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Unraveling Flexible OLED Displays for Wearable Computing

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Abstract

Flexible OLED display technologies are steadily reaching maturity levels where they will soon have the ability to significantly influence the design of wearable computers. We discuss the characteristics and constraints of flexible OLED displays. We propose design concepts incorporating flexible display technology in wearable computers and discuss the impact flexible displays will have on issues such as form factors, user interfaces application design, etc.

1 Introduction

Organic Light Emitting Diode (OLED) technology is ideally suited for mobile and wearable devices due to key properties such as lower power consumption, higher brightness, better contrast, and wider viewing angles. OLED displays are beginning to appear in cellular phones, digital cameras, and car stereos. We have shown a 740dpi 640x480 direct view crystalline silicon AMOLED in a wristwatch prototype [12,15]. OLED displays are expected to be available in larger sizes that could be used for laptop computer displays in the next two to five years.

At present, OLED displays are being prototyped on flexible substrates by Universal Displays, University of Arizona Optical Sciences Center, Philips Research, Dupont, Army Research Labs, other members of the US Display Consortium, etc. Flexible OLED displays are expected to be available in some form within the next two years [1]. Unlike traditional rigid planar displays, flexible OLED displays can be built to conform to shapes with different curvatures. A recent issue of Popular Science even shows a hypothetical device that uses flexible OLED displays [4].

Flexible OLED display technology [2] opens up a wide range of interesting possibilities to improve the design of wearable computers. If displays can be rolled away when not in use, even small form factor devices can support relatively large area displays. OLED displays built on top of lightweight substrates such as plastic, can help lower the total weight of wearable computers. When combined with flexible circuits, flexible displays can help make wearable computers significantly less fragile. Flexible displays may also enable the creation of entirely new wearable computing form factors.

In this paper we present several design concepts that serve as a framework to explore the impacts that flexible displays will have on wearable computing. Our discussions with teams working on flexible OLED display technology suggested several constraints. We have also drawn from our experience of building three generations of wrist watch computers. Wearable computing introduces other constraints [16,17] relating to mobility, form factor, usage patterns, etc. We present our conceptual prototypes to motivate the broader wearable computing research community to proactively think about this space *before* such displays become available in large quantities. Flexible OLED technology deserves more attention from the wearable computing community because such displays have the potential to add a new dimension to wearable computing. Further, the wearable computing community has helped pioneer several concepts in the past that have been adopted more widely later. An example is the use of circuits in shoes were discussed by researchers at MIT [8,13,18]. Adidas has announced a self-adapting shoe few months ago. Another example is electronic textiles [11]. Our community is likely to be amongst the early adopters of flexible display technology and we may be able to influence the way in which this technology evolves.

2 Background on Flexible OLEDs

It is expected that flexible OLEDs will alter the design of variety of devices, including cell phones, PDA's, computer displays, informational displays in vehicles and television monitors. Flexible OLEDs have several desirable properties [1]:

1. low power requirements since no backlight is required,
2. daylight viewable (brightness up to 500 candela/m^2),
3. bright colors using different organic materials,
4. high resolution (< 5 μm pixel size),
5. wide viewing angle since they do not use polarizing filters,
6. high display update rates using better materials (fast switching 1-10 μs),
7. wide temperature tolerance,
8. impact resistance 10 times greater than rigid plastic LCDs and 100 times greater than glass LCDs,
9. thin and conformable form factor using flexible substrates, and
10. the potential for low cost manufacturing processes.

For the above reasons OLEDs are seen as a future replacement technology for cathode ray tubes (CRTs) and liquid crystal displays (LCDs), which currently dominate the growing $40 billion annual electronic display market.

Figure 1 shows an approximate road-map of OLED technology.

Figure 1: OLED Roadmap (Courtesy Universal Display Corporation)

OLEDs are easier to build than conventional LEDs because the materials do not need to be crystalline [7]. The organic materials are applied in thin layers for a slimmer profile, and materials for different colors can be patterned on a given substrate to make high-resolution images.

