WristQue: A Personal Sensor Wristband for Smart Infrastructure and Control

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Abstract

Despite the rapid expansion of computers beyond desktop systems into devices and systems in the environment around us, the control interfaces to these systems are often basic and inadequate, particularly for infrastructure systems. WristQue is a wearable interface for interacting with computerized systems in the environment, providing both explicit remote control with buttons, touch, and gestural interfaces, and automatic closed-loop control using environmental sensors on the device, fused with precise indoor location for context. By placing these sensors and controls on the wrist, they are generally able to sense the environment unobstructed and are conveniently within reach at all times.

WristQue is able to continuously collect and stream sensor data through a wireless network infrastructure, including temperature, humidity, activity, light, and color. A 9-DoF inertial/magnetic measurement unit can be enabled to use the WristQue as a wrist-based gestural interface to nearby devices. Location and orientation data is used to implement a pointing interface that the user can use to indicate a device to control. This interface was implemented and tested using the WristQue and a commercial UWB localization system. The other sensors on the WristQue were validated by collecting several days of environmental data and conducting several controlled experiments.

With these capabilities, the WristQue can be used in a number of sensing and control applications, such as lighting and comfort control.

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Contents

Chapter 1

Introduction

Our interactions with computers today extend far beyond the traditional notion of a box with a keyboard, monitor, and mouse. Even setting aside the recent explosion of touchscreen-driven mobile devices, computers are everywhere in the environment around us. These embedded computers can be found in everything from light switches and thermostats to coffee makers and cars, and the number of devices under computerized control will only continue to increase.

While many of the advantages of computer-controlled systems are clear, the answer to the question of how to control all of these devices and systems is less obvious. A common approach is to simply replace traditional mechanical controls with their computerized equivalents, putting digital control panels where controls like light switches used to be. But often these control panels are too constrained to really take advantage of fully computerized systems, while losing the simplicity of a light switch. Many occupants of modern buildings will find themselves looking at a control panel like the one in Figure 1.1, asking the question, *"How do I turn on the lights?"*

Often, more complex elements of computer-controlled building systems are provided through software interfaces that run on traditional desktop computers. This is particularly common for systems that allow some degree of programmability–for instance, lights that can be set to automatically come on at the beginning of the work day. However, by and large, these interfaces

Figure 1.1: A lighting control panel found in a modern building, allowing control of 24 dimmable zones. (Lutron Grafik Eye 4000 [23] system.)

are not designed for the actual users of the systems that they control; instead, they are meant to be operated by facilities personnel, and as such, are often programmed by people who do not fully understand how the building space is actually used. Furthermore, since this programming is typically done on a building-wide scale, it's hard to account for small variations, such as a particular workspace that is never used in the morning, but the lights come on at 8:00 AM with the rest of the building anyway.

Sensors provide another means through which computerized systems can attempt to control themselves in an intelligent fashion. The thermostat is an example of a simple servomechanism that has been in use since the nineteenth century, monitoring the temperature of a room to control the operation of various heating and cooling machines. This kind of simple control is widespread in modern systems: most building thermostats operate under the same principles, turning parts of a system on and opening valves when the temperature is below some preset threshold, and closing them as the temperature rises. Similarly simple control loops are widely deployed in computerized lighting systems, where the lights are turned off if motion sensors do not detect movement within some pre-set interval. These simple control loops may be a huge improvement over traditional systems with only manual control, and are often a major bullet point in advertisements and white papers for such modern systems. Yet they barely begin to scratch the surface of what is possible. Intelligent control of building systems to improve energy efficiency is of great significance, as buildings are responsible for a large fraction of energy usage. In the United States, building lighting alone accounts for 22% of total energy usage [19].

Current sensor deployments, as part of the building itself, are fixed in place at the time of construction or renovation. As occupants move into the finished building, the sensors might be in entirely inappropriate places for the usage patterns that develop in the space. There are many locations in the Media Lab, for example, from which motion sensors for the lighting system are completely obscured by furniture. During the evening, students working late in the building often find the lights turning off on them, as they are not detected by the sensors. Additionally, simplistic control loops with limited contextual information often make poor decisions: a program such as *turn the lights off when no motion has been detected in the past twenty minutes* sounds reasonable, until one realizes that someone leaving an office late at night will trigger motion sensors all the way from his office to the front door, causing hundreds of watts of lights to turn on and continue to burn for twenty minutes after the person leaves the building.

This thesis describes the development and testing of WristQue, a personal sensing and control device in the form of a wristband (Figure 1.2) that attempts to address these challenges. WristQue aims to be a step toward the *interface to everything*, or at least many of the digitally-controlled systems and devices around us. This work considers a number of challenges related to the control of building systems, but the idea of WristQue as a control interface is not limited to buildings–it could become a general-purpose sensor and gestural interface for any device under computerized control.

WristQue aims to accomplish this goal in a number of ways. First, WristQue

Figure 1.2: The prototype WristQue sensing and control device being worn.

moves sensors and controls off the wall and on to people. This solves the problem of controls that are in inconvenient places and sensors that are too far away or obscured from the areas that they influence. Second, WristQue tries to **improve the control of infrastructure and other systems** by utilizing as much context as possible, such as environmental sensors and the user's location, to create a natural and accessible interface to easily control nearby devices. By **uniquely identifying and locating users within the building**, WristQue enables automatic systems to associate personal preferences with specific individuals and adjust conditions locally to suit the current occupants of the space. The goal is to bring back some of the simplicity of the light switch and provide manual control when the user wants it, while at the same time providing personalized sensor-driven automatic control by learning the user's preferences.

Smartphones have successfully brought wearable computers with sensors, once limited to research platforms, into widespread adoption. Why, then, is another personal sensor device necessary? WristQue places these capabilities on the wrist for two main reasons. First, smartphones spend the majority of their time in people's pockets, where it is difficult to sense the environment. Smartphones would be a workable platform for measuring the user's activity and location, but sensing environmental parameters such as light, temperature, and humidity doesn't work well in a pocket. Placing these sensors on the wrist gets them out into the open where they can more freely sense the environment.

Second, WristQue aims to provide a consistent interface that is always at hand. Controlling something from a smartphone requires the user to remove it from a pocket, unlock it, and launch an app. While the effort it takes to do so may be worthwhile when the control task is complex (and the affordances of the touchscreen to display information are desirable) this may be justified. However, for simple tasks, it places the controls that much further from the user's reach. Ideally, the WristQue would be a device that the user doesn't have to think about–it's always there and ready as a consistent interface on the user's wrist.

Finally, the design of WristQue is intended to make it a wearable sensor platform that people might be willing to wear. While many wearable sensor research platforms have been developed, few are ever worn by users outside of the context of a research study. Many sensor platforms take the form of a badge, which can work in corporate environments, but in settings like the Media Lab, nobody wants to wear a badge outside of a handful lab-wide events. People do, however, wear watches and bracelets.

Chapter 2

Related Work

2.1 Wearable computing and sensing

Wearable sensors have found applications in numerous spaces, such as medical devices, personal fitness monitors, and even smart badges that automatically exchange contact information and measure social interaction. The wrist has long been a natural place for wearable technology in the form of watches, which have declined in popularity with the advent of cell phones, but are making a comeback as wearable displays [44, 35, 1].

The idea of wearable sensing is closely linked with the idea of general-purpose wearable computing and a need to supply context to computers so that they can make more informed decisions to increase their utility. Farringdon et al. [11] describe two early wearable sensing platforms that aim to provide a wearable computer with contextual information about the wearer's pose and activities. They describe a wearable sensor badge with a pair of single-axis accelerometers that can recognize whether a person is sitting or standing based on static orientation inferred from the accelerometers at rest, and basic activity inference (walking, running, etc.) through frequency analysis of the accelerometer data. They also describe a sensor jacket with stretch sensors for posture recognition.

The Mobile Sensing Platform is a more recent sensor badge developed by Intel Research, University of Washington, and Stanford [6]. It contains a sensor set similar to the WristQue, with the addition of a microphone, barometer, and IR light sensor. The badge has a powerful ARM7 CPU and records at relatively high data rates, necessitating a large battery. The sensor data is used to recognize and classify the wearer's activities. They recognized the need for location sensing, and used external GPS modules and Wi-Fi-based localization using an attached PDA or phone.

A number of wrist-worn computers have been developed. The IBM Linux Watch [29] is a general-purpose computing platform with an ARM processor and a display in the form of a wristwatch. The authors discuss several of the advantages of a wrist-worn device, such as quick accessibility and being unlikely to get lost. The applications described are very PDA-like, with limited sensing. Harrison's Abracadabra system [14] is another wrist-based computer with a color display that investigates the challenges of finger-based input on very small screens. Microsoft's SPOT watch [27] is a now-discontinued product that displayed various information feeds on a wristwatch using a special FM broadcast network.

Maurer et al. describe the eWatch [25], which is notable as a wrist-worn device with a sensor set that is very similar to the WristQue (lacking gyroscopes and humidity sensors but adding a microphone and a display.) The authors briefly introduce the idea of a wearable device as a universal interface to smart environments in addition to activity recognition and classification. The authors cite the need for indoor localization, and show an interesting approach to coarse localization using the environmental sensors to infer position.

Texas Instruments' EZ430-Chronos platform [9] is a currently available development kit/reference design for the Chipcon CC430 radio and microcontroller system-on-a-chip (SoC). It includes a 3-axis accelerometer, barometer, and temperature sensor, packaged into a wristwatch with a watch-style 7-segment display and buttons.

The e-AR platform [32] is another wearable sensing platform for healthcare monitoring applications. Rather than a badge or a wrist-worn device, the e-

AR is worn behind the user's ear. Like the wrist, the ear provides a good exposed location for accurate sensing of the environment. The e-AR also uses its proximity to the ear lobe to measure pulse oxygenation using standard visible and infrared light techniques. e-AR was also used for activity recognition and classification, and has since been developed into a commercial product.

TRUSS [26] is a wearable sensor badge for construction workers. It monitors the workers' movement and altitude in addition to various environmental parameters, such as light and sound levels and concentrations of hazardous gases and particulates. The data are sent back over a wireless network and presented in a graphical interface viewed by site safety supervisors. The interface fuses the sensor data with video from the construction site and highlights conditions that may be unsafe or otherwise warrant attention.

Many other wearable sensing platforms exist; surveys such as [43] and [33] reference many more platforms for context-aware computing and health monitoring applications.

2.2 Commercial personal wearable devices

Several commercial personal sensing and interface devices have recently appeared on the market. Fitness monitoring is a popular space for personal sensor devices. Watches that display heart rate (from an EKG strap worn separately) have been available for some time now. Pedometers use simple mechanical accelerometers to count steps and estimate distance walked. More recently, these devices are moving toward using MEMS accelerometers instead. The Nike+ [31] is a small device with an accelerometer and radio that fits into a shoe and transmits pedometer-like data to other devices such as iPods. The fitbit [52] is a newer device that records accelerometer data while carried in a pocket; data are later uploaded to an online service that displays activity and other fitness information that is tracked over time. Several wristband devices are now offering similar capabilities. The Jawbone UP [48] and Nike Fuel [31] are recent accelerometer-based wristband fitness sensors. The Basis [2] is a watch-style device that also tracks the wearer's heart rate.

