A Platform for Ubiquitous Sensor Deployment in Occupational and Domestic Environments

Joshua Lifton, Mark Feldmeier, Yasuhiro Ono*,
Cameron Lewis, and Joseph A. Paradiso
MIT Media Lab
Responsive Environments Group
20 Ames Street
Cambridge, MA, 02142, USA
{lifton, geppetto, ono, camlewis, joep}@media.mit.edu

ABSTRACT

In this paper, we introduce the "Plug" sensor network, a ubiquitous networked sensing platform ideally suited to broad deployment in environments where people work and live. The backbone of the Plug sensor network is a set of 35 sensor-, radio-, and computation-enabled power strips distributed throughout the third floor of the MIT Media Lab. A single Plug device fulfills all the functional requirements of a normal power strip (i.e., four 120V, 60Hz electrical outlets; surge protector circuit; standard electrical connector to a US-style wall socket), and can be used without special training. Additionally, each Plug has a wide range of sensing modalities (e.g., sound, light, electrical current and voltage, vibration, motion, and temperature) for gathering data about how it is being used and its nearby environment. To our knowledge, the Plug sensor network is the first to embody the idea of designing sensor nodes to seamlessly become a part of their environment, rather than play the role of alien, if unobtrusive, observers. We argue this design principle is essential for sensor networks to succeed in the realm of ubiquitous computing.

In this paper, we present an overview of the Plug hardware and software architectures, look at specific usage scenarios of a single Plug, and show example data taken across the entire Plug network to give a sense of the pulse of the building over a span of days. Finally, we present ongoing work interfacing heterogeneous devices with the Plug network for a variety of applications and discuss possible future work.

Categories and Subject Descriptors

C.3 [**Communication/Networking and Information Technology**]: Special-Purpose and Application-Based Systems—*Ubiquitous Computing*; B.10.2 [**Hardware**]: Power Management—*Energy-Aware Systems*

General Terms

Design, Measurement, Experimentation, Human Factors

*Visiting affiliate from Ricoh Company, Ltd, 16-1Shineicho, Tsuzukiku, Yokohama, 2240035, Japan

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1. INTRODUCTION

Most, if not all, sensor network platforms in use today are characterized by an emphasis on a low-power, unobtrusive, versatile design and an understanding, implicit or otherwise, that a network's sensor nodes are to be handled only briefly, if at all, by expert researchers between long periods of unattended operation. Although this paradigm has generally served the research community well and fits many application scenarios, it precludes a full exploration of the sensor network application space. In particular, we claim this paradigm is not fully appropriate for ubiquitous computing settings. Indeed, the commonly cited vision of living in a truly aware environment, one which senses and can respond to our every action, does not necessarily imply that the sensor nodes upon which this vision is built need be low-power, unobtrusive, or versatile.

In this paper, we introduce the "Plug", a sensor node modeled on a common electrical power outlet strip and designed specifically for ubiquitous computing environments. As with most sensor nodes, each Plug has its own microcontroller for tending to a host of sensors, actuators, and wireless and wired communication interfaces. In addition, a Plug node can serve as a normal power strip, providing four standard three-prong US electrical outlets. As such, a Plug node must be plugged into a power outlet to operate, making the issue of extreme energy conservation, such as needed for long-term battery-powered deployments, nearly irrelevant. Furthermore, considering a Plug node's comparatively large size (approximately 20cm×7cm×12cm) and weight (approximately 1kg), it's difficult to argue that a Plug is unobtrusive based on its physical specifications alone. Finally, a Plug node's versatility is limited to that of a regular power strip – it is not mobile, wearable, embeddable, or otherwise easily reconfigurable to be anything but a power strip.

Nonetheless, we claim that, within the context of ubiquitous computing, a network of Plug nodes is ideally suited for sensor network research and applications. By their nature, ubiquitous computing scenarios take place in environments normally inhabited by people, of which the home and the

