SEAMFUL DESIGN: SHOWING THE SEAMS IN WEARABLE COMPUTING

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In this paper, we question the assumption that seamless integration of computer system components is necessarily a design requirement for wearable computing and for ubiquitous computing. We explore Mark Weiser's notions of seamlessness and 'seamfulness', and use them in discussing the design and use of wearable and ubicomp systems. The physical nature of the systems we design reveals itself in, for example, uncertainty in sensing, limited coverage of communications infrastructure, and the transformations needed to share data between heterogeneous tools and media. When such seams show through, as they inevitably do, users perceive and appropriate them for their own uses. However, we suggest that new opportunities for system design arise if we take fuller account of this process. We offer examples of seams and some suggestions for seamful design, drawing from the Equator interdisciplinary research collaboration's work on ubiquitous computing and mixed reality systems. More particularly, we focus on our work in Equator's *City* project, on a system that lets a visitor using a PDA in a museum exhibition or cultural institution co-visit with people using virtual reality and web versions of the same institution.

Our work is strongly influenced by the vision of ubiquitous computing presented by Mark Weiser (1). One of the broader design goals of ubicomp is invisibility:

> A good tool is an invisible tool. By invisible, I mean that the tool does not intrude on your consciousness; you focus on the task, not the tool.

In other words, one no longer needs to attend to the tool when using it. Ubiquity involves multiple, heterogeneous devices providing highly dispersed input, output and computational capabilities. These parts collectively form a tool for interaction that is "literally visible, effectively invisible" because their design, along with one's experience and understanding of them, lets one focus on interaction *through* the whole instead of *on* the parts—just as a carpenter does carpentry without a constant and conscious focus on his hammer.

However, it appears that this notion of invisibility has been translated into requirements for seamless integration of computer system components, as well as the interactions supported by those components. Seamlessness is an attractive prospect, extending the ideas of metaphoric direct manipulation to make our interactions with computers more literal, reducing the distractions that such interactions currently introduce. However, Weiser describes seamlessness as a misleading or misguided concept. In his invited talks at UIST94 (2) and USENIX95 (3), he suggests that making things seamless amounts to making everything the same, and he advocates *seamful* systems (with "beautiful seams") as a goal. Paraphrasing Weiser's talk slides only slightly, and retaining his emphasis: making everything the same is easy; letting everything be *itself*, *with* other things, is hard.

To Weiser, making every place the same meant mobile and distributed technology offering access to information in ways that do not take account of the particular character of the place one is in. Similarly, making every tool the same meant reducing components, tools and systems to their 'lowest common denominator'. Around Xerox PARC, Weiser complained that 'seamless design' meant sacrificing the richness of each tool in order to obtain bland compatibility, for example when one tool is chosen as primary and the others are reduced and simplified so that they conform to it (personal communication). Seamfully integrated tools would maintain the unique characteristics of each tool, through transformations that retained their individual characteristics. Interaction would be seamless even though the features of each tool were apparent. Part of ubicomp was seamful design, where integration may be hard but the quality of interaction is improved by letting each tool 'be itself'.

Weiser suggests to us that "the unit of design should be social people, in their environment, plus your device". A device that senses, models and lets the user take advantage of the context of 'other things', such as nearby people and the non–digital objects in their environment, is of course well–established within the ubicomp community. We suggest, however, that letting a ubicomp system be itself means accepting all its physical and computational characteristics—that may either be weaknesses or strengths. A user's activity is influenced by what they perceive and understand of sensors, transducers and other I/O devices, and the system's internal models and infrastructure.

For example, mobile phone signal strength is a physical property of the system infrastructure that is sensed and made apparent to phone users in everyday use through the phone's interface, and also through whether they can hear people clearly, make a call, get an Internet connection, and so on. Experience of signal strength offers a credible excuse for not returning a call, or for ending a call early—sometimes even when the signal is strong. Users usually do not want or need to know what cell their phone is using, or that their phone has been handed over to another cell. Cell handover remains deep in the infrastructure so that, to the user, cell handover is handled seamlessly. However, mobile phones can be set to display the current cell (if the service provider permits), and some people (including one of the authors of this paper) choose to enable this facility. This is an elegant ambient or peripheral presentation of potentially useful information that is characteristic of the phone as a physical sensor and the phone network as a cell structure. Users can choose whether this information is presented and, for example, whether to seek a stronger signal by moving to a position that forces a perceptible handover to another cell.

