Capture for Wearable Computer Evaluation

Kent Lyons and Thad Starner
College of Computing, GVU Center
Georgia Institute of Technology
Atlanta, GA 30332-0280 USA
{kent,thad}@cc.gatech.edu

1. Introduction

Wearable computers have the potential to offer their users great advantages. Worn like clothing, the machine can always be with its user. A single interaction can be as short as a few seconds, yet some users have relied upon their machines for years. Once a user integrates the machine into her daily life, the persistent, quick access, always–on nature of the machine allows her to take especial advantage of the augmentations the wearable provides [13].

With all of the potential of wearable computing, a critical question becomes how to evaluate the interfaces and applications designed to run on these systems. Researchers and developers need to understand both the utility and the usability of the machines, ensuring that they fulfill real needs and add true benefits while striving for ease of use.

To evaluate wearable computers, we have taken the approach of capturing the user's experience from her perspective. The user's point of view gives the researcher information about the user's interaction with her environment and computer. Placing a capture system on the user also allows the user to remain mobile which enables the researcher to study wearable use in realistic situations. In this article, we present some of the difficulties encountered when evaluating wearable computers and how capture is used to overcome these problems. We present two different implementations of capture systems and discuss their differences. Finally, we present some issues we encountered in using these systems in practice and discuss future directions.

2. Challenges in Evaluation

Traditional desktop computers are often evaluated in a usability lab. The specially outfitted laboratory usually has video cameras to record the user. The computer records the user's interactions with the machine and often the programs the user interacts with in the study are augmented to generate a special log of events useful for the evaluation. Wearable computer evaluation, however, is much more difficult because the use of the computer happens away from a fixed place.

Wearable computers provide their users with several key benefits, such as mobility, privacy, and fast access. Unfortunately, many of these same attributes contribute to the difficulty of studying wearable use. In particular, observing a wearable's use in a realistic setting is problematic because there is a tight physical coupling between user and machine. The ideal physical embodiment of a wearable has it worn as clothing, and wearables are generally used only by their owner in a private manner. For example, a wearable head-up display (Figure 1) is mounted very close to the eye. In this case, the display is opaque, and the user's perception that she can see through it is, in some sense, an illusion supported by user's mind (Figure 2). Thus, the perceived visual interface cannot be captured by the researcher. In addition, wearable keyboards such as the Twiddler (Figure 3) are generally used at the user's side where they are very hard to observe. As a result, a researcher can often only observe the combination of user and machine acting together in the world. Obtaining additional information about the interaction between the user and wearable requires additional tools.

Figure 1. A wearable user's head-up display mounted on eyeglasses.

Another set of issues result from the user's extreme mobility. These include obtaining access to the user and under-

Figure 2. The user's mind merges the images seen by the unoccluded eye and the eye with the opaque display. The resulting perception seemingly overlays the virtual on to the physical environment.

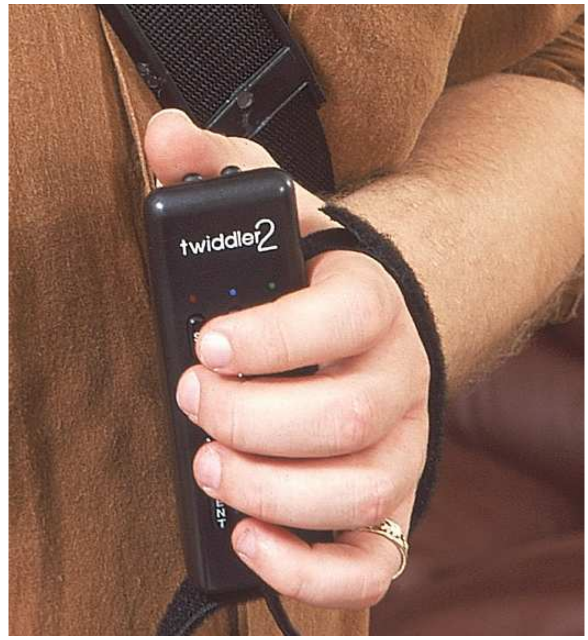

Figure 3. The Twiddler2 one handed chording keyboard with mouse.

standing how the different environments and situations the user encounters influence the machine's use. The mobility of the wearable user can severely hinder the researcher's ability to observe her in person. For example, following a user within a city about her daily life could consume tremendous amounts of resources. In other cases, following the user is not even an option. Some application domains for wearables include potentially hazardous environments where researchers are not permitted. For example, Moffett *et al.* describes the process of designing a wearable application for an offshore oil rig [5]. Access to the work site was prohibited, and even access to the training area was limited. In such a case, the ability of a researcher to examine wearable use without needing physical access to the user would be invaluable.