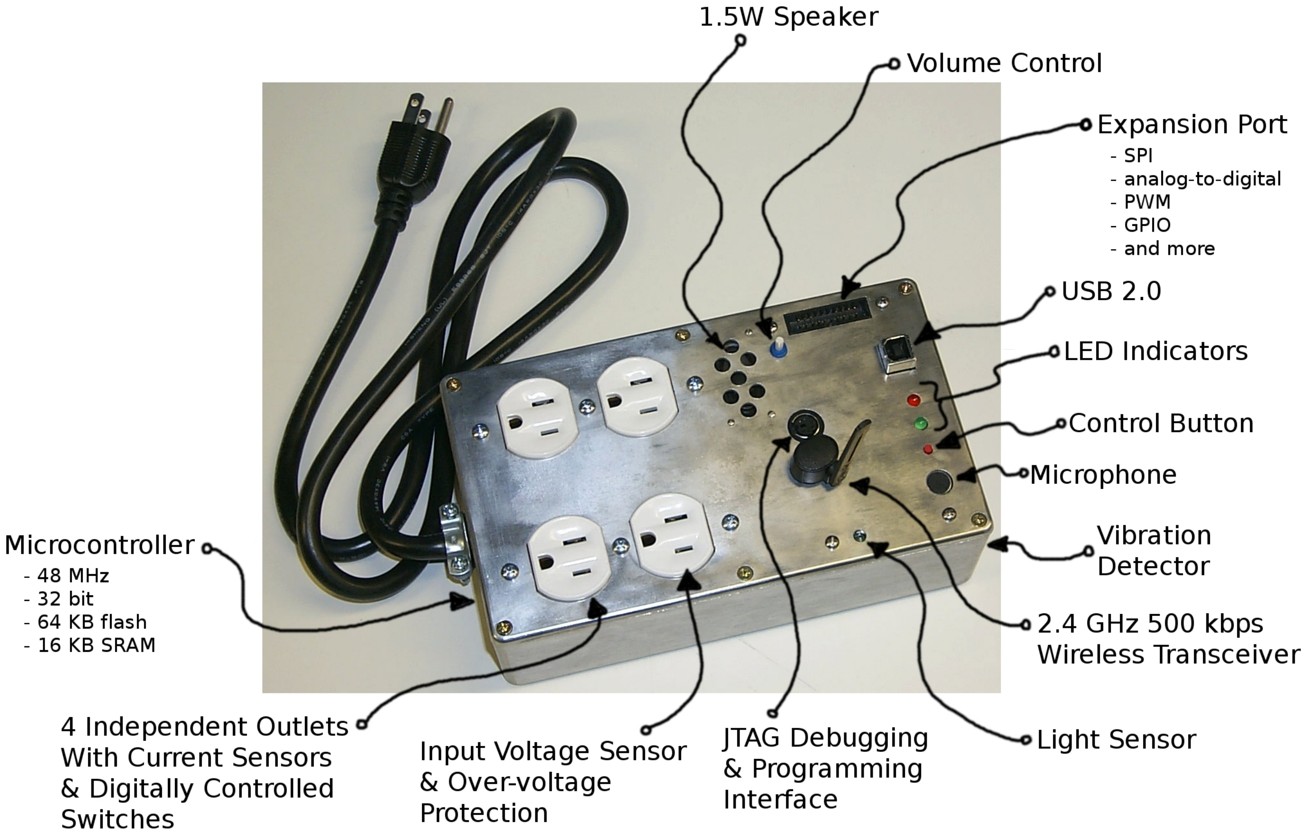

Figure 1: A Plug sensor node.

workplace are the dominant examples. Both these settings are infused with ample electrical power, typically in the form of wall sockets spaced every two or three meters. Thus, the need for exceptionally low-power sensor nodes is mitigated so long as the nodes need not be mobile. Similarly, what is considered unobtrusive depends on the setting. Power strips are common in nearly every home and workplace setting. A cursory examination of one of our lab's typical 14-square meter offices used by three graduate students revealed no less than 10 power strips, not including wall outlets. Despite this pervasiveness, most of the time, power strips go nearly unnoticed. (The exception being when they go missing). A true metric of a sensor node's obtrusiveness must take into account how well it blends with its environment, not just its physical size and weight. Finally, the versatility of a Plug node is somewhat two-sided. For example, like other versatile sensor network platforms, Plug nodes are richly multimodal, with ten sensor channels, and can be expanded upon with a generic digital and analog expansion port. Unlike many other platforms, the Plug node's physical form factor and deployment scenarios are rather limited. However, although the mechanics of how a Plug node is actually used are very narrowly defined (i.e., you can plug electrical devices into it), the uses such mechanics afford are only limited by the uses of electrically powered devices. A Plug is versatile in the same sense modern electrical infrastructure is versatile. Moreover, a Plug node's power switching capabilities and built-in speaker give it significant actuation advantages over most other sensor network platforms, which typically require hardware extensions to enable actuation.

The crux of the Plugs' utility as a sensor network platform lies in part in the tight integration of the observed and the observer. That is, a primary purpose of a Plug is to measure how it is being used or to ascertain context relating to its immediate neighborhood. The fact Plug nodes have a well-defined use at all is unusual in itself and contrasts sharply with most sensor network nodes, which are largely designed to be hidden throughout an environment and not interacted with directly. The Plug platform may be the first to attract the very phenomena it is meant to sense. This principle of designing sensor networks as integral parts of their environments, as opposed to additions layered on top thereof, is central to the Plug platform and will likely play a major role in bringing sensor networks out of the research lab into the real world. Intelligently augmenting commonplace devices already used for dedicated applications is a clear path toward ubiquitous sensing – the cost of adding sensing, networking, and computing capabilities to individual devices is relatively low and even a single device has utility, allowing the cost of the entire network to be spread over time.

2. RELATED WORK

The notion that a sensor network encompasses many different instantiations is well documented. The current formulation of a sensor network is less than 10 years old [6], whereas the term "sensor network" has been in use for at least 30 years [5], and has come to encompass everything from hopping land mines [17] to artificial sensate skins [21]. The Plug platform expands this list to include electrical power infrastructure.

Studying the power consumption of various electrical devices has a rich history. Such information can be used to identify classes of devices [12, 13] or even individual devices [10], detect and predict electrical and mechanical faults in motors [2], monitor energy costs and consumption [19], and as a form of surveillance [9].

The SeeGreen system uses power line communication to monitor and control metering devices attached to electrical appliances, but does not extend to other sensing modalities or communication channels [11]. The "Kill A Watt" is a commercially available surrogate electrical outlet for home energy consumption monitoring, displaying volts, amps, watts, Hz, and VA for a single electrical outlet [20]. A Spy Labs product makes evident the privacy concerns related to embedding sensing capabilities into commonplace objects – the AGS-01 is a power strip with built-in GSM cell phone transmitter which can be used to monitor surrounding audio from anywhere in the world simply by phoning the number of the inserted SIM card [25]. At another extreme, Chip PC Technologies' Jack PC product is a fully functional thin client computer designed to fit into a standard LAN wall socket with a monitor, mouse, and keyboard plugging directly into the wall [3]. Power strips themselves are evolving in form and function – it's common now to see them augmented with surge protectors, noise filters, and pass-through connectors for data, cable TV, and phone lines, and designers are looking at radically new packaging to improve usability, such making the physical form factor reconfigurable and the plugged-in power cords more easily differentiable [23].