The physical characteristics of digital systems are often apparent as uncertainty and inaccuracy. For example, digital sensors such as cameras, GPS receivers and ultrasonic trackers have limited sampling rates and resolution, are prone to communication delays and disconnections, have finite data storage limits and have representational schemes of finite scope and accuracy. As designers, we can be defensive or negative about such seams in devices and infrastructure, and try to design them out. This approach is not always affordable or practical. We may simply not have the resources to improve all aspects of a system's performance in all the places that it might be used. We always have finite resources, and therefore it is likely that seams may be perceptible to users.

We can choose a more positive design approach which allows seams to become a resource for users, rather than a system failing. By letting the tool 'be itself' and accepting its characteristics, we can find a more pragmatic design for our systems. Note that we do not claim that seamlessness is always bad, or that seamfulness is always good. Rather, we suggest that they form a continuum or design space—with lots of room for new seamful design work.

UNCERTAINTY AND HETEROGENEITY

In this section we present examples of seams and seamful design involving uncertainty, in particular uncertainty in sensor technologies and uncertainty derived from imperfect transformations between heterogeneous tools and systems. We focus on an aspect of seamfulness related to the way that users 'design' their activity to take advantage of seams, and even appropriate them i.e. use them in ways that the designers may not have intended or imagined.

The City project has developed a prototype system for the Mackintosh Interpretation Centre, an exhibition in Glasgow. Our system allows a visitor using a PDA in the exhibition room either as part of U. Bristol 'cyberjacket' or carried in the hand (Figure 1, top left) to co-visit with other people using VR and web versions of the same exhibition. The system allowed visitors to talk over a shared audio channel, share location and interact around 'hybrid' museum exhibits. The system design was informed by observational studies of co-visiting in conventional museums, as discussed by Galani and Chalmers (4), the details of the system design were described in MacColl et al. (5), and findings from user trials were described in Brown et al. (6).

In the trials we found that the system effectively supported many, but not all, of the social aspects of a shared visit to a traditional museum. The system was also seamful enough to let the visitors maintain the characteristics of the new media. The PDA user had as a resource the full visual and tactile richness of the exhibition room, which we could not offer the VR and web visitors, but the latter two could use online media unavailable on the PDA. The shared resources that the system provided were effective in allowing users to navigate together, collaborate around objects, share their experiences and talk about the exhibition. The individual resources ensured that each participant had a contribution that only he or she could make.

The system aims to create a shared spatial awareness through mutual visibility, indicating to other visitors what a particular visitor might be viewing. The PDA includes a sensor package that is part of an ultrasonic positioning system described by Randell and Muller (7), and an electronic compass for orientation information. Position and orientation are displayed on a map of the exhibition room, along with positions and orientations of the other two visitors (Figure 1, bottom left).

The VR visitor's position was that of his or her avatar in the 3D model. Other visitors' positions were shown using avatars, as in (Figure 1, top right). Each exhibit is modelled in the VR at a coarse level that shows overall form but not fine detail such as textual labels, and each exhibit has a corresponding web page containing text and 2D images from the exhibition catalogue. By approaching an exhibit in the 3D model, the VR visitor triggers display of information about that exhibit in the web browser. The spatial position of the visitor is converted to a name that represents a spatial extent, or location, in the room.

The web visitor's location was determined from his or her use of a 2D map of the room, as shown in an applet (Figure 1, bottom right). Mouse clicks were interpreted as movements, with the direction from the old location to the new location treated as the new orientation. Moving to a new location triggered display of web information in much the same way as for the VR visitor, except that a menu of links is offered as an alternative to map–based navigation.

