Wireless Sensor Networks for Home Health Care

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***Abstract*— Sophisticated electronics are within reach of average users. Cooperation between wireless sensor networks and existing consumer electronic infrastructures can assist in the areas of health care and patient monitoring. This will improve the quality of life of patients, provide early detection for certain ailments, and improve doctor-patient efficiency. The goal of our work is to focus on health-related applications of wireless sensor networks. In this paper we detail our experiences building several prototypes and discuss the driving force behind home health monitoring and how current (and future) technologies will enable automated home health monitoring.**

I. Introduction

Various economic and technological factors (*e.g.* Moore's Law) have brought sophisticated electronics within the reach of average users. These technologies, when complimented with wireless sensor networks, promise to add a truly ambient intelligent component to our daily lives. Today, these technologies may be integrated into existing consumer electronic and infrastructure already found in the home. The future home represents an opportunity for the convergence of these technologies far beyond what we see today. This future "smart" home would be even more capable, providing an ambient awareness of the home's occupants through an ecosystem of ubiquitous connectivity, disappearing devices, highly-available services, and multi-modal sensing.

One promising application is the area of health care and patient monitoring. The integration of sensing and consumer electronics technologies would allow people to be constantly monitored. One important benefit is to help stem rising health care costs by increasing health observability and doctor-to-patient efficiency. Moreover, constant monitoring will increase early detection of adverse conditions and diseases for at-risk patients, potentially saving more lives. This ability is right around the corner and its beginning will be ushered in with incremental integration of wireless sensor networks and consumer electronics. This is the focus of the paper: crossing that barrier by introducing prototypes for health monitoring for smart home environments.

At the University of California, Berkeley, a project-based graduate course on high-tech design and rapid prototyping has worked for the three months to develop prototype high-tech products utilizing wireless sensor network technology. Several of the projects have focused on developing sensor network based solutions for health care and patient monitoring. More specifically, this paper will discuss several of these projects, highlighting their need, design, implementation, and results.

The contributions of this paper are the following:

- Identify opportunities for health monitoring applications utilizing wireless sensor network technology.
- Demonstrate working prototypes with relatively simple technology which make incremental, but important, steps to toward ubiquitous deployment of health monitoring devices, as well as how they may be integrated into existing infrastructures.
- Discussion of why heath care at home is important and how we believe future technology trends will continue to merge health care and smart home environments.

This paper is organized as follows: §II will briefly discuss the base technologies with which we are working. §III will discuss five prototype designs. These prototypes vary in application from infant monitoring, alerting the deaf, blood-pressure monitoring and tracking, and monitoring fire-fighter vital signs (a generic monitoring technology). After a brief discussion of each prototype, §IV will reflect on the role of technology in the convergence of health care and smart homes. Finally, §V will conclude the paper.

II. Technologies

Our prototypes use two similar sensor network mote technologies: Tmote Sky and SHIMMER. The Tmote Sky is the latest derivative of the Berkeley Telos motes from Moteiv Corp. [1]. The other mote is Intel's Digital Health Group's platform for Sensing Health with Intelligence, Modularity, Mobility, and Experimental Re-usability, or SHIMMER. Several of our prototypes use just Tmotes, while some use a combination of Tmote and SHIMMER motes. Both are nearly identical with respect to processing and communication; each have the Chipcon CC2420 802.15.4 radio and TI MSP430 (with 10k RAM). However, the SHIMMER has additional integrated sensors (*e.g.* 3-axis accelerometer) and has a smaller form factor by approximately 55%. For programming both motes, we use the TinyOS environment [2].

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III. PROTOTYPES

We have developed several prototypes which demonstrate wireless sensor network technologies for heath care at home. Each of these prototypes will be discussed in the following sections.

