categories of bends. Some of these prototypes are input devices separate from the display [1,2], others bend an extended display bezel [6] while the rest bend a flexible display, either functional [3,4] or projected [8]. Their findings are leveraged in our classification scheme and in this current study, informing which classifications of bend gestures should be examined.

Pioneering the flexible display research field, Schwesig et al. [6] created Gummi, a compact, flexible mobile computing system using bend gestures as input. As they used a rigid display, users navigated the content by bending both sides of the device, made to be an extended bezel. Gummi integrated single and double bends, and used the flat state to distinguish between actions.

Twend investigated the use of deformation as input, and presented a prototype which allowed for the measurement of at least eighteen unique bends, mostly located along the sides and the middle axis of the rectangular prototype [2]. Similar to Gummi, the authors used both analogue and discrete bends. They found bends to be preferred over familiar input methods in certain contexts such as zooming. While the Twend prototype was thick and sponge-like, Watanabe

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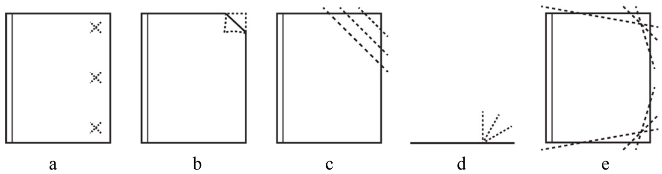

Figure 2. Classification of bend gestures: (a) location, (b) direction, (c) size, (d) angle, (e) edge. Size and Angle illustrate 3 magnitude levels.

et al. [8] created Bookisheet, a thin bendable input device using acrylic sheets, which leverages the metaphor of turning book pages. In Bookisheet, users leafed through a book by bending the side of the device. With its Foldable Input Device [1], Gallant et al. introduced the metaphor of flipping a page by bending the top corner of a page. Their interaction techniques were based on the qualities of paper, as studied by Sellen and Harper [7].

Lee et al. [5] generated a set of interaction gestures for deformable displays. In this study, participants were given paper, plastic and elastic cloth as imaginary displays. The participants were instructed to deform the displays to execute specific tasks, e.g. zooming or navigating to the next page. Their results included a number of bend gestures, such as bending upwards, downwards; bending the middle, the side or the upper corner of the artificial display.

PaperPhone was the first prototype to use a fully functional flexible display [4]. With this smartphone prototype, Lahey et al. asked participants to define bend gestures, and associate those gestures with functionalities. They proposed a classification scheme that categorized bend gestures by location (top corner, side, or bottom corner) and their polarity (up or down). More recently, Nokia presented the Kinetic device [9], a deformable mobile phone which has rubber-like properties. Using this device, Kildal et al. [3] explored bending and twisting, and proposed a set of design guidelines with deformable devices, such as the appropriateness of discrete bend gestures to trigger discrete functionality.

BEND GESTURE CLASSIFICATION SCHEME

Bend gestures can have a variety of complexities: they can be defined according to a simple classification scheme composed of *location* and *polarity* of the force, such as in PaperPhone [4], but their large number of degrees of freedom suggests more complex gestures can be implemented. We build on PaperPhone's initial bend gesture definition to create a classification of bend gestures. Figure 2 illustrates five characteristics. We work with design constraints of current flexible displays, which contain a rigid bezel, but we believe our classifications can be extended to devices without rigid elements.

- **Location**: Where the bend takes place on the device: e.g. top corner, side, bottom corner (Figure 2a).
- **Direction**: The direction of the bend: upwards (toward the user), or downwards (away from the user) (Figure 2b). This was referred to as polarity in PaperPhone.
- **Size of the Bent Area**: The bent surface area of the device, e.g. 1/5th of the device bends (Figure 2c).
- **Angle**: The degree of perpendicularity of the bend in relation to the device plane. These bends can be spoken of in terms of angle in relation to the plane (Figure 2d).
- **Edge**: A bend performed by holding an edge of the device (Figure 2e).
- **Speed of Bend**: The time taken to move the device from the neutral position to the bend position.
- **Duration of Bend**: The length of time the bend is held in place before returning to neutral position.

To determine the subset of classifications to use in the current study, we first performed a pilot study where we observed users bend pieces of paper. We saw users naturally performing gestures based on location and direction (also found by Lee [5] and Lahey [4]). The next most common variables were size and angle. We find that our classification yields a hierarchy of importance: one must first classify a bend by location and direction, then by size and/or angle, before discussing speed and duration of bend. To create a succinct study, we concentrated on the higher level descriptors of natural bend gestures: location, direction, size and angle.