The ultrasonic positioning, in common with all physical sensing, is subject to error, leading to uncertainty about the position of the PDA visitor. In addition to sensing error, the exhibition space is challenging, split into two large areas by a partial wall, with some display areas covered by roofs. The space includes surfaces that are acoustically very reflective. For aesthetics and coverage, ultrasonic transmissions

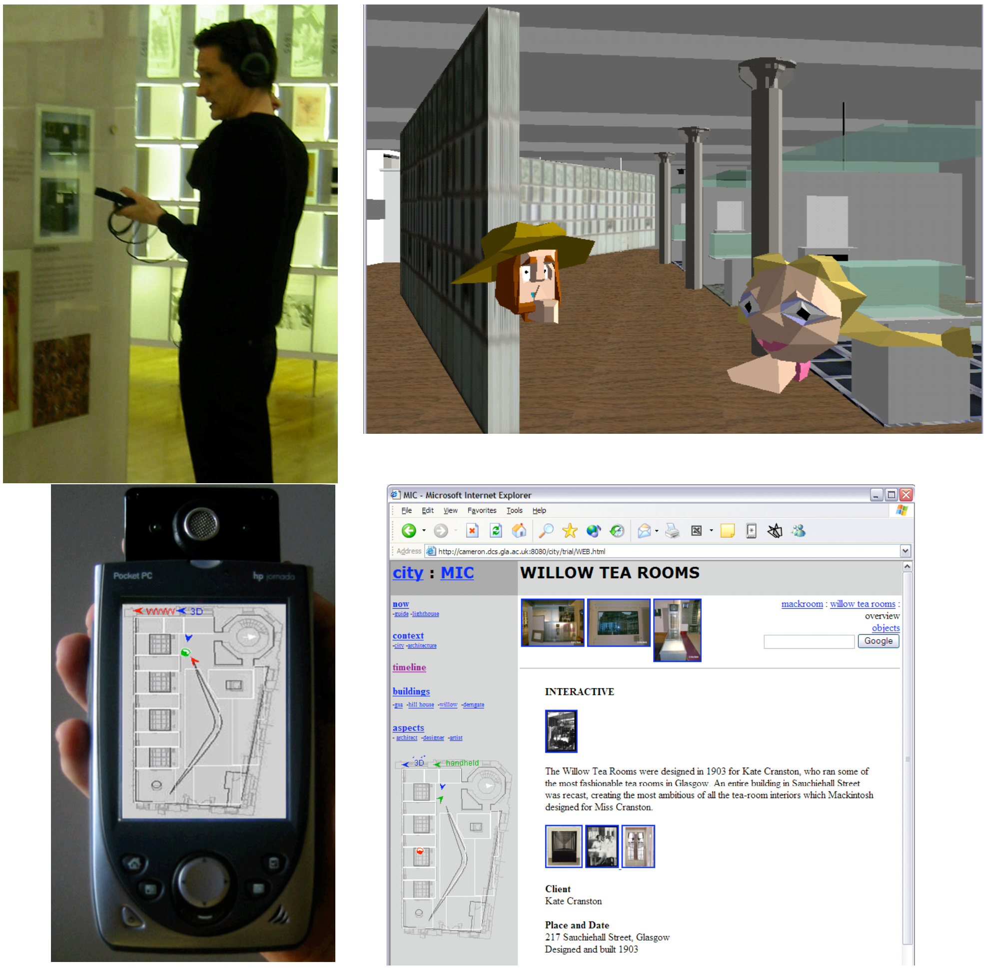

Figure 1. The image top left shows a visitor in the Mackintosh Interpretation Centre with a PDA, ultrasonic receiver, headphone and microphone. A close up view (bottom left) shows the PDA and receiver, with the PDA showing a map of the centre with all three visitors' locations. The image top right shows the VR visitor's 3D graphical display, with avatars for co–visitors. The web visitor's browser can be seen bottom right, with a map in an applet as well as a page of content describing the Willow Tea Rooms.

are reflected off the ceiling. Testing indicates 50% accuracy of 0.52m, 95% accuracy of 1.83m, and an overall standard deviation of 1.29m.

