Presented at the IPSN/SPOTS '05 Conference in Los Angeles, CA on April 25-27, 2005

A Compact Modular Wireless Sensor Platform

Ari Y. Benbasat and Joseph A. Paradiso
Responsive Environments Group, MIT Media Lab
Cambridge, MA 02139, USA
Email: {ayb,joep}@media.mit.edu

***Abstract*— We have designed and constructed a modular platform for use in compact wireless sensing. This platform is based around a series of circuit boards (or panes), each of which instantiates a specific sensing modality - *e.g.* inertial sensing, tactile sensing or ambient sensing. As opposed to similar architectures, this system treats the sensor panes as discrete design objects that have data collection as their primary purpose. The main goals achieved by this design are ease of prototyping (and revision) and encapsulation of design knowledge.**

We describe a number of different projects instantiated with this system. Key among them are a wearable gait measurement system which exploited the modularity of the system, a novel musical controller which benefited from the design encapsulation and a study of dynamically low-power sensor nodes based on the structure of the panes (*i.e.* multiple sensors for a single modality). Several other applications are discussed. Lessons learned in the areas of software design, sensor placement and mechanical stability are commented on.

I. INTRODUCTION AND MOTIVATION

Streaming wireless sensor systems have become a staple for a variety of applications over the last decade. Recent examples from the Responsive Environments Group alone have included wireless systems to capture the expressive movement of a dancer[1], to quantify the movement of a pair of foam rubber buns for experiments in human-computer interaction[2], and to extend the capabilities of *ad-hoc* networks by making the nodes parasitically mobile[3]. Many of these systems are quite similar, sharing portions of their hardware and software infrastructure. More importantly, they share large amounts of low-level design, in the forms of the sensing, processing, wireless transceiving hardware and software written to interface with or control their functionality. However, each system, because of its unique form factor and choice of sensors, needed to be prototyped from scratch, thereby incurring needless effort in design and debugging.

To overcome these problems in general and simplify the rapid prototyping and testing of wireless sensor systems, it was decided to design a modular sensor platform. Overall, the goal was to allow the user to treat sensing as a commodity, *i.e.* allowing an application to trivially incorporate different kinds of measurement. There were three keys to achieving that goal in this project:

Encapsulating knowledge: As mentioned above, the greatest benefit from a modular sensor architecture is the ability to encapsulate knowledge (*i.e.* low-level design). A single pane of a modular system can encapsulate the best practices in a given field, save a large amount of design time, and allow for easy upgrades. Further, code can be associated with various operations on a given pane, encapsulating them as a functional block rather than simply a hardware block. For example, radio frequency (RF) transceivers are very sensitive to layout, and even the smallest changes can be disastrous. A single pane with a proper high-frequency transceiver and antenna layout based on current best practices can solve this problem. The same argument applies to the software for data encoding and decoding, which can often be less than transparent.

Reducing repetition of circuit design: While the encapsulation of design knowledge works to maintain the quality of the circuitry, the reduction of repeated circuit structures is aimed at saving time. It is quite common for a large part of any particular system to be the reuse of known circuit blocks, with only the slightest change in most cases. Key examples are serial line converters, sensor conditioning circuitry, power regulators and microcontroller support circuitry. The creation of individual panes containing one or more such circuits can eliminate much of the drudgery of the design process.

Simplifying prototyping: While the form factor and generality of such a platform may not be appropriate for the final design of most of our systems, they are certainly acceptable in the early stages. Therefore, rather than proceeding directly to a stage where the whole system is laid out in its final form, this platform makes it possible to quickly lay out a new pane solely for the application at hand, which can then be attached to other available panes to produce a version of the new system. This version, while likely not optimal for final deployment or mass production, will nonetheless collect the relevant data, provide a valuable proof of concept, help detect flaws in the design and provide a basis to begin the construction of necessary interface and analysis software. Further, it is also possible to quickly determine which sensors are of benefit in a given application simply by adding the appropriate panes to the system and examining the resulting output data.