A handful of new watch-style computers are also now in development. Sony's SmartWatch [44] is a wrist computer with a color display and touchscreen interface that runs the Android operating system. The Pebble [35] is a watch with an E-ink (electrophoretic) display. Both devices are intended to be paired with a smartphone, displaying notifications and allowing access to some of the phone's functions from the wrist.

A number of patents cover aspects of wrist-worn control devices relevant to WristQue. [38] describes a handheld device that can send data to specific devices by pointing it at them. [16] describes an arm, wrist, and hand worn system of sensors, including accelerometers and a dataglove, for recognition of sign language gestures for transcription. [49] more generally covers gestural interfaces using a motion capture system. A wrist-worn control device for controlling building infrastructure systems, including lights and HVAC, with the user's physiological parameters as input is covered by [28].

2.3 Localization

There are many different approaches to solving the indoor localization problem. Refer to Chapter 3 for a full discussion of the related work in this area.

2.4 Building controls

WristQue builds on the idea of building automation, or "smart buildings" [46]. Most modern commercial buildings are now constructed with computer-controlled infrastructure systems. These provide flexibility, programmability, and some degree of sensor feedback, providing more control to facilities managers and often promising energy savings. Many attempts have been made to further unify these systems and include more sensors, including wireless, self-configuring devices [40].

Several other Media Lab research projects have explored specific areas within this space, such as enabling personalized comfort control based on sensor feedback from a wearable device, with a comfort model trained for each user from simple input like "too hot" or "too cold" [12]. Another project investigates control strategies for solid-state lighting to automatically provide optimal lighting for users while minimizing energy usage [34].

Chapter 3

Localization

The key to useful ubiquitous computing is context. Computers cannot automatically react in useful ways unless they are aware of the conditions and events around them. Some of that context can be provided by small and inexpensive sensors that can tell ubiquitous computers about their environment–temperature, humidity, motion, and sound to name just a few. But for any mobile computer, an important part of that context is simply its current location. For a sensor node worn by a person, location alone is useful information, revealing, for example, whether a person is in a particular room, and over time, what parts of different rooms that people use most often. Coupled with other sensors, location provides information about where those sensor values were recorded.

3.1 Motivation

In the context of building controls, uniquely identifying and tracking the locations of people allows building systems to not only control conditions based on occupancy, but on the specific preferences of the people who are currently occupying a particular space. Location sensing provides the context for movable sensors, whose values cannot always be assumed to be measured at the same location.

To explore many sources of sensor data, the DoppelLab project [8] provides a graphical interface to sensors within the Media Lab, integrating data from multiple sensor networks within the spatial framework of the building. One shortcoming of the current DoppelLab system (and building sensor networks in general) is that most of the sensors are installed where it is convenient to install sensors: on the walls and ceilings, with a concentration of sensors in the hallways and common spaces. While this provides information about what is going on in those parts of the building, the lab spaces tend to be under-instrumented relative to the number of people working in them. By instrumenting people in the building with their own wearable sensors, the highest sensor density is automatically where the people are. The data from these "roving" sensor networks, provided that the sensors can be precisely localized, could be visualized within the spatial framework of DoppelLab, providing higher density visualizations in the most heavily utilized spaces.

As the WristQue aims to be the "interface to everything," enabling the wearer to easily take control of the computerized things in the environment, it is necessary for the user to be able to easily *select* objects to control. Pointing is a very natural way of identifying a specific object nearby. As a wrist-worn device, the WristQue can infer the orientation of the user's wrist using inertial and magnetic sensors, and thus (at least assuming a straight wrist) the direction in which the user's finger is pointing. Combined with the precise location of the user, the orientation and position can be used to infer which object the user is pointing toward.

More generally, knowing the location of the user enables a broad class of *proxemic interactions* [13], in which various devices in the environment can react to the presence and proximity of the user. An example application might be a dynamic information display (such as the Glass Infrastructure [15, 4] at the Media Lab) that recognizes that someone is approaching, and at a distance provides a large display of important items on the user's calendar, notifications of new messages, et cetera. As the user approaches, the display could show additional detail, and the display vanishes as the user walks out-of-sight. The information could also vary if multiple people walk up to the same display.

The Glass Infrastructure currently uses RFID readers that enable each display to determine which tag-holding users are in front of it, but currently only as binary presence. Signal strength from the RFID reader may be able to provide an estimate of the user's relative distance to the display, but this is not implemented in the current iteration of the system.

3.2 Existing approaches

Outdoors, relatively precise and reliable localization can be obtained from Global Positioning System (GPS) satellites, given a relatively unobstructed view of the sky and limited reflections. GPS works poorly indoors, since the signals do not pass well through building materials. Indoor localization is a more difficult challenge, with many groups researching different approaches [17].

2-dimensional laser rangefinders and simultaneous localization and mapping (SLAM) algorithms [45] have effectively solved the indoor localization problem for mobile robots. However, 2-D laser SLAM requires an expensive sensor and requires the sensor to remain at the same vertical position as it was in when the map was made—reasonable for a robot but less so for a sensor worn by a person. 3-D SLAM approaches [50, 18] also exist, either using visual features, 3-D depth information/point clouds, or a combination. These are more suited to being worn by a person and cameras are generally less expensive than laser rangefinders, but the algorithms are often extremely computationally expensive and not suited for a small battery-powered device.

Radiolocation encompasses a variety of methods using radio frequency energy to deduce location. As RF energy falls off with distance, received signal strength (RSSI) can be used as a crude estimate of distance between radio nodes. However, RSSI is easily confounded by many other factors, such as objects between the transmitter and receiver, the orientation of the antennas, other sources of RF energy, and reflections off of surfaces in the environment. Angle of arrival (AoA) uses arrays of antennas (usually on the base stations where size is less of a concern) to determine which direction a signal is coming from. Time difference of arrival (TDoA) and time of arrival (ToA) measure how long a burst of RF energy takes to travel from the transmitter to the receiver/to multiple receivers, and the distance can be directly computed based on the speed of light.

RSSI-based approaches to indoor localization have been in use since the early days of wireless networks. Since most radios used for digital communication already contain hardware to measure the received power associated with a radio event, no specialized hardware beyond what is already used for communication is required. Several commercial services [42] provide databases of Wi-Fi access point locations, which can be used by a portable internet device with only Wi-Fi to infer location within about 25 to 50 meters. Some enterprise-grade Wi-Fi access point systems (e.g. Cisco [51]) also provide a localization service that can achieve 10 meter precision when multiple access points on the same network are within communication range of the device being located. RSSI-based localization has also been a popular topic in sensor networks research, often using 802.15.4/ZigBee radios. With careful calibration under controlled conditions, some systems are able to achieve several meter precision [10, 5, 47].

While RSSI-based systems are generally precise enough to identify the room that the wearer of a wireless sensor device currently occupies, this is still not enough precision for some applications of truly location-aware computing. For example, if the user is pointing at something, a meter of error could indicate a different object entirely. Ultra-wide-band (UWB) systems [39] are able to achieve higher precision by using TDoA (sometimes combined with AoA) to locate nodes. These systems can be capable of locating active tags with precisions approaching ten centimeters–close enough to enable applications like recognition of pointing gestures.

Currently, UWB localization systems are available as commercial systems for tracking people and assets [37, 20] These systems typically cost tens of thousands of dollars and are standalone systems that track dedicated tags. The infrastructure for these systems is usually installed and calibrated in controlled spaces by experts in a manual procedure. Cabling is generally required between the receivers for wired time synchronization. It is only a matter of time before UWB localization technology becomes available in a commodity radio chip, such as the evolving Qualcomm Peanut [30], which would enable integration into devices like the WristQue. Readily available commodity hardware would also enable the exploration of rapidly infrastructure, with less stringent power and wiring requirements and more automatic algorithms for calibration. Lower-cost base stations and more automatic configuration would enable rapid and inexpensive coverage of large indoor areas, such as entire buildings.

Another promising localization technology is the Nokia HAIP system [3], which uses low-energy Bluetooth 4.0 devices as the tags and an antenna array on a hemispherical dome as the base station. The mobile devices are located through an AoA-based algorithm. HAIP is particularly relevant in the context of the WristQue due to the fact that it uses commodity Bluetooth radios which are easy to integrate into custom designs, rather than dedicated single-function tags. HAIP is able to achieve better than meter accuracy.

3.3 Localizing WristQue

While the ideal WristQue device would contain an UWB radio capable of localization within a few centimeters, no solution exists at the time of this writing that is sufficiently small, low-power, and inexpensive to integrate into the current WristQue prototypes. Commodity UWB chips capable of such localization will likely be available within the next few years.

As a compromise, the WristQue is able to perform basic RSSI-based localization, which is sufficient for identifying the room that the wearer currently occupies. In addition, the current WristQue hardware is paired with existing UWB localization systems: a Ubisense system installed in part of the E14-548 lab space and an IsoLynx system installed in a large multipurpose space on the sixth floor of the Media Lab. These systems require an active tag to be carried in addition to the WristQue, and cover limited areas of the building, but do allow limited testing of applications requiring precise localization.

Chapter 4

The WristQue System

This chapter describes the prototype WristQue hardware and the related software infrastructure that was developed for this work.

4.1 Design

The physical form of the WristQue prototypes was chosen to strike a balance between style, compactness, and wearability and the flexibility to iterate on and develop the hardware inside.

Some inspiration for the wristband device comes from simple silicone bracelets, such as the ones originally sold by Livestrong to raise cancer awareness [21] and now popular in a variety of colors and bearing various messages. The bracelets are lightweight, unobtrusive, and many people wear them regularly. In an ideal version of the WristQue, small and flexible electronics would be embedded within a small, thin silicone band. However, there are significant engineering challenges posed by such a design. The electronics would need to be flexible yet resilient to the bending and stretching, and twisting that occurs when the bracelet is put on and removed. Either a flexible battery technology or multiple smaller batteries would be required as well to prevent a large, rigid, and potentially fragile section of the band.