There are several types of OLEDs [1]. Small molecule OLEDs are built by depositing molecules of organic compounds, which emit light when energized, on to the display substrate. Polymer OLEDs can be printed using ink jets, where the ink contains active suspended molecules, and displays built this way can be generally larger than those with small molecule OLEDs.

OLED display lifetimes are increasing. Currently OLED displays last for several tens of thousands of hours before their brightness reduces by a factor of two [9]. Flexible OLEDS with thousands of hours of lifetime have been shown [20,21].

The displays can be flexible (see Figure 2) since the substrates could be plastic or even metal foil. The substrates could be transparent plastic as well, as shown in Figure 3.

Toshiba has shown an 8.4inch (diagonal) SVGA flexible LCD with a bend radius of 20cm at SID 2002. In May 2004, Philips showed a prototype 13” wide screen TV based on a polymer OLED display.

Several organizations have been working on flexible OLED technology for many years. The US Display Consortium has several members and also serves as a catalyst for industry efforts on flexible displays. Annual conferences on Flexible Displays have been held for the last three years focused on problems related to materials, circuits, display lifetimes, color fidelity, etc.

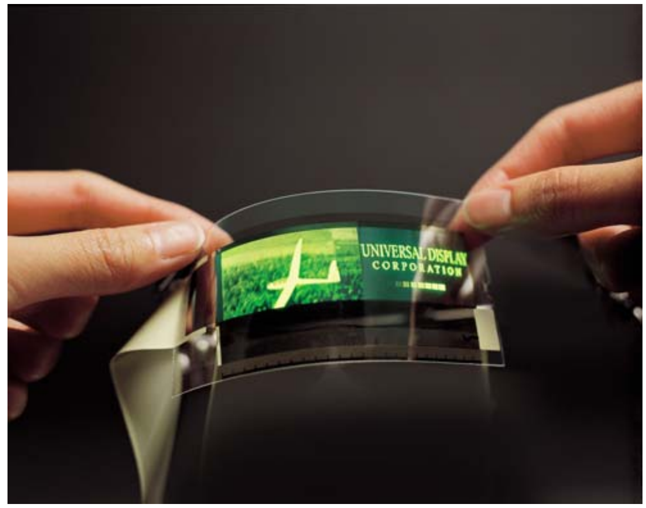

Figure 2: Flexible OLED

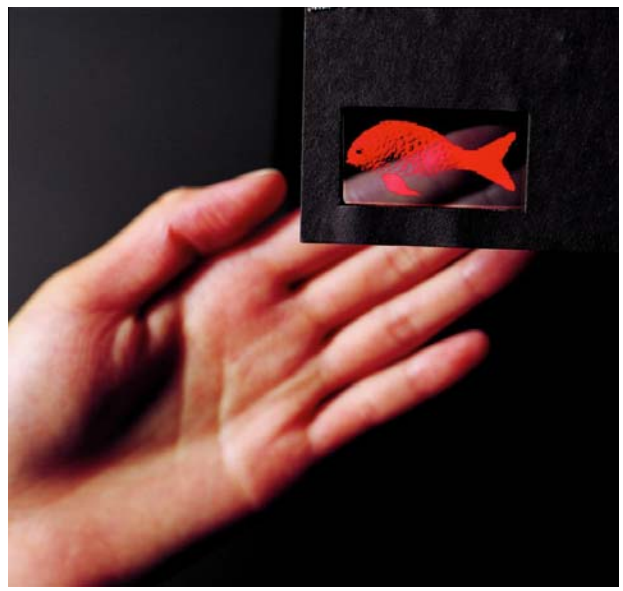

Figure 3: Transparent OLED

Display manufacturers are attempting to lower the cost of manufacturing flexible OLEDs, improve display qualities and lifetimes as well reducing the *bend radius*. Manufacturing costs are being addressed by moving to a roll to roll (RTR) manufacturing process. In this process, the steps consist of first applying coating to plastic substrate followed by an embossing step, filling, sealing and a final step of lamination and cutting. Some of the barriers that need to be overcome to improve display characteristics include – compatible substrate and process set, yield, encapsulation and sealing against moisture [10], differential aging between red, green and blue pixels, etc. Bend radius of a flexible display is the radius of the smallest cylinder into which the display can be rolled to. It also defines the geometries that the display can map to.