EXPLORING BEND GESTURES STUDY

While computers may be able to recognize even the smallest movement in a bend sensor, human abilities are not as precise. The goal of this study is to determine how many degrees of freedom individuals can consistently differentiate within the four classifications chosen.

Prototype

We created a prototype to detect the location, direction, size, and angle of bends (Figure 3). We used six 3" Flexpoint bidirectional bend sensors. Sets of sensors were placed in three *locations* (top right corner, right side, and bottom right corner). By design, the sensors provide us with the *directionality* of the bend (up or down). However, the value obtained from the sensor is a combination of size and angle. To distinguish between size and angle, we used pairs of sensors in each location. We partially overlapped them to create three zones per pair. We determined the *size* of the bend by observing which bend sensors are activated (the inner sensor, both sensors, or the outer sensor). We correlate the sensor values to obtain *angle*.

We designed the letter sized prototype to be thin and flexible to minimize the physical constraints of performing bend gestures. In this sense, our prototype was closer to that used in the participatory session of Lee et al. [5] than the more rigid PaperPhone [4]. A bezel was affixed to the left side of the device, similar to current deformable display prototypes such as PaperPhone [4]. We fabricated a flexible printed circuit (FPC) to minimize the device's thickness. The bend sensors are connected to an Arduino Uno microcontroller through the FPC.

Figure 3. Left: the prototype used in the study. Right: the bend sensors layout at the back of the prototype.

Study Design

Participants were 13 university students and employees (9 males, overall mean age of 25). All but one were right handed. None had prior experience with flexible devices.

Participants were asked to perform a series of bend gestures with minimal instruction. They were given a magnitude (small, medium or large), a characteristic (angle or size), a direction (up or down), and a location (top corner, side, bottom corner), for instance, "large size, bend down, bottom corner". Participants were directed to perform the bend gestures naturally. They performed 36 unique bends during each of three trials for a total of 108 bends per participant. In the first trial, participants performed the bend gestures grouped by direction, then size or angle, then location, and finally magnitude (e.g. small size bend up with the top corner, medium size bend up with the top corner, large size bend up with the top corner, etc.). The remaining sets of trials were presented in a random order. At the end of the study, a semi-structured interview was conducted to measure user preferences. Participants were asked questions regarding their experience relating to preferred location, direction, size, angle, and overall bend.

Hypotheses

We hypothesized that bending down would result in smaller bends than bending up (H1) since bending down presents a larger ergonomic challenge. We expected small and large size bends to be easy to complete and interpret, but medium size bends to often be mislabeled, as their sensor values would overlap with large bend values (H2). We predicted that bending the top corner up would be the preferred bend for users (H3), and similarly, that the bottom corner down would be the most difficult or least preferred (H4). Finally, we hypothesized that small size and angle bends would be preferred over medium or large (H5), as they require the least amount of wrist movement and visual occlusion of the screen is minimal.

RESULTS

Quantitative

We analyzed the bend sensor values by performing a repeated measures factorial analysis of variance using bend location (3) * bend direction (2) * bend magnitude (3) for angle and size. We transformed the data so a value of zero represents flat. A higher value meant a larger activation, independent of the direction of the data. We examined only the two sensors corresponding to the location of the bend.

Results showed that users performed larger bends in the top location, followed by the side and the bottom location, for size (F(2, 22)=4.645, p=0.031) and angle (F(2, 18)=4.648, p=0.024). Users performed smaller downward bends than upward for size (F(2, 18) = 4.648, p=0.024) as well as angle (F(2, 22)= 4.645, p=0.031). We found a significant effect for angle magnitude (F(2, 22)=14.403, p=0.001), indicating that users can differentiate between three angle magnitudes. This holds true for each location (F(4, 44)=3.064, p=0.041).

We used the Friedman test to evaluate the size magnitudes using zone values. The difference between zones was significant for each location (top corner: X^2=12.056, p=.002; side: X^2=26.694, p=.000; bottom: X^2=32.263, p=.000).