An additional consequence of the user's mobility is that her context can change drastically as she moves through her world. The context of a situation influences the interactions a user has with the machine in two ways. First, context has direct impact on the user. The effect can range from very subtle moment to moment influences to high level changes in state. For example, a wearable computer user might use a calendar differently in the middle of a conversation with another person than when walking down the street alone. Cognitive models such as Situated Action [14], Activity Theory [6], and Distributed Cognition [3] consider the user's context. While there are significant differences in the details of these theories, they all take into account the greater context of the user [7].

Context and user ingenuity can change use even more drastically as the user opportunistically solves a problem encountered by using the wearable in an unexpected way. For example, wearable users have been known to use their wireless networks and head-up displays to edit papers cooperatively while facing each other in conversation. While the interface was not intended or supported for this use, the availability of the infrastructure allowed the users to spontaneously create a method for seemingly more effective brainstorming. If feasible, evaluation of such occurrences might reveal new applications or methods of encouraging such user innovation.

The second major role of context in wearable computing is context-aware computing. Context-aware applications may significantly change the user experience based on information about the user's context [2]. For example, the Remembrance Agent [10] can use data about a user's location, other people around the user, and notes from the current conversation to search for information on the user's machine that might be relevant to her situation. Such programs alter their functionality to adapt to the current situation or provide contextually relevant information. This adaptability further complicates evaluation.

Problematic access to the user, the tight coupling between user and computer, and context's dual roles of affecting user and application behavior all contribute to the difficulty of examining interfaces and applications built for wearables. A critical issue is how to evaluate interfaces and use under these conditions.

3. Previous Work

Previous efforts have relied upon laboratory studies or using the wearable in the field but in a restricted area. Several studies have used direct observation for evaluation [1, 11, 8]. These studies utilize data that is externally observable about the wearable user's task and often videotape the user's actions. The number of errors, magnitude of mistakes, number of people required, and time for task completion are common metrics available with this technique. However, by only looking at the user's task, the researcher does not have direct information about the interaction between the user and computer.

Other studies have used custom solutions to collect data directly about the user's interaction with her machine. For studying a mobile multimodal system, Oviatt used wireless transmission to send data to a researcher at a field station. This method enabled the researcher to monitor the information for various errors and also permitted real-time observation of data [9]. Similarly, Moffett *et al.* sent data to a remote observation station. In addition, they transmitted video taken of the user by a researcher following him which provided some context of the user's interactions [5]. One downside of sending data to a fixed observation point is that the user's interaction is still limited to the area of wireless coverage.

An alternative configuration that overcomes this limitation transmits data about the machine's use to a researcher with her own mobile device used to monitor the data [15]. This configuration only needs a point to point wireless link, and there is no longer a geographical restriction. However, in addition to the challenge of augmenting the user's machine to provide the needed data, the researcher needs to carry additional monitoring equipment into the field.

Many of these studies also rely upon various form of user self-report in the form of interviews, questionnaires, or informal comments. Another self-report technique, Think Aloud, has been used with wearables by Siegel and Bauer [12]. With this technique, the user reports on her interaction with the machine as they execute a task.

4. Capture and Evaluation

Laboratory studies are convenient, but they constrain the user to a fixed location. Simulating the various effects of context in a laboratory can be very difficult, and as a result, a researcher can only evaluate a subset of the issues involved. Allowing the user to work in a mobile fashion, but constraining her to a fixed environment improves the situation but limits the types of applications and uses of wearables that can be examined. As these machines become more common and move into daily life activities, these restrictions will become more problematic.