The smallest bend radius is between 0.5-1 inch at present. It is expected to reduce over time.

Companies such as Gyricon and eInk work on related technologies of flexible LCD displays. Such displays consume no power once the display is written and are more suited to quasi-static content .

We believe the time is right for investigating how we might be able to incorporate these displays into the next generation of wearable computers. Systems issues such as form factors, applications and user interfaces need to be addressed.

3 Possible application areas

It is generally accepted that one of the drawbacks of wearable computers is their limited I/O capabilities. Wearable devices used by large audiences such as PDAs, cell phones, and wristwatches can be revolutionized by having large flexible OLED displays that roll up and fit inside. Wearable devices used by different professions can benefit from flexible displays. Military personnel could use wrist or thigh mounted computers with foldable displays and helmets with transparent displays. Flexible displays can also be mounted on their clothing. Our interviews with medical personnel indicate that they want to wear compact equipment, but would like the added information that a flexible display could provide. So doctor's equipment such as stethoscopes, otoscopes, ophthalmoscopes, blood pressure cuffs, etc. would be good candidates for flexible displays. Sports players could receive strategy and play information on displays mounted on clothing. Clearly it is possible to categorize the application of flexible OLED technology for several other professions. Over time, flexible displays could be incorporated into designer clothes to make fashion statements and dynamically change the look of clothes and accessories.

One common wearable form factor, a pen, is often advertised as the ultimate device that will adopt flexible displays. At present the bend radius for most prototypes is around one inch. The display bend radius would have to reduce to few mm to fit into a pen form factor. The bend radius would have to reduce even further before the form factor shown in Popular Science [4] can be realized since the display rolls up and then folds in half.

With flexible displays, the form factor of wearable devices will be constrained more by the size of the input mechanisms than by display size. By increasing the adoption of voice input for interaction, these devices can be made even smaller. As we mention in Section 4, flexible displays could be used as input devices if they are augmented with mechanisms to detect the amount of flexion.

Curved displays are also ideal for immersive applications. Personal movie players may use domes or half cylinders to show movies that have IMAX-type immersive experiences. Display software would have to know the curvature of the display and the location of the viewer to draw the right image. Fortunately, work related to texture mapping in 3D graphics can be used in this regard.

We now consider how different types of flexible displays can be used in wearable/portable devices. Just as magazines and books are easier to hold and read compared to newspapers, interactive programmable display on wearable devices cannot afford to be large and unwieldy. Therefore, we believe in most situations it is better to have several regular size displays than to have a single oversize display. Moreover, extremely large displays will have challenges with the user interface and power.

3.1 Single Unfurled

Figure 4: Default View

We first look at novel ways of using a single flexible display that can be rolled up completely and stored inside the device. An interesting trade-off is to allow variable unrolling of the display. Such a capability allows the application designer to provide the right level of detail based on the current display size.

Figure 5: Display partially unrolled

Consider the design concepts illustrating a calendar application in Figure 4 through Figure 6. These pictures show how a flexible display may be added to a pager like the Blackberry™.

In the default view, when only a small part of the display is unrolled, a calendar application may just show the current appointment. If the user wishes to get more detail he can partially unfurl the display and get a summary of each appointment for the day. Unfurling the display fully may get even more detail and show things such as the location of the appointment, necessary phone numbers, and other context for the appointment.

Applications designed to work with such rollable displays need to be adapt themselves to the extent to which the display is unfurled.