II. MODULAR DESIGN PHILOSOPHY

The key to implementing the above goals - to making a general system instead of a specific one - is to make the platform as modular as possible. Therefore, the choice of sensors and their layout on the individual panes must be undertaken with care so as to construct functional blocks rather than system blocks. Further, no single subcircuit on a particular pane should be requisite for use of the pane (*i.e.* a combined capacitive-proximity/pressure-sensing pane should allow for use of just one of the two modalities). Ideally, individual panes should be combinations of circuitry that in general either cannot or should not be separated (such as a six-axis inertial measurement unit). This same modularity should apply to any software written for the individual panes. A single master processor pane will contain the basic software for data collection and transmission and communication with other panes. Each of those panes should be associated with blocks of code (or a library) that can be included in the main code when the sensor pane is attached to the processor pane.

Also, to be able to exploit the modular design, it must be as easy as possible to combine and recombine the available panes into different configurations for different applications. This will require a simple interconnect system between the boards that allows for repeated insertion cycles as well as for as many lines (for data, control and power) as reasonably possible to run between the panes (to increase the number of possible interactions between them). The goals of simplicity in both the pane design and interaction suggest that a direct connection scheme is the best approach. While this requires a central nexus, it avoids the need to place a processor on each pane and provides for much faster data transfer than higher-level schemes (such as ethernet or USB). Mechanically, there are two other requirements: that the interconnects be available on the top and bottom of each pane (allowing the panes to be stacked in any order), and that they provide enough structural strength that a stack of panes connected together cannot accidentally disconnect, especially in wearable application where a high levels of mechanical stress can be expected. Also, the software for each pane must be designed such that the appropriate code for any given configuration can be easily composed and compiled.

Finally, for the platform to be most useful, it must be possible for future users to extend it in a variety of ways. Mechanically, this requires that the footprint and height of the individual panes be such that new circuits can easily meet those constraints. Further, exclusive use of interconnect lines between the individual panes should be avoided. Finally, in the case of the software, the main code needs to allow for inclusion of library files (without source code) for ease of integration. Monopolization of limited processor resources can cause conflicts and should be avoided. Also, the core software for the processor should contain as many helper functions (to set up timers, analog to digital converters, *etc.*) as possible to allow those with a limited knowledge of the particular platform to still be able to code efficiently and quickly.

III. RELATED WORKS

Other research projects are currently working towards similar ends and producing similar systems. However, each is attempting to solve a slightly different problem, leading to important differences.

The best known system in this space is the Motes hardware designed by UC Berkeley[4] and produced by Crossbow[5]. Each typical mote is a 1 in by 2 in board with attached power source, processor and wireless transmitter. This main board can be supplemented by only a single sensor board, which includes an assortment of inertial, optical, and other sensors. This approach eschews modularity for the sake of size and integration (*e.g.* incorporating another degree of sensing implies the addition of another wireless sensing node). Further, their associated research concentrates much more on building an *ad-hoc* peer-to-peer network of these boards, rather than collecting large amounts of data for either on-board or central processing.

The Smart-Its project[6], comprised of a consortium of European institutions, is building a similar system to our own which mostly concentrates on instrumenting objects rather than individuals. Their main board, featuring a processor and a wireless transceiver, is under an inch square. A number of sensor boards have been built, though as above, only one can be used at a time. Further, their system and attachments do not appear to have mechanical strength in mind, making wearable applications difficult.

Finally, the Tower project[7], also at the MIT Media Lab, is in the same genre, at least in some respects. The Tower features a main processor board to which multiple extensions can be added. Each board is designed towards a single input (*e.g.* light sensors, microphones) or output (*e.g.* LEDs, speakers) functionality. The whole system is programmed and accessed via a real-time command line interpreter running on the main board. This system is designed mainly for system exploration and building, rather than for testing and deployment. Therefore, the boards are quite large (about 3 in square) and stacks of boards can grow to be 6 in or taller.

In contrast to the projects described above, our work concentrates on the sensor portion of the design, rather than networking or pedagogical concerns. Further, our system was designed primarily for module (stack of panes) to basestation transmission of real-time sensor data from wearable sensors, which often require continuous updates of 75 Hz or more (per node).

IV. HARDWARE INSTANTIATION

A. Mechanical Structure

The system itself is comprised of boards 1.4 in square and 0.4 in high, which are interconnected electrically by two headers totaling 26 pins (14 for one, 12 for the other) at opposite corners. The connectors are Molex Milli-Grid shrouded headers and mating receptacles, and are rated for 100 insertion cycles (reasonable for prototyping). The other two corners are used for mounting holes that allow for structural reinforcement of the full stack, which is particularly important for wearable applications. An earlier board layout, while 60% smaller because of more compact connectors, was replaced because of these concerns.

