Gummi: A Bendable Computer

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ABSTRACT
Gummi is an interaction technique and device concept based on physical deformation of a handheld device. The device consists of several layers of flexible electronic components, including sensors measuring deformation of the device. Users interact with this device by a combination of bending and 2D position control. Gummi explores physical interaction techniques and screen interfaces for such a device. Its graphical user interface facilitates a wide range of interaction tasks, focused on browsing of visual information. We implemented both hardware and software prototypes to explore and evaluate the proposed interaction techniques.

Our evaluations have shown that users can grasp Gummi's key interaction principles within minutes. Gummi demonstrates promising possibilities for new interaction techniques and devices based on flexible electronic components.

Author Keywords
Handheld devices, mobile computing, interaction design, GUI, embodied interaction, flexible electronics, smartcards.

ACM Classification Keywords
H5.2. [Information interfaces and presentation (e.g., HCI)]: User interfaces – Graphical user interfaces (GUI), Input devices and strategies, Interaction styles, Screen design; J.7 [Computers in other systems]: Consumer products.

INTRODUCTION
Gummi is a concept of a novel device and interaction style based on bending of a deformable handheld computing device (Figure 1). Ideally, the proposed device would consist of several layers of flexible electronic components: a flexible organic, light-emitting display (OLED) on top, flexible electronic circuits in the middle and a flexible, touch-sensitive panel on the bottom. Embedded sensors would measure physical deformation of the device. The resulting bendable computer would be extremely thin, flexible and have no mechanical parts. We envision a device, approximately the size of the credit card, that can be comfortably put into a pocket or slipped into a wallet.

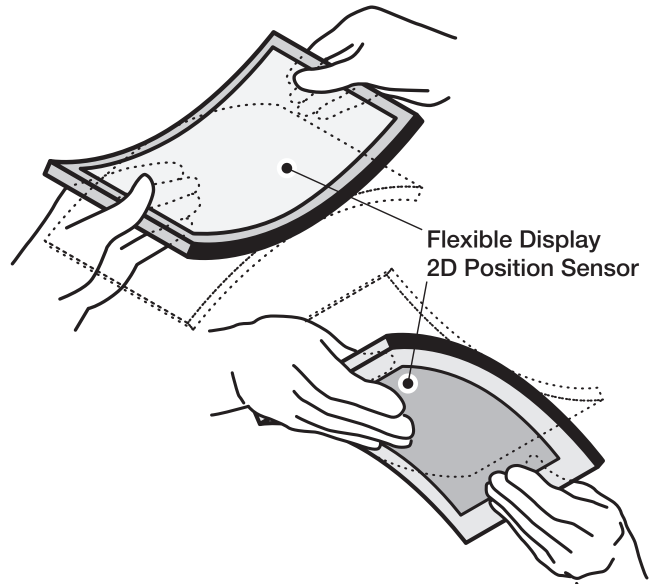

Figure 1: Gummi Device and Bending Interaction

The development of such a deformable computer may seem a very remote possibility. However, rapid advances in flexible electronics make such a device feasible in the near future. A range of flexible electronic devices and components has recently been demonstrated, such as flexible transistors and full color, high-resolution flexible OLEDs with a thickness of 0.2mm [5, 12]. Flexible electronics are predicted to become one of the core technologies that would facilitate the creation of small, thin, efficient and inexpensive mobile devices for future pervasive computing environments [19]. This technology was one of the main sources of inspiration for the Gummi project.

Interaction is a major challenge in designing a flexible, bendable computer. Even if we could develop a bendable computer the size and thickness of a credit card, how would users be able to interact with it? Previous ideas for applications of flexible electronics typically disregard interaction and instead focus on ergonomic and aesthetic aspects. Recurring themes are digital newspapers, electronic maps, roll-out and wearable displays, but not much thought

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Photo courtesy of Junko Kimura

Figure 2: Mock-Up Model of a Bendable Computer

has been given to human-computer interaction with such devices. Gummi exploits a key property of flexible electronic technology – physical flexibility – to create a new interaction style and device concept (Figure 2).