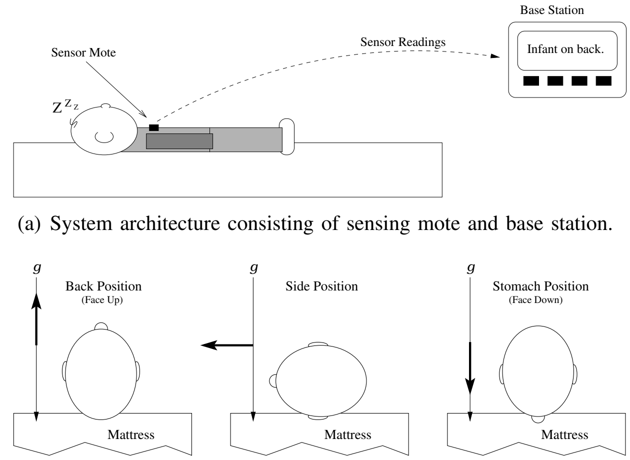
A. SleepSafe

Sudden Infant Death Syndrome (SIDS) strikes without warning causing unexplained death to infants one month to one year of age. While experts cannot fully explain the causes of SIDS, research shows there are several factors which increase the incidence of SIDS. Foremost among the risks is allowing the infant to sleep on their stomach. An infant sleeping on their stomach is up to 12.9 times more likely to die from SIDS [3]. To reduce the likelihood of SIDS, doctors warn parents to put their children to sleep on their backs. This has reduced the incidence of SIDS by 40%. However, SIDS still remains the leading cause of death for infants less than one year old, with approximately 2,500 deaths per year in the United States [4].

Between the ages of 4 to 7 months, infants gain the ability to roll onto their stomachs. Parents and other care givers may be worried about this new ability. We have built a simple prototype (called SleepSafe) which detects the sleeping position of the infant. It alerts the parents when the infant is detected to be lying on its stomach, offering them peace of mind without having to constantly watch their child while it sleeps. Our prototype does this by attaching a sensor to the infant's clothing. This sensor detects if the infant is sleeping on their back, side, or stomach. When the later two are detected, the parent is notified. The sensitivity and delay can be adjusted to accommodate the user's preferences (*e.g.* different risk levels and false-alarm frequency).

Our prototype consists of two sensor network motes. One sensor mote is attached to the infant's clothing, while the other acts as a wireless base station to receive and process sensor readings. Depending on the SleepSafe settings, the base station will alert the parent. It is expected that this system could be integrated into existing monitoring infrastructures, such as those for audio and video. Additionally, alerts could be sent to a pager-like device or cell phone. This prototype architecture is shown in Figure 1(a).

The mote attached to the infant's clothing is a SHIMMER mote. It is expected that with technology trends the reduction in physical size will allow it to be seamlessly integrated into the fabric of the clothing. This mote has a 3-axis accelerometer; a single axis is used to sense the infants position relative to gravity. With the mote oriented "face-up" on the infant's chest, 3 discrete positions (back, side, and stomach) are measured as anti-parallel, perpendicular, and parallel to the force of gravity. Figure 1(b) illustrates how these positions are measured relative to gravity. The mote's processor, running a small TinyOS program, reads the accelerometer values periodically via the on-board analog-to-digital converter (ADC), packetizes the values, and sends the packet wirelessly to the base station for processing.



(a) System architecture consisting of sensing mote and base station.

(b) The accelerometer detects the position of the infant in one of three states relative to gravity (g).

Fig. 1. SleepSafe baby monitor for detecting infant sleeping position.