B. Electrical Interconnects

The electrical interconnects provide for signal, control and power lines to be run between individual panes. The main method of data transfer is a shared multiplexer bus, which uses 3 address lines, 4 enable lines, and a shared output bus. Data can also be transferred between suitably equipped parts using Serial Peripheral Interface (SPI, 4 lines). Finally, 8 lines connected to the microcontroller on the master board (see below) provide for direct communication of any kind and the 2 lines connected to the external interrupt pins provide for time-critical communication. Finally, four pins transfer power between the boards in the form of $+12\,\text{V}$, $+5\,\text{V}$, $+3.3\,\text{V}$ and ground. Power regulation is handled by a separate board, due to the wide variety of different approaches that can be taken and their respective efficiencies and noise characteristics.

C. Individual Panes

Master: The master board (figure 1, left) is responsible for the data collection and transmission to the central basestation and is included in every project. It currently contains a 22 MIPS Silicon Labs C8051F206 processor with 12-bit ADC as well as an RFM TR1000 916 MHz transceiver running at 115.2 kBps. The processor pins are broken out to the interconnects mentioned above. Each pin can function as either a digital input, digital output or an analog input, and this state can be changed in real-time (adding to the flexibility of the system).

A central basestation is also built using this master board that manages a simple TDMA wireless protocol. While it can technically handle an arbitrary number of stacks (group of boards), the practical limit is determined by the size of the data packet from each stack and the desired update rate. This star network configuration is a product of the wearable applications driving our development. Conversion of the platform to operate in a peer-to-peer mode should be fairly straight-forward.

This board draws approximately 35 mW under normal operation, which includes roughly 1000 ADC conversions per second. Wireless transmission of that data requires an additional 15 mW.

IMU: The sensor board shown in figure 1 (centre) is a six-degree-of-freedom inertial measurement unit (IMU). Acceleration is measured via two Analog Devices ADXL202 accelerometer ($\pm 2\,\text{g}$), one of which is orthogonally attached to the side of the pane to achieve the third axis of sensing. Angular velocity is measured via two Murata ENC03J gyroscopes and a single Analog Devices ADXRS300 gyroscope (all $\pm 300^\circ/\,\text{sec}$). This combination allows for full 6-axis inertial sensing in a nearly flat package. A four-way