Intel Research and USC/ISI built and deployed a conference room monitoring and reservation system using a sensor network [4]. This system is notable because it involved a real-world sensor network application within a workplace environment and it demonstrated how existing infrastructure, in this case motion detectors for turning on and off lights, can be leveraged by the sensor network.

In his seminal article introducing the concept of ubiquitous computing, Mark Weiser gives the electric motor as an example of how technology can disappear into the background [26]. Aside from being coincidentally topical, this example illustrates a likely evolution of sensor networks. Taking his example further, when electricity production first began, the thought that it would be available from holes spaced every couple of meters in every wall in every house was looked upon as absurd and highly impractical. Sensor networks must achieve exactly this scale of infrastructure if they are ever to leave the research lab. Just as electricity, and indeed every major utility, is put to use in ways unforeseen at the time of deployment, so too will sensor networks find application. The Plug platform is a step in this direction.

3. PLATFORM OVERVIEW

The Plug platform augments the utility of a standard power strip with sensing, communication, and computational abilities to effect a sensor node for active use in domestic and occupational settings while at the same time forming the backbone of a ubiquitous computing environment. To these

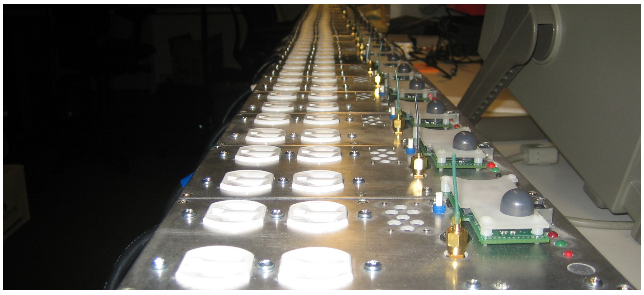

Figure 2: Plug sensor nodes in preparation for being programmed.

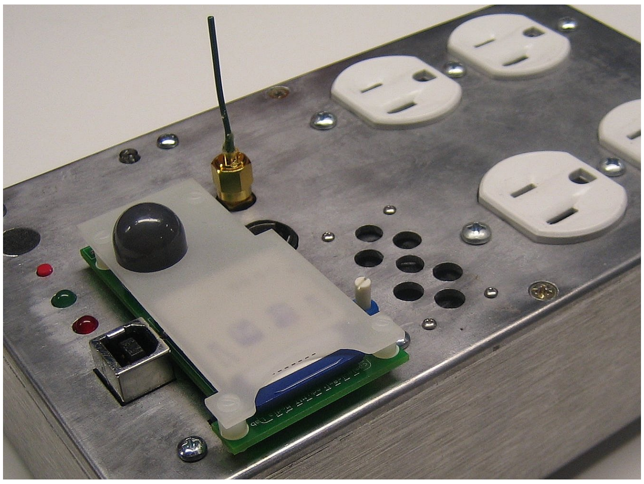

Figure 3: A Plug node equipped with the latest expansion module. Other expansion modules have included a full spectrum light sensor array, inflatable privacy indicator, accelerometer, LCD display, and sound localizing microphone array, among others.

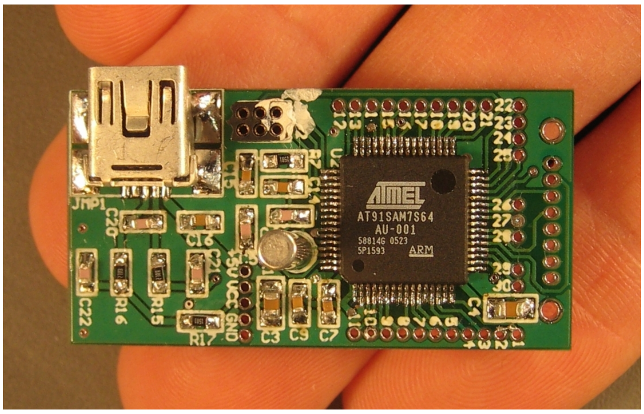

Figure 4: A Lug node without radio or battery. The Lug uses the same processor and radio as the Plug. The radio can be mounted on the back of the Lug to maintain a small footprint or as an extension off one end of the Lug, in this image the right end. Adding a 5V to 3.3V regulator allows the Lug to be powered directly over USB.

ends, each Plug offers four standard US electrical outlets supplying 120VAC at 60Hz. High turn ratio transformers sense the current drawn from each outlet and triacs allow power to be quickly switched on or off on each outlet. A varistor provides protection against electrical surges. The four current sensors and four switches are monitored and controlled by an Atmel AT91SAM7S64, a peripheral-rich microprocessor based on the 32-bit ARM7 core running at 48MHz with 16KB of SRAM and 64KB of internal flash memory. The same microprocessor controls all other aspects of the Plug as well, including two LEDs, a push button, a small speaker, a piezoelectric cantilever vibration sensor, a microphone, a phototransistor, a 2.4GHz ChipCon CC2500 wireless transceiver, a voltage sensor, a USB 2.0 port, and an extensive expansion port for adding custom hardware to the Plug. The voltage sensor has a dynamic range of $\pm$280V relative to the neutral line and the current sensors have a dynamic range of $\pm$4.1A, but can withstand up to 30A. An analog volume knob ensures that the speaker can be manual deactivated. Figure 1 shows a single Plug node. Figure 2 shows some of the 35 Plugs we've built to date.