Uncertainty about the actual position of a PDA visitor showed in the spatial awareness displays by apparent jumps of up to 2m. This had effects on other aspects of the system, such as the generation of location-sensitive web content for PDA visitors. While this uncertainty sometimes made it difficult for trial participants to establish shared context, they developed habits and strategies, such as verbal description and physical movement, which allowed them to focus successfully on the tasks they were set in the trial, rather than tools such as the handheld and the ultrasonics.

Here, we were being excessively seamless, in the sense of choosing a precise VR–like representation as primary, and simplifying or reducing the other visitor representations to conform to it. We transformed the estimated position of the PDA user to positions on maps and in the VR, and users' interaction soon revealed to them that these apparently precise representations were not as clean and accurate as they seemed. Showing the PDA visitor as a spatial extent or probability distribution might have been more useful for them.

Each user trial of our system in the Mackintosh Interpretation Centre only lasted an hour, on average. Nevertheless, we did observe some simple examples of users designing their activity to take account of the heterogeneity of our system, for example VR activity being shown in maps (and vice versa). For example, a VR visitor developed a 'wiggle' gesture to show others using maps where he was. He moved his avatar to run back and forth, and initially also said that he was running back and forth. This would seem excessive or eccentric in everyday interaction, and also in VR–only interaction, where smaller scale gestures would be appropriate, such as raising or waving a hand. Here, however, the scale of presentation on small maps meant that a larger gesture was necessary and appropriate to producing the desired communicative effect.

Another example of users' accommodation of heterogeneity in our system involved trial participants shaping their talk to the different resources they each had. The PDA visitor could see all of a long 'timeline' wall of chronologically ordered panels that described an artist's life. The VR and web visitors could only see information for a single year at a time. The sensing of the position of the PDA visitor as well as the display of all the visitors' positions were both too coarse–grained for position to be used as a gesture or reference towards a particular panel. The visitors developed a way to verbally guide each other to particular images and panels. They emphasised and repeated the year far more than would be necessary among traditional visitors to the Centre, and in ways that would seem very odd among such visitors.

Another Equator project, CityWide, involved longer–term use of ubicomp technology for collaboration —or, more accurately, for competition. CityWide ran a mixed reality game called "Can You See Me Now?" (CYSMN) for two days in 2001. As described by Flintham et al. (8), this involved the use of handheld computers and augmented reality displays while moving through the streets of the city of Sheffield. It was a fast–paced chase game in which online players (members of the public using the Internet) were chased across a map of the city by three runners. The runners were moving through the city streets and their positions were determined using wearable GPS antennae—whereas players' positions were controlled through their map tools. Analysis of system logs shows estimated GPS errors ranged from 4m to 106m, with a mean of 12.4m. Error varied according to position in the game area, with some of the more open spaces exhibiting typically only a few meters error while the more narrow built–up streets suffered considerably more.

Of the 214 online players who took part, the best time—time without being caught—was 50 minutes. The worst was 13 seconds. In contrast, the runners were active for almost all of the two–day event, and had time to talk with each other and develop tactics. For example, runners became increasingly aware of GPS inaccuracy and where on the city streets it was most likely to be experienced. By the second day, they had begun to exploit this knowledge by waiting for players to enter areas with higher GPS accuracy, i.e. where a runner could benefit from moving more quickly. On the first day of play, runners struggled to catch many players, but on the second day the runners' appropriation of inaccuracy significantly changed the balance of the game.

Sensor accuracy is, of course, an isolated example of the much larger problem (or opportunity) of uncertainty. Ubiquitous computing systems must increasingly deal with complex and dynamic technical problems related to bandwidth, power, latency, disconnection, and so forth. As we have tried to show in this section, non-technical aspects, such as awareness of others' locations and activity, are also affected by uncertainty. These are often apparent through the patterns of social interaction more than through interaction with devices and interfaces. Privacy, for example, can be seen as explicit control of the degree of certainty we permit others to have about us, e.g. by permitting others to know roughly, but not exactly, where we are.