The Gummi project is also part of a wider area of research into user interfaces for mobile devices. Designing mobile device interfaces that are easy and pleasant to use has been a challenging problem for the HCI community. One of the key problems is that although standard Windows, Icons, Mouse and Pointer (WIMP) interfaces are reasonably effective for desktop computer environments, they are difficult to use on small, handheld computing devices. Mobile HCI research tends to either adapt WIMP interfaces to the limitations of mobile devices [20] or to enhance existing WIMP interfaces with new input modalities [6]. In most cases, however, the underlying WIMP paradigm is unchanged: whether we use a pen, a mouse or a trackpad, pointing and clicking remains the conceptual basis for most human-computer interaction.

It is certainly important to enhance and improve WIMP-based mobile interfaces, but we believe that it is also relevant to explore new, non-WIMP interaction paradigms for mobile devices. New technologies that allow different and unexplored input modalities present an opportunity to create novel, non-WIMP interaction styles. Flexible electronics are certainly one of those technologies.

Gummi differs from WIMP interfaces in both its physical interaction elements and in its GUI. Users interact with a Gummi device by physically deforming it and by touching the sensor on its back (Figure 1). No buttons, mechanical switches or traditional touch screens are used, so that the display can cover the entire surface of the device. Gummi's graphical user interface facilitates a wide range of interaction tasks and applications: browsing hyperlinked visual information such as web pages, viewing maps and photographs, playing games, reading e-mail and even writing short messages. Many Gummi interface elements were inspired by existing GUI techniques, such as zooming interfaces and use of transparency [11, 8]. However, key elements of the WIMP paradigm are absent from Gummi, for example we do not have the concept of a pointer in our user interface. At the same time, the Gummi interface remains systematic and consistent: our informal evaluations have shown that first-time users can grasp key ideas of Gummi in a matter of minutes. In this paper we present the basic concept of this new device and its interaction style.

RELATED WORK

With the proliferation of small mobile computing devices, the importance of creating effective and easy to use interfaces for them has become evident. The challenges are well known in the HCI community: small displays limit space for visual information, there is little room for buttons or other electromechanical controllers. It has been recognized that traditional desktop GUI are difficult to adapt to mobile devices [17, 8, 6]. There have been several research directions that address these challenges.

Commercial personal, digital assistants (PDA) often adapt the traditional WIMP interaction paradigm. Equipped with pen and touch-sensitive displays, they feature familiar GUI elements, such as dialog boxes, scroll bars, widgets and buttons. This approach is problematic because, as devices and screens become smaller, pointing and clicking on small interface elements becomes increasingly difficult. Furthermore, icons and widgets occupy precious screen estate and external input devices, such as pens, occupy a second hand and are easily misplaced [17, 15].

Context-aware and location-based interfaces propose to present content on mobile, handheld devices depending on current user context, defined in terms of location, time or activity. This approach promises to use context as an intelligent filter of data, limiting displayed information to what is currently relevant to the user [14, 16, 3]. Determining context, however, remains a difficult challenge.

To cope with a small screen size, a variety of zooming and fish-eye viewing techniques have been proposed [17, 11]. These techniques intelligently distort visual information so that only information within the user's attention focus is presented in detail, while peripheral data is simplified or abstracted [17, 4]. Another approach is to reformat visual content to adapt it to mobile devices – examples are systems like Digestor [2] and M-links [20]. Transparent overlays of control widgets were also proposed as a solution for the small screen size [8]. One particular problem in using all these techniques is in providing interaction techniques to control levels of distortion, transparency and zooming: adding additional widgets on the screen to control levels of fish-eye distortion or zooming defeats the purpose of these techniques - saving screen space [17, 8]. In Gummi, we use bending to control zooming and transparency.

Research into embodied interfaces is perhaps most relevant to Gummi. It suggests the augmentation of handheld devices with sensors to allow users to interact with the device by physically manipulating it in their hands. Typical examples include tilting and touching parts of the device [6, 15, 7]. For example, users can navigate a large graphical map by tilting the device [15]. On the output side, some information can be displayed as tactile feedback or sound instead of visual form [13, 18]. Embodied interfaces, however, were mostly designed as extensions to WIMP interfaces for specific tasks, such as browsing lists [6].

Our work extends and further develops previous research on embodied interfaces. Like embodied interfaces, Gummi proposes to use the entire body of the device for interaction. Whereas current research typically uses tilting and touch-sensitive surfaces [6], we propose to interact with a mobile device by physically deforming its entire body. Although bending and shape sensing has been used to create novel input devices for 3D user interfaces and virtual reality [1], we are not aware of any previous research that uses these techniques for mobile interaction. The concept of a bendable computer is a key innovation of the Gummi project.