Qualitative

The majority of participants indicated the top corner was their preferred *location* for bends (69%), followed by the side location (31%). The majority of users preferred the small *size* of bend (54%), versus 15% preferring the medium size and 15% preferring the large size (15% of participants indicated no preference). The majority of users preferred also a small *angle* bend (62%), versus 15% preferring a large angle. Finally, 31% participant had no preference about angle. When asked about their *overall bend* preference, the majority of participants indicated a combination of top corner location and up direction (77%), with significant variability in size and angle preferences. 40% of participants indicated difficulty differentiating between three magnitudes and would prefer two.

DISCUSSION

The results showed support for most of our hypotheses, with strong agreement on bend gesture preferences. Our quantitative results supported our first hypothesis, participants did perform smaller bends downward than upward. We also found that many users indicated bending downward to be more awkward than upwards. Participants performed the largest bends in the top corner location, followed by side. This may be due to the ease of bending in the top corner and side locations reported by participants.

Users showed a preference for the top location, followed closely by the side location. This preferred location corresponds to that of previous work [4,5]. The overall preferred gesture, the top corner upwards, supports H3, but differs from that noted in PaperPhone, i.e. the side location [4]. We also confirm H4, users found the bottom corner bends most difficult to perform. Participant observations revealed an ergonomic explanation for this trend, as most participants attempted several hand positions in the bottom corner location before settling on the most comfortable to perform the bend. This suggests the bottom corner to be the least ergonomic. Finally, we confirm that small angle and size bends are preferred over medium or large (H5), being more ergonomic and providing the least amount of screen occlusion.

In general, we observed a disconnect between the user perception of accurate bends performed and their actual performance. For instance, our results both support and counter H2, where we hypothesized that users would have difficulty differentiating between three levels of magnitude. While the statistical analysis supported the use of three levels of magnitude, this result is not meaningful once we observe the zones activated, and how users performed bends. Our participants typically performed small and medium size bends at a sharp angle, activating the outer zone for small size bends (48%) and the outer and middle zones for medium size bends (28% and 65% respectively). However, their large size bends were quite curved (instead of sharp), often activating both sensors, which activates the middle zone (68%), instead of the inner zone (17%). Hence our current prototype cannot reliably detect large bends (inner zone only). In addition, many users indicated a preference for two magnitudes rather than three for both size and angle. Therefore, we recommend only two magnitudes, to improve accuracy and user experience.

Limitations

It is important to note the impact of physical constraints of the prototype. The bezel led the user to only manipulate the device with their right hand, which is not ideal for all users. The prototype's size and rigidity had a large impact on the gestures produced. However, we believe our results generalize to other sizes. In addition, we acknowledge that visual feedback is important to bend-gesture research and that it was omitted here: we chose to focus our study on the attributes of physical deformations without the potential bias of visual feedback (similar to Lee et al. [5]).

DESIGN RECOMMENDATIONS

When designing bend gestures the function and complexity of the application should be taken into careful consideration. The following are general design recommendations:

Map frequently used functions to the top corner

The top corner was the most preferred location followed by side and then bottom corner. We recommend mapping frequently used functions the top corner to optimize usability.

Use two levels of magnitude

We recommend two levels of magnitude to increase the distinction between bend gestures for deformable devices with similar physical attributes to our prototype. While users of a different prototype design may be able to detect three levels reliably, we base this guideline on our results, which include users reporting confusion relating to three levels of magnitude, and a strong preference for two.

Select either size or angle, unless using expert users

The distinction between concepts of size and angle was often unclear to users, based on how users performed bend gestures, as well as their interview comments. For instance, several users described bends using the term "curvature", which is a combination of size and angle. If one needs to describe a gesture precisely, we recommend selecting either size or angle. However, we predict expert users will be able to make this distinction.

Create an adaptable classification algorithm

We suggest developing classification algorithms that take into account the significant variability observed in the magnitude of bends for each location and direction.

CONCLUSION

In this study, we explored how users performed bend gestures using four criteria: location, direction, size and angle. Our study identified that the top corner was preferred of the three locations. We observed that upward bends were larger than downward bends. Two levels of magnitude showed optimal distinction with our prototype. Lastly, we recommend the use of size or angle for clarity with novice users. The granularity achieved by our study further extends past research done on bend gestures.

Given that most users are unfamiliar with bending as an input method, it is worthwhile to investigate user's bend gesture performance and preference with a longitudinal study. It would also be valuable to determine how to effectively guide users when performing bend gestures as well as how to indicate when a bend is available. A study of the use of visualizations to inform and guide users to perform correct bends in cases of collocated gestures is warranted.

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