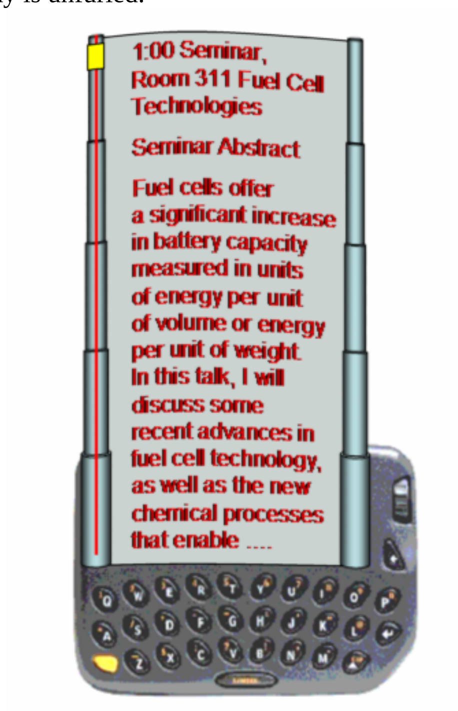

Figure 6: Display fully unrolled

Other applications such as email or EMR (Electronic Medical Records) can use this paradigm as well. For example a quarter-view EMR could include the patient's name and the most recent medication and vital signs. A half view could include past history and full view can provide the patient's demographics information such as address and insurance information. The contents of these views could further depend on whether the device is being used by a doctor, a nurse or the front office personnel. For example the front office personnel will see the demographics and insurance information in the default view. The role of the user can be communicated by the wearable device to the server if the content is generated by a server.

A device could have hardware buttons for quickly launching some applications. Depending on which application is launched, the display may be configured to different sizes. For example, an address book may use only a quarter of the display whereas the full display may be used for web browsing.

We envision that applications would be made aware of the physical size of the display in a dynamic fashion. The display hardware must be able to detect what part of the display is still folded and turn off power to that section to save energy and to avoid heat generation.

It is instructive to compare an eye mounted display with a large rollable flexible display. Advantages of an eye mounted display include: it is hands free, has high resolution for augmented and virtual reality, and is also highly private. The disadvantage with eye mounted displays is that they are still heavy and cumbersome especially when the user does not need it. On the other hand with rollable displays larger sizes and higher resolutions are available when necessary. Flexible displays can also be shared with other viewers. Finally, flexible displays could be used as input devices as discussed in Section 4.

3.2 Two sided unfurled

The next step in this direction is to make the flexible display two-sided. Since flexible displays can be less than 1 mm thick, making a display two sided does not add much weight or volume to the device but adds convenience.

Usage mode of two sided displays will depend on the privacy of the content and the how the display is used. When the two sides face different users, the information may be presented differently. For instance, one side could show a presentation to an audience while the other side shows notes and the presentation.

When used by a single user, applications may judiciously place information on one side or the other to control how readily the user can view the content. Information that is non-critical and distracting can be sent to the back side and an optional notification can be sent on the visible side informing the viewer that information is available on the other side.

Consider an example illustrating the addition of a two sided rollable OLED display to a cell phone. As shown in Figure 7 and Figure 8, one side shows a crossword puzzle and the other side could have the solution.

An email application could send the sender's name on the visible side and the subject and content could be rendered on the other side. The two sides can also be used to present different levels of details. One side could show textual driving directions and a small map, whereas the second side could show a larger map. In a mobile situation, flipping the display is much simpler than navigating a UI to change the display contents. Taken to the next level, an application could be assigned a fixed side of the display. This may help the user with focusing his attention on the task at hand. The applications can be given the necessary semantics and interfaces to draw on two different displays.

