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Wearable Sensing for Dynamic Management of Dense Ubiquitous Media

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***Abstract*— Most visions of ubiquitous computing anticipate a world permeated by a dense sampling of sensors, many of which will be capable of capturing, analyzing, and transmitting personally relevant and potentially privacy-sensitive media, such as video, audio, and identification information. This paper describes a set of sensor platforms that we have designed to experiment with personalization, interaction, and control in such dense media capture environments.**

Keywords-wearable sensors; ubiquitous media; distributed sensor networks; in-situ interaction; privacy

I. INTRODUCTION

People commonly experience difficulty and frustration organizing the diverse media that they collect throughout their lives. Despite the many software tools and organizational aids that have appeared, media capture technology is exploding, and image/video/audio acquisition capability is pervading many of our common digital devices (e.g., laptops, cell phones, appliances, toys, etc.), providing opportunities for even more personal media generation and potential challenges to privacy. Although research projects such as Microsoft's My Life Bits [1] work to address challenges implicit in organizing burgeoning streams of heterogeneous digitized personal media, the problem will soon expand enormously when we have access to information coming from ubiquitously deployed sensor networks, many of which will possess the capability of gathering audio and video, as the associated costs and implementation overhead quickly drop while the utility afforded from this information (and the ability to meaningfully process it) rises. Compelling scenarios of life in such a world can be found in recent work by highly-regarded speculative fiction authors (e.g., [2]). In such musings, it becomes clear that people need to be able to dynamically access, browse, and restrict information gathered about them from these distributed multimodal sensors.

In this paper, we describe a set of systems that we are developing to conduct research in this area. In the experiments that we are pursuing, captured media and sensor signals are labeled and constrained from parameters that are collected and broadcast by wearable systems – namely badges and wristbands that collect data from which personal affect and social parameters can be derived, and another badge that is dedicated to asserting a dynamic privacy protocol.

Figure 1. A Ubiquitous Sensor Portal (USP)

II. MEDIA AND SENSOR INFRASTRUCTURE

Through the use of this variety of devices, our system positions its capabilities where they can be the most effective. The wearable devices are tightly integrated with their subject, allowing access to data pertaining to ID, affective state, social behavior, and human gestural motion. The networked devices in the surrounding environment provide features that require too much power to be included in the wearable suite, are location/environment specific, or otherwise benefit from an objective perspective. Although some audio capture can come from our electronic badges and some experiments will also exploit first-person-perspective video from high-quality cell phone cameras (like that on the Nokia N95) worn around the neck as in [3], the main infrastructure for capturing media are wall-mounted, sensor-rich Ubiquitous Sensor Portals (USPs), one of which is shown in Figure 1. We have currently built 45 of these devices, which are installed throughout our building to form a dense ubiquitous media environment.

The portals are input-output devices. In addition to their myriad of sensors, described below, they also provide a small touch-screen display (see Fig. 2) and audio speaker. This way, information doesn't just stream away from the user's environment – the portals can also manifest virtual and remote phenomena into the user's space.

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Figure 2. A badged user interacting via a wall-mounted USP's touch screen interface

The main feature of the USP is its video camera, capable of recording and streaming DVD-quality video and snapping 3.1 megapixel still images. The video board is based around a TI DaVinci Processor [4], which sports two cores – one a dedicated video DSP and another an integral ARM9 that runs Linux. The camera is directly wired to the DaVinci's DSP, which can be used to process the pixels, perform vision computations, and execute video CODECs for compression. The video board accommodates slotted flash memory, allowing a large local video store in addition to enabling fast streaming over the wired network. The devices also have motorized pan, tilt, and auto-focus for automatic shot composition.

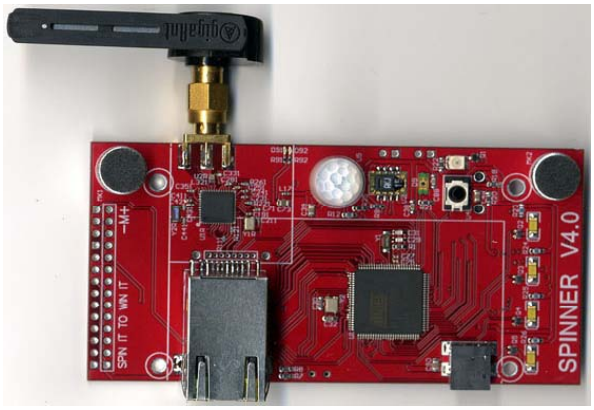

Figure 3. The environmental sensor board

Besides the audio and video capabilities, the USPs sport a full-suite of environmental sensing. This is provided on a separate circuit board shown in Figure 3 that can plug into a wired network for standalone use or be slaved to the video board (its current configuration in the USP). The supported sensors include stereo audio (the board is managed by an AVR32 processor [5], which has audio DSP capability), temperature, humidity, motion, vibration, light, and an IR communications port. These sensors can provide information about the environment and/or can be used to control the video capture parameters. For example, the video frame rate can be set according to the light sensor reading and the detected activity level - more motion requires a faster frame rate whereas low light conditions can benefit from a longer exposure time.