The Gummi user interface draws on previous research into zooming interfaces and transparent interface elements, as well as fundamental GUI concepts. However, unlike previous research that tended to focus on single-case techniques for information input or display on mobile devices, we propose a consistent and unique interface model, distinct from WIMP, that incorporates a set of embodied interaction techniques. We are not aware of any attempts to design an embodied interaction style that would allow users to accomplish a wide range of interaction tasks. Designing such an interaction style is the second major contribution of the Gummi project.

We believe that the development of new interaction styles is an important research direction in the HCI field. New technologies, such as flexible electronics, can inspire new interaction techniques because there is a strong correlation between the physical properties of devices, their form-factor and their on-screen interaction possibilities. Indeed, new technologies for physical input facilitate the creation of new techniques to interact with visual information. Likewise, screen interfaces that take full advantage of the physical properties of new technologies can stimulate development of those technologies and their practical applications.

GUMMI DEVICE CONCEPT

An ideal Gummi bendable computer would consist of several layers of flexible electronic components: flexible processing and memory circuits, bending sensors and a flexible power source are sandwiched between the flexible organic display on the top and a 2D position sensor on the bottom of the device (Figure 3). A variation of the proposed device would be partially flexible, for example incorporating a rigid power source attached to one side of the device.

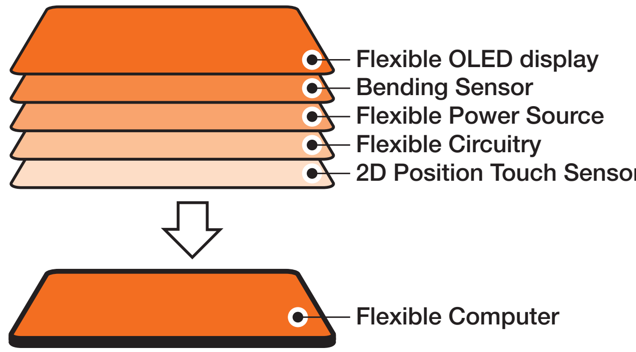


Figure 3: Components of a Bendable Computer

We imagine the Gummi device to be extremely thin and slightly larger than a credit card. It would have no mechanical parts, such as buttons and sliders, and it would be rigid enough to return to a flat state when no bending force is applied to it. Space is an important resource on any mobile device and Gummi would therefore not incorporate any buttons or switches: the entire body of the device is used for input and output simultaneously. A user would hold the Gummi device with two hands and interact with it by physically bending it, touching the position sensor on the back of the device and observing interface response on the flexible display that covers the top of the device.

The flexible electronic components required to implement such a device are not available to us at this moment. Therefore, to evaluate the feasibility of the Gummi interaction techniques, we developed a prototype that emulates the most important properties of such a flexible computer. The functional Gummi prototype, presented in Figures 4 and 5, consists of conventional, rigid components mounted on a flexible plexiglass base. A TFT color display is attached to the center of the base in such a way that the base can be easily bent by the user without affecting the viewing position of the display. A USB trackpad is mounted on the bottom of the base and is used as a 2D position sensor. Two resistive bending sensors are mounted on opposing sides of the flexible base. Each sensor measures bending in one direction, so that the combined measurements of the opposed sensors can be interpreted as two directions of bending.

Display, trackpad and bending sensors are connected to a personal computer running the Gummi application. An analog-to-digital converter with appropriate circuitry is used as an interface between bending sensors and computer and the TFT display on the prototype is connected to the computer using a VGA to NTSC converter. Plastic handles on the sides of the base indicate the intended two-handed grip and make the prototype more comfortable to hold.

The actual Gummi prototype is shown in Figure 5. Although it is bigger than the envisioned device, it closely simulates the properties of the proposed bendable computer: Users can easily bend the device up and down while controlling position using the trackpad mounted on the back of the device. In the