The design used in this research is a compromise, with the intent of simplifying the engineering requirements of designing a fully flexible and minimalis-

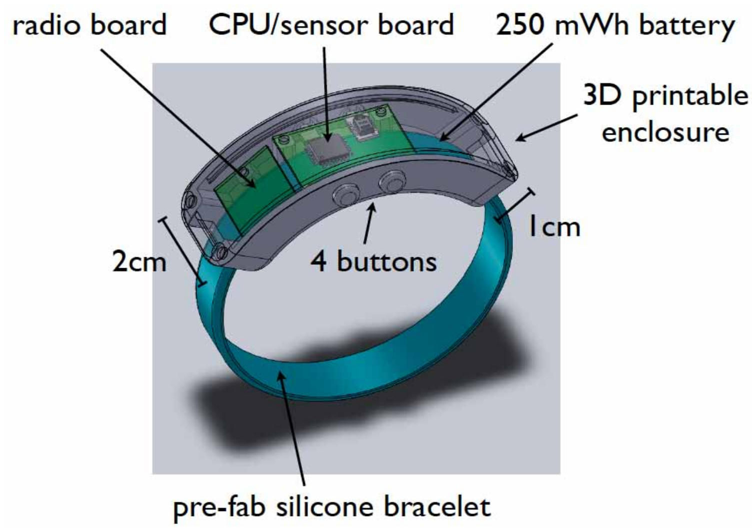

Figure 4.1: Early design sketch of the WristQue concept.

tic band, facilitating easier prototyping, while still retaining better wearability (and perhaps style) than most existing wearable sensor research platforms.

The first design sketches of the WristQue (Figure 4.1) combined a curved rigid plastic enclosure with a pre-fab silicone bracelet. The housing contained all of the electronics and the battery. A 3-D printed mock-up of this configuration was produced (Figure 4.2) but was problematic for several reasons. Silicone bracelets tend to be available in a limited number of sizes, and are generally worn loose-fitting, with the degree of looseness defined by the individual wearer's wrist. Since the band has no clasp and must be stretched over the wearer's hand, some looseness is necessary. While a loosely-fitting lightweight band is fine, when a rigid enclosure containing electronics is added, the loosely fitting band becomes distracting. Furthermore, the sensors are less useful if they are not reasonably fixed to the same location on the wrist; a light sensor, for example, is best pointing outward at the wearer's environment and not down at the floor or into clothing. For inertial sensing of gestures, it is also helpful for the inertial sensors to move consistently with the wearer's wrist and not flop around with movement.

The second revision (Figure 4.3) is constructed entirely from semi-rigid plastic,

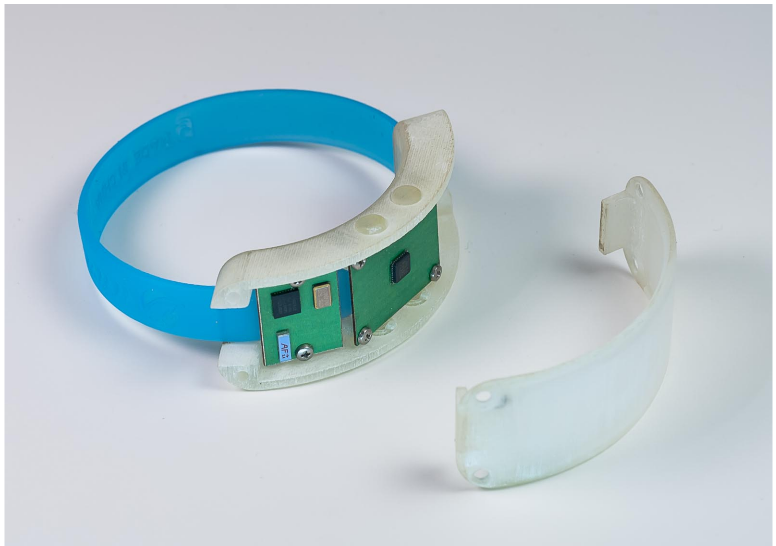

Figure 4.2: 3-D printed mock-up of the first WristQue prototype design.

Figure 4.3: Final design of the WristQue prototype, in 3-D printed acrylic (left) and colored laser-sintered nylon (right).

Figure 4.4: The two halves of the WristQue, separated, showing the magnets that hold it together.

with the enclosure comprising the whole wristband instead of fitting over a silicone bracelet. It exploits the fact that wrists are not perfectly cylindrical, but instead flatten out on the top and bottom of the arm. This allows a longer flat PCB section to be used on the top of the wrist, and the battery fits in the flat section of the bottom of the wrist. The band splits into two halves (Figure 4.4) for removal, and is held together by small magnets when it is being worn.

The enclosure is designed as a parametric SolidWorks model in four parts (the two halves, and covers for each.) The dimensions of the model are driven by a small set of wrist measurements, while the dimensions of the internal components are fixed. This allows a custom-fit model to be automatically computed from a pair of wrist measurements. The resulting model files can be 3-D printed to produce a custom-fit comfortable wristband for each wearer. On-demand 3-D printing from services like Shapeways [41] also allows each wearer to choose from a variety of colors (and potentially materials, though some materials affect RF performance) for each individual part, further customizing the band to the wearer's preferences.

Each custom wristband fits the wearer comfortably without being too loose, and does not easily rotate on the wrist because of its shape.

4.2 Processor

The WristQue's main processor is an Atmel ATXmega32A4, which is a recent 8-bit microcontroller with an advanced peripheral set. The processor is optimized for low-power applications and runs at 2.5 volts, simplifying communication with the 2.5 V sensors. It is clocked at 1 MHz by an internal RC oscillator, but is able to dynamicall scale its clock up to 32 MHz with an integrated PLL when more computational power is necessary.

The processor runs a custom real-time operating system with a basic task scheduler and network stack. The OS handles association with wireless routers, transitions between the various power modes, and schedules sensor measurements and reports.

4.3 Environmental and personal sensing

The WristQue contains a set of environmental sensors (labeled in Figure 4.5) to enable testing of lighting and comfort control applications.

4.3.1 Light

Two light sensors are on the sensor board. The first is a color sensor (Avago ADJD-S311-CR999) with red, green, blue, and clear filters over the sensor elements. It is a digital sensor with integrated A/D converters and an I^2C interface. The gain of the sensor is digitally controlled, providing a wide dynamic range. The color filters allow this sensor to sense both the intensity and the quality of the light.

A second light sensor (Intersil 290006) is also on the sensor board. This is an analog, monochrome sensor with a spectral response reasonably close to that of the human eye. This sensor has a smaller dynamic range and only measures

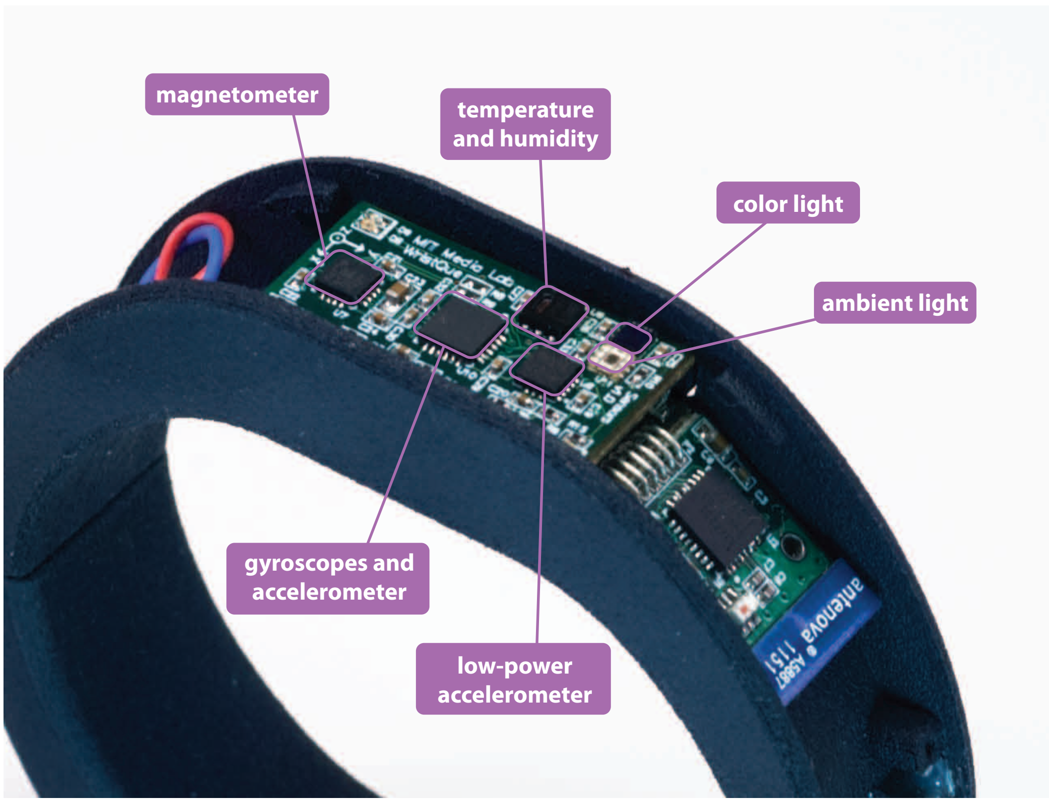

Figure 4.5: The WristQue sensor set.

the intensity of the light, but is much faster than the color sensor, which means that it could be used to detect high-frequency codes modulated into the intensity of a light source. Such modulation would be too fast to be perceptible to the human eye, and unique codes modulated in various light sources could allow the WristQue to identify how much light is coming from various sources in the wearer's environment. The analog output of this sensor is digitized by the 12-bit A/D converter in the main CPU.

4.3.2 Temperature and humidity

Automated comfort control is enabled by a combined temperature and humidity sensor (Sensirion SHT21). This is a high-quality digital sensor that provides precise, calibrated temperature and humidity measurements. This is a newer, smaller version of the SHT15 sensor commonly used in high-end climate research applications.

4.3.3 Activity

A low-power 3-axis accelerometer (Analog Devices ADXL346) is used to measure the wearer's movement as a metric for physical activity, giving the WristQue some of the functionality of the multitude of accelerometer-based personal fitness monitoring devices now appearing on the market. The low-power accelerometer is configured to sample at 12.5 Hz on all three axes, with a continuous power draw of about 60 μW. The accelerometer has an internal 32-stage first-in, first-out (FIFO) buffer. It is configured to wake up the main processor when the FIFO reaches 25 samples, so the processor only needs to read data from the accelerometer every two seconds. The change in acceleration between each successive sample is integrated together for all three axes as a heuristic for the amount of movement the wearer made during each sample period, indicating physical activity. The acceleration is also averaged for each sample period, which provides an estimate of the orientation of the wristband.

Figure 4.6: The LED display acting as a bargraph, displaying a range of levels.

4.4 Controls

The WristQue has three hardware buttons on the left side of the band. These buttons can be used to provide basic control input (such as adjusting light dimmers up and down.) The buttons are also used to switch the WristQue in and out of the interaction mode, which enables control based on movement and gestures. The mode switching is currently manual (the user must push a button to enter the higher-power interaction mode) but future work may enable automatic mode changes based on other context.