The Ubiquitous Sensor Portals are equipped with wired Ethernet, an infrared communication interface and an 802.15.4/Zigbee radio network, for which they serve as base stations. The infrared interface is used for line-of-sight communication to identify users of the wearable devices that have approached or are otherwise facing the USP. Two IR ports are supplied – one using a custom IR protocol developed for our own badges [6] (which can also be used as a reflection-based proximity indicator to detect people in front of the portal) and the other supporting IRDA, which is spoken by another set of badges that are commonly used by our social dynamics researchers [7]. The radio network provides peer-to-peer communication between the USPs and the wearable devices together with time synchronization, allowing wearable sensor data to be aligned with the recorded audio and video. The USPs also act as radio beacons for a coarse location system based on TI's 802.15.4 localization engine [8]. In benign and stable RF environments, we have seen this system provide the wearable devices with X-Y position better than a meter, as given in TI's specifications [8]. Although it easily downgrades to several meters in canonical nonideal and dynamic environments [9], it is still adequate to identify which wearable devices may be in view of the camera – in cases where proximate badged users are facing the portal, the IR interface provides more specific identification.

III. Wearable Platforms for Media Labeling

We have developed two wearable sensor devices, the Micro-Badge shown in Figures 4 and 5, and the wrist-worn device, shown in Figure 6.

Both devices are equipped with an inertial measurement unit. The included IMU contains a 3-axis tilt-compensated compass that provides absolute heading information, a 2-axis angular rate sensor, and a 3-axis accelerometer. The IMU in the wrist-worn device is intended to capture hand gesture data that identifies the activity of the subject. The Micro-badge is worn on the body like a nametag, so its IMU looks at general body motion, fidgeting, and social signaling. The heading information collected from the compass can be used to capture the subject's direction of attention. This is important information for the camera system, which can be told to record video of an action from a viewpoint that captured the attention of one or more subjects.

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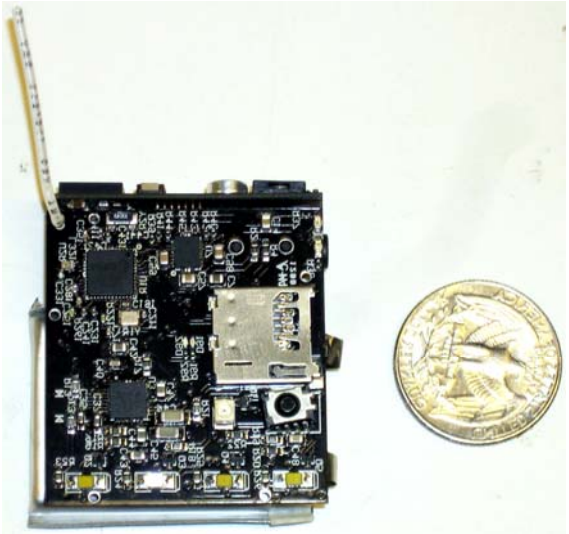

Figure 4. Micro-badge Board next to a US Quarter

Figure 5. Micro-badge in case with OLED screen

Both types of wearable devices use the same 802.15.4 RF communication capabilities as the USP. This allows the wearable devices to access the USP network and take advantage of its features. This includes the location system, hence all the wearable devices can calculate their X-Y position. The Micro-Badge also has the custom infrared communication interface that can be used by multiple Micro-badges to identify face-to-face encounters and conversation dynamics between Micro-badge wearers. This interface can also identify the badge wearer to a USP, which can display specific information when approached by a badge wearer.

The Micro-badge adds a microphone with the AVR32 audio DSP, enabling simple affective speech analysis. This microphone can also record audio, which can be synchronized with the video captured using the USP camera system. As it faces upward and the badge is to be worn close to the neck, the microphone predominantly responds to the user's voice. The Micro-badge also features an SD slot for accepting flash memory cards, allowing copious data to be locally logged. Although the badge of Figure 4 shows only a simple LED array display, our devices now entering production feature a full OLED display, enabling the badge to show arbitrary graphics.

The wrist-worn sensor devices also sport a small OLED display, allowing immediate review of any video captured by nearby USP cameras. Together with a set of buttons at the edge of the housing, the display also offers a simple wearable user interface for local interaction with the system (e.g., for stopping recording, explicitly labeling data or tagging events, etc.). In addition, the wrist-worn sensor device has a galvanic skin response (GSR) sensor in the wristband, which can identify change in the physiological excitation of the wearer. Recent studies [10] have shown that GSR measurements in wristbands can be much more reliable than previous wearable GSR systems (e.g., in the palmtop [11]]).