By using capture for wearable evaluation we can:

- Maintain user mobility
- Gain access to the user's perspective
- Examine the interaction between user, machine and environment
- Study real situations and the various effects of context
- Evaluate everyday wearable use

By creating a generic capture system, we augment a user's wearable computer with the ability to capture data needed for evaluation. In many senses, we bring the laboratory to the user in order to provide the researcher with access to the user's perspective. This view lets the researcher see the interplay between the user and machine, and examine the various effects of context on those interactions.

The first component of capturing data from the user's point of view is logging her interaction with the computer. Similarly to studying a desktop system, we need to obtain information about the direct interaction with the machine. A large set of possible items could be of interest, such as user input and system output, applications run and their state, and system events.

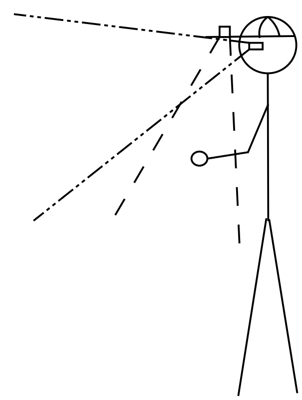

Figure 4. A sample configuration of cameras used to capture the user's context.

The other major component of data collected from the user's perspective is her environment. To capture this information, we employ outward–looking cameras mounted on the user as shown in Figure 4. These views include:

- The user's view: A forward–looking miniature camera mounted on the user's eyeglasses can capture a sense of what is in the user's visual field.
- The user's hands: The hands are the user's primary means of manipulating the world. A camera mounted

on the brim of a hat can capture the view looking down towards the user's hands.

- Environmental View: While the user cannot see behind her, the user does have tacit knowledge of her environment through localized hearing, temporary visual memory, and other cues. A 360 degree view camera can provide more information about of the user's surroundings. In some instances, having surround video may illuminate interactions where the user is not directly facing the object or person to whom she is addressing or attending.

Together these views and the data captured on the wearable provided the researcher with information about the user's perspective. Similarly, a noise canceling microphone mounted in front of the mouth and an ambient sound microphone can provide information as to the user's utterances and the environmental sounds respectively [13].

5. Capture Systems

We have built two separate capture systems that are based on the principles discussed in the previous section. Both are generic systems that augment existing wearables with the ability to collect data from the user's perspective under realistic conditions. However, these systems differ fundamentally in their implementation because they are designed to address different types of wearable evaluation questions.

5.1. Capture Vest

Our first capture system, the Capture Vest, is designed to collect data for usability testing [4]. It records very detailed information from the wearable and uses cameras to record the user's view of her environment. Extra hardware needed for capture is worn in a vest attached to the wearable.

For capturing the interaction between the user and machine, we log information about the X Windowing System run on the user's wearable. By using a modified X Protocol proxy, we record detailed information about input events generated by the user's mouse and keyboard as well as output events rendered to the user's display. Recording the X events has the advantage of being application independent and gives the researcher the ability to log information about legacy programs.

X events provide a low level view of interaction. In theory, the events could be used in conjunction with system and application state to reconstruct the user's display at a given time. Unfortunately, such a system is difficult to maintain. Instead, the video shown on the wearable's head mounted display (HMD) is also recorded. The video provides the researcher a holistic view of what the user sees on her screen.

The researcher can configure this system to capture several streams of video from cameras placed on the user which provide views of the user's interaction with her environment. Our default configuration uses a forward–looking high quality miniature camera mounted on the user's eyeglasses. The top left of Figure 5 shows a typical view from this perspective. The full frame rate video generated by the cameras is encoded and saved using commercial mini Digital Video (DV) decks. A vest, shown in Figure 6, is used to carry all of the hardware needed for capture. In addition to the DV decks, it houses batteries, the camera control units and all of the extra cabling required. A custom circuit injects a tone onto one audio track of each of the DV decks. The circuit is controlled by the capture software run on the wearable, and the tone is used later to synchronize the multiple streams of video to each other and to the X events.

Figure 6. The Capture Vest and wearable computer worn by a user. The vest contains the hardware needed to capture the video from the user's perspective.