Limited visual feedback is presented through a 5-LED linear display (Figure 4.6) on the right side of the top surface of the band. The LEDs can act as a bargraph display to indicate the value of a parameter that the wearer is adjusting, and can also convey information about the current operating state through patterns and animations. The WristQue hardware could support a more sophisticated display, which would enable a better interface to be presented on the device itself. However, given the engineering challenges of integrating and powering a small display in such a compact device, this version of the WristQue omits the complex display and focuses instead on control based on sensing. The display will be an important point to address in future work. Particularly, users who wear watches (including the author) have expressed that the WristQue would need to at least replicate the function of their existing watches to be practical.

The WristQue also contains hardware to implement a capacitive touch slider on the side of the band opposite the buttons, which would be convenient to operate with the wearer's right index finger while the device is being worn on the left wrist. As of this writing, the electrodes for the slider have not yet been fabricated, but this is planned as a means of providing an interface for adjusting continuous parameters from the WristQue. The sensor chip is an Atmel ATtiny44, which is a small microcontroller with a hardware capacitive sensing peripheral and software libraries for implementing buttons and sliders. The LED display described above is aligned with the touch sensor and is intended to provide visual feedback as the user operates the touch slider.

4.5 Inertial sensing and gestures

Pointing and gestural control are facilitated on the WristQue by a 6-DoF inertial measurement unit (IMU) and a 3-DoF magnetometer. The 6-DoF IMU consists of 3-axis MEMS gyroscopes and accelerometers, packaged into a single part (the Invensense MPU-6150.) This part provides 16-bit angular velocities and linear accelerations, with ranges configured to $1000°/\text{sec}$ and ± 4 g, respectively. The magnetometer (Honeywell HMC5883L) provides a 12-bit magnetic field vector, with a full-scale range configured to ± 1.3 Ga. These sensors are labeled in Figure 4.5.

The inertial and magnetic sensors in the WristQue are manually calibrated for optimum performance. The accelerometer scale factor and offset were obtained by placing the wristband in three orthogonal orientations, each with a different axis parallel to the ground, and measuring the resulting acceleration due to gravity, which was scaled to 1 g. The gyroscope scale factors were determined by recording the reported angular velocity at rest and on a phonograph turntable and scaling the difference to $200°/\text{sec}$ (the angular velocity of a $33^1/_3$ RPM LP.) The gyroscope offsets vary with temperature (to a different degree with each individual axis) and were calibrated by chilling the sensor to approximately 4 °C, and recording the reported angular velocity and temperature (the gyroscope part has an on-die temperature sensor) with the sensor at rest as it was warmed to approximately 35 °C. A first-order function was fit using least-squares approximation to the resulting data for each axis to obtain expressions for the offset of each axis as a function of sensor temperature. Finally, the magnetometer was calibrated by rotating the wristband through random orientations and fitting a sphere to the resulting point cloud. This is perhaps the most important calibration, as the uncalibrated magnetometer shows significant hard-iron offsets, likely due to the magnets that hold the two halves of the wristband together.

While in interaction mode, the IMU and magnetometer are brought out of sleep and configured to produce measurements at 20 Hz, with a hardware low-pass filter at half the sample rate. The magnetometer is wired as a slave device to the IMU, which automatically requests magnetometer values at the same time that accelerometer and gyroscope samples are taken. The resulting synchronized 9-DoF samples are stored in the IMU's FIFO buffer. At approximately 10 Hz (depending on other activity) the main processor requests the contents of the IMU's FIFO and transmits the resulting data via the wireless network. This allows the orientation filter to run at 20 Hz while reducing radio power and bandwidth usage by transmitting several samples per packet. The effective interaction latency is 100 ms.

The WristQue server software receives the raw IMU data packets, applies the calibrated scale factors and offsets, and uses the algorithm described in [24] to fuse the 9-DoF sensor data and obtain the orientation of the wristband. When entering interaction mode, the gyroscope measurement error β is set high initially so that the filter quickly converges on the orientation inferred from the magnetometer and accelerometer, and then is quickly reduced to place more weight on the integrated angular rates for more stable results. The resulting orientation is published to the rest of the WristQue software infrastructure for use in various applications.

Figure 4.7: The WristQue battery on the charging base (left). The battery attaches to the charger through magnets, just like it attaches to the band (right).

4.6 Power

The WristQue is powered from a small (110 mAh) lithium polymer battery (Figure 4.8) in the bottom half of the band. The battery couples electrically to the circuitry in the top half of the band through the magnets that hold the two halves together. The polarity of the magnets is arranged to make it difficult to connect the battery backwards, and the magnets on the battery side are recessed to prevent shorting if the bottom of the band is placed on a metal surface.

To charge the battery, the two halves of the band are separated and the bottom half is placed on a special charging base (Figure 4.7). The battery lasts for several days of normal operating conditions (continuous low-rate sensing and radio communication and intermittent high-power interaction) and recharges in about an hour.

Power is conserved by switching between three different operating modes, which are described in the following subsections.

Figure 4.8: The bottom of the WristQue band with the cover removed, showing the battery inside.

4.6.1 Interaction mode

Interaction mode consumes the most power, and is only entered when the wearer is actively interacting with the WristQue (e.g. using it for gestural input.) In the current prototype, the user enters interaction mode by pushing the middle button. While in interaction mode, the processor and the full set of sensors are powered up. The gyroscopes, accelerometer, and magnetometer are sampled at 20 Hz, and IMU data packets are transmitted via radio at 10 Hz. All of the normal sensing tasks described in the quiescent sensing mode are still performed.

The WristQue draws 14.3 mA when in interaction mode, allowing about 7.6 hours of use before the battery is depleted.

4.6.2 Quiescent sensing mode

The quiescent sensing mode is the normal state of the WristQue. In this mode, the processor and sensors are powered down most of the time, consuming 400 μA quiescent current. The secondary microcontroller, responsible for controlling the LED display and the capacitive touch interface, does not currently enter sleep mode, which accounts for the majority of the quiescent current draw. With the implementation of sleep mode on the secondary microcontroller, quiescent current draw should drop to about 100 μA.

The WristQue periodically wakes up to perform three functions:

- Every three seconds, it wakes up and broadcasts a "beacon" packet, which can be received by radio base stations placed around the environment to coarsely estimate the wearer's position. These packets are small and require no response, so the processor and radio are able to quickly go back to sleep after transmitting. Each beacon packet requires about 54 μAs, making the average current draw about 18 μA.
- Once every several seconds, the low-power accelerometer's FIFO triggers a watermark interrupt that wakes the processor, which stays awake just long enough to transfer the contents of the FIFO and update its integrated activity counts. Reading the contents of the FIFO requires about 60 μAs, making the average current draw about 20 μA.
- Every ten seconds, the WristQue collects samples from the color and monochrome light sensors, the temperature and humidity sensors, and computes activity based on data received from the low-power accelerometer. These data are then transmitted via the radio. The radio remains awake to listen for an acknowledgment packet, retransmitting up to three times until an acknowledgment is received. If no response is received after three attempts, then the WristQue infers that it is out-of-range of the network and transitions into sleep mode. Reading from all of the sensors and transmitting the report packet consumes 1 mAs, requiring an average current draw of 100 μA.

In addition to the functions described above, the processor awakens briefly every 32 ms so that the OS's scheduler can check if any task needs to run. The average current draw from these wakeups is about 40 μA. In total, the

WristQue draws an average current of 614 μA while in sensing mode, allowing it to run for 7.5 days from a single charge.

4.6.3 Sleep mode

The WristQue enters sleep mode when it is out of contact with the wireless network. While in sleep mode, it stops transmitting beacon and sensor data packets, and primarily attempts to re-associate with a network base station.

The rate at which the WristQue makes reassociation attempts is variable. It begins attempting re-association every three seconds, and after subsequent failures the interval is increased to three minutes. This allows it to re-associate quickly after a brief network dropout, while slowing down to conserve power when the network is truly not in range. Once the WristQue successfully re-associates with a base station, it leaves sleep mode and returns to quiescent sensing mode.

Each re-association attempt consumes approximately 2 mAs (primarily from enabling the radio receiver to listen for a response.) When the association interval has stabilized at three minutes, the average power draw for the radio is 11 μA. With the quiescent current of 400 μA (as discussed earlier, this could be significantly released by implementing sleep on the secondary microcontroller) the total in sleep mode is about 411 μA, yielding a battery life of 11 days.

4.7 Communication

The WristQue communicates sensor and control information back to the infrastructure using a low-power wireless radio. The radio chip is the Atmel AT86RF231, which implements the physical layer of the 802.15.4 radio standard. The chip supports both the standard 802.15.4 data rate of 250 kb/s and non-standard data rates up to 2 Mb/s. The higher data rates are currently not used by the WristQue, but could potentially enable lower power operation by

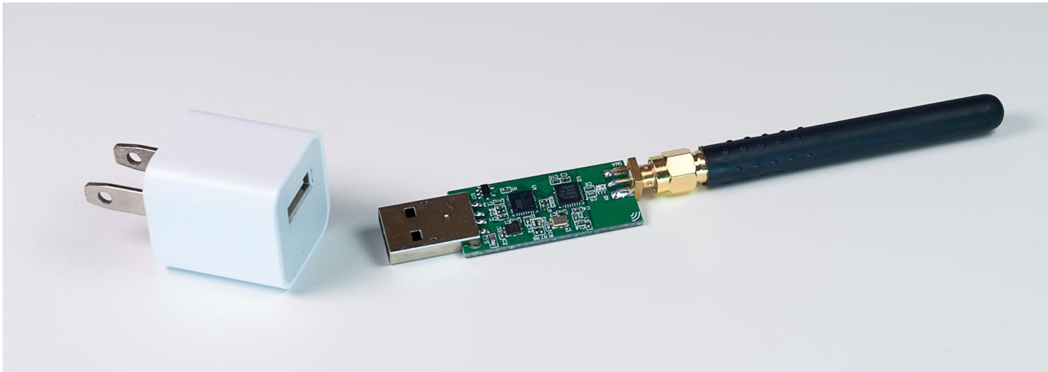

Figure 4.9: One of the base stations for the WristQue wireless network. The base station can either plug into a USB port on a computer, which connects it to the WristQue back end IP network, or to a USB charging adapter as a wireless relay.

reducing the amount of time that the transmitter is required to remain on.

The WristQue network implements the standard 802.15.4 MAC layer, using 16-bit statically-assigned addresses. The fixed infrastructure consists of base stations (Figure 4.9) that can either plug directly into a computer (and thus into the back-end IP network) or into a power source only (in which case the base station simply relays data towards a base station with a computer connection.) The routing tables are statically assigned during commissioning of the base stations. A small command set enables the WristQue to automatically associate with a nearby base station.

4.8 Software infrastructure

The WristQue software infrastructure is complex, requiring communication between many systems, databases, and hardware devices. In order to enable the various parts of the system to be separately implemented, the software infrastructure is built within the framework of the Willow Garage Robot Operating System (ROS) [36]. ROS is a publish-subscribe/remote procedure call system that allows various programs ("ROS nodes") to communicate with each other on shared "topics." While it is intended primarily for use in robotics research, it also works as a general-purpose framework for building systems with many components.