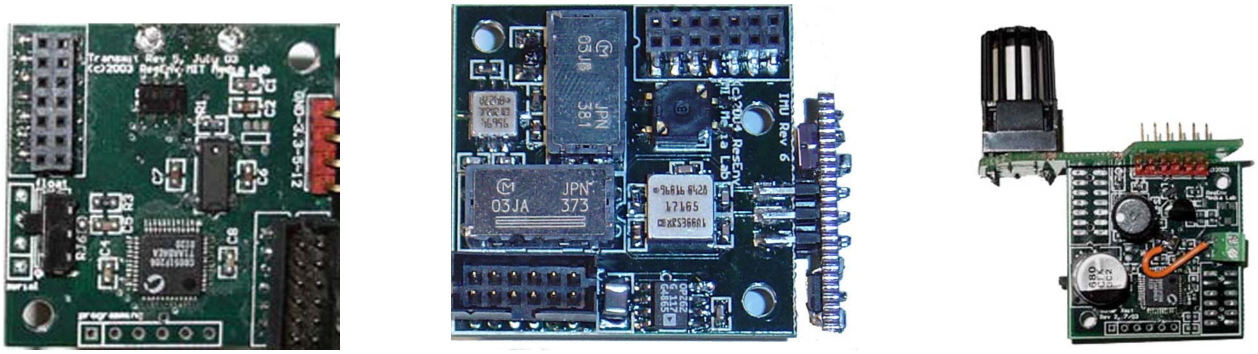

Fig. 1. Master, IMU and Ranging Boards

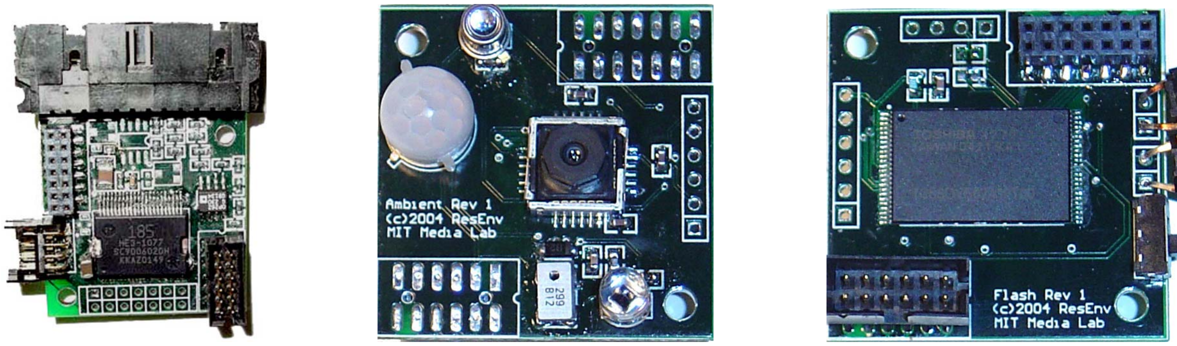

Fig. 2. Tactile, Ambient and Storage Boards

static tilt sensor (ALPS SPSF1000) provides for micropower single-bit acceleration measurement.

This pane draws roughly 65 mW, with the ADXRS300 responsible for over a third of that amount.

Ranging: Distance measurements can be achieved using a matched pair of sonar receiver and transmitter boards. The transmitter board sends a single 40 kHz pulse from an omnidirectional transceiver (MSI 1005853), which is then received by two pickups (Gibson Tech V-MA40A5R) on the receiver board placed a fixed distance apart. A measurement of differential time-of-flight is allowed by synchronizing to the basestation's TDMA messages, hence the two receivers allow both displacement and relative angle to be calculated. It is shown at the right of figure 1.

The transmit and receive modules each draw approximately 120 mW when pinging at a rate of 50 Hz.

Tactile: A fourth sensor board is shown at left in figure 2. It allows for inputs from a number of different tactile and pressure sensors. It includes inputs for four single-ended force-sensitive resistors (FSRs) via common-collector BJT amplifiers, two back-to-back FSR bend sensors via a differential op-amp pair, and two piezoelectric sensors via common-drain FET amplifiers. This pane also contains the circuitry for a Motorola 33794 9-channel loading-mode capacitive proximity sensor[8]. These are attached via a header at the top of the board, allowing them to be spatially distributed as desired (such as sensate gloves or shoe insoles).

When configured for use with a shoe insole (see section VI), this pane draws 65 mW. Note that the 33794 is responsible for over three-quarters of that total.

Ambient: The ambient sensing board (figure 2, centre) provides a range of methods of detecting audible and visible contents in the local environment. This includes a narrow cone (10°) Osram BPX43 phototransistor and a wide cone (70°) Osram SFH314 phototransistor. Dynamic heat sources are detected with an Eltec 442-3 pyroelectric sensor. Finally, a complete visual of the environment can be acquired using the ALPS FPDB0 VGA camera module. Acoustic pickup is provided by a SiSonic SP0103 microphone and a SiLabs F206 for preprocessing.

This board draw roughly 100 mW for the sensors alone (almost entirely for the camera). Enabling the F206 to allow for *in-situ* signal processing (*e.g.* of camera data) will double that amount.

Storage: On-board data storage is provided by the board shown in figure 2 (right). Data is stored in a 1 Gbit flash memory chip (Toshiba TC58DVG02A1) and I/O is controlled by a SiLabs F206. Data is input to the board over SPI and is output via an RS232 connection.

Under the same conditions as given for the master board, 40 mW are needed to store the collected data. We note that this is almost triple the amount of power necessary to wireless transmit the data.

Power Regulation: Finally, a simple power regulation board was also constructed. It is designed to use a single 9 V battery, which is directly attached to the board. Voltage conversion is done via switching regulators for efficiency, and therefore the board must be isolated from the transceiver to avoid interference.

It should be noted that this selection of boards merely represents the specific sensors that were necessary for project constructed within our research group. New boards can be easily created and source code examples and PCB templates are provided for this purpose. A number of applications designed with this platform (and new boards created for them), both by our group and others at the MIT Media Lab, are discussed in section VI.