Although useful for collecting usability data, this methond is a heavyweight approach. First the system generates a very large amount of data. A short 20 minute study resulted in 7.2 gigabytes of data. The vast majority of this information is from the two DV streams used to capture the user's screen and a single view from her perspective. An 8 hour day would generate approximately 175 GB of

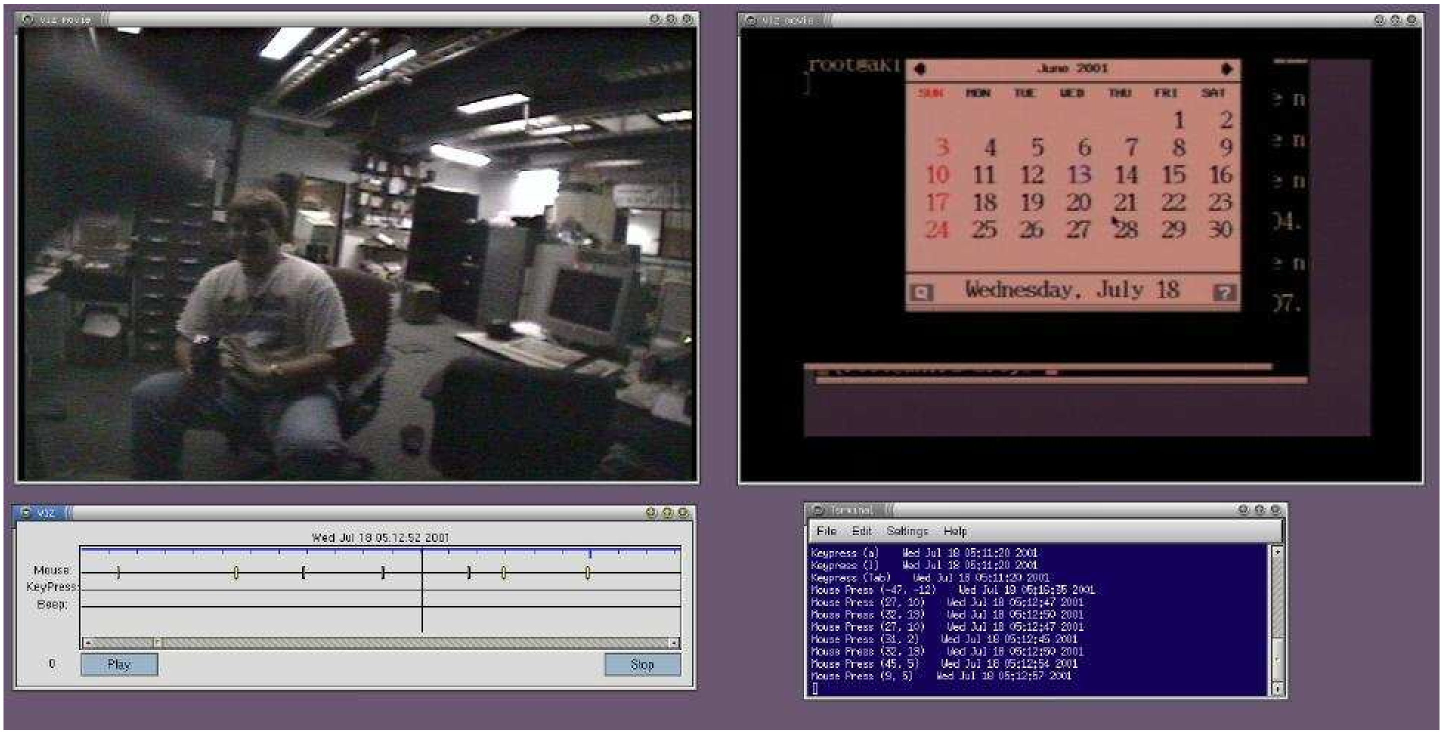

Figure 5. VizWear, the analysis program for data collected with the Capture Vest showing data of a user sitting interacting with a calendar program.

data, and adding extra views would raise that number farther. Even on a workstation, these are nontrivial amounts of information and managing it on a wearable is extremely challenging. Because of the huge data requirements, capture is limited by the length of a DV tape to approximately two hours. In addition, the user must contend with a significantly heavier and bulkier system.