This simplifies the development of various application programs, as each can subscribe to the relevant sensor data and take control of the services that it needs to operate. The ROS framework also provides libraries for manipulating 3-D geometry, maintaining state about the locations and orientations of objects and the various transformations between their coordinate frames. These libraries are useful for implementing the pointing and gestural control functions of the WristQue.

Chapter 5

Applications and Results

This chapter describes a number of functions and applications that have been implemented using the WristQue prototype, and presents preliminary results from the sensors and control interfaces.

5.1 Pointing interface

As a control interface for many different devices, the WristQue requires a means for users to indicate which device they want to control. As discussed earlier, pointing is a natural way that people already use to indicate objects in their immediate surroundings to each other.

In order to determine which object a user is pointing toward, it is necessary to know both the location and orientation of the user's index finger. As a wrist-worn device, WristQue makes the assumption that the user's wrist is straight while pointing at distant objects, which allows the orientation of the wrist to be used instead. Note that this assumption is not necessarily true in all cases (and may also be affected by culture; pointing with one's finger might not always be considered socially acceptable.) However, this seems to be a fair assumption for the purposes of testing the WristQue prototype. Future work should investigate how reliable this assumption is, and whether users can be expected to point with their whole arm/wrist instead of just a finger as a tradeoff for not needing to instrument the finger itself with orientation sensors.

The location of the wrist is measured by an ultra-wide-band (UWB) localization system, as described in Chapter 3. These systems are able to locate tags in indoor environments with an accuracy of about 30 centimeters (and sometimes better, depending on the environment and system calibration.)

The wrist orientation is measured by the WristQue's IMU. To begin a pointing gesture, the user first switches the WristQue into the interaction mode (Section 4.6.1) which enables the gyroscopes, accelerometers, and magnetometers and initializes the orientation filter. The filter integrates the angular rates from the gyroscopes to track the wrist orientation, using gravity as a reference for absolute wrist pitch and roll, and the earth's magnetic field as a reference for absolute yaw.

5.1.1 Indoor magnetic field distortion

Unfortunately, while gravity always provides a stable reference for pitch and roll, the earth's magnetic field is heavily altered by metal objects in the environment, making it a challenge to use inside buildings. Metal furniture, structural materials, ductwork, et cetera all distort the magnetic field. Figure 5.1 shows the direction and magnitude of the magnetic field in the X-Y plane (parallel to the floor) in a cluttered indoor office environment. Figure 5.2 shows the direction and magnitude of the magnetic field measured on the same grid in a large, open space, with no furniture or other objects, in the same building. These plots were obtained by sampling the magnetic field with the WristQue's magnetometer while it was held in a fixed orientation at each location on a 2-foot grid. It is clear from these plots that there is significant distortion, making the magnetic field useless as a reference direction without first compensating for the distortion.

Knowing the user's location, it is possible to compensate for the distortion in the direction of the field. After creating a map of the field, such as those shown in Figs. 5.1 and 5.2, the known direction of the magnetic field at the user's location can be used to correct the yaw angle of the user's wrist orientation in

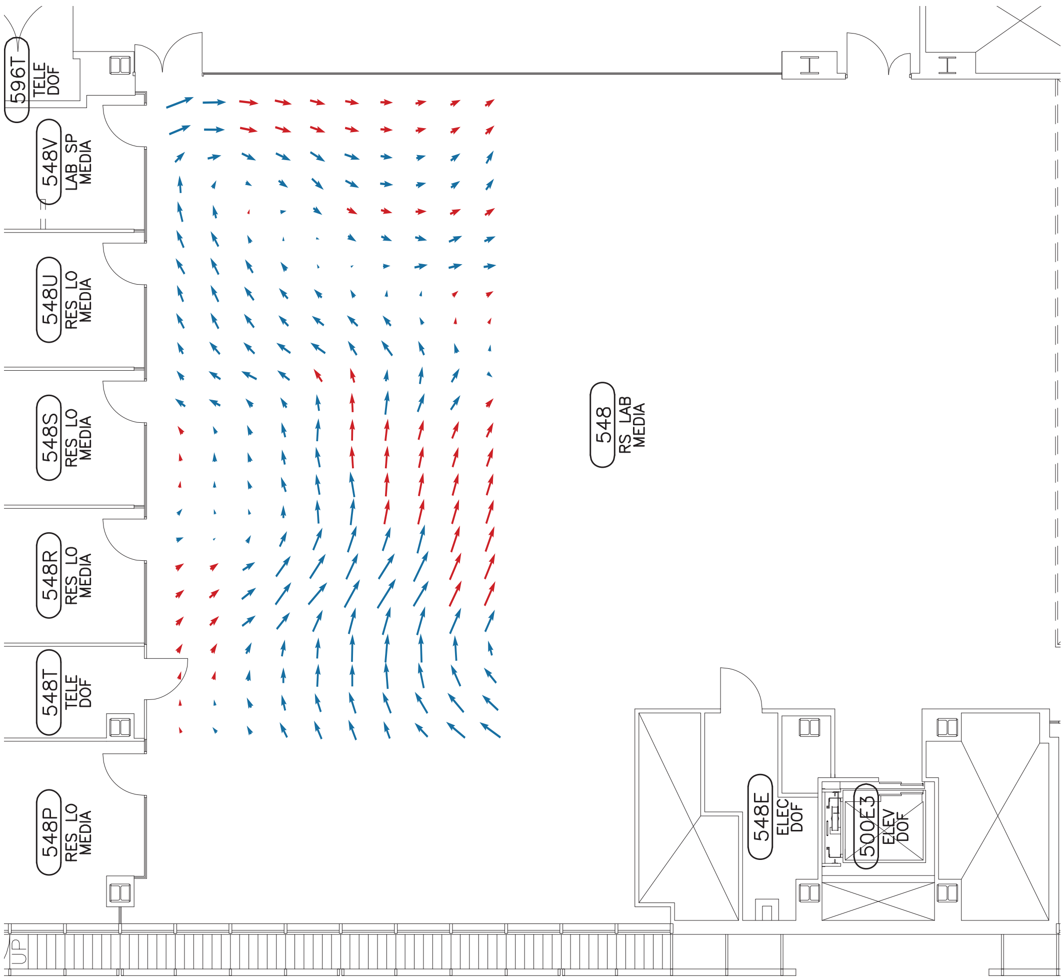

Figure 5.1: Indoor magnetic field distortion in a cluttered space. The arrows indicate the direction and magnitude of the magnetic field in the X-Y plane. Blue vectors are measured values; red vectors are at locations where it was impossible to measure due to the presence of furniture and were interpolated from the measured values.

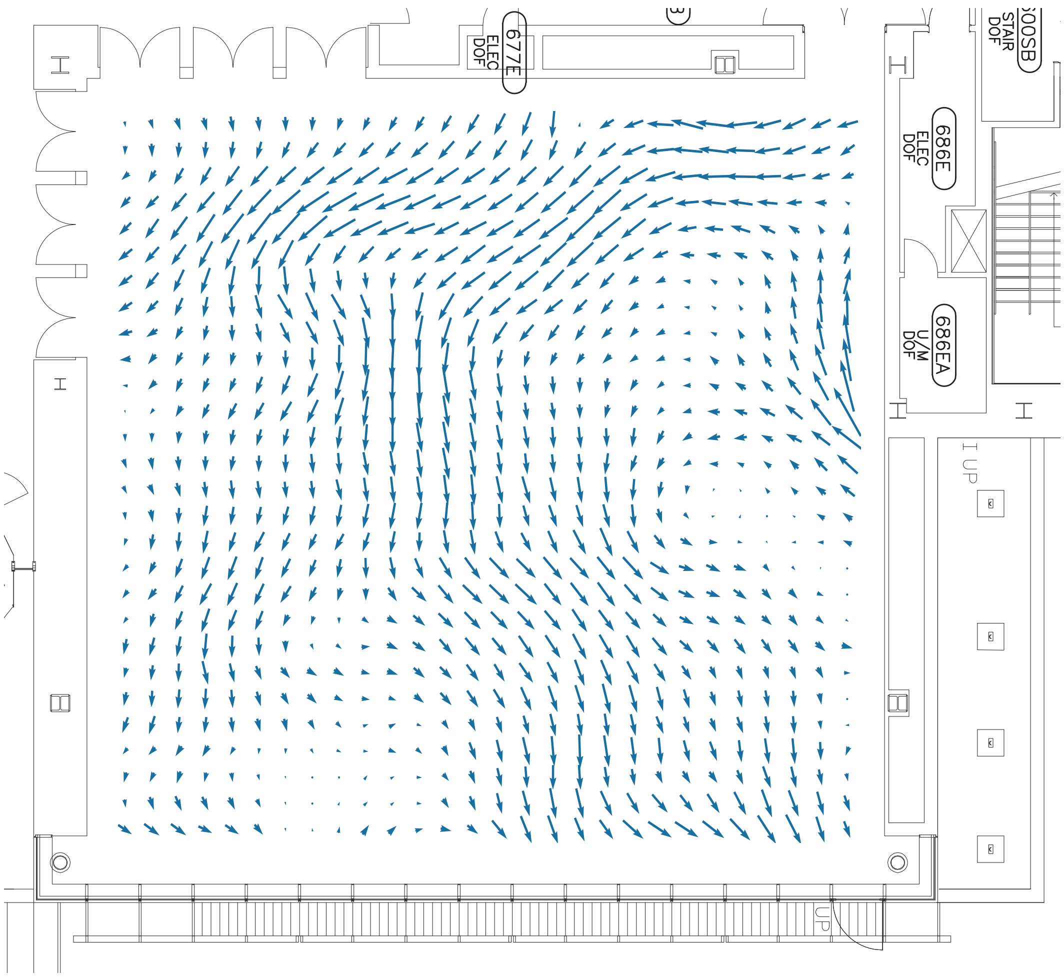

Figure 5.2: Indoor magnetic field distortion in a large space (multipurpose room on the 6th floor of the Media Lab building.) The arrows indicate the direction and magnitude of the magnetic field in the X-Y plane.

most places. Note that there are a few locations on both plots where the magnetic field is weak and reverses direction quickly over small changes in position, such as the region around (1.5, 11.5) in Figure 5.1. These are the locations where the correction is most likely to fail due to small errors in detecting the user's location. In most places, however, the magnetic field shows a clear direction and does not change significantly within the accuracy of the location measurement.

The distortions in the direction of the magnetic field are not limited to the X-Y plane; the direction varies with height as well. Calibration data at multiple heights has not been obtained as part of this work; however, other than a few pathological locations, calibration data taken at standing height appears to be usable for the range of heights that the sensor moves through while the user is pointing at objects in the environment.