The base station is implemented using a Tmote and a laptop. This mote is used to bridge the wireless to a serial port. A Java program running on the laptop is listening for packets from the SHIMMER mote. The Java program is very simple: it detects the infant's sleeping position given the sensor values and sends an alert when infant is on its stomach. To adjust the sensitivity of detection, the Java program keeps the last N values in a buffer known as the *sensing window* (w, where $|w| = N$). The values of the sensing window are averaged to produce α: $\alpha \leftarrow \sum w_i/N$. To determine the actual sleeping position of the infant, α must be mapped to one of the three discreet sleeping positions s_i (back, side, and stomach) of set $\mathbf{S}$. A *threshold* t ($0 < t \leq 1$) is used to determine intervals P_{s_i} for mapping α to $\mathbf{S}$: $P_{s_i} \leftarrow (s_i - (1-t), s_i + t]$. For example, suppose $t = 0.5$ and $\mathbf{S} = \{-1, 0, 1\}$ (*i.e.* the states are: stomach $\rightarrow -1$, side $\rightarrow 0$, and back $\rightarrow 1$). Then the intervals for mapping α are: $P_{-1} = -1.5 < \alpha \leq -0.5$, $P_0 = -0.5 < \alpha \leq 0.5$, and $P_1 = 0.5 < \alpha \leq 1.5$. If the average over the sensing window is 0.78, then the infant is on their back. The user's preferences determine the size of the sensing window and the threshold. Think of this processing by the base station as an adjustable low-pass filter: a high-risk infant might have a smaller sensing window and higher threshold value, while to reduce false-alarms, a larger sensing window and lower threshold would be used.

Experimentation shows the infant can move very slowly without loss of detection. Furthermore, the delay between the infant changing positions and the base station issuing an alert is not observable. Future work may be to integrate this into an existing commercial baby monitor, as well as adding additional sensing to the SleepSafe infrastructure. For example, adding sensing for body temperature which is also correlated to SIDS incidence rate [3].

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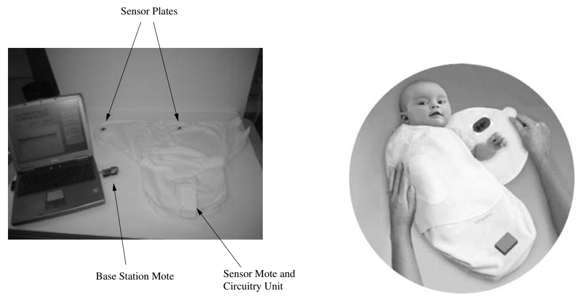


(a) Experimental setup. (b) Baby glove swaddle.

Fig. 2. The Baby Glove prototype.

B. Baby Glove

Due to their tiny nature, premature infants are susceptible to a variety of health problems based on the lack of proper thermal regulation. Their underdeveloped state and low body mass limits their ability to sweat which makes them vulnerable to hypo- or hyperthermia, whereupon they become increasingly susceptible to illness and death. Currently, children born with a Low Body Weight (LWB) (weight < 5.5 lbs), which account for 7% of all US births, incur a 68% mortality rate [5]. As the weight of children decreases, the mortality rate increases. Many of these statistics are due in part to their extreme sensitivity to temperature fluctuations, which must stay within a consistent range of 36°C to 38°C. With these very tight restrictions, very sensitive, bulky and rather expensive devices are implemented to closely monitor vitals. In turn, we have developed an integrated health monitoring device, contained within a swaddling baby wrap (called The Baby Glove). The wrap design provides a comfortable method of securing the child, with strategically placed sensors that monitor their temperature, hydration and pulse rate, three main health considerations important to development [6].

The Baby Glove prototype, as seen in Figure 2, encompasses two integrated sensor plates, which contain a thermistor temperature sensor along with electrodes that monitor the childs pulse rate and hydration. The sensor plates are placed posterior and anterior to the childs upper torso, which is the bodys largest thermal mass. The device consists of two sensor network motes, one connected to the swaddling wrap and the other to a base station computer. The first mote, connected to the wrap, is a SHIMMER mote. It monitors the vitals information coming from the sensors via an ADC, organizes the measurements into packets and transmits them wirelessly to the second mote, connected to the base station computer, for processing. The mote's sensitivity and sensor delays can be adjusted based on user preferences.

The temperature sensor for the device calculates the baby's temperature (°C) based on thermistor input voltages and resistances using a predefined equation: $T = ((V/R)(100/(3.3-V))-1)(1/0.0039)$. The pulse rate electrode sensors operate based on electrical signals that emanate from the heart as it pumps blood. To ensure accurate readings, electrodes are placed in two locations on the wrap. The hydration sensors, operate using these same electrodes (with its own respective circuitry) and calculates the childs hydration based on resistivity measurements taken between them.