Figure 5 shows our custom analysis tool VizWear which presents a synchronized view of the data collected with the Capture Vest [4]. The top left window contains video taken from the user's perspective which is synchronized to the wearable's display shown in the top right window and to the time line in the bottom left window. The time line displays the events collected during capture. In this configuration it has a line for mouse clicks, key presses, and the audio tone used to synchronize the video streams. By hovering over any event on the time line, the corresponding details, such as the coordinates of mouse clicks and the letters pressed on the keyboard, are displayed in the bottom right window. Finally, the time line window is the main control for playback.

The Capture Vest configuration allows us to capture the detailed information needed for usability analysis. As an initial test of the system, we collected data for the simple task of navigating a calendar application. We tested two common pointing devices with a user sitting and walking. For the cases where the user was sitting (Figure 5), the difficulty of using the mouse pointer on the wearable could be seen in the captured log shown by VizWear. The user's walking caused further deterioration which was manifested as erratic movements in the mouse pointer. Often errors made in the interaction resulted in the user slowing down or momentarily stopping. Using VizWear, the changes in the user's pace could be seen in the video of the forward–looking camera while the errors made on the computer are shown in the video of the user's display.

The combination of Capture Vest and VizWear allows the researcher to distinguish fine-grained interactions between user, wearable, and the environment. In the experiments above, the effects of the user's movement on the mouse pointer while walking is immediately apparent. The user's subsequent compensation of slowing or stopping is also obvious. With more light weight systems such as will be described next, these artifacts would be much more difficult to observe. However, light weight systems are needed to avoid the significant inconvenience of the user's wearing of the Capture Vest.

5.2. Lightweight Capture

For a more recent study we built another capture system, the LightWeight Wearable Capture (LWWC) system. The purpose of this study was to acquire data about an expert user's daily usage of his machine. Instead of collecting fine grained data needed for evaluating usability, we wanted more long term general usage data. Our primary goal was to capture real user interactions that spanned weeks. The Capture Vest was too heavyweight, and the very high resolution data it provides would have required significant processing by the researcher to extract the usage trends of interest.

Instead, we created a lightweight software system to collect the needed data. Like the Capture Vest, this system collects information from the user's point of view about both the machine's use and environment; however, we gather data from fewer sources and with less temporal resolution.

While the Capture Vest records a detailed event log and full frame rate video of the user's display, the LWWC only takes screen shots a few times a second. The program acquires new images and buffers them in memory. Because the user's display often remain unchanged for long periods of time, the system only saves an image if it is different from the previous one. This minimizes the storage space needed and reduces disk I/O which saves power. However, due to this compromise, the LWWC can miss user activity. It is not uncommon for a user to make many changes or switch between screens faster that images are recorded. The capture rate needs to be set to an appropriate rate for the study undertaken.

The LWWC also captures video from the user's perspective of his surroundings. In keeping with its lightweight nature, it uses a small low quality black and white NTSC camera and a USB digitizer to grab a frame once every few seconds. This system gives the researcher coarse information about the user's environment.

Along with the capture system we wrote a analysis program, LW VizWear, to view the data. Figure 7 shows some typical data from a session. The wearable user's display is shown in the bottom left window. The top window has two time lines. The first time line is a histogram of when screen shots were saved. Because we only record unique images, this view provides the researcher with a rough indication of the amount of interaction with the machine. In this case, the view shows data for approximately 12 hours with several distinct bursts of use. There is always some activity because the user's display has a clock that updates once per minute. Notice there is an absence of activity in the middle of this session. This deficit indicates that the capture program was not running during this period either because it was explicitly stopped or because the wearable was off. The bottom right window allows the researcher to enter text annotations to tag data. The time and duration of all of the annotations are displayed on the second time line in the topmost window as brackets. This top window also has the controls for playback of the data. The second window from the top shows a zoomed in view of the section of the main histogram highlighted with white. At this resolution the researcher can see when individual images were recorded.