At present, the 20-pin expansion port houses a module with a passive infrared (PIR) sensor for detecting motion, an SD memory card slot for removable data logging, a 4Mbit external flash memory for storing persistent state (e.g., calibration constants and unique identifiers), and a digital 13-bit temperature sensor. See Figure 3. A separate breadboard expansion module allows for quick prototyping. The pins of the expansion port can be variously multiplexed by the Plug's internal microcontroller to provide up to 17 general purpose digital input/output (GPIO) pins with interrupts, Universal Synchronous Asynchronous Receive Transmit (USART), two wire interface (TWI), serial peripheral interface (SPI) with two chip selects, one fast interrupt, one analog to digital converter channel, and electrical ground. Of the GPIO pins, three can continuously source up to 16mA and the others can source up to 8mA, so long as the total current sourced is less than 150mA. Of course, an expansion module can also plug in directly to one of the Plug's electrical outlets if it needs more energy.

Significant effort was put into accommodating all the features of the Plug while still maintaining the highest safety standards. To begin with, the Plug case is a sturdy die cast aluminum box that can easily support the weight of several adults jumping up and down on it. The Plug node's ungainly aluminum case is a conservative design tailored for rapid construction and safe operation within the lab – a proper design for mass production would have the sensors more seamlessly integrated into what would look more like a conventional power strip. Internally, the Plug comprises two separate circuit boards, one that handles all high voltage signals, such as voltage sensing, and another that handles only low voltage digital signals, such as driving the speaker. All components protruding from the case, except for the outlets themselves and the power cord, have connections only to the low voltage board. A transformer on the high voltage board supplies up to 500mA at 3.3V to the low voltage board and expansion port. No high voltage signals are externally accessible through the expansion port or otherwise. The apertures in the case are precision cut by a waterjet cutter to ensure a tight fit around all protruding components. As is standard with conductive enclosures, the entire Plug case is grounded. The total current sourced by a Plug is limited by a slow-blow 8A fuse, which precludes using high current appliances such as heaters. As well as being a safety precaution, the fuse also protects the triac switches from being over driven.

The software running on the Plug microcontroller includes interrupt-driven, double-buffered modules for interfacing to and managing the SPI bus, GPIO pins, radio, USB port, ADC, speaker, LEDs, push button, real-time clock with settable alarms, SD memory card, vibration and motion sensors, random number generator, data flash, and temperature sensor. At present, applications are pieced together from these modules predominantly through the use of asynchronous callbacks. Section 5 introduces more ambitious and ongoing software development. Since the Plug platform is essentially free of energy constraints (rate of consumption is limited, but not cumulative consumption), the Plug software modules are designed to be time efficient, not energy efficient. For example, the default behavior of the ADC module is to continuously sample all eight analog channels at 8kHz with 8-bit resolution in a 256-byte buffer per channel with logging of periodic averages, minima, and maxima over several seconds. If needed, a single ADC channel can be configured to sample at as high as 191kHz and with 10-bit resolution, such as might be required, for example, to distinguish different kinds of fluorescent light ballasts [1]. However, even without tight energy constraints and all subsystems active, the Plug only draws approximately 60mA at 3.3V.

For wireless networking, the Plug uses a simple carrier sense multiple access (CSMA) scheme with random backoff upon collision detection and a straightforward gradient routing scheme evolved from the code base that we developed for the Pushpin Computing platform [14]. The Plug's wireless networking was designed to allow for simple communication between network-adjacent nodes and data collection with arbitrary nodes in the network simultaneously serving as base stations. In the context of this paper, only a single base station was used, but with this networking scheme any number of the Plugs could just as easily act as a network-wide data sink.

To complement the fixed network of Plug nodes, we also developed a more standard sensor node, called the "Lug", based on the same microprocessor, radio, and code base. In this way, the Plugs act as the always-on backbone network among which Lugs are put to use as wearable or battery powered sensor nodes. The microprocessor and all subsystems support low power modes suitable for such battery powered applications, although we haven't focused on this problem specifically. See Figure 4. The Lug's primary use is prototyping on-body or otherwise mobile sensor nodes that interact with the surrounding fixed Plug network. Section 5 touches on an example application of a Lug.

4. INITIAL RESULTS

Figure 5 shows some of the data taken from a single Plug during a rudimentary scenario – a desk lamp is plugged into one of the Plug node's electrical outlets and turned on. Even scenarios as simple as this make clear the value of the Plug's multi-modal sensing abilities for disambiguating the context of the event. For example, the current sensor data indicate precisely when the lamp was turned on, but cannot be used to discern whether or not the lamp was already plugged in but turned off. The microphone data, on the other hand

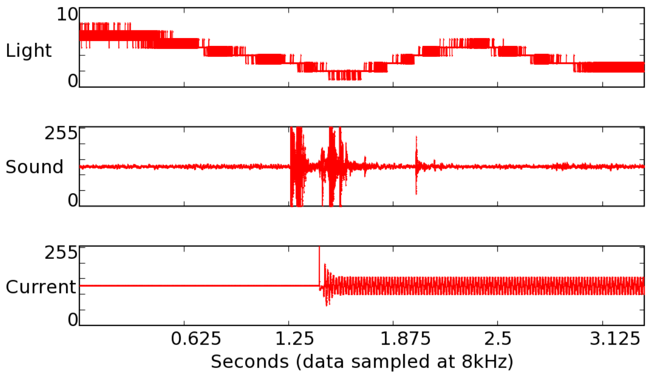

Figure 5: Data taken from a single Plug node as a desk lamp is being plugged into one of its electrical outlets. The vertical axes are in arbitrary units. The vertical axis of the "Light" plot has been scaled to show greater detail. All data were sampled at 8-bit resolution.

strongly indicate the event included the lamp being plugged into the outlet. This is further corroborated by data from the light sensor, which show the shadow of the hand passing over the Plug as the lamp is being plugged in. These hypotheses are strengthened by looking at the binary motion and vibration indicators. Finally, given that a lamp was plugged in, which might be inferred directly by a more detailed analysis of the current signature, we can safely guess from the relatively constant light reading that the lamp is not shining on the Plug directly and may be far removed due to an extension cord, as was the actual case.