Figure 7: One side shows crossword and clues

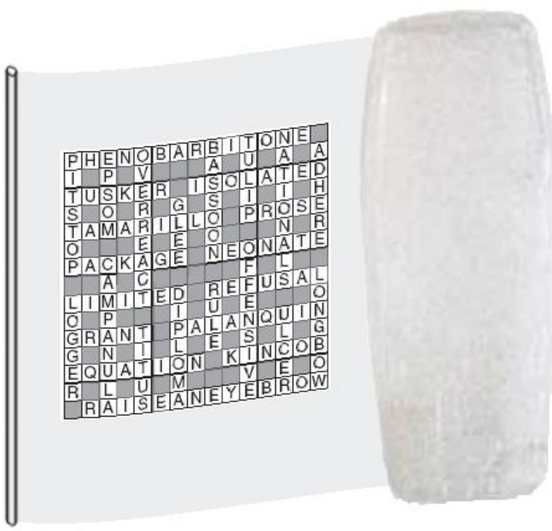

Figure 8: Other side shows the crossword solution

3.3 Multiple unfurled

A prototype flexible display built by Universal Displays has a thickness of 0.7mm and a bend radius of 1 inch. Based on the above numbers, having more than one rolled display does not significantly increase dimensions of the device. A 10 inch display would need $10/(2\pi \times 1)$ or approximately 1.5 revolutions and add only 1-2mm to the cylinder on to which the is rolled.

Therefore it is reasonable to think about using multiple rollable displays per device that can be viewed simultaneously. Multi-head displays have shown significant benefit in traditional computing. For example cutting and pasting from one window to another is much simpler when the two windows (too large to fit in one display) are on two different displays attached to the same computer. Having multiple displays rolled up introduces a few more mechanical challenges that however can be surmounted. Paradigms of multiple desktops are easily realized when multiple display surfaces are available. For example as shown in Figure 9, one screen can be used as a work area for editing documents, and another screen can be used for receiving notifications, instant messages and so on. As shown in Figure 10, the two displays could be rolled on a single spool inside the device. Alternatively, the two displays could be positioned above the keyboard as shown in Figure 11.

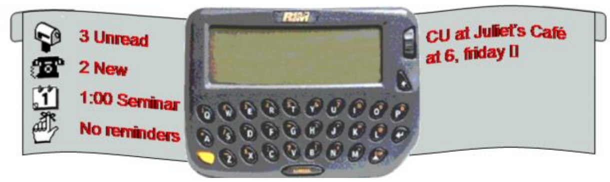

Figure 9: Multiple displays

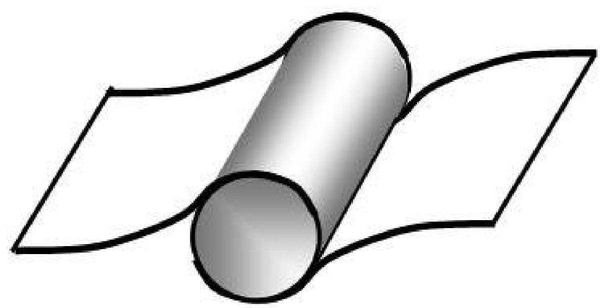

Figure 10: Packaging two displays on one spool

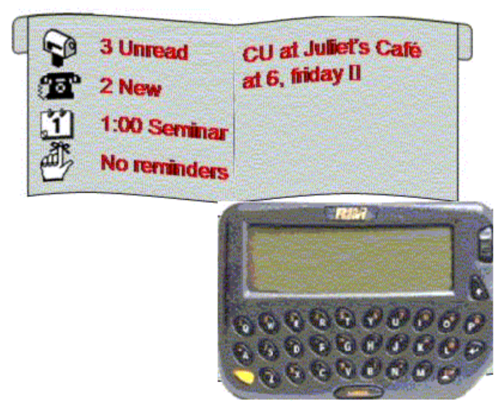

Figure 11: Multiple Displays above Keyboard

The power really increases when the multiple displays are themselves two sided. Applications such as electronic books shown in Figure 12 become possible. In addition we see potential for reducing context swapping and simplifying the UI navigation since multiple displays contain information and switching from one to another is possible with a simple turning of the page.

Figure 12: Electronic Newspaper Concept (Courtesy IBM)

3.4 Transparent OLEDs

Transparent flexible OLED displays can enable other usage modes. As an example, a traditional wristwatch could have a transparent OLED display instead of regular glass. The watch appears traditional, elegant and fashionable when the display is not used. The display is activated when the watch has information to present. Two layers of transparent displays may be needed to get the best effect, one to provide a background that hides the mechanical watch face and another to show the electronic content. The same concept can be applied to other jewelry such as pendants.