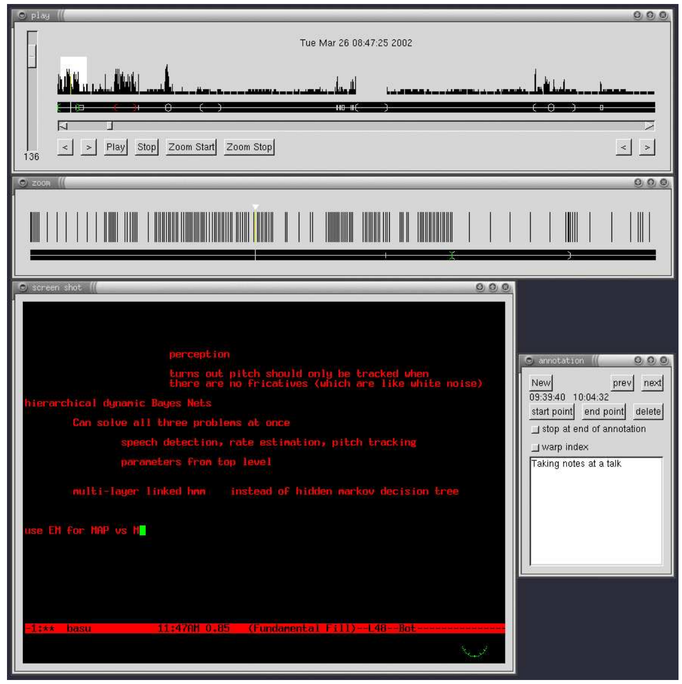

Figure 7. The analysis program for the lightweight system.

Since the system is very lightweight and requires little extra hardware, it can be used in many more situations than the Capture Vest, as was desired. We used the LWWC to collect data of an expert wearable user's use of his machine in his daily life for five weeks. The nature of the system made it easy to capture a significant amount of the user's interaction with his machine over that time period while he maintained almost unaltered usage of his wearable. As expected, we captured data about common day to day activities such as taking notes at a talk. We were also able to collect information about the user's interactions that ranged from a late night impromptu meeting in a hotel lobby to using the machine on a trip to a foreign country. Thus, this lightweight system allows access to data that would have been very difficult to obtain by other means.

6. Dimensions of Capture

These two systems follow the same principles presented earlier of augmenting a user's wearable to collect data in the field from the user's perspective. However, the two implementations differ in their data capture requirements. The differences center around three key aspects that together define a space of capture systems. The two implementations we have presented represent two solutions with different features in this space.

The different dimensions in capture requirements can be characterized by:

1. **The sources of data:** The type and number of data sources, such as cameras, microphones, interface event loggers, etc., can significantly impact a study.

2. **The resolution of data:** For the different sources, there are potentially several options for sampling rate. For example, this dimension refers to the quality and frame rate of images saved.

3. **The length of capture.**

Because of limited storage, a system cannot record high resolution data from many sources for long periods of time. Even if there were not the storage limitation, selectively limiting the data saved would be useful. Without such a limitation, there would be a large amount of excess data not directly relevant to the current evaluation. This extraneous data could overwhelm the researcher and would need to be filtered. By examining the evaluation to be undertaken, the various tradeoffs can be weighed and a point in this space can be selected that provides the researcher the appropriate type and amount of information.

With the Capture Vest we took the approach of storing as many different sources of information as possible. It has the ability to record several streams of video from various views of the user's environment and logs a broad range of information about the user's interaction with the machine in the form of detailed X events. The system saves high resolution data from the various sources including the 30 frame per second video that captures the user's context. Finally, the vest is limited by storage to capture interactions that last at most a few hours.

The lightweight system, on the other hand, merely uses two sources of information. It takes screen shots and saves images from a single camera. Compared to the Capture Vest, the LWWC has a relatively low resolution, saving at most a few images per second. However, this system has the ability to collect interaction with the machine for periods that span weeks.