The Baby Gloves wireless feature allows it to monitor and transmit vitals information to a variety of computing systems such as PDAs, cell phones and laptops. As health condition information is received by a computer, specialty software analyzes the data and determines whether the childs vitals have exceeded predefined health settings. If settings are exceeded, an alert is sent to a parent or nurse as to the condition of the child. The Baby Glove device software also has the ability to send instructions to the environmental controls within an incubator or thermostat to update the thermal conditions autonomously.

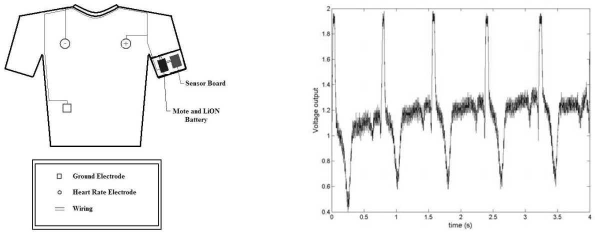
C. FireLine

Note that while this prototype is geared toward monitoring firefighters, it can easily be adapted to monitor the same vital signs of patients in the home environment.

In 2005, there were 1,136,650 firefighters (both career and volunteer) recorded protecting communities across the United States. On average, U.S. fire departments respond to fire-related emergencies every 20 seconds. Though firefighting technology, protective gear, and operation procedures have improved within the last three decades, the annual number of on-duty firefighter deaths still remains around 100. Of those fatalities, 50% are determined to be caused by stress, with most firefighters experiencing sudden cardiac arrest. Furthermore, 24.1% of injuries occurring during fire-related emergencies have been attributed to strain [7]. The majority of firefighter cardiac related complications can be traced to the physical and psychological strain associated with having to carry over 75 pounds worth of tools, equipment, and protective gear [8]. Coupling labor intensive tasks with the heat stress developed from extreme, hostile environments, the heart rates of firefighters often exceeds maximal “healthy” rates.

Because of these alarming statistics, there has been great interest in real-time monitoring of firefighter health. Any irregularities in a firefighters heart rate can signal imminent cardiac failure, so detecting these abnormalities immediately and relieving the firefighter can prevent causalities. FireLine is a wireless heart rate sensing system that can be used to decrease stress related fatalities and injuries through real-time firefighter health monitoring.

FireLine, illustrated in Figure 3(a), includes a wireless sensor device (Tmote), a custom-made heart rate sensor board, and three reusable electrodes. All components have been integrated into a fire retardant shirt worn under the users protective clothing and equipment. The wireless mote, sensor board, and battery packs are housed in two slim cases that are sewn into the inner right sleeve of the shirt. The case locations were chosen to minimize any interference with equipment that a firefighter must wear, such as backpacks and the breathing apparatus, and to minimize the wiring length. The electrodes and wires were sewn inside the shirt such that the positive and negative electrodes are attached to each side of the chest, and



(a) Diagram of FireLine shirt embedded with sensors, electronic hardware, and wiring.

(b) EKG waveform measured using FireLine. Each spike with an apex past 1.8V represents one heart beat.

Fig. 3. The FireLine prototype.

a ground electrode is attached to the stomach. The embedded electrodes sample a voltage signal from the heart every 10 ms, and these readings form an EKG waveform. An example waveform is shown in Figure 3(b). These measurements are wirelessly transmitted from the mote on the firefighter's sleeve to a "base station" mote attached to a laptop monitored by an incident commander. The readings are recorded and processed by custom software that calculates the firefighters beats per minute (bpm). The current bpm, EKG, and a graph of heart rate over time are displayed in a Java based GUI.

If the heart rate were to increase or decrease past certain limits, dependent on the firefighters resting heart rate, an alert will appear on the laptop. For our test subject, a healthy heart rate was approximated to be between 50-140 bpm. In the event that a firefighters heart rate has increased substantially, the commander (or patient's doctor or care-giver) can use the readings to make an informed decision to remove the firefighter from the scene of the fire.