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Rather than fighting against uncertainty, we could make a deliberate choice to present and use it. There are several presentation policies (suggested by our colleague, Steve Benford) that may be suitable:

- *pessimistic:* only show information that is known to be correct
- *optimistic:* show everything as if it were correct;
- *cautious:* explicitly present uncertainty; and
- *opportunistic:* exploit uncertainty.

We are considering opportunistic presentations that may be discordant, in the sense of being deliberately designed to use ambiguity and uncertainty in interesting ways that make users pause or reflect—as has been discussed by Gaver et al. (9). However, our current work on seamful design involves developing cautious presentations that accommodate uncertainty in 802.11 communications and in ultrasonic- and GPS–based positioning. For example, we are experimenting with showing a sensed position as a spatial extent, rather than as a point, and showing the estimated spatial distributions of communications strength and positional accuracy in the exhibition room and city streets.

An example experiment is illustrated in Figure 2, where an estimated distribution of 802.11b signal strength is shown as a map layer, overlaid on a section of an aerial photograph displayed on a Hewlett–Packard iPAQ. Such photographs and maps are shown within an archaeological survey application being developed and tested in and around our university, but intended for field surveys where high–bandwidth network connectivity is even patchier than around our campus. This application keeps the map (or photograph) roughly centred on where the user is according to a GPS sensor attached to the PDA, or according to where the user indicates by clicking. The application also supports multiple overlays, and supports panning and zooming. We added the 802.11 overlay to help the user understand where he or she can (and cannot) use our wireless Ethernet, access a shared database of surveyed features, and communicate with colleagues. In other words, each user of the survey application has a resource that should aid them in understanding how to change an aspect of their non-digital context—position—in order to change digital aspects of their context such as database accessibility, and social aspects such as being reachable by one's boss.

As the user walks about with his or her PDA, a C# program periodically samples 802.11 signal strength and OSGB position. When there is a wireless network connection, this data is sent to a PGSQL database