The storage requirements of the system can be determined by choosing a point in the three dimensions of source, resolution, and duration. Differing storage requirements result in varying impacts on the user and machine. With very high data requirements, the wearable must be augmented to capture the extra information. For instance, with the Capture Vest we used DV decks to encode and save the video streams. Although this method minimizes the impact on the computer, the user bears the extra burden of carrying additional hardware. The other approach, if the data requirements are sufficiently low, is to place the extra task of capture on the wearable. This reduces the burden on the user but does impact the machine. Even the lightweight capture system caused a minor decrease in the responsiveness of the user interface of the computer. More significantly, the battery life of the machine, a precious resource for everyday-use wearables, was also reduced due to the need to capture and save the periodic data.

As technology progresses and storage space on the user increases, these issues will lessen to some extent. However, wearable computers for the foreseeable future will continue to have scarce resources such as processing power, storage space, and battery life that can all be affected by adding the extra task of capture.

7. Capture in Practice

Although capture proved useful for evaluation, there were still some issues encountered in using these capture systems in practice. In particular, as the length of study increased, issues of durability, access to the user, and privacy became more prevalent.

By augmenting the user's wearable with the ability to capture we are effectively extending his machine. With this configuration, problems in the capture system can affect the wearable. Therefore, the capture system needs to be as reliable and durable as the wearable. With our five week study using the lightweight system we had severe issues with the camera used to capture images of the user's environment. Our first problem was the stability of the system. We prototyped and debugged the capture system on a wearable nearly identical to the target user's machine. However, once transfered to the user's wearable, the driver for the frame grabber would occasionally freeze the computer. As a result the user disabled that portion of the capture system. Fortunately, the system was sufficiently modular that the entire capture system was not turned off. After finally working out the driver issues, the camera physically broke.

The Capture Vest also has issues of durability. Adding the additional hardware needed for capture increases the number of points of possible failure. In particular, managing the extra cables needed to connect all of the components is problematic; the extra connectors and cables need to be as rugged as the wearable itself. When the user critically depends on their machine, problems induced by the capture system are intolerable to the user. Also, if part of the capture system breaks, the data for a session can become useless.

Capture greatly reduces the need for the researcher to have direct access to the user; however, it is still required. For our long term study our user would often be traveling for a week at a time which made the camera debugging process difficult. The researcher also needs access to the machine to collect the captured data and maintain the capture software. When this is done on a user's machine which is used daily, the researcher must work around the user's schedule.

To help overcome the failure of the camera during our five week study we utilized interviews. The captured screen shots were used to situate the user to a given point in time. Questions were asked about the context of the user and the applications being used. Although a researcher must be cautious of post hoc rationalization by the user, this method provided a very detailed account of the interactions involved. The screen shots worked surprisingly well as a prompt to aid the user in recalling events. Combined, this data gave us a rich account of the user's interaction with his machine and environment.

Another key issue is privacy. By capturing from the user's perspective there is the concern for the privacy of the user and the privacy of the people the user encounters. Because wearables are so personal, the data entered into a wearable and maintained there can be very sensitive. This can include the user's passwords, credit card numbers, email, or even sensitive medical information. During our long term study, the user would on some occasions deliberately stop the capture. On a few occasions, the user manually edited the log to remove small portions of data. After some discussion, we added the ability to suspend, examine, and delete portions of the log. However, it is interesting to note that this feature was never actually used in practice once implemented. Upon reviewing the data with the user, he remarked that on a few occasions he forgot about the capture and would have otherwise censored the log. This highlights an interesting tension between the researcher's desire to minimize the bias induced by study, where having the user forget about the capture is beneficial, and the desire to maintain privacy. Another option would be to have the user review and censor the log after capture was complete. However, this requires a great deal of extra effort from the user and could introduce other biases.

8. Future Work and Conclusions

With the great potential that wearable computing holds, evaluation becomes critical to ensuring the success of the field. Unfortunately, the wearable's benefits of enabling user mobility and providing a tight coupling with the user also contribute to the difficulty of examining the machine's use. Bringing the laboratory to the user allows us to overcome these problems by capturing data from the user's perspective. This technique enables the user to remain mobile so that evaluation can take place in the field under realistic conditions.

Different evaluation questions impose different needs on the capture system used. The Capture Vest, designed for studying usability issues, collects high resolution data from multiple sources but only for a short duration. Our lightweight capture system collected usage data from an expert user for weeks but has fewer information sources and courser granularity.