Transparent OLEDs can also be used for augmented reality applications where the real world is seen in the background. For example researchers have built systems where useful information is overlaid on real objects such as buildings [3,19]. Medical professionals can overlay a transparent display on a body part and say compare a rash on a patient with a standard set of images of rashes to help determine the condition of the patient. Transparent displays can also be combined with light and optics to project larger images. Novel uses for transparent displays needs to be investigated further. Is there a use for overlaid displays? Applications must be made *layer-aware* to exploit this feature.

3.5 Displays on input devices

Flexible OLEDs can be incorporated on surfaces of physical buttons used to interact with a device. The tactile feel and unique shapes of buttons help user interaction. This is one of the main reasons why people still prefer hard keyboards and buttons to touchscreens. For instance a universal remote control with OLEDs on each button might remap keys for different appliances by relabeling the buttons. The color and brightness of the buttons can also be adjusted per application or depending on ambient light to improve the user interface. Another advantage is that buttons that are inactive can be turned off to reduce the button clutter. Help menus can show button sequences by animating the buttons to be pressed for a certain function by turning on the OLEDs for the buttons in sequence.

3.6 Conformal mapped skins

Common wearable objects with curved geometries can start displaying information using flexible displays. For example, bands on wristwatches, belts and pockets could become displays.

By depositing OLED displays on the cases for devices, the *skin* of the device can be changed dynamically. For example the color of the case could indicate something about the caller when the phone rings. Given the vast market for cell phone covers, we anticipate that customers will appreciate the ability to change the look of their devices. Skins on medical monitoring equipment such as a blood pressure monitor may indicate measurements.

3.7 Adding displays to garments

Display flexibility makes it feasible to mount displays on fabrics, without making them uncomfortable to wear. It is unlikely that flexible OLED displays will be machine washable in the foreseeable future, so these displays may be thought of as being temporarily attached to clothing.

From a design standpoint, jewelry could change colors to coordinate with clothes, shoes and clothes could change patterns and shades.

4 Additional design issues

Designing a device with a flexible display requires several mechanical and thermal developments as well. As flexibility of the display increase, (i.e., bend radius reduces), it becomes important to support the display when it is unfurled. One way could be using telescoping support bars/trusses or special materials that can be polarized to increase rigidity.

In order to save power, CPUs in wearable computers prefer to go into low power states at every available opportunity. For usability, the display should have an option where it maintains its contents even when the CPU has gone to sleep. If this feature is supported, the CPU may display a page of information and immediately enter a lower power state till the next event.

Since the flexible display may be used in various states of unrolling, it should be possible to detect the extent of unroll and also save energy by turning off the circuitry associated with the non-visible portions of the display. The degree to which the display is unrolled should be passed on to applications through an interface.

The preferred mode of usage is to roll up the display immediately after use. So any heat generated while the display is in use should be rapidly dissipated to avoid damaging the display or other circuits inside the wearable.

The telescoping bars could also possibly conduct away excess heat. The spindle for the display spool can also conduct away excess heat. Applications may also adaptively reduce heat generation, perhaps by reducing the brightness when the user is expected roll up the display soon.

Flexible displays should be able to tolerate a large number of roll and unroll cycles in order to be used in this manner. Displays should preferably have sensing mechanisms that measure any degradation as a result of roll/unroll cycles or usage and applications should be able to adapt to display degradation, if any.

