Some Novel Applications for Wireless Inertial Sensors

J.A. Paradiso

Responsive Environments Group
MIT Media Laboratory
20 Ames St. E15-327
Cambridge MA 02139 –USA-

ABSTRACT

This paper surveys several recent and ongoing projects from the MIT Media Lab's Responsive Environments Group that leverage compact, low-cost inertial sensing into scenarios that range from wearable biomotion measurement platforms to interactive badges and musical controllers.

Keywords: biomotion sensing, badge platforms, wireless sensors, sensor networks, ubiquitous computing

1 INTRODUCTION

Sensors have followed a corollary of Moore's Law as they progressively decrease in size, cost, and often power. Nowhere is this more evident than with inertial sensor systems, as MEMS-based devices become steadily smaller and exhibit better performance. A designer can now implement a sensor suite that was once restricted to heavy platforms such as satellites onto the form factor of a wristwatch – when wedded with low-cost RF networking and every-more capable embedded processing, many novel applications are enabled. This paper overviews a selected subset of projects from the Media Lab's Responsive Environments Group that result from this trend and exploit compact inertial sensing in different ways.

2 WIRELESS & WEARBLE

One theme pervading several of our projects is multimodally capturing the gesture and motion of a person wearing a wireless sensing device. Our first project in this area was the "Expressive Footwear," a dancer's shoe that telemetered 16 continuous channels of data from a host of embedded sensors that included a 2-G dual-axis accelerometer for detecting foot swings, a 3-axis high-G piezoelectric accelerometer for detecting kicks and jumps, a rate gyro for detecting spin about the ankle, a 3-axis magnetometer for measuring foot angle in the Earth's magnetic field, a tracking sonar, a capacitive height sensor, and a tactile-sensing insole. The first working design, prototyped in 1997, was an early example of a multimodal, compact wireless sensor node, as well as being at the forefront of digital interactive dance - a performer wearing these shoes could control a complicated real-time audio stream by driving a musical rule base with the sensor data generated via their motion [1].

Figure 1: Expressive Footwear (top) & Gaitshoe (bottom)

Our next efforts in this area were for medical applications, seeded by a collaboration with the Biomotion Lab at the Massachusetts General Hospital aimed at producing a wearable platform that could gather biomechanical data for an extend period of time outside of a dedicated motion capture laboratory (e.g., at home or in a doctor's office). This resulted in what we termed the "GaitShoe" – a pair of instrumented retrofits installed into a pair of shoes that measured up to 20 different parameters each (all relevant to clinical gait analysis), wirelessly transmitting all data off both feet via a simple TDMA scheme with 75 Hz full state updates [2]. The GaitShoe was validated against the Biomotion Lab's gait monitoring system and used in clinical data mining, with 26 dynamic features extracted for recognition of relevant gait characteristics [3]. The system was also used for real-time gait intervention via musical feedback with patients suffering from injuries or festination from Parkinson's Disease, with the audio from a music player changing appropriately in tonality and rhythm to reinforce proper walking [4].

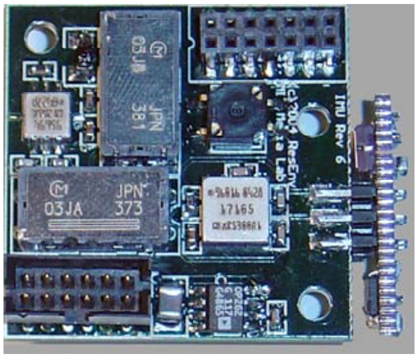

Figure 2: The Inertial (IMU) Layer of a Sensor Stack

Each GaitShoe had a Sensor Stack [5] – a compact, modular toolkit that we developed to host a variety of embedded and wearable wireless sensing projects – mounted behind its heel. The Stack is configurable for different applications by layering circuit boards atop one another that serve different sensing themes – the GaitShoe, for example, used an RF/CPU board stacked atop a tactile board (conditioning a variety of resistive, piezoelectric, and capacitive sensors mainly in the insole), which was stacked atop a 6-axis inertial board, which was sometimes stacked atop a sonar board that measured inter-foot distance and angle. The Stack's IMU was made essentially flat by using two brands of miniature gyros (a MEMs device from Analog Devices and two vibrating reed gyros from Murata) that sense along orthogonal axes.

While dense multimodal sensor platforms like the Stack provide a rich description of phenomena via several different flavors of measurement, extending battery life mandates that the sensors can't be continually powered, but must rather spend most of their time sleeping or turned off. Accordingly, we are developing an automated framework that we term "groggy wakeup" [6] where, by exposing an analysis to labeled data from particular phenomena to be detected and general background, we evolve a power-efficient sequence of hierarchical states, each of which requires a minimal set of activated sensors and calculated features, that ease the system into full wakeup. Accordingly, the sensor system only comes full on only when an appropriate stimulus is encountered, hence resources are appropriately conserved – sensor diversity is leveraged to detect and measure target states with minimal power consumption. The Stack has been redesigned to support this framework – for example, the current IMU incorporates passive inertial tilt and acceleration switches for "zero-energy" sensing and controlled powering of all active components.