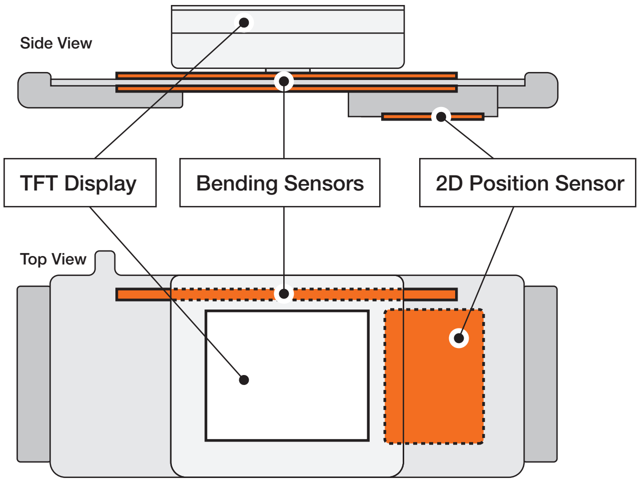


Figure 4: Gummi Prototype Components

next section we present the interaction techniques that we developed using the prototype described above.

GUMMI INTERACTION

The Gummi user interface prototype combines a simple interaction vocabulary of physical gestures with a graphical user interface, allowing users to perform familiar, basic tasks, centered around the browsing of visual information. We evaluated the Gummi interface within a number of basic applications: hypertext and map browsers, a simple game, a messaging application and a media player. Our aim was to make Gummi interaction simple enough for first-time users to understand it with few explicit instructions.

Physical Interaction

Gummi's interaction vocabulary of physical gestures is based on bending and 2D position control. The user holds the Gummi device with two hands, allowing easy bending of the whole device and simultaneous 2D position control.

Bending

Gummi senses one-dimensional bending. It is assumed that the device's flexibility is comparable to that of a credit card: easy to deform but rigid enough to return to a flat state when no bending force is applied. The flat, "*Neutral*" state of the device is important for the Gummi interaction style.

We considered other types of deformation: twisting, folding and stretching would potentially allow much richer gestural interaction than simple bending. But, in the absence of established paradigms for interaction by deformation, we deliberately simplified the design of Gummi. We were looking for a core set of features that would lead to a cohesive system of embodied interaction techniques. Once established, such a system could be extended to include other interaction modalities.

Figure 5: Gummi Prototype

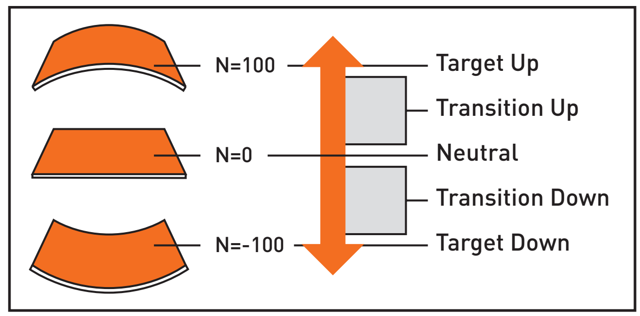


Figure 6: Bending States and Events

Bending States and Events

Starting from a flat state (*Neutral*), the device can be bent in one of two directions, either up or down (Figure 1). In both directions, transitional states between *Neutral* and maximum bending are continuously measured (*Transition Up* and *Transition Down*). When Gummi is bent to its maximum in either direction, a discreet event is issued (*Target Up* and *Target Down*). The maximum level of bending that triggers these events is customizable and can be set in software. To avoid triggering successive actions when the device remains in the maximum bending state, the Gummi device has to be returned to the *Neutral* state before new *Target Up* or *Target Down* events can be issued. Bending states and events are illustrated in Figure 6.

In addition to these basic states and events, gestural controls can be incorporated, such as a quick succession of *Target Up* and *Target Down* states, which would issue a *Double Up* or *Double Down* event. Gummi's discreet bending events loosely correspond to mouse button clicks and double clicks in desktop user interfaces. The combination of discreet events of maximum bending and continuous transitional states form a basic interaction vocabulary that is used to implement a variety of interaction techniques, most importantly for selection, scrolling and hierarchical navigation.

2D Position Control

The Gummi device also includes a touch-sensitive 2D position sensor (Figure 1). Placing this sensor on the back of

Table 1: Mapping of Bending to Interface Operations

Target Down	***Target Up***
Select	Deselect
Start Playback	Stop Playback
Descend Hierarchical Directory	Ascend Hierarchical Directory
Follow Hyperlink	Return to Previous Page
Transition Down	***Transition Up***
Zoom In	Zoom Out
Increase Playback Speed	Decrease Playback Speed

the device, rather than the front, allows users to control 2D position without changing the two-handed grip of the device. Furthermore, this sensor placement avoids occlusion of the display by fingers as in the case of touch-sensitive screens.

