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# A Wireless Modular Sensor Architecture and its Application in On-Shoe Gait Analysis

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## Abstract

*We have developed a compact wireless modular sensor architecture, which contains a number of circuit boards (panes), currently used in an application for on-shoe gait analysis. Each pane instantiates a major function – e.g. inertial sensing, tactile sensing or data collection and transmission. As opposed to similar architectures, this system treats the sensor panes as discrete design objects that have data collection as their primary goal. This architecture has allowed us to develop a shoe-mounted system that is capable of measuring gait parameters outside of a traditional motion laboratory. The small size of the circuit boards allows for a compact attachment that fits on the back of the shoe, and the integrated wireless transceiver allows the data to be collected continuously and in any environment.*

## Keywords

modular sensors, wireless sensors, sensor clusters, dense sensing, medical monitoring, gait analysis.

## INTRODUCTION AND MOTIVATION

Streaming wireless sensor systems have recently become a staple for a variety of applications. Examples just within the last several years from the Responsive Environments Group have included wearable systems to capture the expressive movement of a dancer[1], to measure the passage of cars over a roadbed[2], and to quantify the movement of a pair of foam rubber buns[3] for experiments in human-computer interaction. 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, the processing, the wireless transceiving hardware, and the 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 architecture. Overall, the goal is 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 huge 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 examples, 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 in the case of the software for data encoding and decoding, which can sometimes 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 during their design. It is quite common to find 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 conditioners, power regulators and microcontroller support circuitry. The creation of individual panes containing one or more of such circuits can eliminate much of the drudgery of the design process.

**Simplifying prototyping**: While the form factor and generality of such an architecture 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 design stage were the whole system is laid out in its final form, this architecture 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 systems and examining the resulting output data.

This paper presents a detailed example of an application using this architecture in an on-shoe gait analysis system to illustrate the value of a design meeting the above goals.

# HARDWARE

## Overall Design

For the greatest utility, this architecture must be as modular as possible. Therefore, the choice of sensors and layout on the individual panes must be undertaken with care to avoid constructing system blocks rather than functional blocks. Further, no single subcircuit on a particular pane should be required for use of the whole 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 main processor pane will contain the basic software for the operation of the processor and communication with other panes. Each of those panes should be associated with a block of code (or a library) that can be included in the main code when the pane is attached to the main processor pane.

Also, to be able to take advantage of the modularity, it must be as simple 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. Also, the interconnects should allow for as many lines as reasonably possible to run between the panes, to increase the number of possible interactions between them. 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 a single application for a given configuration can be easily composed and compiled.

Finally, for the architecture 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) to allow those with a limited knowledge of the particular platform to still code efficiently and quickly.

## Related Works

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

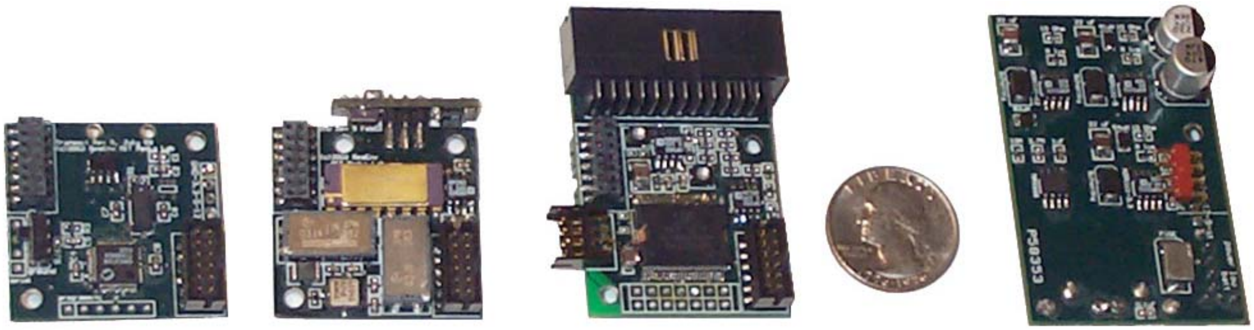
The best known system in this space is the Motes hardware designed by UC Berkeley[4] and produced by Crossbow[5]. Each typical mote is a 1in by 2in board with attached power source, processor and wireless transmitter. This main board can be supplemented by a single sensor board, which includes an assortment 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 adhoc peer-to-peer network of these boards, rather than collecting large amounts of data for either on-board or central processing. The motes also include TinyOS[6], a real-time operating system designed to manage a wireless sensing system using a hierarchical event driven structure, which allows for strong functional embedding on the single expansion board.