In the future we will work to improve our capture systems. We have already identified some issues when using the systems in practice involving reliability, and privacy concerns pose another interesting area of future work. The evaluation tools could also benefit from improvement. Currently they provide the basic set of features needed but other views and analysis capabilities would be valuable. Additional ways to analyze the data at different time scales would be useful. VizWear could also benefit from the ability to query and highlight events.

Although capture on the wearable is a powerful method, a researcher should not be limited to the data provided by the capture system. Additional Human-Computer Interaction techniques such as field observation and user self-report provide alternative views of user interaction. When appropriate, they can provide valuable complementary data and give the researcher further insight for the challenging task of wearable evaluation. Extending the capture tools to work directly with these methods is another area of improvement. As some experiments in the related work have shown, the ability to monitor the data remotely would be useful and is a likely candidate for inclusion.

9. Acknowledgements

Funding provided, in part, by NSF CAREER grant #0093291 and the Rehabilitation Engineering Research Center on Mobile Wireless Technologies for Persons with Disabilities (Wireless RERC). The Wireless RERC is funded by the National Institute on Disability and Rehabilitation Research of the U.S. Department of Education under grant number H133E010804. The opinions contained in this publication are those of the grantee and do not necessarily reflect those of the U.S. Department of Education.

References

[1] M. Billinghurst, S. Bee, J. Bowskill, and H. Kato. Asymmetries in collaborative wearable interfaces. In *Proceedings of IEEE International Symposium on Wearable Computing (ISWC 1999)*, San Francisco, CA, 1999.

[2] A. Dey. *Providing Architectural Support for Building Context-Aware Applications*. PhD thesis, Georgia Institute of Technology, Atlanta, GA, December 2000.

[3] E. Hutchins. *Cognition in the Wild*. MIT Press, 1995.

[4] K. Lyons and T. Starner. Mobile capture for wearable computer usability testing. In *Proceedings of IEEE International Symposium on Wearable Computing (ISWC 2001)*, Zurich, Switerland, 2001.

[5] J. Moffett, D. Wahila, C. Graefe, J. Siegel, and J. Swart. Enriching the design process: Developing a wearable operator's assistant. In *IEEE Intl. Symp. on Wearable Computers*, pages 35–42, Atlanta, GA, 2000.

[6] B. A. Nardi, editor. *Context and Consciousness : Activity Theory and Human-Computer Interaction*. MIT Press, 1995.

[7] B. A. Nardi. Studying context: a comparison of activity theory, situated action models, and distributed cognition. pages 69–102, 1995.

[8] J. Ockerman. *Task Guidance and Procedure Context: Aiding Workers in Appropriate Procedure Following*. PhD thesis, Georgia Institute of Technology, Atlanta, GA, April 2000.

[9] S. Oviatt. Multimodal system processing in mobile environments. In *Proceedings of the 13th annual ACM symposium on User interface software and technology*, pages 21–30. ACM Press, 2000.

[10] B. Rhodes. *Just-In-Time Information Retrieval*. PhD thesis, MIT Media Laboratory, Cambridge, MA, June 2000.

[11] D. A. Ross and B. B. Blasch. Evaluation of orientation interfaces for wearable computers. In *Proceedings of IEEE International Symposium on Wearable Computing (ISWC 2000)*, pages 51–58, Atlanta, GA, 2000.

[12] J. Siegel and M. Bauer. A field usability evaluation of a wearable system. In *IEEE Intl. Symp. on Wearable Computers*, pages 18–22, Cambridge, MA, 1997.

[13] T. Starner. *Wearable Computing and Context Awareness*. PhD thesis, MIT Media Laboratory, Cambridge, MA, May 1999.

[14] L. A. Suchman. *Plans and Situated Actions: The Problem of Human-Machine Communication*. Cambridge University Press, 1987.

[15] R. Suomela, J. Lehikoinen, and I. Salminen. A system for evaluating augmented reality user interfaces in wearable computers. In *Proceedings of IEEE International Symposium on Wearable Computing (ISWC 2001)*, Zurich, Switerland, 2001.