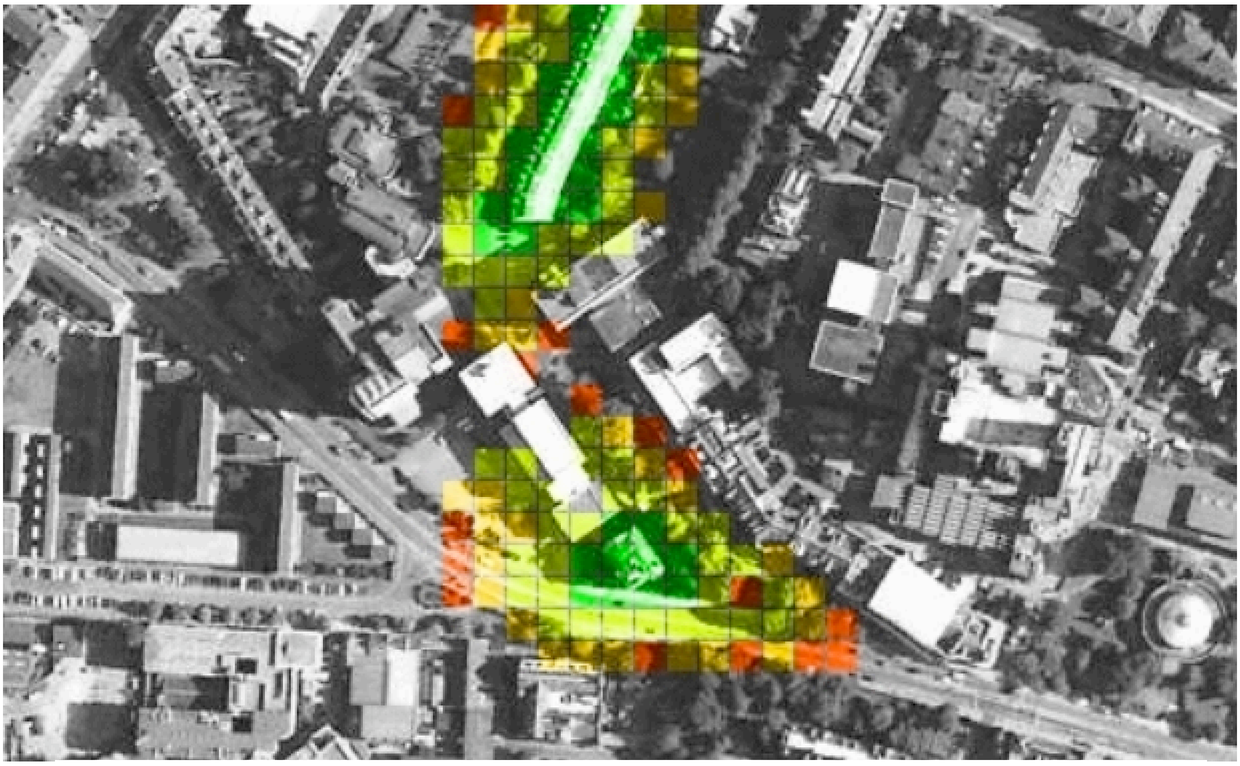

Figure 2. A map layer showing the estimated distribution of signal strength for one of our department's 802.11b networks, overlaid on an aerial photograph of the university campus within a PDA-based archaeological survey tool. This tool uses a shared database running on a PC on this network, and knowledge of where one can get a network connection can be used to judge how to manage the survey and collection of data from a wider area than the network covers. Showing the infrastructure in this way lets the user decide when and where to go in order to put his or her survey data into the shared store, retrieve new information, and communicate with colleagues.

running on a machine within the department. When there is no connection this data is added to a queue, pending a new network connection that will trigger a flush to the database. Communication to the database is handled by an ASP .NET XML web server. Depending on whether the PDA is being used, or a tablet or laptop, 802.11 signal strength can come either from an API specific to the HP5450 iPAQ or from the more widely usable Windows Management Instrumentation (WMI).

In order to respond to a user's street movement or map click, another client program asks the XML web server for map data that corresponds to the currently displayed region of the map or aerial photograph. (Clearly, this server is only accessible when one has a net connection. Otherwise, cached map data is used.) The client also specifies a scale for the overlaid grid of squares. The database server searches the database for the last 10 entries for each square metre in each of the map squares, averaging them to provide the final value for each square. All the requests go through the ASP .NET web service as XML but, to decrease net traffic, we send all the map data as a coded string whose size is less than 3% of the size of corresponding XML version of the same data.

Reflecting on this simple example of seamful design, the survey application helps users 'design' their activity, in ways that take account of the characteristics of the digital resources that form part of their work context. While network infrastructure is not traditionally considered as part of the user interface, the characteristics of wireless networks clearly affect user interaction and therefore are good candidates to be part of the interface. By revealing such seams, users can better understand when and where to use digital resources such as network connectivity—and when *not* to—as they go about their work and use our systems in their ways. We see this as appropriate to ubiquitous computing which, as Weiser suggested, aims to let people select from and combine both digital and traditional media in ways that suit their changing priorities of everyday life.

CONCLUSION

It might be considered heretical to suggest that ubiquitous computing might be invisible, but not seamless. On the other hand, there is the danger of uncritically treating Mark Weiser's words as gospel truth. However, we do not see our work in either of these ways. We have tried to understand Weiser's discussion, how he drew his ideas from fields such as philosophy, psychology and sociology, and the systems that arose from his design proposals. Our experience with system design and users' interaction, as well as our understanding of other studies and systems, lead us to suggest that seamfulness is a useful and practical issue for system designers in general, and for designers of sensor–rich systems in particular.

We do not see seamlessness as always bad and seamfulness as always good. Supporting appropriation may be a bad design choice in some situations, e.g. where consistent interaction is desirable for legal, medical or educational reasons, and a good choice in others e.g. where personalisation, adaptation and exploration are required. However, we suggest that deliberately affording knowledge and use of seams can be not merely pragmatic but empowering. We should treat seamful and seamless design approaches as different tools, to be understood and used in ways that suit the settings, technologies and users we design for.

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