Collecting the calibration data is a time-consuming process that requires sampling the magnetic field at many locations. However, Chung et al. found in [7] that the magnetic field within buildings is stable, and that most movable objects do not have a significant effect on the magnetic field provided that they are a sufficient distance away from the sensor. This suggests that once the calibration data was collected, it would be usable in the long term. The calibration process could also be automated by a mobile robot with another sensor (such as a scanning laser rangefinder) to use as ground truth for orientation. The robot could be allowed to roam the building and automatically build a map of the magnetic field.

5.1.2 Test and results

To test the pointing system, an experiment was conducted in which a user wearing the WristQue pointed at a fixed target at a known location in the environment. The orientation data from the WristQue was augmented with a Ubisense UWB localization system with six receivers mounted just below the ceiling around an approximately 6 by 14 meter region of a Media Lab workspace. The Ubisense tag was worn on the user's wrist directly adjacent to the WristQue. As the present WristQue hardware does not contain UWB localization inside the band itself, the external Ubisense tag provided the required location information.

The orientation filter was fed raw sensor data from the WristQue's gyroscopes, accelerometers, and magnetometers at 20 Hz. A correction was applied to the reported yaw angle based on the user's location to compensate for the direction of the magnetic field, as shown in Figure 5.1.

The user was instructed to point at a fixed target with known location (one of the UWB receiver antennas in the corner of the room) from each of 30 different locations within the space, covering an approximately 6 by 10 meter region around the target. At each location, 20 data points consisting of a wrist position and orientation were collected as the user pointed at the target.

Each ray described by a position and orientation was projected onto the plane of the wall behind the sensor. The resulting intersections are plotted in Figure 5.3. The color of the points indicates the distance between the user and the target. Blue points were from locations where the user was standing closer to the target, and red points were locations where the user was farthest away from the target.

The same data are presented in the histogram in Figure 5.4. The histogram shows the magnitude of the error between the actual location of the target and the pointing system's determination of where the user was pointing. The error in both of these plots includes (1) error in the user's wrist location as measured by the Ubisense system, (2) error in the user's wrist orientation as measured by the gyroscopes, accelerometers, and magnetometers in the WristQue, and (3) error in the user's aim at the target.

This test suggests that WristQue is usable as an indoor pointing device for large objects or target areas (those at least a meter or two in size.) This makes it sufficient for selecting regions such as lighting zones, which occupy several square meters of ceiling space.

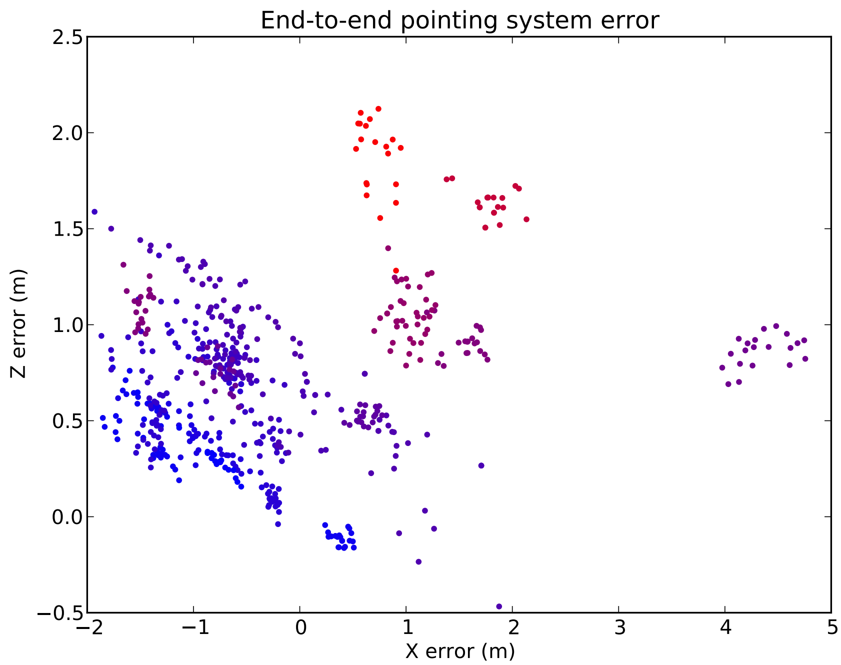

Figure 5.3: End-to-end pointing system error. The plot shows where the ray extended from the user's wrist would intersect the wall behind the target (at the origin.) The target was one of the UWB system antennas, mounted just below the ceiling in the corner of the room. The color of each point indicates distance; red points are more distant (10 m) than blue points (1.5 m).

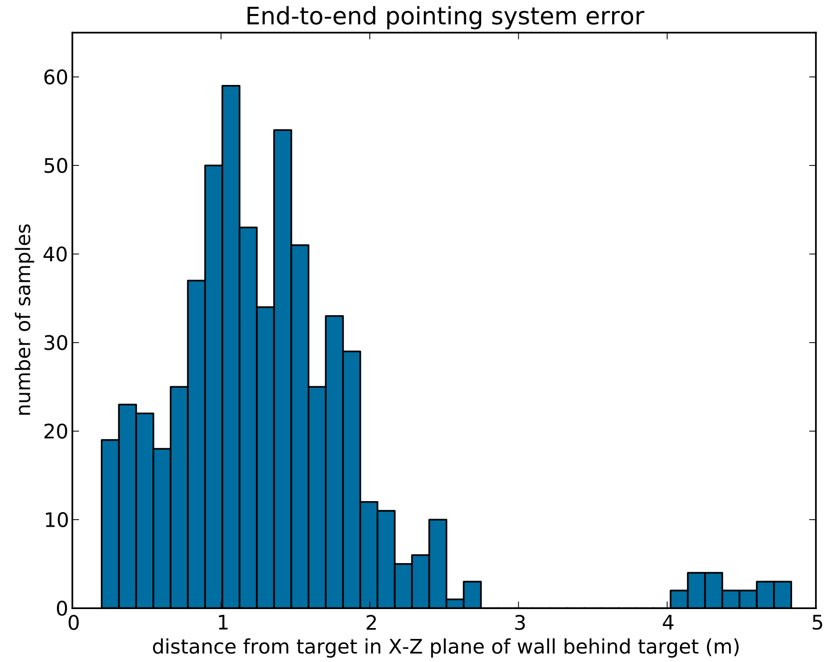

Figure 5.4: Histogram of end-to-end pointing system error.

Given a means of providing feedback to the user about where the system thinks they are pointing, it is less necessary for the pointing interface to have high absolute accuracy. Figure 5.5 shows the noise in the system ignoring the absolute location of the target in the plane. This noise includes (1) error in the wrist location as measured by the Ubisense system, (2) noise in the orientation reported by the WristQue's IMU, and (3) noise due to the user's wrist shaking, but excludes absolute errors due to the magnetic field and the accuracy of the user's aim. Combined with the above result that shows that the pointing has an absolute accuracy of a few meters, and a means of highlighting which object the system thinks the user is pointing at (such as having an indicator light on each controllable object that would light up when it is pointed at) the user should be able to make corrections and point at much smaller targets on the order of a few tens of centimeters.

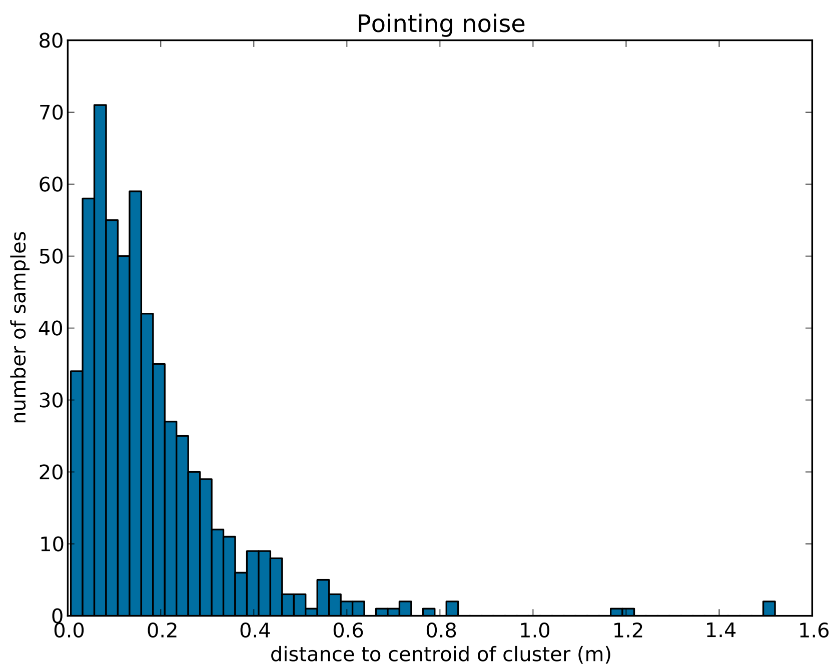

Figure 5.5: Relative noise measured in the pointing system with the user holding still and pointing at a target from different locations. The system assumes the intended target to be the centroid of the points where the ray intersects the wall plane; the histogram shows the noise between each sample and the centroid.

5.2 Passive sensing

While the WristQue is being worn, it is continuously collecting data from its sensors and streaming this data back over the wireless network. Figure 5.6 shows the data collected over an afternoon and evening as the WristQue was worn by a person working.

The discontinuities in the data are times that the wearer was out-of-range of the network infrastructure. Between 13:00 and 14:00, the wearer was eating lunch outside; note the temperature sensor rapidly cooling off once it comes back in range. Brief breaks were taken shortly before 16:00 and 18:00, where the sensor was exposed to cooler temperatures outside of the lab space.

Between 14:00 and 17:00, the wearer was sitting at a desk, primarily typing. Note the relatively low levels of activity. The accelerometer traces show the Z-axis (blue trace) facing upwards, indicating that the top of the wrist was pointed up, which one would expect with hands on a keyboard. After 17:00, the wearer was doing other work at his desk, with the top of the wrist still facing up but with more movement/activity. After 18:00, the wearer was meeting with other people, primarily standing up and making occasional hand gestures.

The lighting in the lab space where the data were recorded primarily comes from fluorescent fixtures with a color temperature of 3500 K. The color light plot shows a slightly reddish, warm light for most of the afternoon, as expected. Between 15:00 and 15:30 and at the end of the day, a desk lamp with blue LEDs was turned on. The light sensors have a directional response; the spikes in the data occur when the top of the WristQue is pointed directly towards a light source.