The Smart-Its project[7], comprised of a consortium of European institutions, is building a similar system to our own that is mostly concentrating 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 human-borne applications difficult. Their plug-and-play perception API simplifies integrating new sensor boards.

Finally, the Tower project[8], 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 3in square) and stacks of boards can grow to be 6in or taller.

## Specifications and Artifacts

In contrast to the projects described above, this work concentrates on the sensor portion of the design, rather than networking or pedagogical concerns. Our system was designed primarily for module (stack of panes) to basestation transmission of sensor data for wearable sensors,



A B C D

**Figure 1: The majority of the modular panes currently available**

which often requires continuous real-time updates of up to 100 Hz or more.

The system itself is comprised of boards 1.4 inches square and 0.4 inches 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. The previous version, while 60% smaller because of smaller connectors, was replaced because of these concerns.

Several of the panes that have been built so far are shown in Figure 1. The main board (a) contains a 22 MIPS processor with 12-bit ADC as well as a 115.2 kBps 916 MHz transceiver. Many of the pins of the processor are broken out to the headers mentioned above. This provides for a shared multiplexer bus as well as address and enable lines and is the main method for data transfer from the sensor boards. Data can also be transferred via SPI, or direct connection to either multipurpose analog/digital I/O pins or external interrupt pins on the processor. This main board is responsible for the data collection and transmission to the central basestation (described below) and is included in every project. Power regulation is handled externally, due to the wide variety of different approaches that can be taken and their respective efficiencies and noise characteristics. Raw battery voltage, +5V, +3V and ground are then connected to the main board, and sent to the other boards via the headers.

A central basestation (not shown) is also built using this main board, and allows for a simple TDMA wireless protocol. While it can technically handle an arbitrary number of stacks, the practical limit is determined by the size of the data packet from each stack (group of boards) and the desired update rate.

The sensor board shown in Figure 1b is a six-degree-of-freedom inertial measurement unit (IMU). Acceleration is collected via two Analog Devices ADXL202 accelerometer, 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 ADXRS150 gyroscope. This combination allows for full 6-axis inertial sensing in a nearly flat package.

Distance measurements can be achieved using a matched pair of sonar receiver and transmitter boards (not shown). The transmitter board sends a single 40 kHz pulse, which is then received by two pickups on the receiver board placed a fixed distance apart. A measurement of differential timing is allowed by synchronizing to the TDMA messages, hence the two receivers allow both displacement and relative angle to be found.

A third sensor board allows for inputs from a number of different tactile and pressure sensors. It includes inputs for four single-ended force-sensitive resistors, two differential bend sensors, and two piezoelectric sensors. This pane also contains the circuitry for a 9-channel loading-mode capacitive sensor[9] (the Motorola 33794). 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). This board is shown in Figure 1c.

Finally, Figure 1d shows a simple power regulation board. It is designed to use a single 9V 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 the current projects of interest. New boards can be easily created and source code examples and PCB templates are provided for this purpose. This architecture has been used in a gait analysis application, as discussed in the following section. Also, a number of other groups at the MIT Media Lab have already used this system in their work.

**Figure 2: The sensor stack alone, and mounted on a shoe.**

## APPLICATION TO GAIT ANALYSIS

### Background

Gait and changes in gait are surrogate markers for a variety of medically important phenomena, such as developmental maturation, likelihood of falling, and recovery from a stroke. Change in gait over extended time is used in neurological exams to diagnose dementias, and can be used to assess the adequacy of pharmacologic therapy in a number of neurologic/psychiatric disorders.

Clinical gait analysis is carried out in one of two ways: in a motion analysis lab for quantitative analysis, and by visual observation for fast qualitative analysis. Motion analysis labs quantify both kinematic data (motions) and kinetic data (forces and torques); they are expensive to set up and maintain, both in terms of equipment and physical space (usually a minimum of 1000 square feet). The size of the motion lab limits the data collection: the patients typically walk about 20-30 feet per trial, crossing two adjacent force plates hidden beneath the floor covering. While labs have been built with additional cameras and additional force plates to extend the testing area, the testing space is still constrained. Despite these limitations, the analysis can yield results for multiple body segments of position within 1 mm and 3D orientations within one degree. At the other end of the spectrum is visual observation; this method is “free” after the cost of the physician’s time. While well-trained physicians are no doubt capable of discerning a great deal of info about their patients' gait, small changes may be hard to detect, and a qualitative observation is difficult to compare between office visits or different physicians.