Gummi GUI

We established a series of Gummi user interface principles and interaction techniques that can be used to perform fundamental GUI interaction tasks, such as selection, 1D and 2D scrolling, text input etc. All these tasks can be completed by a combination of 2D position control and the bending states and events described above. We implemented these principles and techniques in several prototype applications, resulting in a cohesive, easy to learn user interface. The following describes the main interaction principles and concrete examples of Gummi interaction.

Consistent Mapping of Bending

A central feature of Gummi interaction is the consistent mapping of bending directions to semantically opposed operations, making the Gummi interface coherent and easy to use. For example, bending the device to *Target Down* is used to select items, descend menu hierarchies or follow hyperlinks. *Target Up*, on the other hand, is used to deselect items, ascend menu hierarchies or to return to the previous page in hyperlinked documents. Table 1 illustrates this consistent mapping across all Gummi applications.

WIMP interfaces must rely on widgets or keyboard shortcuts to accomplish opposed tasks, one example being the "*Back*" button in web browsers. Two-directional bending in Gummi allows the navigation of the GUI without using widgets, saving screen space and simplifying interaction. In informal evaluations, most users intuitively grasped the mapping of bending directions and could use it effectively.

Selection and Scrolling

The WIMP concept of a pointer is absent from Gummi. Instead of a moving point of focus in the form of a cursor, Gummi uses a fixed point of focus in the center of the screen.

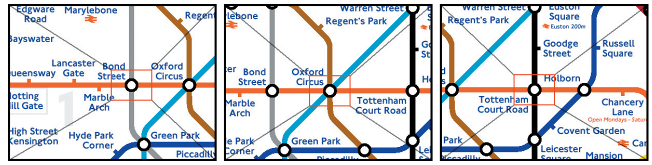


Figure 7: Combined Scrolling and Selection

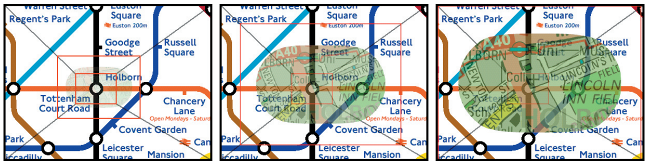
To select an actionable item, such as a hyperlink or a menu item, the user simply scrolls the entire visual content in one or two directions using a 2D position sensor on the back. When the item comes close to the focus point in center of the screen, it is automatically selected and can be activated by bending Gummi to *Target Down*. Similar to rollover effects common in WIMP interfaces, selected items are highlighted to indicate their state. Figure 7 illustrates scrolling and selection. The trajectory of finger movement on the 2D position controller (Figure 1) is directly mapped to direction and amount of scrolling of visual content. Because the finger moves directly under the screen, this technique provides an effective visual feedback, creating the illusion that the user directly touches and drags the displayed content. In the case of menus and hypertext documents, scrolling can be limited to one dimension.

The proposed technique has a number of advantages for mobile interaction. Firstly, compared to WIMP interfaces, Gummi's combination of scrolling and selection greatly simplifies the browsing of menus and large hyperlinked documents. In traditional WIMP interfaces, scrolling and selection are two separate tasks: to navigate hyperlinked documents, users have to move the pointer repeatedly between scrolling widgets and hyperlinks. Remarkably, this deficiency of WIMP interfaces has inspired the development of new input devices – physical scroll wheels on mice. In Gummi, the user only needs to scroll the content until the desired item comes into focus. No widgets or scroll bars are needed and fewer positioning movements are needed to scroll the content.

Secondly, because item selection is determined algorithmically, selection is very easy as it does not require accurate pointing. Even small graphical elements can be selected easily. Currently, Gummi simply selects the item closest to the center of the screen, but more complex selection algorithms can be implemented. For example, in case of ambiguity, items can be selected based on their frequency of use.