5.3 Lighting control

Two applications were implemented to demonstrate the WristQue's utility as a lighting control device. The first application simply uses a button on the

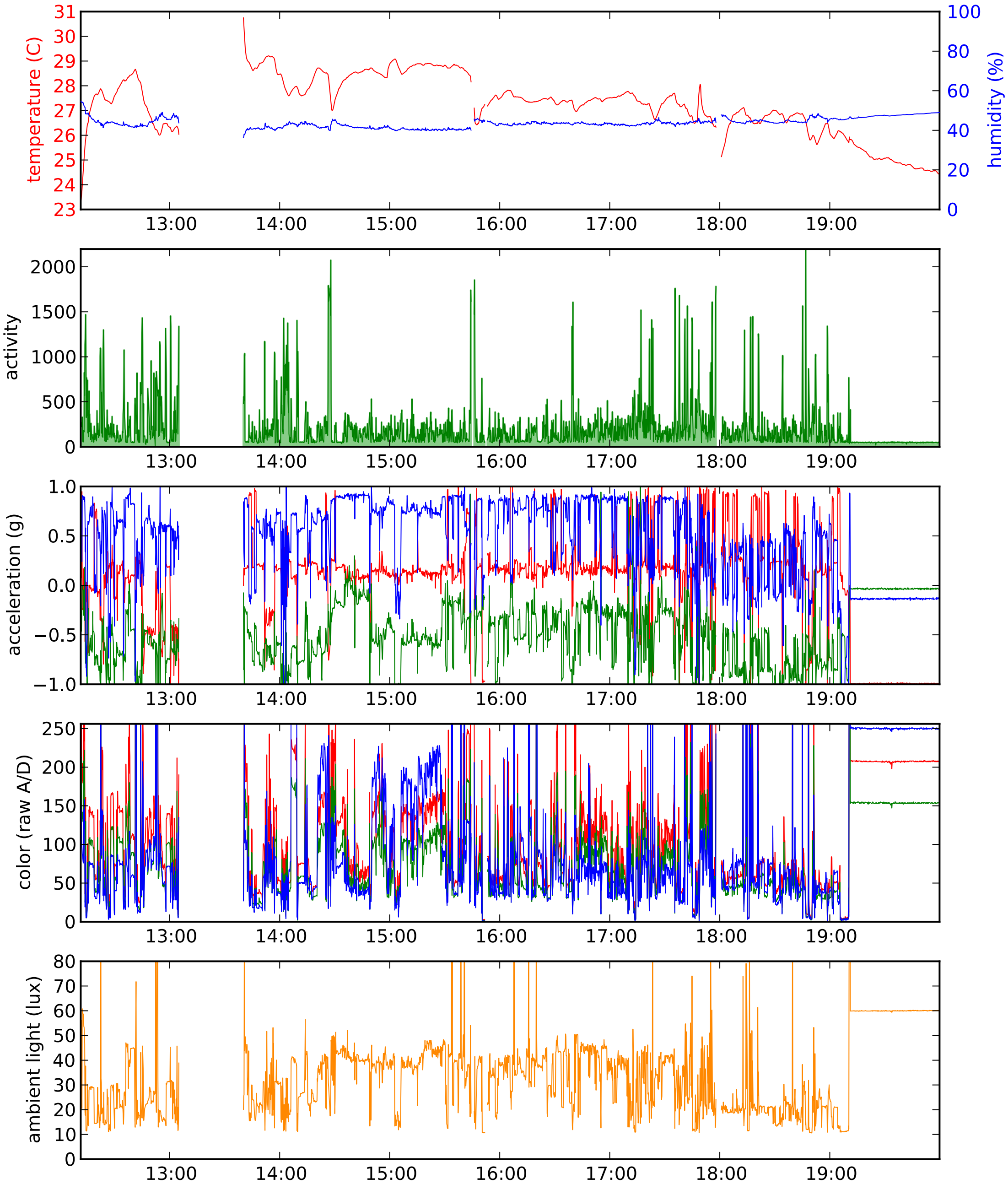

Figure 5.6: Data recorded by the WristQue sensors while it was worn on the afternoon and evening of August 23, 2012.

WristQue to toggle the nearest bank of lights on and off. This replicates the simplicity of a light switch and makes it conveniently available on the user's wrist. The user's location is used as contextual information to determine which bank of lights should be controlled.

The second application demonstrates that the WristQue could be used as the sensor device described in [22], which can measure the contribution of individual solid-state light sources in the environment. The system normally uses pulse width modulation (PWM) to drive the lights at 240 Hz, while a single light source whose contribution is to be measured is driven at 120 Hz. The light sensor on the WristQue records 1,000 samples from its monochrome light sensor at 2 kHz, which are then transmitted back to the server over the wireless network. The server performs a Fourier transform on the recorded data to isolate the 120 Hz signal. By cycling the lower frequency PWM signal through each light source in the space and making a measurement for each configuration, the contribution of each individual light source can be measured without perceptibly changing the illumination. An example of the data recorded by the WristQue's light sensor and the frequency components of the signal are shown in Figure 5.7.

The solution of the linear program and actual control over the solid-state light fixtures has not yet been implemented in the WristQue system. However, these preliminary results show that it has the necessary sensing capabilities to implement the control that the authors described.

5.4 Personalized comfort control

In his Ph.D. thesis, Feldmeier [12] describes a system for personalized comfort control. The user wears a device with temperature and humidity sensors, and indicates comfort (too hot, too cold, or neutral) by pressing buttons on the side of the device. The system uses the data to train a model for each user's preferences, which is subsequently used to control the building HVAC based on the temperature and humidity measurements from the device. The WristQue pro-

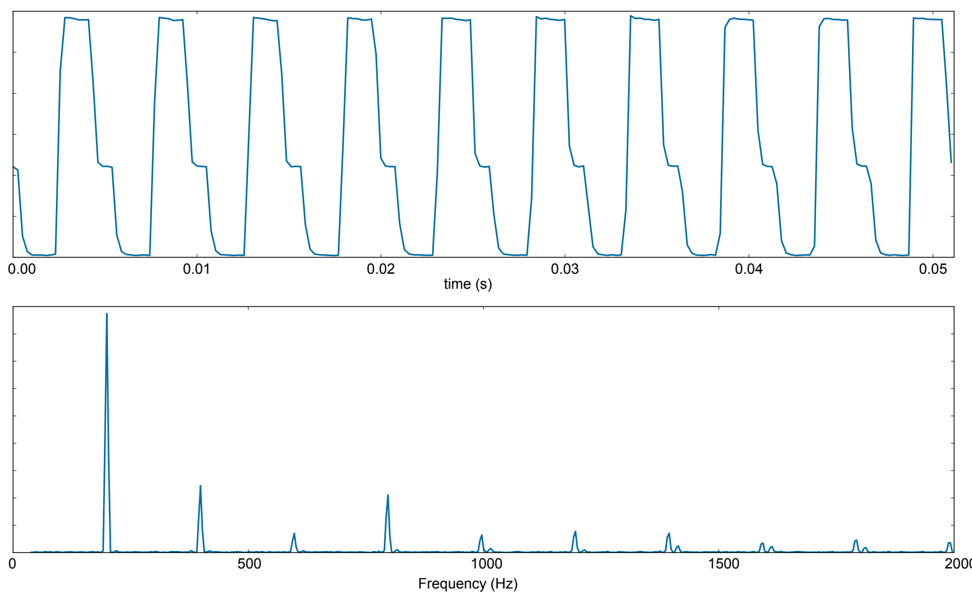

Figure 5.7: The sample buffer recorded by the WristQue's light sensor while under the solid-state lighting fixtures described in [22]. The top plot shows a portion the raw data recorded by the light sensor and the bottom plot shows the Fourier transform of the entire buffer, with the first peak indicating the contribution from a single light source in the system.

totype includes the necessary sensors and buttons to include this functionality. A plot of the temperature and humidity data from the WristQue is included in Figure 5.6. Due to the limited amount of time available to conduct tests with WristQue, this has not yet been implemented, but it should be possible to replicate Feldmeier's results using the WristQue hardware.

5.5 WristQue as a platform

One of the aims of WristQue is to be a general-purpose platform for personal sensing and control. Section 5.2 shows that the WristQue device can collect sensor data similar to other wearable sensor research platforms, but in a compact wristband form. It can be extended to include other sensor sets by replacing the sensor board, which is independent of the CPU, radio, buttons, and touch interface (Figure 5.8).

Live streamed sensor data is available from the current WristQue system through the ROS pub-sub system, and could easily be extended to include other protocols such as Open Sound Control or a web API. Historical sensor data is also available through an SQL database. This enables users to build their own applications on top of the WristQue platform using the sensor data, pointing interface, buttons, and IMU data.

Figure 5.8: The WristQue sensor board is separate from the CPU, buttons, touch interface, and radio, allowing the sensor set to be changed without reimplementing basic functionality.

Chapter 6

Conclusions and Future Work

This work so far shows that a small, personal wearable device can enable personal control based on sensing, and that orientation and location data can be used to implement an interface based on natural gestures, such as pointing. Moving forward, there are a plethora of applications to be built upon the technology demonstrated in the WristQue. The beginnings of the pointing interface can now be extended to start controlling actual devices in the environment. The orientation sensors, combined with machine learning algorithms, may enable gesture recognition, further extending the natural interface without depending on cameras everywhere in the environment. And personal sensors have widespread uses–from personal health applications to better understanding building controls and systems and more context for closed-loop automatic control. So far, applications have been demonstrated for lighting and HVAC, but personalized sensor-driven control is not limited to these areas. Further work on the WristQue will consider how wearable and other sensors can be used in other areas of control. Other small features could also be added to increase the WristQue's utility and encourage users to wear it, such as emulating the user's RFID tag to open the building door locks.

Power usage on the WristQue could be further optimized–while the current power usage provides several days of runtime, more careful optimization could allow much longer times between recharges, further supporting the idea that the WristQue should be a device that is always there and ready without the user having to constantly remember to maintain it. Transitioning between power modes is also important–the current WristQue automatically switches between sensing and sleep modes based on proximity to the network infrastructure. A future version of the WristQue could dynamically scale power usage dynamically from sleep all the way up to full power interaction mode with high sample rates based on the user's activity, location, environment, or the way that they are interacting with the device.

Finally, the WristQue is part of a larger system that includes fixed infrastructure in addition to the wristband itself. Cameras and depth sensors (such as the Microsoft Kinect) in the environment could help the WristQue with more accurate pointing and gesture recognition, while the WristQue could help camera systems by uniquely identifying users.

As even more embedded computers appear around us, it is important that unified interfaces exist, or we will become lost among an array of controls. Sensors and localization are critical parts of ubiquitous computers–without them, ubiquitous computers have no context with which to make decisions. The WristQue prototype described in this work is a step toward being a personal and universal "interface to everything," both in providing natural control through pointing, gestures, and readily accessible buttons and indicators, and by providing valuable context in the form of location and environmental data.

References

[1] *Apple - iPod nano with Multi-Touch*. URL: http://www.apple.com/ipodnano/ (visited on 09/05/2012).

[2] *Basis – health and heart rate monitor for wellness and fitness*. URL: http://mybasis.com (visited on 07/11/2012).