Our application of this architecture to gait analysis[10] seeks to develop an inexpensive wireless wearable system for the analysis of the motion of feet during gait. A portable system that can allow quantitative gait analysis to be performed outside of traditional, expensive motion labs has the potential to be highly informative via data collection throughout the day in a variety of everyday environments, thus providing a vast quantity of long-term data and enabling real-time interactive corrective therapy.

### Related Work

There has been extensive prior work investigating shoe-based sensing systems for gait analysis. The obvious advantage of directly measuring the pressure distribution beneath the foot has driven many of the early systems, such as work by Wertsch et al [11]. More recently the shrinking size of data storage has further encouraged the development of non-tethered devices. Such systems include a simple standalone "footswitch" system consisting of two force sensors in an insole [12], an insole-based system to quantify the conditions inside the shoe, including pressure, temperature and humidity sensors [13], as well as a shoe and insole system consisting of three force sensors in an insole and a gyroscope attached to the back of the shoe (to measure rotation in the sagittal plane) [14].

In addition, our experience with shoe-based sensor system grows out of prior work done by the Responsive Environments Group[1]. The *Expressive Footware* project consisted of a pair of running shoes that were each equipped with a wireless sensor board and an instrumented insole. This highly instrumented shoe, first designed in 1997, was worn by dancers and the outputs of the sensors were used to interactively control music. It was completely wireless, with all hardware located directly on the shoe, and provided real-time control of the musical mappings. It received high acclaim in the dance community, and was recognized with the Discover Award for Technical Innovation in 2000[15].

### Results

A compact system measuring many parameters useful for gait analysis (see bottom of Fig. 3) was built using the sensor architecture described above. The four boards are stacked together and attached to a universal shoe attachment that was designed and constructed from thermoformable plastic. The complete assembly is shown in Figure 2. The inertial measurement board is the "bottom" board, separated from the shoe attachment by 1/8 inch spacers. The IMU is connected directly to the shoe attachment with a screw through a hole located along the top edge, then the other boards are connected to the IMU via the headers/receptacles. Plastic spacers are placed between the boards at the locations of the corner holes,