Figure 6 clearly shows how individual and classes of electronic devices can be identified and classified by their current signature alone, as mentioned in Section 2. For example, the digital oscilloscope, LCD monitor, and desktop computer all have distinctive, predictable startup sequences. The ballast of the fluorescent desk lamp must power up before the gas in the bulb will fluoresce, whereas the halogen desk lamp is an almost purely resistive load and therefore its current draw is proportional the voltage applied.

Naturally, not all inferences can be made at the node level; some inferences are either too computationally demanding or in need of extra information. In this case, a likely solution is to reduce the raw data to features at the node level and then communicate these features elsewhere for further processing. As proofs of concept, simple versions of such algorithms have been developed for the Plug by other researchers in our lab to classify types of light (e.g. fluorescent, incandescent, halogen, and natural) and types of electrical devices (e.g. resistive, switching, and inductive). A more complete analysis of the Plug's data processing and inference abilities are left as future work.

Looking at the network as a whole, we can easily see general trends of activity across the building. Figure 7 shows a map of the third floor of our lab and the locations of each Plug during a data collection run lasting about 20 hours starting very early Monday morning and going until late Monday night. For this run, 31 of our 35 Plugs were deployed. The data collected from each Plug include five-second windowed and rectified minima, maxima, and

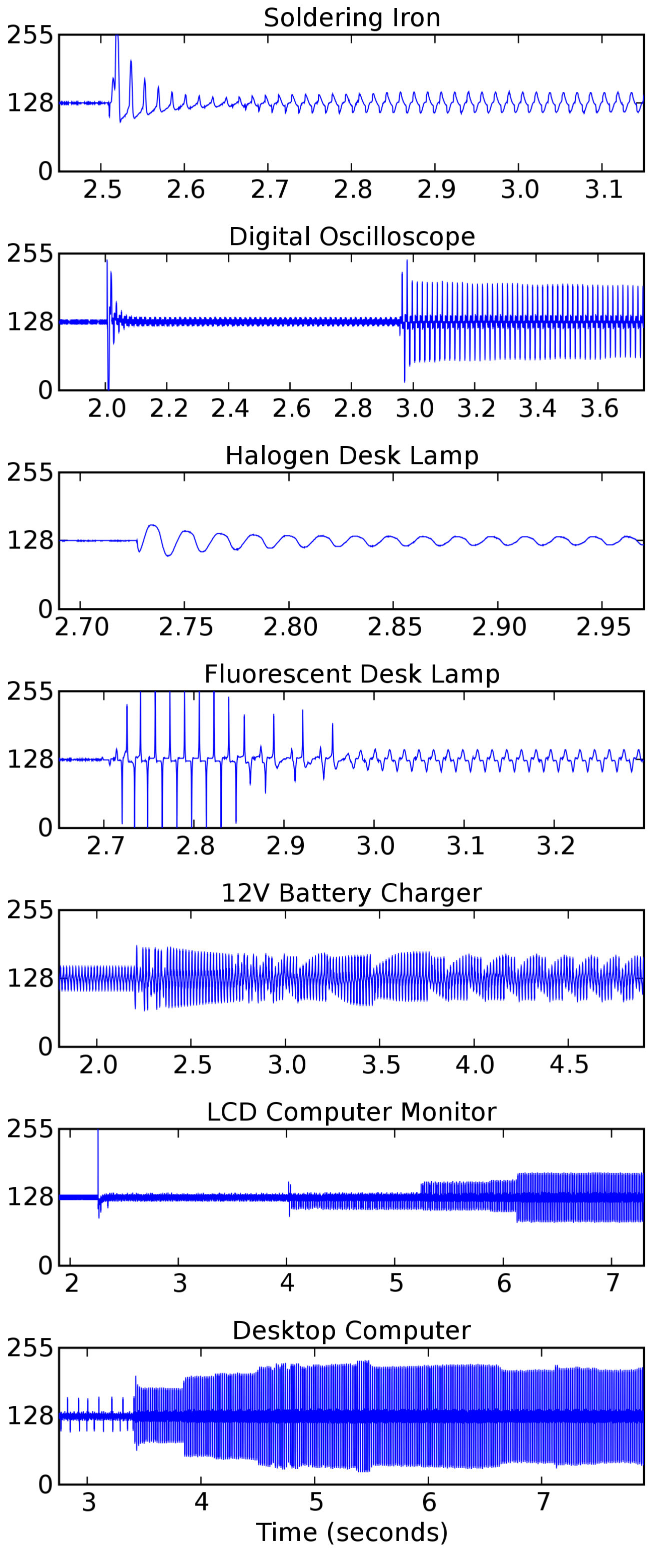

Figure 6: Plots of current versus time taken from a Plug sensor node for a variety of common electronic devices. Each plot shows current data from a several second window encompassing the time at which the device was plugged into the Plug node's electrical outlet. All data were sampled at 8kHz. All data are in arbitrary units.