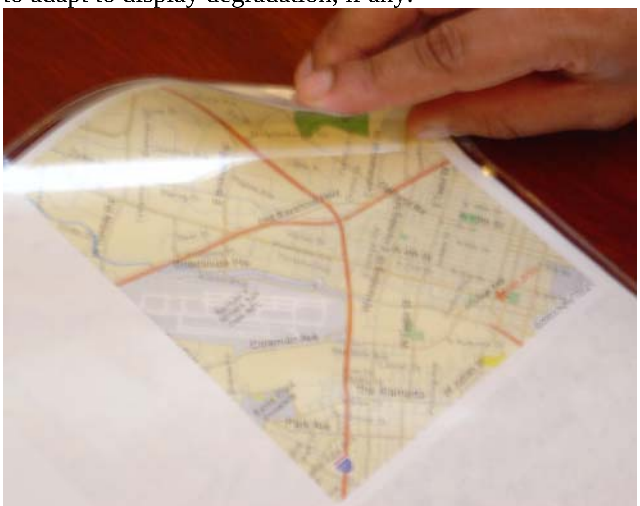

Figure 13: Interfaces based on curvature detection

Sensors to detect the curvature of the display at different locations could be used by applications to tailor content that is presented. One possible mechanism is to use strips of piezoelectric materials. Gloves [5] to control VR systems [22] and glove based keyboards have successfully used this idea. For example, more private views may be provided when the curvature of the display is higher.

With reliable indications of curvature, it may be possible for a user to flex and unflex the display as an input mechanism. We feel this mechanism is superior to a touch screen since the user gets a tactile feedback when he flexes the display. For example a gesture similar to turning a page in a book, as shown in Figure 13, may be used to scroll the information presented on the display. As shown in folding the top right portion of the display could scroll up or perform some other action. It is easy to extend this concept and recognize other gestures. Flexible displays can then serve as both input and output devices and thus reduce the footprint of the device. In order to save cost and complexity it is possible that only part of the display has the curvature sensing mechanism. In a multiple display system one of them may allow input by flexion.

It may be possible to add flexible touch sensitive films on top of flexible OLEDs. With this step, touch based user interfaces become possible. A combination of touch and flexion sensing may be used in novel ways to create input interfaces that do not require additional space.

Several issues arise with two sided displays. The device has to know which side the user if looking at or referring to. This could be done with explicit actions by the user such as indicating which display he is looking at by positioning a cursor. The idea of using multiple cursors for multiple displays needs to be investigated. Could multiple displays possibly share wiring? Over time it is conceivable that flexible solar cells [6] could be deposited on one side of the display to help charge the battery for the device.

5 Flexible displays in the environment

Wearable devices can augment their capabilities if they can easily leverage other computing and display devices in the environment. In a recent article [14], we discussed some of the inherent limitations faced by portable devices. We also described how enhanced user experience is possible when displays are elevated to first class network objects that can advertise their services, and such services are leveraged by handhelds or other portable computers that users carry. Environmental devices and personal wearables establish symbiotic relationships to enable the user to interact with displays at greater levels of ease and comfort.

With flexible OLED technology, it becomes possible for many more surfaces in the environment to sport displays. Flexible OLED properties such as impact resistance and temperature tolerance enable us to deploy displays in environments where traditional display devices may be considered to be too fragile.

The ability to unfurl the display, use it and store it away compactly is a key advantage that flexible displays offer. A usage situation that is commonly known is the unfurling of a screen to project the image from an LCD projector. The ability to roll away the screen when not required allows us to place something else on the wall behind the screen (such as a chalk board, for instance). With flexible OLED displays, several environmental surfaces can support multiple uses. For instance there may be paintings, photographs or even a window on a portion of wall that is temporarily obscured when the user needs to use a display. Roll up OLED displays may be used on a refrigerator door to show recipes, shopping lists, etc., when needed.

One may consider adding mechanisms that enable network connected displays to unfurl by themselves to notify users of events that have occurred. The movement of an unfurling display may be more capable of attracting user attention compared to a fixed display and is less annoying than an audio alert.

6 Conclusions

We summarized the recent advances in flexible OLED display technology and have explored the ways in which one might add flexible OLED displays to wearable computers. We believe that flexible OLEDs open up several interesting opportunities to make wearable computers lighter, more compact, more energy efficient, as well as more usable. We discussed several configurations of displays and how these might be used. We hope the wearable computing community will play a key role in influencing flexible OLED technology and accelerate the realization of the immense potential of such displays.