D. Heart@Home

Heart disease is the number one cause of death in America; as our population ages, people are getting more and more concerned about their high blood pressure as it leads to serious cardiovascular diseases. This increased health awareness pushes people to take their health into their own hands, into their own home. Doctors nationwide agree that tracking blood pressure daily at home is one of the best ways to live with high blood pressure and preventing more serious health issues. Keeping track of blood pressure at home is already a booming business in the health care industry; millions of blood pressure monitors are sold every year with quick and accurate readings. At the same time, hundreds of websites are popping up with suggestions, tips, and isolated tracking services to help people keep track of their health stats, especially their blood pressure. Furthermore, the user has to write down or manually enter these stats into one of a dozen sites.

To remedy this deficiency, we have developed a blood pressure monitor and tracking system we call Heart@Home with a wireless sensor network as its core technology. The Heart@Home blood pressure monitor is focused toward the aging baby boomer population who are concerned with their high blood pressure, are interested in maintaining a personal health regime, and are comfortable with home PCs. It also demonstrates integration of sensor network technology with consumer electronics (*i.e.* an existing blood pressure monitor).

A SHIMMER mote is located inside the casing on the wrist cuff connected to the electronic pressure sensor. When the start button is pressed, it computes the user's blood pressure and heart rate using the oscillometric method. Initially, the wrist cuff is inflated to restrict blood flow along the patient's arm (pressure sensor reads a constant value). As it deflates, the pressure sensor value is monitored: the point at which its value begins to oscillate is the pressure at which the blood flow is no longer entirely restricted (systolic pressure), and the point at which it returns to a constant value is the pressure at which the blood flow is entirely unrestricted (diastolic pressure). Also, the user's heart rate can be inferred by measuring the time between pressure peaks while the blood flow is partially restricted and the pressure sensor value is oscillating.

The SHIMMER mote then broadcasts these readings, along with a time-stamp, over the radio. This message is received at the base station, which is plugged into the user's computer through the USB port. This base station contains a Tmote Sky, which forwards the received message through the USB port to the user's computer. The included software application, which is running on the user's computer, monitors the specific USB port for traffic. When a message arrives, the values are recorded along with the time-stamp. If the wrist cuff is unable to communicate with the base station, it will store the readings and periodically broadcast them until it gets notification that the base station received the message. Similarly, if the software application is unable to retrieve the readings from the base station, they will be stored locally until they are confirmed to have been received by the application.

The software application provides a graph of the user's blood pressure and pulse rate over time (see Figure 4). The software also offers helpful medical advice that is tailored to the individual's physical profile, taken from a database filled with medical tips collected from doctors. The user can enter their height and weight, along with any medications they are taking and other health problems they have, in order to better provide health tips. If alarming anomalies appear in the user's heart readings, such as a spike or steady increase in blood pressure, the software alerts the user. To easily communicate the readings to a physician, a report of the user's health can be emailed to a doctor or printed out in an easily readable format.

E. LISTSENse

About 2 to 4 of every 1,000 people in the United States are functionally deaf. However, if people with a severe hearing impairment are included with those who are deaf, then the number is 4 to 10 times higher. That is, anywhere from 9 to 22 out of every 1,000 people have a severe hearing impairment or are deaf. At least half of these people reported their hearing loss after 64 years of age [9]. Age is not the only cause of hearing impairment. Recent studies show that one million American children of school age have hearing impairments and

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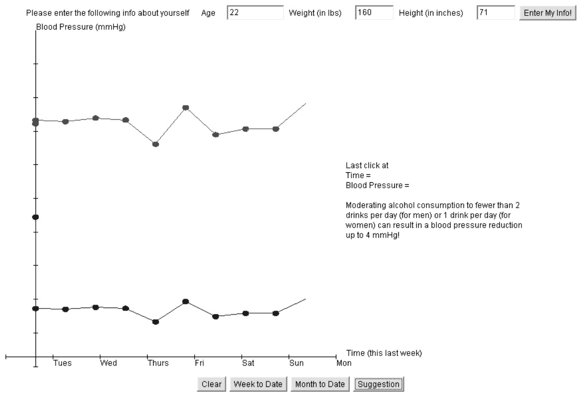


Fig. 4. Heart@Home prototype GUI output.