V. Software Instantiation

This architecture is currently exclusively being used for wireless data collection and streaming applications. Therefore, the current software implementation is somewhat skeletal. Running on the master board, its sole purpose is to collect the data from the various sensor board and transmit them to the basestation. Since a TDMA scheme is used, these actions are taken in response to a prompt from the basestation. The rest of the time, the processor idles (awaiting commands) with the radio in receive mode.

The software itself is constructed in a modular format and contains three main sections: initialization, data collection and data transmission. The addition of a new board to an application can be accounted for in the code by adding an appropriate routine to each of these sections. A header file may also be necessary for local variables. Also, macros and helper routines exist within the main code to aid in common operations. These include data collection tasks such as setting the channel on the shared multiplexer bus, mutual exclusion on the multiplexer enable lines, and ADC sampling. Data transmission is facilitated by a hard-coded 6 to 8 bit DC balancing scheme (for use with the 12 bit ADC data), as well as by macros for SPI and UART communication. Miscellaneous tasks such as timer start, stop, store and reset and port input/output mode selection as also handled.

VI. Applications

A. Wearable Gait Laboratory

Fig. 3. Wearable Gait Analysis Platform (sensors on heel)

One of the first, and most important, applications built using this platform was a wearable gait laboratory[9]. Changes in gait (manner of walking) are surrogate markers for a variety of medically important phenomena, such as developmental maturation, likelihood of falling, and recovery from a stroke. Clinical gait analysis is usually carried out in a confined environment - the patients typically walk less than $10\,m$ per trial - using expensive vision-based motion capture systems.

Stacy Bamberg applied our platform to develop a prototype inexpensive wireless wearable system for the analysis of the motion of feet during gait. The system consisted of the master, IMU, tactile and sonar boards, as well as the power regulation board. The stack was screwed down to a piece of thermoformed plastic, which was connected to the patient's shoe using plastic screws (figure 3). A sensor insole was connected to the tactile board via the header and was placed inside the shoe. Validated against data from the Massachusetts General Hospital Biomotion Lab, the system produced nominally identical results at far lower cost. Further, its wireless nature allows for real-time feedback to the patient during daily wear (which is not possible with a fixed lab).

This application took advantage of the extensibility of this architecture in a number of ways. To increase the mechanical strength of the system, a third mounting hole was added to the IMU board. Also, the sonar board was added to the system near the very end of the design revision cycle to increase the accuracy of the foot-to-foot distance measurements (compared to the IMU). In both cases, none of the other boards needed to be altered in any way to accommodate these changes. We also note that the entire system was designed with modularity in mind. The insole could be changed depending on the size of the patient's foot and the entire system could be easily attached and detached from the patient's shoe.

B. Novel Musical Controller

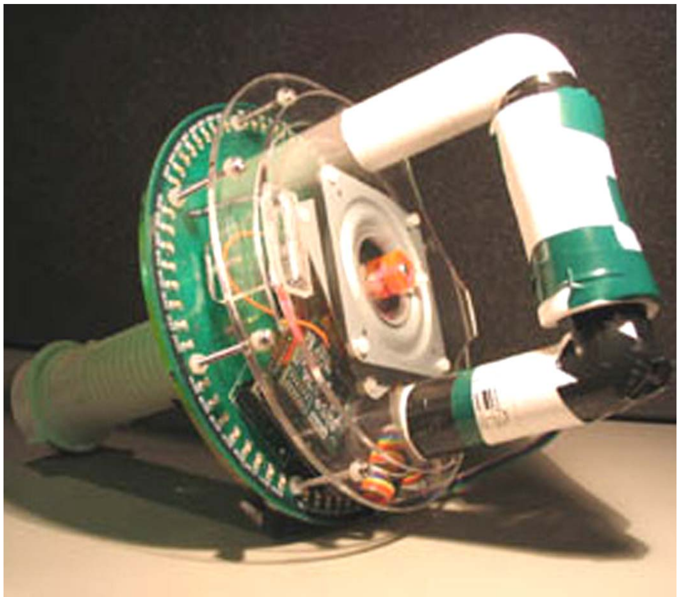

Fig. 4. FlexiGesture Controller (sensors between plexiglass and large PCB)

Another application implemented using this platform is a trainable adaptive musical controller[10]. In traditional musical instruments, each input gesture is connected to a specific output sound through the law of physics (which are cleverly manipulated to create the instrument). The advent of digital sound synthesizers and electronic music controllers has decoupled action and reaction, making a large range of input-to-output mappings possible, as well as an infinite set of possible timbres. However, this revolutionary change brings with it the problem of design - intuitive, natural mappings from gesture to sound now must be created in order to create a playable electronic music instrument.