[3] F. Belloni et al. "Angle-based indoor positioning system for open indoor environments". In: *Positioning, Navigation and Communication, 2009. WPNC 2009. 6th Workshop on*. 2009, pp. 261 –265. DOI: 10.1109/WPNC.2009.4907836.

[4] M. Bletsas. "The MIT Media Lab's Glass Infrastructure: An Interactive Information System". In: *Pervasive Computing, IEEE* 11.2 (2012), pp. 46–49.

[5] J. Blumenthal et al. "Weighted Centroid Localization in Zigbee-based Sensor Networks". In: *Intelligent Signal Processing, 2007. WISP 2007. IEEE International Symposium on*. 2007, pp. 1 –6. DOI: 10.1109/WISP.2007.4447528.

[6] T. Choudhury et al. "The Mobile Sensing Platform: An Embedded Activity Recognition System". In: *Pervasive Computing, IEEE* 7.2 (2008), pp. 32 –41. ISSN: 1536-1268. DOI: 10.1109/MPRV.2008.39.

[7] Jaewoo Chung et al. "Indoor location sensing using geo-magnetism". In: *Proceedings of the 9th international conference on Mobile systems, applications, and services*. MobiSys '11. Bethesda, Maryland, USA: ACM, 2011, pp. 141–154. ISBN: 978-1-4503-0643-0. DOI: 10.1145/1999995.2000010. URL: http://doi.acm.org/10.1145/1999995.2000010.

[8] G. Dublon et al. "DoppelLab: Tools for Exploring and Harnessing Multimodal Sensor Network Data". In: *IEEE Sensors*. IEEE, 2011.

[9] *EZ430-Chronos*. Oct. 12, 2009. URL: http://processors.wiki.ti.com/index.php/EZ430-Chronos (visited on 07/11/2012).

[10] E. Elnahrawy, X. Li, and R.P. Martin. "The limits of localization using signal strength: A comparative study". In: *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*. IEEE. 2004, pp. 406–414.

[11] J. Farringdon et al. "Wearable sensor badge and sensor jacket for context awareness". In: *Wearable Computers, 1999. Digest of Papers. The Third International Symposium on*. 1999, pp. 107 –113. DOI: 10.1109/ISWC.1999.806681.

[12] Mark Christopher Feldmeier. "Personalized building comfort control". PhD thesis. Massachusetts Institute of Technology, 2009.

[13] Saul Greenberg et al. "Proxemic interactions: the new ubicomp?" In: *interactions* 18.1 (Jan. 2011), pp. 42–50. ISSN: 1072-5520. DOI: 10.1145/1897239.1897250. URL: http://doi.acm.org/10.1145/1897239.1897250.

[14] Chris Harrison and Scott E. Hudson. "Abracadabra: wireless, high-precision, and unpowered finger input for very small mobile devices". In: *Proceedings of the 22nd annual ACM symposium on User interface software and technology*. UIST '09. Victoria, BC, Canada: ACM, 2009, pp. 121–124. ISBN: 978-1-60558-745-5. DOI: 10.1145/1622176.1622199. URL: http://doi.acm.org/10.1145/1622176.1622199.

[15] Catherine Havasi et al. "The Glass Infrastructure: Using Common Sense to Create a Dynamic, Place-Based Social Information System". In: *Innovative Applications of Artificial Intelligence*. 2011. URL: http://www.aaai.org/ocs/index.php/IAAI/IAAI-11/paper/view/3531.

[16] Jose L. Hernandez-Rebollar. "Method and apparatus for translating hand gestures". Pat. US2010/0063794. Mar. 11, 2010.

[17] J. Hightower and G. Borriello. “Location systems for ubiquitous computing”. In: *Computer* 34.8 (2001), pp. 57 –66. ISSN: 0018-9162. DOI: 10.1109/2.940014.

[18] A.S. Huang et al. “Visual odometry and mapping for autonomous flight using an rgb-d camera”. In: *Int. Symposium on Robotics Research (ISRR),(Flagstaff, Arizona, USA)*. 2011.

[19] Navigent Consulting Inc. *Solid-state lighting research and development portfolio: multi-year program plan FY’09-FY’15*. Lighting Research, Development Building Technologies Program, Office of Energy Efficiency, and Renewable Energy, US Department of Energy, 2009.

[20] *IsoLynx Real-Time Player Tracking and Game Analysis Technology*. URL: http://finishlynx.com/isolynx/ (visited on 08/31/2012).

[21] Tim Layden. “Armstrong’s bracelets, cultural phenomenon”. In: *Sports Illustrated* (Nov. 10, 2004). URL: http://sportsillustrated.cnn.com/2004/writers/tim_layden/09/10/layden.0910/index.html (visited on 07/11/2012).

[22] B. Lee, M. Aldrich, and J.A. Paradiso. “Methods for measuring work surface illuminance in adaptive solid state lighting networks”. In: *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*. Vol. 8123. 2011, p. 22.

[23] *Lutron GRAFIK Eye 4000 System Overview*. URL: http://www.lutron.com/Products/WholeBuildingSystems/Grafik4000/Pages/Overview.aspx (visited on 07/15/2012).

[24] S.O.H. Madgwick, A.J.L. Harrison, and R. Vaidyanathan. “Estimation of IMU and MARG orientation using a gradient descent algorithm”. In: *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on*. 2011, pp. 1 –7. DOI: 10.1109/ICORR.2011.5975346.

[25] U. Maurer et al. “eWatch: a wearable sensor and notification platform”. In: *Wearable and Implantable Body Sensor Networks, 2006. BSN 2006. International Workshop on*. 2006, 4 pp. –145. DOI: 10.1109/BSN.2006.24.

[26] Brian Mayton et al. "TRUSS: Tracking Risk with Ubiquitous Smart Sensing". In: *IEEE Sensors*. IEEE, 2012.

[27] Josh McHugh. "Wrist-Top Revolution". In: *Wired* 11.04 (Apr. 2003). URL: http://www.wired.com/wired/archive/11.04/fossil.html.

[28] Matti Myllymäki. "Control system for building automation controlled by human physiological signals". Pat. US6348867. Feb. 19, 2002.

[29] C. Narayanaswami and M.T. Raghunath. "Application design for a smart watch with a high resolution display". In: *Wearable Computers, The Fourth International Symposium on*. 2000, pp. 7 –14. DOI: 10.1109/ISWC.2000.888452.

[30] Chris Nerney. "Qualcomm reveals details of Peanut wireless technology". In: *IT World* (Sept. 22, 2010).

[31] *Nike+*. URL: http://nikeplus.nike.com/plus/ (visited on 08/29/2012).

[32] Julien Pansiot et al. "Ambient and Wearable Sensor Fusion for Activity Recognition in Healthcare Monitoring Systems". In: *BSN*. Ed. by Steffen Leonhardt, Thomas Falck, and Petri Mähönen. Springer, 2007, pp. 208–212. ISBN: 978-3-540-70993-0.

[33] A. Pantelopoulos and N.G. Bourbakis. "A Survey on Wearable Sensor-Based Systems for Health Monitoring and Prognosis". In: *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on* 40.1 (2010), pp. 1 –12. ISSN: 1094-6977. DOI: 10.1109/TSMCC.2009.2032660.

[34] Joseph A. Paradiso and Nan Zhao. "Energy-efficient control of solid-state lighting". In: *SPIE Newsroom* (Mar. 25, 2011). DOI: 10.1117/2.1201102.003543. URL: http://spie.org/x47317.xml.

[35] *Pebble*. URL: http://getpebble.com/ (visited on 08/29/2012).

[36] Morgan Quigley et al. "ROS: an open-source Robot Operating System". In: *ICRA Workshop on Open Source Software*. 2009. URL: http://www.willowgarage.com/sites/default/files/icraoss09-ROS.pdf.

[37] *Real-time location systems and geospatial consulting - Ubisense*. URL: http://www.ubisense.net/ (visited on 09/03/2012).

[38] Louis B. Rosenberg. "Method and apparatus for point-and-send data transfer within a ubiquitous computing environment". Pat. US2006/0241864. Oct. 26, 2006.

[39] Z. Sahinoglu, S. Gezici, and I. Güvenc. *Ultra-Wideband Positioning Systems: Theoretical Limits, Ranging Algorithms, and Protocols*. Cambridge University Press, 2011. ISBN: 9780521187831. URL: http://books.google.com/books?id=e_mdcQAACAAJ.

[40] L. Schor, P. Sommer, and R. Wattenhofer. "Towards a zero-configuration wireless sensor network architecture for smart buildings". In: *Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings*. ACM. 2009, pp. 31–36.

[41] *Shapeways 3D Printing*. URL: http://www.shapeways.com/ (visited on 07/11/2012).

[42] *Skyhook: Location Technology*. URL: http://www.skyhookwireless.com/location-technology/ (visited on 09/03/2012).

[43] Asim Smailagic and Daniel Siewiorek. "Application Design for Wearable and Context-Aware Computers". In: *IEEE Pervasive Computing* 1 (2002), pp. 20–29.

[44] *SmartWatch | Android Watch - Sony Smartphones*. URL: http://www.sonymobile.com/us/products/accessories/smartwatch/ (visited on 08/29/2012).

[45] R. Smith, M. Self, and P. Cheeseman. "Autonomous robot vehicles". In: ed. by Ingemar J. Cox and Gordon T. Wilfong. New York, NY, USA: Springer-Verlag New York, Inc., 1990. Chap. Estimating uncertain spatial relationships in robotics, pp. 167–193. ISBN: 0-387-97240-4. URL: http://dl.acm.org/citation.cfm?id=93002.93291.

[46] D. Snoonian. "Smart buildings". In: *Spectrum, IEEE* 40.8 (2003), pp. 18–23.

[47] F. Sottile et al. “Design, deployment and performance of a complete real-time ZigBee localization system”. In: *Wireless Days, 2008. WD ’08. 1st IFIP*. 2008, pp. 1 –5. DOI: 10.1109/WD.2008.4812912.

[48] *UP by Jawbone*. URL: http://www.jawbone.com/up/ (visited on 07/11/2012).

[49] Hirotaka Uoi and Katsutoshi Kimura. “Gesture input system, method and program”. Pat. US2010/0138785. June 3, 2010.

[50] J. Weingarten and R. Siegwart. “EKF-based 3D SLAM for structured environment reconstruction”. In: *Intelligent Robots and Systems, 2005. (IROS 2005). 2005 IEEE/RSJ International Conference on*. 2005, pp. 3834 –3839. DOI: 10.1109/IROS.2005.1545285.

[51] *Wi-Fi Location-Based Services 4.1 Design Guide - Cisco Location-Based Services Architecture*. May 20, 2008. URL: http://www.cisco.com/en/US/docs/solutions/Enterprise/Mobility/wifich3.html.

[52] *fitbit*. URL: http://www.fitbit.com/ (visited on 08/29/2012).