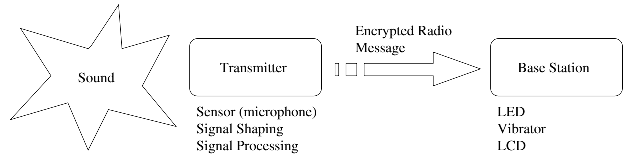
the figure is growing [10]. This is either genetic or due to the excessive use of personal electronic audio devices. Therefore, hearing impaired people represent a growing percentage of the nation's population.

LISTENse is a prototype that empowers the hearing impaired with the perception ability of critical audible information in their environment (*e.g.* doorbell, smoke alarm, crying child.) It is comprised of at least two wireless sensor network motes. User carries one mote – the Base Station – on his wrist, belt, etc. and each of the other motes – the Transmitters – is placed close to the sound source that it is to be "heard."

Form factor and cost are the two major shortcomings of the existing similar technologies compared to our prototype. They have either a non-portable table-top Base Station or a bulky pager-like device. Sensor mote technology and miniature electronic parts enable us to shrink the form factor by a great extent. We envision our product to be as small as a regular watch and very convenient to use. The deployment of mote technology further reduces the cost of our prototype.

The prototype Transmitter consists of an omnidirectional condenser microphone with flat frequency-domain characteristics within the range of audible frequencies. It is connected to the sensor network mote through signal shaping and processing electronics. The prototype Base Station components such as the vibrator and LEDs are similarly interfaced to its mote through corresponding driver circuitry.

Figure 5(a) depicts a simple communication scheme of the LISTENse basic network that consists of the Base Station and one Transmitter. Transmitter periodically samples the microphone signal at a rate of about 20 Hz (which is adjustable) and compares the sample with a reference value that is internally defined based on the user-defined Transmitter sensitivity. Once the measured signal surpasses the reference value, an encrypted activation message is sent to the Base Station that incorporates the Transmitter address. The encryption is implemented to prevent the false alarms caused by any similar existing wireless devices in the environment. As soon as the Base Station receives the activation message, it extracts the Transmitter address, turns on the vibrator and lights up the corresponding LEDs to warn the user that a



(a) LISTENse's simple communication scheme.

(b) Transmitter device with microphone.

(c) Base Station with LCD, LEDs, and acknowledge button.

Fig. 5. LISTENse prototype.

sound source has been activated. It will stop as soon as the user presses the acknowledge button or, to save power, after a certain amount of time (*e.g.* one minute.). In addition, it may display an appropriate text message on its LCD screen. Figures 5(b) and 5(c) shows the manufactured Base Station and Transmitter prototype that were successfully tested and evaluated. The prototype size currently follows the Tmote Sky sensor network mote dimensions that is expected to shrink substantially in a near future.

IV. Discussion

Sophisticated, low-power, cheap, small, and mobile electronics will continue to permeate the home environment for a variety of applications, ranging from multi-media entertainment to home automation. It is a natural step to augment or extend these technologies to enable a seamless patient experience between home and the hospital or clinic.

Let us be clear why this must happen – cost. Health care in the US, EU and much of Asia is now a significant part of the economy. The US spends \$2 trillion per year in health care, approximately 16% of the GDP [11]. Figure 6 shows a major concern for the future and the need for the products described in this paper for maintaining health at home rather than care in a hospital. The figure can be explained with the following points:

- The figure shows in the shaded region to the right, that the age groups (in deciles) where the care-costs are greatest are between ages 55 and 95.
- Today, the current workforce shortages pose difficulty with costs of care in this age range since 55-60% of hospital health care is labor cost and hospital care of the elderly poses proportionally higher costs.
- Given this graph is from the 2000 US Census, as todays baby-boomers grow into the regions on the right of the