FlexiGesture, created by David Merrill, is a device that allows flexible assignment of input gesture to output sound, thus acting as a laboratory to help further understanding about the connection from gesture to sound. It is controlled in a two-handed fashion, with a main handle and twistable top as shown in figure 4. Manipulations of the device relative to itself (bending, twisting, *etc.*) are measured using the tactile board. Movement of the device in the world frame is measured using the IMU board. All the data is (of course) collected and transmitted using the master board. Two new boards were also created. An output pane was built with circuitry to control a pager motor and LEDs for user feedback as well as transmit circuitry for electric field position sensing[11]. An electric field receiver board was built to detect these signals, and formed part of the basestation (normally comprised of a just master board).

We quickly note two main benefits of the system here. The first is the obvious exploitation of the extensibility, as described in the section above. The second is the benefits derived from encapsulation, which allowed the designer to reuse the circuitry of the IMU board, the master board (twice) and the tactile board in a new arrangement. This resulted in a significant reduction in design time for the electronics, allowing the designer to concentrate on the interaction aspects of the project rather than the data collection.

C. Real-time Adaptive Sensor System

This platform is still being used in a prototyping capacity, notably in work examining techniques for reducing the power usage of wearable wireless sensors[12]. Prototype wireless sensors (such as those described above) typically collect from their sensors as much data as possible as quickly as possible. While this is a reasonable approach in the design stage of a system, it is untenable in a production device due to the extreme power usage. The wearable gait lab, for instance, consumes an entire 9 V battery in approximately six hours. Using some of the techniques described in the citation above, it is possible to extend this life by a factor of twenty.

These techniques, being examined by the authors, reduce the sensor system's power drain by varying the sampling rate and accuracy of the sensors (as well as the choice of sensors) such that the amount of data collected by the system is reduced without affecting the amount of useful information collected. This work is being tested using a prototype stack consisting currently of the master and IMU boards. Future work will be based around the ambient board and possibly other boards as well (depending on sensing needs).

This work primarily exploits the completeness of each sensing modality as expressed by the stack panes. For instance, the IMU board provides both low and high power (and accuracy) sensors for measuring acceleration. The ambient board provides a variety of differential visual sensors - the phototransistor detects light from reflective objects, the pyroelectric sensor detects heat from radiative bodies, and the camera images both. Also, the extensibility of the architecture is of great benefit as the necessary techniques for lowering the power usage are discovered. The master board is slated for redesign with a more powerful processor and the sensor boards will likely be redone to include the ability to individually deactivate sensors.

D. Prototyped Systems

Not all applications use the boards from this platform for their final implementation. Many times the boards are used simply for prototyping and design, and the circuitry is then redesigned depending on the particular physical constraints of the systems. Two such systems are touched on below.

A forearm controller and tactile display[13], designed by David Sachs, allows the wearer to control a braille output scheme by rotating or raising or lowering their arm. It used components of our platform in its original incarnation. The IMU board was used in the motion tracking system, with its data collected by a different processor than that on the master board. A new board was also created to test the benefits of magnetic sensors for tracking. Eventually, these components were integrated with a previously constructed circuit board which managed the output portion of the application.

Also, Dan Lovell is constructing a compact coordinated gesture system[14] which will allow a group of individuals to concurrently collect motion data from various points and then have that data analyzed *en masse* for similarities. The initial goal application of this system will be the instrumentation of a half-dozen dancers at four points each (ankles and wrists), with the output data used to create music on-the-fly. This is a direct extension of the work in the Expressive Footwear project[1] (identical in goal, but with a single dancer) and the wearable gait laboratory (described above). Having prototyped the system using the IMU, tactile and master boards, the hardware is now being reconfigured into a package with nearly identical functionality, but planar and a third the size.