Previews and Transition Feedback

The Gummi GUI provides dynamic visual feedback on the current state of the device between its *Neutral* state and maximum target levels of bending. For example, in a map application, a user selects a subway station hyperlink to access a local area street map. A small highlight box is displayed around the selected station in the *Neutral* state. To follow the link, the user has to bend the device until the *Target Down* event is issued. In transition between *Neutral*

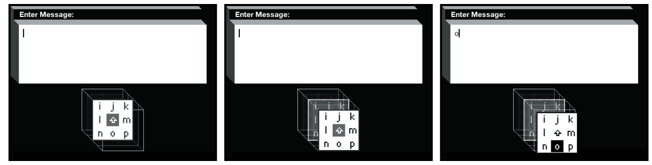


Neutral *Transition Down* *Target Down*

Figure 8: Analog Link

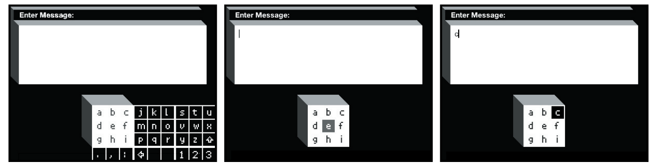
Neutral *Transition Down* *Target Down*

Figure 9: Map Blending



Group Selection Character Selection Character Entry

Figure 10: Text Input with Layers



Group Selection Character Selection Character Entry

Figure 11: Text Input with a Nested Grid

and *Target Down* (we refer to this state as *Transition Down*) the amount of bending is continuously mapped to the size of the highlight box. When the *Target Down* state is reached, the highlight box fills the entire display and the link is activated. Throughout the *Transition Down* state, a preview of the selected link, in this case a street map, is displayed in the highlight box (Figure 8).

The analog properties of Gummi allow gradual visual transitions between user interface states. We call this feature "*analog links*". Analog links are used throughout the Gummi interface and serve two important purposes. Firstly, they provide a continuous visual feedback on bending: by observing the size of the preview images, the user can clearly judge the amount of bending required to activate the link. This creates a highly responsive interface, giving the user feeling of being in control of the device. Secondly, analog links provide preview of linked content. They can contain thumbnail previews or textual descriptions of selected content such as web pages, photographs or menu items. This is comparable to Tool Tip previews commonly used in WIMP interfaces, providing additional information on a selected item before it is activated.

Use of Transparency

In addition to analog links we use transparency to interactively blend between multiple views of related information. Figure 9 shows how an aerial photograph of a city and a street map of the same area are simultaneously displayed as overlapping layers. By bending the Gummi device, users can interactively control the opacity of the top layer to quickly navigate between the two images. Photograph and map can be compared by adjusting the transparency so that both images are visible simultaneously.

Transparency can be a powerful tool for mobile devices: the simultaneous display of independent information views is problematic since mobile devices are small and multiple windows are not feasible. Gummi uses continuous bending control to change the opacity of information layers – multiple documents can be displayed on a small screen.

Text Input

Text input is a central challenge for new mobile interaction styles [9]. We developed two systems for text input for Gummi GUI: 1) *layer text input* and 2) *nested grid text input* systems. Both systems utilize analog control and are based on a two-step character selection process: First, a group of characters is selected, then a character from within the chosen group is selected and entered into the text field.

Figure 10 illustrates a text input system based on layered character groups. First, a layer is chosen by bending the device (Transition Down), each layer corresponding to a level of bending. Then a character is chosen from that layer by using 2D position control. The selected character is entered by bending slightly in the other direction (*Transition Up*). If the user bends the device to Target *Down*, the current selection is canceled. *Target Up* exits input mode.

An alternative system is shown in Figure 11: characters are displayed in a nested 3x3 grid. While the device is in the *Transition Down* state, a group of characters is selected with 2D position control. Then a character is selected with 2D position control while the device is in the *Neutral* state. The selected character can be entered with *Transition Up*. As in the layer-based system, selection is cancelled with *Target Down* and text input mode can exited with *Target Up*.

Continuous control has been largely ignored in text input systems (with a notable exception of Dasher [21]) and could be an interesting direction for exploring new techniques. The presented techniques should be seen as explorations, not as finished proposals for new types of generic text input.

Gestures and menus

Gummi's bending interaction lends itself to gestures. We have used two such gestures in the Gummi GUI: two successive *Target Up* or *Target Down* events are interpreted as distinct input events, *Double Up* and *Double Down*. In our implementation, these two gestures allow direct access to menus that are otherwise invisible in the Gummi GUI. The *Double Up* gesture opens a menu of system-wide commands

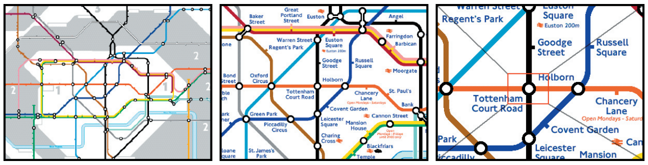


Figure 12: Continuous Zooming

that allow users to navigate between Gummi applications. The *Double Down* gesture opens contextual menus specific to the currently active application; they fulfill a similar role as application menu bars in WIMP interfaces. These menus work with the generic scrolling and selection techniques described above.