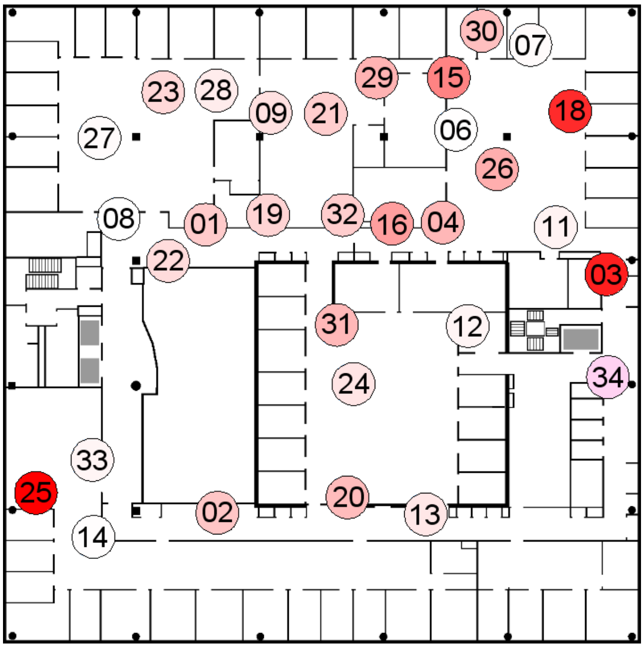

Figure 7: A map of the third floor of the MIT Media Lab. The 31 large circles indicate the location of Plug sensor nodes. The number within each circle is the ID of the Plug at that location. The darker the circle, the more activity occurred at that node over the span of a 20-hour data collection period. Here, "activity" is defined as the sum of the number of motion sensor and vibration sensor activations.

averages of light, sound, voltage, and current, as well as cumulative motion and vibration activations (the motion and vibration sensors being binary) and the route by which the network packet arrived to its destination. The samples from which the extrema and averages were calculated were taken at 8kHz. The shade of each circle represents the total "activity" seen over the entire course of the data collection, where activity is defined as an equally weighted sum of total motion and total vibration activations. All data were routed to a single Plug over the radio network (the dark circle in the upper right corner, number 18) and siphoned off to a personal computer via a single USB connection. This graph of activity level corresponds well with our impressions of how active different parts of the building are. For example, Plug 03 was placed next to a heavy door leading to the main kitchen and cafe area, making its high activity level unsurprising.

Figure 8 shows light (maximum over five-second window), sound (maximum over five-second window), and current (average over five-second window, averaged across all four outlets) data over time from three specific Plugs during the same data collection period mentioned above. In this case, trends taking place over an entire day become apparent. For example, the light readings from Plugs 22 and 30 clearly show the sun rising and setting. (Although the map indicates Plug 22 is located near the middle of the building, it was placed next to a window that overlooks a large atrium with sky lights). Plugs 23 and 30 show office lights being turned on and off, albeit at different times of day. The

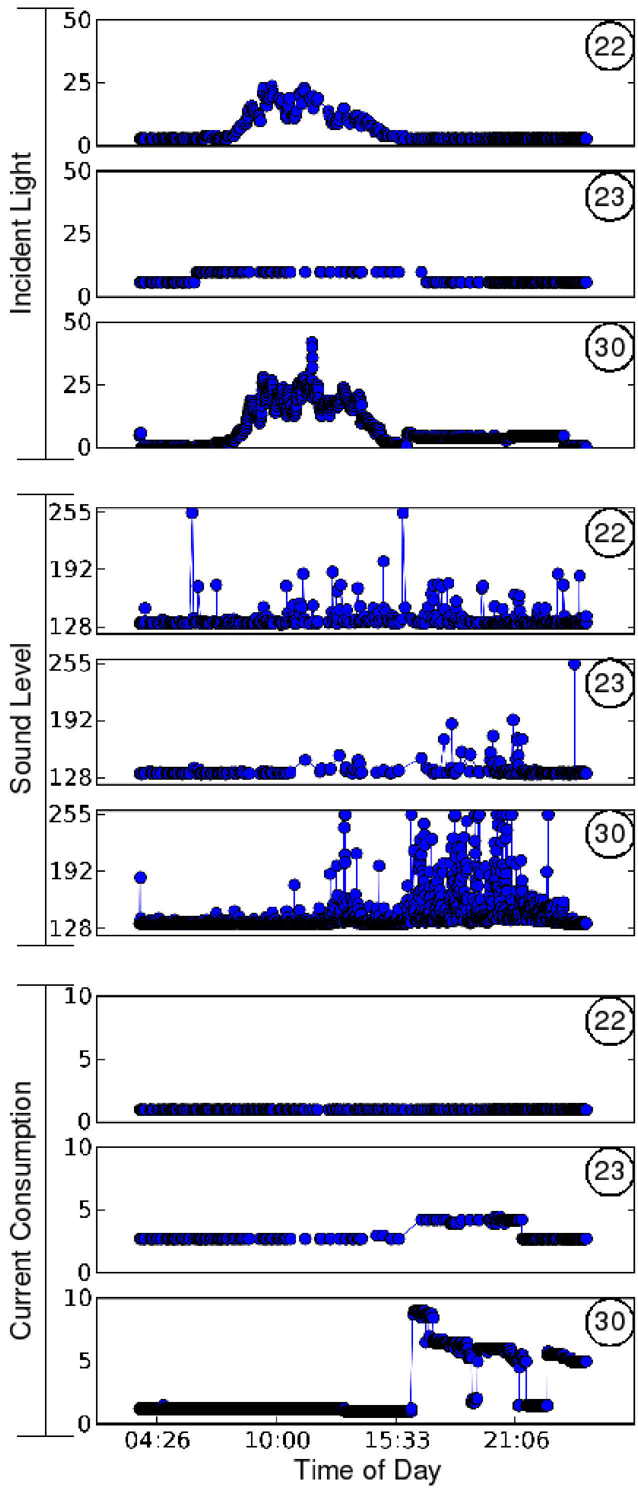

Figure 8: Light (top three graphs), sound (middle three graphs), and current (bottom three graphs) data versus time of day for three of the Plug sensor nodes shown in Figure 7. The circled number in the upper right-hand corner of each graph is the ID of the Plug and corresponds to the location shown in Figure 7. All data are in arbitrary units.