In both cases, the modularity of the architecture was exploited to quickly prototype new systems. In the case of the forearm controller, we note that once the software to read data from a single board was incorporated into an existing system, it was trivial to have it read data from a second, newly created board. In the case of the gesture system, each of the individual subsystems was tested and revised (both individually and as a whole) as part of the gait laboratory project before the combined system was designed. This new design will be vetted more quickly and will have a higher assurance of success because of this prior work.

VII. LESSONS LEARNED

A. Electrical

A number of important design lessons were learned in the electrical engineering portion of this project. In terms of ease of use of the system, experience has shown that the underlying software needs to mimic the modularity of the hardware. As discussed above, the current software running on the master board requires the addition of calls to specific functional routines (initialization, data collection and transmission) for each new board. This creates a few stumbling blocks. First, there is no clean way to deal with possible conflicts over shared resources (such as timers). Further, it is assumed that none of the routines are time sensitive, as both the order and the frequency at which they are called can change. Finally, it unnecessarily complicates adding new boards to the stack. While all that is physically necessary is snapping two boards together, the software needs to be rewritten (admittedly minimally), recompiled and downloaded to the processor. The best way to simplify the situation would be to make each board self-identifying, such that when plugged into the stack it could inform the master board of its sensors and how to collect their data. This could easily be achieved using a lightweight microcontroller on each pane, thereby making the system plug-and-play.

In terms of the sensor data itself, often ignored timing details can become quite important. In polling-based systems, where each pane (or sensor) is powered up only when sampled, start-up time can become an issue. While most sensors become ready quite quickly, others (such as the ADXRS gyroscopes) can take a substantial amount of time, limiting the update rate. This can also occur with sensors using digital pulse width modulation output. While acceptable for small collections of sensors, the time necessary to collect data in this fashion (roughly 1.5 periods of (nominally) 1 ms) can quickly add up if used for multiple devices. Fast-settling analog outputs can be processed significantly faster.

Finally, it is important to comment on the choice of power supplies and regulation. Since this platform uses a large number of different sensors on its boards, it is not surprising that they run at a number of different voltages. While most require 3 V, a few require 5 V and some (such as the sonar) as high a voltage as possible (12 V was chosen). The power regulation board provides all of these voltages through switching regulators, though individual applications with less varied needs would benefit from the reduced complexity and lower RF noise of a pared down circuit. The output voltage of analog sensors also become an issue. This is solved in our architecture by dividing down larger signals such that they fit in the $0 - 2.5\,\mathrm{V}$ range of the Cygnal microcontroller's ADC. However, local ADCs communicating to the master board via SPI are also an option (particularly in the plug-and-play example given above), at the cost of an increase in pane complexity.

B. Mechanical

The mechanical engineering portion of the design also provided a number of lessons. One of the most important, especially in wearable systems, is the strength of the connectors between the individual boards. The original design relied on a single subminiature 25 pin header. This header tended to fail after a small number of insertion cycles (often less than 20) and provided little structural strength. While the board had mounting holes, they are rarely used in the early stages of prototyping because of the effort involved in removing and replacing the supports. The new headers have a standard 100 mil pin spacing and are placed a opposing corners, providing enough structural support alone for most applications.

The strength of the packaging is also at issue. While not technically part of the platform, it must be possible to mount the stack to some form of case or attachment to complete the application. This can be done using the mounting holes, with the added third hole on the IMU board providing extra rigidity. For body-worn attachments, it is important to remember that three points of attachment are necessary to avoid extraneous motion which could corrupt the data.

Finally, to preserve the modularity of the system, the boards should be able to connect in any fashion. Therefore, it is important to avoid constructing boards which need to be on top of the stack. In the case of the ambient board, which contains a camera, this is unavoidable. In the case of the IMU or the tactile board, which have a daughter board and a connector (respectively) which protrude from the board, careful design can ensure that these parts do not interfere with other board. This is best achieved by minimizing their size, though ensuring that protrusions are not all on the same side of the boards is also acceptable.