Figure 6. A Prototype Wrist-worn Sensor/Interface with GSR electrodes attached

IV. System Applications

This building-wide infrastructure will be used to support many applications. For example, Figure 1 shows a display from a simple application suite that allows badged users to locate one another and to look from one portal into any other (connections are reciprocal – you aren't allow to look out of a portal without appearing on the other side), dynamically connecting disparate sections of our building. Two application areas are dominating our group's current research activities with this facility, however – Cross Reality and Spinner, which are described below.

Cross Reality explores the seamless blending of real and virtual online worlds, blurring the notion of presence [12]. In our current environment [13], each USP has an equivalent structure in SecondLife (Figure 7). This allows people to

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visit our laboratory in virtual space, seeing into and appearing through any portal and floating from one to the other without real-world constraints of physics, walls, etc. – in essence a fluid approach to browsing and interacting with the physical world. Figure 7 shows the view of a SecondLife user during one of our system tests – the virtual portals show a recent photo at the front screen, but also extend into the past, offering images and media clips of prior events upon request. The signal trace at the bottom of each portal represents an activity metric composed of compositing audio amplitude and detected motion – it extends into the past as the line moves towards the back of the portal, allowing a virtual user to identify periods of activity in the portal's area. A white "ghost" is drawn in front of the virtual portal when a user is detected in front of the real USP – if the user is identified, their name appears above the ghost.

If a virtual user requests a real-time connection, video (and audio if authorized) from the portal is streamed to the screen at the front of the virtual structure, while information from SecondLife is shown at the real-world portal. Right now, we show a static avatar icon on the real USP and allow text to stream from SecondLife to the portal (texting is still the standard communication medium in SecondLife) – we are now working on full video/audio connections to and from virtual and real portals for bidirectional immersion.

Figure 7. Two views of a virtual USP in SecondLife

Spinner is an application that explores automatic assembly of video and media content in response to a narrative-based query [13]. Users with wearable devices (badges and wristbands described earlier) are "characters" in the media assembled by the Spinner system. The signals from the wearable system identify the characters in view of a USP camera and also produce signals that can be analyzed to extract socially relevant [6,14] and affective [15] parameters. Spinner maps these values onto variables that are used in analyzing narrative structure [16]. A media query in the Spinner framework is then a scripted narrative timeline or storyboard specified between the instrumented participants. Over time, the captured video clips that correspond to wearable and other sensor signals that best fit the narrative specifications are dropped into storyboard where they fit best, producing a "movie" of real people that aligns with the specified narrative. Although previous work has looked at taking images when certain wearable sensors are stimulated (e.g., [17,18]), very simple, immediate triggers were used generally with simple wearable cameras. Spinner is aimed at putting together videos taken from a distributed camera network that have higher-level structure, allowing large sensor-labeled video databases to be queried in humanistic terms and providing participants a deeper means of organizing media content and reflecting upon their life.

V. Badge-Mediated Dynamic Privacy

The systems introduced here have the potential of being very invasive, as many have the capability of streaming intimate data (e.g., video and audio) to potential eavesdroppers. As we are about to live within this network, it is vital that residents of the Media Lab building establish some kind of control over the boundaries of this system and attain confidence that its capabilities will answer to local concerns. There has been much recent speculation and discussion about privacy protocols for Ubiquitous Computing [19,20] and distributed sensor networks [21]. We have decided that we will pursue a solution that works at several levels.

At a fundamental physical level, we have decided to implement a standard in-line lamp switch on the DC power cord that attaches to each USP, allowing people in its vicinity to easily turn it off. As the portals are conventionally mounted near average head height, this switch is easily accessible and very obvious. When the power to a portal is cut off, the servo motors that rotate it along pitch release, causing it to obviously slump down, emulating the "nodding" of sleep (in addition to the display and LEDs extinguishing) – an obvious indication of power-off.

We describe several concepts that we are implementing to manage privacy at a logical level below – all of these assume that code verification and network security is regularly monitored on our devices, just as it is in the PCs and diverse computers that already populate current networks.

The portal software is architected such that any video streaming and recording will produce very obvious visuals on the corresponding USP displays. In the case of end-end

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streaming, all video is reciprocal – you see the entity on the portal screen that is watching remotely. In the case of recording, the portal display will flash an obvious indication that a recording is in progress. In either case, anybody nearby can easily stop the recording or streaming by hitting a very visible STOP button on the touchscreen. In the Cross Reality installations that we have performed thusfar at our Laboratory, we inform everybody via email that video can stream into SecondLife freely during specified times of the day, but audio (which is generally much more sensitive) must always be authorized explicitly at the touchscreen of each real-world portal every time a virtual avatar requests a conversation with a person physically there.