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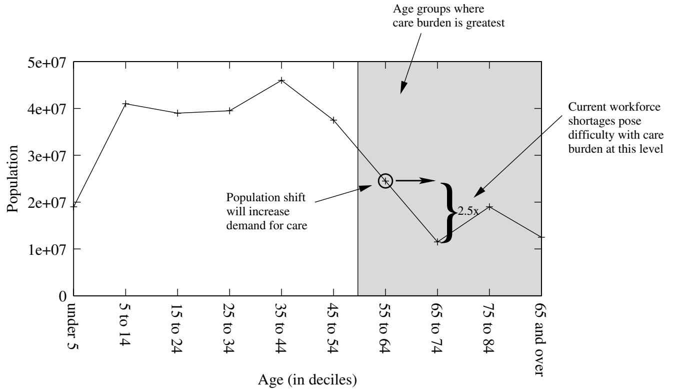

Fig. 6. The US age distributions from the year 2000 US Census. As the aging "baby-boomers" grow into the shaded region as shown by the horizontal arrow, hospital costs will rise sharply prompting the need for products of the kind shown in this paper.

graph (shown by the horizontal arrow), the data indicate that the US population in the "over 60" group is expected to grow by 25% by the year 2030.

Therefore, this figure shows that hospital costs will rise sharply and health-care at home is one way of alleviating this problem. Furthermore, early detection of symptoms will allow doctors to treat diseases earlier, before they progress too far and more expensive to treat.

Several technologies will be important to this evolution: sensor networks, RFID, and mobile consumer electronics. We have mainly addressed sensor networks in this paper. Sensor networks will make up the small, ubiquitous active sensing and actuation components of future smart homes. For example, measuring blood sugar and injecting insulin when it's needed. As battery and energy scavenging technologies continue to improve, these devices will be become more widely available and cost effective. Radio Frequency Identification, RFID, will also play a major role to meet low-power needs for passive objects. For example, RFID can be used to tag items such as medicine bottles – doctor's can automatically know what drugs are currently being administered and a computer can check for undesirable drug interactions. Finally, existing consumer electronics and home infrastructure (*e.g.* Internet, WiFi, telephony, etc.) will be used by patients for self-monitoring and communication with the doctor, bridging the experience between home and hospital care. For example, software may be deployed on these devices to remind patients of their responsibilities (*e.g.* taking their pills and how much to take) and performing real-time analysis of patient data, given parameters set by their physician. Furthermore, these devices will play an important role in data aggregation for larger health statistics gathering, analysis, and studies.

Integration will likely happen incrementally – initially only small set of these technologies will appear in stand-alone manner. Future, more general, systems will perform monitoring, connectivity, and analysis in a more comprehensive manner for a variety of health care functions. We have addressed these problems by focusing on the sensor network and in some cases, the consumer electronic integration. We have demonstrated simple and generic technologies geared towards real needs, while considering form-factor and the business proposition (there must be always be monetary incentive for this technology to transition from research to mainstream consumers). For example, Heart@Home, LISTSENse, and FireLine all demonstrate a generic sensing and display which can be adapted to other applications.

V. Conclusion

Falling electronics prices and their increasing power, coupled with sensing technologies, promise to make health monitoring in one's home, rather than frequent trips to the hospital, a reality. In this paper we have demonstrated several prototypes, including infant monitoring and heart-related monitoring. All the prototypes described in this paper address wireless sensornet and monitoring applications that can prevent illness and increase doctor-patient efficiency, thus reducing health care costs. Reducing health care costs is a huge incentive for hospitals and patients; it will become even more important for the US as today's baby-boomers reach the age range when health care costs sky-rocket. Each of the demonstrated technologies are generic with respect to their sensing, notification, and logging functions, and can easily be extended or adapted to support a variety of applications. These prototypes represent incremental, but important steps towards ubiquitous deployment of health monitoring devices for the betterment of human lives.

VI. Acknowledgments

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