current draw from Plug 30 shows a desktop computer being started, shutdown, and rebooted at various points in the evening, whereas Plug 23 only had small DC converters plugged into it. The sound level graphs indicate discrete events (spikes in the graph) and general activity level. The several visible gaps in Plug 23's data sets are cases of packets being dropped in the network. In general, packet loss increased with increased network distance from the data collection node, most likely due to node-to-node packet transfer being unacknowledged. The most recent version of the Plug networking software makes use of acknowledged packets.

5. ONGOING AND FUTURE WORK

Several ongoing or planned projects in our lab take advantage of or build upon the Plug sensor network.

In the fall semester of 2005, we offered a graduate-level introductory course about sensor networks [18]. Students in the course built Plugs and Lugs, and then prototyped various applications with them. Although the course long ago concluded and can no longer be considered ongoing or future work, the repercussions of the course are still being felt around the lab, mostly because it got a largely graphic, industrial, and interaction design group of people thinking about the interplay between sensor networks and their own disciplines. It is exactly this sort of interaction we hope will help flesh out how sensor networks will ultimately be woven into our environments and lives.

Browsing through the data generated by the Plug sensor network has come up as a challenge in and of itself. Gathering, viewing, and making sense of live sensor network data while physically roaming around the network, or reviewing already recorded data present a formidable human-network interface problem. To this end, we've taken inspiration from the original *Star Trek* television series and constructed a hand-held navigation unit based roughly on *Star Trek*'s "tricorder" device. The fictional tricorder was a self-contained device that provided relevant information about whatever it was being pointed at (e.g., life signs 50 meters back, magnetic disturbance above, or plot thickener ahead). Our tricorder device aims to achieve the same goals, but by different means. Instead of being self-contained, our tricorder pulls sensor data off the surrounding Plug sensor network. Like the original, our version knows its absolute orientation thanks to a high-end 3-axis compass. This, combined with coarse RSSI-based localization from the Plugs, allows for real-time point-and-browse functionality from within the sensor network itself. Specifically, the orientation information is used to maintain the displayed map of our lab at a fixed orientation relative to the actual lab and the map re-centers itself according to the RSSI information gathered from nearby Plugs, whose locations are assumed to be known. We recently completed a working first prototype of our tricorder using a battery-powered Lug to interface to a Nokia 770 web tablet via USB, to an off-the-shelf PNI TCM3 compass module via USART, and to the Plug sensor network via a 2.4GHz ChipCon CC2500 radio. The tricorder's user interface consists of a floor plan of our lab overlaid with Plug icons depicting sound (concentric blue circles), light (radial red lines), RSSI (green central circle), current consumption (black central dial), and motion (orange ring around the green circle). The icons jitter slightly to represent vibration. An auxiliary side panel shows bar graphs of the average and extrema data for all sensor modalities from a single Plug. The exact Plug shown in detail is either selected automatically according to the strongest radio signal or manually via the touch screen. See Figure 9.

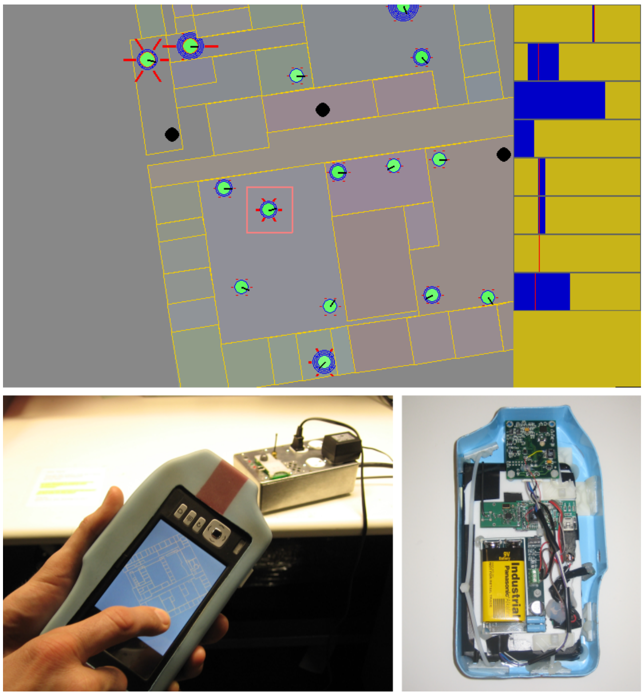

Figure 9: *Bottom Left*: **The tricorder device displaying a map of the third floor of the Media Lab and a Plug node in the background.** *Bottom Right*: **The opened backside of the tricorder device, showing a Lug, battery power supply, compass module, and Nokia 770.** *Top*: **A screenshot from the tricorder device.**

The increasing sophistication of online virtual worlds presents another approach to browsing sensor data – model the virtual world after the real world and then browse real data from within it. We have a preliminary version of this, called Shadow Lab and shown in Figure 10, set up for our lab within the Second Life online virtual world [15]. Shadow Lab consists of an actual-size floor plan map of the entire third floor of our building, which is greater than $2400m^2$ in area. Our group's specific lab space, in the foreground of Figure 10, has been rendered as a photo-realistic replica of our real lab space. The remainder of the building is filled with metaphorical representations that are, at the time of writing, still in the process of being mapped to reflect sensor data being collected in the Plug sensor network. Data from the sensor network are fed into the virtual world by means of a relatively low-bandwidth XML-RPC protocol that can provide updates approximately ten times per second. These restrictions will force data aggregation, context extraction, and sensor fusion techniques to play an important role in the final interface between the real and virtual worlds.