Other Interaction Techniques

The Gummi GUI also includes a number of application-specific interaction techniques that explore continuous bending control. The playback speed of movies or sound files can be controlled by bending – media files play at regular speed when the device is in its *Neutral* state and can be slowed down or sped up with *Transition Up* and *Transition Down*. Accurate and quick image zooming with variable speed is also controlled with *Transition Up* and *Transition Down* (Figure 12). In another simple application, a game character's movement can be controlled with a combination of bending and 2D position control.

DISCUSSION

We evaluated Gummi in a series of informal usability studies where we observed approximately 30 of our colleagues in their use of the Gummi prototype device. We were interested to see how easily first-time users would understand Gummi interaction concepts and whether they would find them useful and enjoyable. We were particularaly interested in observing users' reactions to the unique properties of Gummi, such as continuous control for zooming, blending and preview. Informal observations proved to be a cost-effective tool for rapid evaluation and revision of the interface design. As the underlying technology matures, we would like to conduct formal experimental studies of the Gummi user interface.

Our users had no difficulty understanding how the Gummi device can be used: after brief (2-3 minutes) explanations of the basic interface principles, they would grasp Gummi's interface concepts and would continue discovering functionality by using the device. Users had no difficulties with Gummi's basic selection and browsing techniques. Many users noted the consistency of the interface. It did take some time, however, for the users to start using continuous control functionality effectively, such as blending and preview. We speculate that this functionality is not expected: our users could not rely on previous experiences because existing handheld computing devices do not provide any comparable functionality. However, after understanding how links can be previewed or map layers interactively blended, these features were met with enthusiasm and delight.

Placement of the touch panel on the back of the device did not seem to cause any difficulties. This may be due to Gummi's immediate visual feedback. Interaction techniques for selection and navigation seemed particularly suited for such a device configuration.

Reactions to Gummi's text input techniques were mixed. Although text input was possible using our prototype, it was not effective for entering any substantial amount of text. The speed of text input with Gummi can certainly not be compared with a keyboard or Palm's Graffiti system, both of which are significantly faster. We found, however, that Gummi's text input system was sufficient for entering very short text strings such as search terms or song titles. Gummi's text input system could possibly be enhanced by predictive mechanisms such as those used on mobile phones [10]. We also consider the development or adaption of other text input techniques based on continuous control mechanisms [21].

We found that Gummi's interaction techniques are best suited to simple tasks like the navigation of hypertext or zooming maps. More complex tasks, especially text input, are difficult to perform comfortably with the Gummi device and interaction. We certainly do not expect handheld, bendable devices to replace traditional desktop computers and the proposed interaction style cannot replicate the whole range of functionality offered by WIMP-based user interfaces. But the interaction techniques presented in this paper may be useful in more specific contexts: if flexible electronic components become a reality, credit-card sized computers could provide casual access to specific types of information like maps, schedules, electronic books or games. As flexible electronic components are predicted to be inexpensive, such small devices could be distributed as hotel key cards containing local area maps. In another scenario, Gummi interaction could allow easy access to the limited but dynamic information contained in smartcards.

In summary, our evaluation and extensive experimentation with the prototype showed that a handheld bendable computer controlled only by embodied interaction techniques could be used effectively and enjoyably to perform a wide range of simple interaction tasks. The development of such a device therefore represents an interesting and feasible direction for future applications of flexible, organic electronics.

CONCLUSIONS AND FUTURE WORK

This paper presents Gummi, a concept for a bendable, handheld computer and interaction techniques designed for such a device. The interface design emphasizes embodied interaction with a handheld computer – Gummi does not rely on traditional interaction techniques involving buttons, pen or WIMP-based pointing and clicking. Evaluations of the prototype demonstrated Gummi interaction techniques to be feasible, effective and enjoyable.

Gummi is a first attempt to design a device and interface style based on the unique physical properties of flexible electronic devices. Flexible electronics are likely to become a key technology of the near future. We hope that Gummi will stimulate and encourage further research into new applications of flexible electronics, especially in the area of human-computer interaction.

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