7 Acknowledgments

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8 References

1. J. N. Bardsley, *International OLED Technology Roadmap: 2001-2010*, U. S. Display Consortium, http://www.usdc.org/technical/downloads/OLED_Techroadmap_nbtext.pdf
2. A. Chwang, M. Rothman, S. Mao, R. Hewitt, M. Weaver, J. A. Silvernail, K. Rajan, M. Hack, J. Brown, X. Chu, L. Moro, T. Krajewski, N. Rutherford, *Thin-Film Encapsulated Flexible Organic Electroluminescent Displays,* Applied Physics Letters, Vol. 83(3) pp. 413-415, July 2003.
3. S. Feiner, B. MacIntyre, T Hollerer, A. Webster, *A Touring Machine: Prototyping 3D Mobile Augmented Reality Systems for Exploring the Urban Environment*, ISWC 1997, pp 74-81.
4. M. Frauenfelder, *This PDA is a Real Pocket PC,* Popular Science, May 2004, pp. 70-71.
5. G. Grimes. *Digital Data Entry Glove interface device*, Patent 4,414,537, AT & T Bell Labs, November 1983
6. J. R. Heflin, *Thinner more flexible silicon panels*, National meeting of the American Chemical Society, April 7-11, 2002, Orlando.
7. W. E. Howard *Organic Displays Coming to Market*. Scientific American, Jan 2004.
8. J. Kymissis, C. Kendall, J. A. Paradiso, N. Gershenfeld, *Parasitic Power Harvesting in Shoes*, Proceedings of ISWC 1998, pp 132-139.
9. R. Kwong, *Long Lifetime Electrophosphorescent Devices,* 3rd International Conference on Electroluminescence of Molecular Materials and Related Phenomena, 2001.
10. W. A. MacDonald, *Engineered films for display technologies*, Journal of Materials Chemistry, No 14, 2004, pp 4-10.
11. D. Marculescu, R. Marculescu, N.H. Zamora, P. Stanley-Marbell, P.K. Khosla, S. Park, S. Jayaraman, S. Jung, C. Lauterbach, W. Weber, T. Kirstein, D. Cottet, J. Grzyb, G. Tröster, M. Jones, T. Martin, Z. Nakad *Electronic Textiles: A Platform for Pervasive Computing*, Proceedings of the IEEE, Vol.91, No.12, Dec. 2003.
12. C. Narayanaswami et al., *IBM's Linux Watch: The Challenge of Miniaturization*, IEEE Computer, 35(1): 33-41, Jan 2002.
13. J. A. Paradiso, K. Hsiao, A. Y. Benbasat, Z. Teegarden, *Design and implementation of expressive footwear*, IBM Systems Journal, 39(3/4):511-529, October, 2000.
14. Mandayam Raghunath, Chandra Narayanaswami and Claudio Pinhanez. Fostering a Symbiotic Handheld Environment, IEEE Computer 36(9): 56-65 Sept 2003.
15. J. Sanford, E. Schlig, O. Prache, D. Dove, T. Ali, W. Howard, *Technology and design of an active matrix OLED on crystalline silicon direct view display for a wrist watch computer*, SPIE, The Intl Symp on Optical Science and Technology, Aug 2001.
16. T. Starner: *The Challenges of Wearable Computing: Part 1*. IEEE Micro 21(4): 44-52 (2001).
17. T. Starner: *The Challenges of Wearable Computing: Part 2*. IEEE Micro 21(4): 54-67 (2001).
18. T. Starner, *Human Powered Wearable Computing*, IBM Systems Journal, 35(3/4):511-529, October, 1996.
19. Bruce H. Thomas, Victor Demczuk, Wayne Piekarski, David Hepworth, Bernard K. Gunther, *A Wearable Computer System with Augmented Reality to Support Terrestrial Navigation,* ISWC 1998, pp168-171.
20. M. S. Weaver, L. A. Lichalski, *Organic Light Emitting Diodes with extended Operating Lifetimes on Plastic Substrates*, Applied Physics Letters, vol 81 No 16, Oct 2002, p2929.
21. M. S. Weaver. *Plastic Video Displays Using OLEDs*, 3rd International Conference on Electroluminescence of Molecular Materials and Related Phenomena, 2001.
22. T. G. Zimmerman and J. Lanier, *Hand gesture interface device*, In *CHI + GI Conference Proceedings*, pp 189-192, 1987.