VIII. CONCLUSIONS

We have developed a compact wireless modular sensor platform, which contains a number of circuit boards (panes). As opposed to similar architectures, this system treats the sensor panes as discrete design objects that have data collection as their primary goal. Seven boards have been designed so far: master (processor / transceiver), tactile (pressure, bend, proximity sensing), inertial measurement, ambient (visual and audio), sonar, data storage and power regulation. These boards encapsulate design knowledge and allow for rapid prototyping of applications. A simple software framework, running on the master board, provides for data collection and transmission. It allows for new boards to be added to a module through the addition of calls to specific functional routines. Two major applications, a wearable gait laboratory and a novel musical controller, have been built and user tested. The platform is currently being used to help develop algorithms for a real-time adaptive sensor system with the goal of reducing power drain without loss of useful information. Also, a number of systems were first prototyped using this platform before being implemented in a more compact fashion.

A number of lessons have been learned in the process of designing this system. The value of plug-and-play software for the boards was highlighted by the cumbersome steps necessary to update the code to match the easily-connected boards. Timing issues in sensor wake up and data collection require a higher level of care in the selection of parts that interact with an unknown number of others. Finally, mechanical issues of the strength of interconnects (especially in the early prototyping stage) and the positioning of daughter boards and other protrusions raise physical design issues not present in individual circuit boards.

While the platform is completely functional today, it continues to evolve as it is used. Our experiences to date suggest some areas for future work, but in the end the greatest improvements will likely come as the user base of the platform grows and the system is altered and expanded to suit their widely varied needs.

ACKNOWLEDGMENTS

We thank all those who aided in the development of the individual sensor boards, particularly Stacy Bamberg and Dan Lovell. We also thank all those who worked with this platform and gave invaluable feedback: Stacy Bamberg, Dan Lovell, David Merrill, David Sachs and Larissa Welti-Santos.

The authors would like to acknowledge the support of the Things that Think Consortium, as well as all the sponsors of the MIT Media Lab. Mr. Benbasat acknowledges the support of the MIT Center for Bits and Atoms and Media Lab Europe.

REFERENCES

[1] J. A. Paradiso, K. Hsiao, A. Y. Benbasat, and Z. Teegarden, "Design and implementation of expressive footwear," *IBM Systems Journal*, vol. 39, no. 3&4, pp. 511–529, 2000.

[2] A. Y. Benbasat and J. A. Paradiso, "An inertial measurement framework for gesture recognition and applications," in *Gesture and Sign Language in Human-Computer Interaction*, Ipke Wachsmuth and Timo Sowa, Eds., 2002, pp. 9–20.

[3] M. Laibowitz and J. A. Paradiso, "Parasitic mobility in dynamically distributed sensor networks," in *Proceedings of the First ACM Workshop on Applications of Mobile Embedded Systems*, June 2004.

[4] Berkeley Wireless Embedded Systems Project, http://webs.cs.berkeley.edu/.

[5] Crossbow Technology Inc, http://www.xbow.com/.

[6] L.E. Holmquist et al., "Building intelligent environments with Smart-Its," *IEEE Computer Graphics and Applications Magazine*, vol. 24, no. 1, 2004.

[7] T. Gorton, "Tangible toolkits for reflective systems modeling," M.S. thesis, Program in Media Arts and Sciences, Massachusetts Institute of Technology, June 2003.

[8] F. Eady, "E-field evaluation module," *Circuit Cellar*, pp. 60–66, June 2003.

[9] Stacy J Morris, *A Shoe-Integrated Sensor System for Wireless Gait Analysis and Real-Time Therapeutic Feedback*, Ph.D. thesis, Division of Health Sciences and Technology, Massachusetts Institute of Technology, June 2004.

[10] David Merill, "Flexigesture: An sensor-rich real-time adaptive gesture and affordance learning platform for electronic music control," M.S. thesis, Program in Media Arts and Sciences, Massachusetts Institute of Technology, June 2004.

[11] J. A. Paradiso and N. Gershenfeld, "Musical applications of electric field sensing," *Computer Music Journal*, vol. 21, no. 2, pp. 69–89, 1997.

[12] Ari Y. Benbasat, "Design of a real-time adaptive power optimal sensor system," in *Proceedings of IEEE Sensors 2004*, October 2004.

[13] David Sachs, "A forearm controller and tactile display," M.S. thesis, Program in Media Arts and Sciences, Massachusetts Institute of Technology, June 2005.

[14] Dan Lovell, "A system for real-time gesture recognition and classification of coordinated motion," M.S. thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, February 2005.