Although our original Expressive Footwear worked well at the feet of one dancer, we became interested in ways to instrument multiple points on the bodies of a small dance ensemble. The current Stack architecture proved too bulky for this purpose – although its footprint was sufficiently compact, it extended too far when modules were stacked atop one another. Accordingly, we developed a compact IMU that also contained a high-bandwidth 1 Mbps radio, low-power microprocessor, and capacitive proximity sensor (for inferring the rough proximity of one node from the other). The entire device is the size of a big wristwatch - 1.65"x1.65"x0.5", not including the protruding antenna and external lithium polymer battery, hence is easily worn. Our TDMA scheme is able to support an array of circa 25 nodes updating all states at 100 Hz. We are currently developing efficient signal processing algorithms that operate on this data stream in order to reduce it to a small set of real-time features and variables that reflect ensemble activity, upon which a choreographer or composer can author interactive content [7].

Figure 3: A wrist-mounted Dance Ensemble IMU

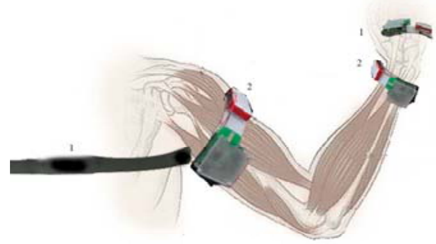

Figure 4: IMU Layout for Instrumented Pitcher

This system also has applications in interactive exercise (e.g., a portable intelligent music player that can synch up to a jogger's rhythm while leading/lagging tempo and tweaking timbres and musical structures in order to keep them at their metabolic target) and sports training. We have recently began a project to measure the performance of actual baseball pitchers on the mound – a challenging task, as various parts of a pitcher's arm can exhibit peak rates of up to 10,000°/sec and maximum accelerations of over 80 g's [8]. Figure 4 shows the sensor configuration that we are planning to run at Spring Training in Ft. Meyers, FL. Six dance ensemble sensor platforms will be strapped at various points along the pitcher's arm and shoulder, with high-rate/g sensors paired with lower-range sensors in the areas where peak values are expected, in order to provide high relative resolution throughout the entire pitch. High-speed data will be directly logged into flash memory onboard each device, with the RF system used to synchronize all units and offload the data after each pitch.

The MIT Media Lab has been a pioneer in developing electronic badges that mediate interactions between people. Our most recent badges are also sensor platforms that capture data for analyzing human dynamics and behavior.

The UbER-Badge was designed as a flexible platform that can be used to facilitate large social events as well as a tool to capture data. Sporting a multitude of features, the badge includes a large, highly-visible LED display for scrolling text and showing simple animations, a line-of-sight IR port for communicating with nearby badges or active IR tags, and an onboard radio for wireless networking. The badges have been used by over 100 simultaneous attendees at several events at the Media Lab and its sponsor companies. Although the badges facilitated practical applications such as wireless messaging, voting, and bookmarking of other badges or tagged demos that the wearer was particularly interested in during our open house, they were extremely effective at timekeeping during tightly-scheduled presentations, where all badges in the audience flashed bright time cues to the speaker, becoming increasingly insistent as talks ran over. The badges also continuously logged accelerometer (reflecting body language) and audio spectral data (reflecting vocal modalities). An analysis has shown that the badges' measurements of body motion and voice characteristics, together with the IR beacon data, effectively determine a user's state. For example, we can predict with roughly 80% accuracy that users will be interested enough in a nearby demo or facing colleague to hit their bookmarking button. We can also predict affiliation – we have determined features indicating that users come from the same company or group with over 90% accuracy – a key determinant is the fact that affiliated users tend to move in synchrony. Details can be found in Ref. [9].

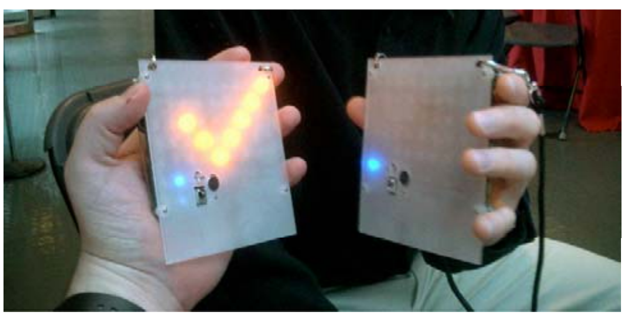

Figure 5: A Pair of UbER-Badges Bookmarking

3 GRASPABLES

In addition to wearable systems, we have also embedded a variety of sensors, including inertial suites, into handheld controllers. One of the most extreme of these is shown in Fig. 6. The "FlexiGesture," [10] supports many interaction modalities, including multiple pressure-sensitive buttons, biaxial bending, twisting, capacitive translation monitoring, and full inertial sensing courtesy of the Stack IMU. This device was used to explore adaptive mapping strategies for complex multimodal musical controllers. As an electronic instrument's input space grows in complexity, it becomes increasingly difficult to manually assign musical responses to individual sensor signals. Accordingly, the FlexiGesture learns by example, training on gestural data collected when a player manipulates the instrument in a way they find natural when hearing the launch and dynamics of a particular sound. In this fashion, the instrument hones its technique from the musician rather than vice-versa, the status quo for traditional instruments.