Already with 45 Portals distributed through portions of our laboratory, video/audio capture is dense enough to make it difficult to make sure that all the USPs in range are manually deactivated when privacy is needed. This will only become worse as Ubiquitous Computing truly arises, and potentially invasive media capture becomes an intrinsic property of devices scattered all over our environments. Rather than surrender to this situation and keep the network open [22], we have elected to use badge systems, which periodically beacon a unique ID, to wirelessly mediate privacy. Using received signal strength and/or the localization engine, the Portals know which badges are potentially within sensor capture range, and can control data access according to user preference.

When we execute our Spinner experiments, we will be running purely in an "opt-in" mode. No cameras will be recording or streaming video unless a Spinner participant (who is wearing the badge and wristband of Figs. 4 and 5) is within range. When recording is happening, the portals that are capturing media will display accordingly, as described above, and any badges within fiducial range (which will also be capturing audio) will flash a red "record" alert in an obvious fashion to notify anybody with whom they are interacting that media capture is in progress. Recording can be deactivated and back-scrubbed both at the Portal and by pushing a panic button on the badge or wristband. We also plan to also give participants a means of scrubbing their video archive after data is collected. All media will be time-stamped and labeled with the IDs of any badges in the vicinity of the portal that collected it (if a non-Spinner bystander who doesn't have a badge wants to scrub clips that they may be in, they can request an ID at the portal screen). Using an interface similar to that described in [23], users can subsequently enter their ID into a website that will enable them to review and delete any video that they participated in.

We have also built a simple badge for explicitly controlling dynamic privacy in our environment [24]. Shown in Figure 8, it is aimed at collecting real data about acceptance of a ubiquitous sensing system with regards to personal privacy and at developing tools and methodologies for assuring personal privacy in the future of user-created pervasive media.

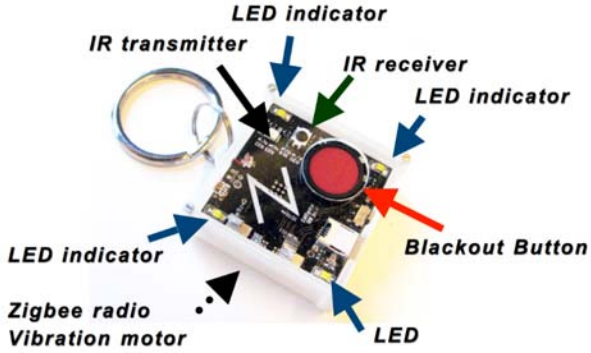

Figure 8. Prototype badge for dynamic privacy control

This Privacy Badge can communicate with the above-mentioned USP network of media capture and display devices through infrared (IR) and 802.15.4 radio. The badge periodically transmits a code that informs the USP to control the behavior of particular sensors and informs associated servers of the fidelity with which the badge user wishes to appear in any browsing/querying utility. Each badge will have a unique randomly generated ID that points to its user, who can login to a web interface and configure privacy settings on the basis of both their physical location and the identity or affiliation of the other users or entities who are launching queries that intersect with sensor data collected about the badge wearer. After the USP receives the badge ID and compares it with the privacy preferences set up by the user on the web server, sensor data will be restricted by the preferred settings. By sending out a unique ID, the badge can also be used for tagging sensor data in order to claim ownership for further editing. When the red "NO" button is pressed, an immediate opt-out signal is transmit to block any sensors in range – an important option if a sensitive conversation is initiated. The current protocol answers to the most restrictive privacy setting that is received. If we have any indication that the wireless network is being jammed or spoofed, the portals will revert to a conservative privacy level.

With this device, users can have in-situ control of their privacy and immediate feedback of the privacy levels in different scenarios. When a users' instantaneous privacy level changes (e.g., entering another sensing region, or when the sensor system settings are overwritten by another user), immediate notification comes from the labeled LED indicators and a vibration coin motor within the device.

VI. Conclusions

As diverse sensors and media capture capability progressively pervade our environment through the march towards Ubiquitous Computing, users will need to both harness this facility for their own purposes as well as dynamically throttle the access granted to the outside world in order to accommodate privacy concerns. This paper describes a set of approaches that are being explored in a large live-in ubiquitous media testbed now under deployment

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at the MIT Media Laboratory. A set of wearable platforms are used to regulate streaming and recorded data according to dynamic privacy specifications and to label locally collected media with contextually-relevant parameters for a narrative-guided search. This paper discusses the custom hardware systems that have been developed and previews the applications that they will shortly enable.

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