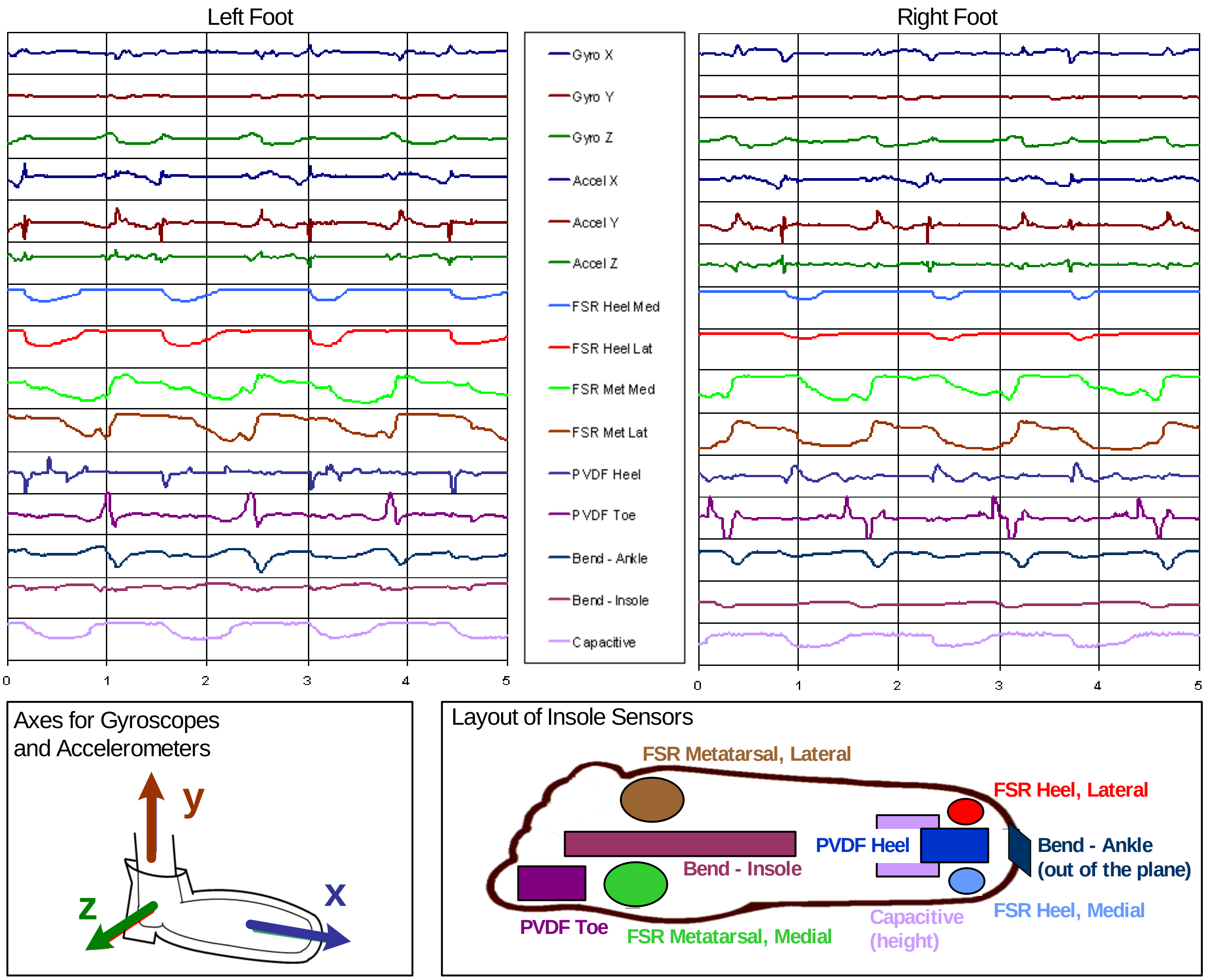



**Figure 3: Sample Data: Five Seconds of Normal Gait**

and a long screw is used in each corner to complete the mechanical stabilization. The power board is connected to the main board via a right angle connector, which is permanently soldered, and is held in place by a bracket, also made from thermoformable plastic. The tactile board has a header used to connect to the sensor insole, which is placed inside the shoe. An electrode for the height-measuring capacitive sensor is placed on the bottom of the shoe. The system consisting of IMU, tactile, main, and power boards, and insole has a mass of 300 g.

Initial results obtained with this system are shown in Figure 3. Current work is focused on analysis of the data, including calibration, analysis of sensor outputs, and pattern recognition, in order to extract clinically relevant gait information.

Visual inspection of these plots demonstrates the many degrees of sensing freedom encompassed in this system. The test subject was told to walk in a straight line at her usual pace. The data is nicely repeatable from step to step (the left foot data includes four footfalls, and the right foot data three). For example, the capacitive sensor measures height of the foot above the floor, and is at its lowest value when the foot is flat on the floor. The FSRs at the heel are compressed (magnitude decreases) just before the capacitive sensor reaches its low value, signifying "heel strike"; the FSRs at the metatarsals are compressed as the capacitive sensor begins to increase, signifying weight transfer in order to reach "toe off." In the gyroscope data, the gyroscope measuring rotation about the z-axis has the largest magnitude changes, corresponding to the foot swings.

## CONCLUSIONS AND FUTURE WORK

We have developed a compact wireless modular sensor architecture, 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. Five boards have been designed so far: main (processor/transceiver), tactile (pressure, bend, proximity sensing), inertial measurement, sonar, and power regulation. This architecture has allowed us to develop a shoe-mounted system that is capable of measuring gait parameters outside of a traditional motion laboratory. The small size of the circuit boards allows the whole system to be contained on a small attachment that fits on the back of the shoe, and the integrated wireless transceiver allows the data to be collected continuously and in any environment.

There are two main goals for the future of the hardware. On the architectural side, it would be very beneficial to simplify the software aspect of building a modular stack. The most straightforward way to do this would be to make each board self-identifying, such that when plugged into the stack it could inform the main board of its sensors and how to collect their data. This could easily be achieved using a lightweight microcontroller on each pane. Further, making the system plug-and-play would make third-party boards a real possibility, among other benefits.

On the application side, work is in progress to allow for stand-alone applications using this system. This would involve replacing the main board with one with greater processing power and storage (the transceiver could possibly be omitted). This capability would allow for data collection and analysis such as that describe in the gait example in an unconfined environment. For people with Parkinson's disease, it has been suggested that lab-based studies investigating straight line walking of subjects, while of interest, are ultimately not very illuminating, and that the field should try to move to studies within subjects' homes and communities involving more complex gait activity[16]. A device such as ours would allow easy collection of such enlightening data.

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