The exponentially increasing popularity of online virtual worlds, and Second Life in particular, suggests a potential incentive for sensor networks. What better application is there of abundant real sensor data than to inform, enrich, and drive a heavily populated, but relatively sterile virtual

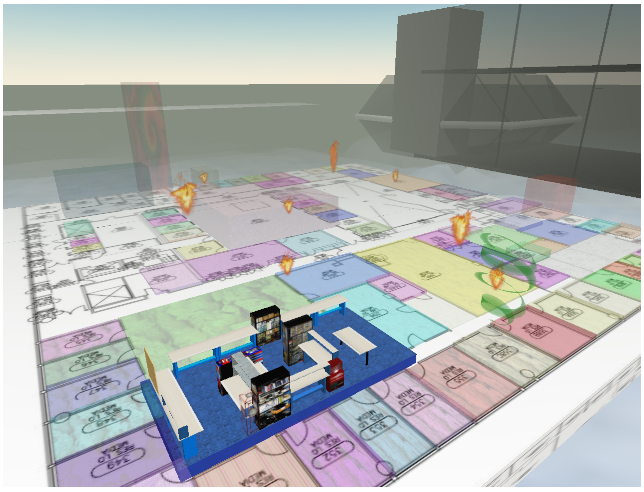

Figure 10: A rough virtual representation of the third floor of the MIT Media Lab in the Second Life online virtual world. Sensor data from the Plug sensor network streams into the virtual lab space (Shadow Lab) and drives metaphorical representations, such as the size of a fire for energy consumption or the speed of a dust devil for motion. Conversely, visitors to Shadow Lab can exert influence in the actual lab through subtle sound indications played over the Plug speakers, for example.

world? We predict that, just as today people trade images and songs over the Internet, in the future they will be trading and reacting to sensor data, however abstracted from the original reality from which it was collected, in online virtual worlds. In this way, data from sensor networks could become the next major creative medium.

Finally, we have made some progress toward a new programming framework for sensor networks based on an open source microcontroller version of the Python programming language [8]. Though still in the preliminary stages, we believe a dynamic interpreted language tailored to the needs of sensor networks will make programming and interfacing to sensor networks easier and more scalable. Our first version of this framework, called Snarf (Sensor Network Application Retasking Framework) is targeted for the Plug platform.

Aside from using the Plug platform as a basis for other projects, improvements could certainly be made to the platform itself. The Plug platform's communication capabilities in particular could be improved. For example, although not as energy constrained as most sensor network platforms, the Plug platform may yet benefit from some hybrid of energy efficient and always-on MAC layers [28]. Such an approach would more closely mirror the heterogeneous nature of the platform, with small battery-powered devices roaming among a fixed powered network of Plugs. Even incorporating into the Plug an IEEE 802.11 (Wifi) radio is a possibility that shouldn't be overlooked. The robustness of the network, a necessity for long-term deployment, would benefit from a more agile channel sharing and link determination algorithm.

An obvious and significant improvement to the platform would be the addition of some form of power line communication to integrate the Plugs even more tightly with their deployment environment [7, 16, 22]. Even low-bandwidth power line communication could provide a valuable side channel for network discovery, network maintenance, and even sensing – certain electrical failures could be detected and isolated by network means alone. Just as network connectivity in a wireless network reveals information about the surrounding environment, such as rough localization, so to does the network connectivity in a wired power line network. Of course, any power line communication would have to be tolerant of highly variable line noise and would have to rely on another communication channel, such as wireless, to bridge between different electrical phases or feeds, as are common in large buildings. Between standard Wifi and power line communication, the only reason for the Plugs to have the lightweight CC2500 radio is to communicate with power constrained sensor nodes that have no other means of communicating. Nonetheless, this is a compelling reason given the centrality of mobile sensor nodes in our current vision of ubiquitous computing.

On a more abstract level, equipping living and working spaces with a host of sensors raises many unaddressed privacy concerns. The most common concern revolves around the Plug's embedded audio microphone. However, there is evidence to suggest that the motion sensors coupled with other sensing modalities are possibly more invasive [24, 27]. This is especially true given the already near-ubiquity of microphones embedded in desktop computers, laptops, cell phones, and hand held devices. Clearly, the questions of privacy involved with ubiquitous sensor networks do not yet have well-defined answers and deserve closer inspection.

Perhaps the most pressing work yet to be done is the automatic detection, classification, and estimation of high-level contexts and events from low-level sensor data. Without the need to conserve battery life, the Plugs are free to continuously monitor their environment and perform such calculations collaboratively within the network rather than offline.

6. CONCLUSIONS

This paper introduces the Plug sensor node, a functional power strip with sensing, networking, and computing abilities. Initial data gathered from a day-long deployment of 31 Plug sensor nodes across the third floor of our lab show a variety of easily detected phenomena and the potential for many more.

The Plug sensor network presents itself as a viable platform for collecting data in the home or office environment. In doing so, each Plug will not only be monitoring its environment, but also be playing an active and useful role therein, thus making the data collected richer and more meaningful than could be hoped for with a more detached system. Per the founding concept of ubiquitous computing, the Plug sensor network can disappear into its environment by virtue of its utility. The Plug sensor network is a foot in the door of sensor-rich ubiquitous computing.

7. ACKNOWLEDGMENTS

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8. REFERENCES

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