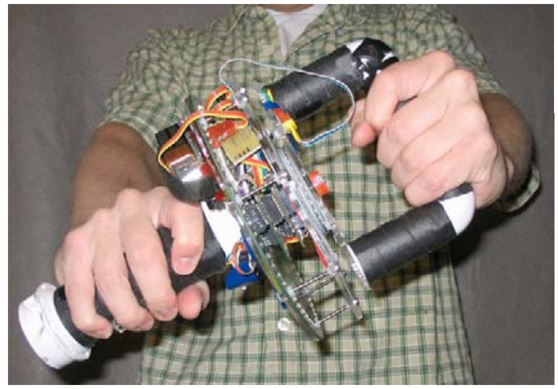

Figure 6: FlexiGesture – An Adaptive Musical Interface

Although sensors indeed grow progressively smaller and cheaper, a platform as diverse as a fully outfitted Stack is still somewhat expensive, potentially running up to hundreds of US dollars. Another approach is to employ ultra low-cost wireless sensors that measure very few parameters, but are so cheap that they can be very widely deployed. One such "featherweight" sensor system that we have developed is a compact acceleration detector that sends narrow RF pulse when it is jerked [11]. Although there are many applications for such a device (e.g., activity tagging and detection in smart homes), we have used it to explore interactive entertainment in very large groups, where these cheap sensors can be given out with tickets, and real-time statistics run on incoming data can discern ensemble trends (e.g., a "wave" at a sports stadium or parameters that indicate how a group of people are dancing) and facilitate a dynamic media response to crowd interaction. As the electronics are directly woken up by the sensor signal, the batteries in these devices last close to their shelf life – units that we have built four years ago are still working fine.

Figure 7: An UltraLowCost Wireless Motion Sensor

4 STATIONARY PLATFORMS

As the cost of sensors decreases, it may not be unusual to see them incorporated into devices that are mainly intended for other purposes in order to widen their domain of application. Accordingly, we have recently embedded a multimodal sensor network node into a very useful and common item found in homes and offices - a power strip (Figure 8). This device has access to power (and potentially networking) through its line cord, can control and measure the detailed current profile consumed by devices plugged into its outlets, supports an ensemble of sensors (microphone, light, temperature, and inertial vibration sensors are intrinsic, while other sensors such as thermal motion detectors and cameras can be added easily), and hosts an RF network that can connect to other PlugPoint sensors and other nearby wireless sensors (accordingly acting as a sensor network base station). We are exploring a host of ubiquitous computing applications and variety of navigation/representation paradigms for sensor network data that can be developed on these devices when they are massively deployed across our laboratory over the next several months.

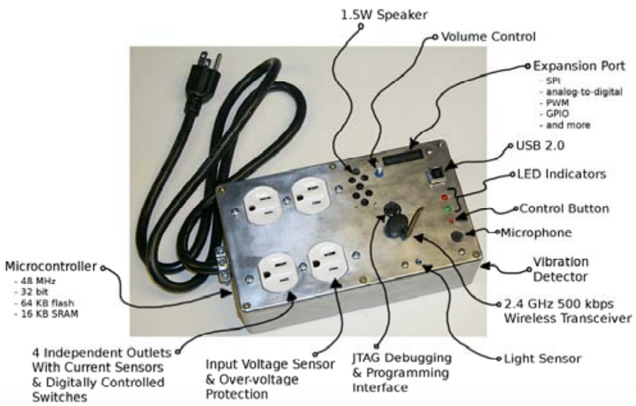

Figure 8: PlugPoint – A Power Strip as Sensor Node

5 CONCLUSIONS

I see Ubiquitous Computing as having grown into something like a religion evolving at enormous speed. The original doctrine of Mark Weiser [12] has been reinterpreted and adapted by many Calvins, Luthers, and perhaps even a few King Henrys over the past 1.5 decades, giving the field over a dozen different dogmas and monikers. While this dialog continues, Moore's law marches on, and sensors continually shrink in size and power while the cost of embedding computation and communication progressively falls. Complex sensor packages will inevitably diffuse into places where they were never anticipated, enabling applications that we can now barely conceive of, forming the backbone of what Ubiquitous Computing becomes.

6 ACKNOWLEDGEMENTS

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