Scalable Alert Medical Response Technology

SMART

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Abstract

In many medical settings, patients are well monitored by caregivers. However, sometimes a patient's condition deteriorates while he or she is unmonitored. This can happen at a disaster site, where patients judged at triage time to have minor injuries wait for caregivers to become available. Similarly, in overloaded emergency rooms there may be a long time between triage and care. While patients are waiting, caregivers can monitor them only minimally. Patients discharged from the hospital after undergoing certain surgical procedures are also unmonitored, even though some are at an increased risk for complications. We believe that technology has reached a point in which we can start monitoring some of these unmonitored patients. In this report, we present the design of a system that addresses some of the technology aspects of this problem in a health care environment. The SMART System architecture leverages off-the-shelf technology to support caregivers in recognizing problems that arise between triage and care. Patients' vital signs are transmitted wirelessly to a central computer that analyzes them. The locations of the patients, caregivers, and equipment are tracked. The central computer uses this information to provide decision support and alerts to the caregivers. Parts of the architecture and technology are expected to be applicable to other healthcare situations, such as recovery rooms, intensive care units, hospital wards, some home/workplace environments, and in mobile or makeshift sites in which health care is provided. Results of a study in which 140 patients were monitored for various periods of time are currently under review.

1. Introduction

Emergencies in both mass casualty and disaster situations as well as in hospitals can quickly become chaotic: caregivers have little time to assess and triage patients, locate appropriate monitors and equipment, and treat patients. The ideal disaster management system would allow large numbers of patients to be monitored and continually triaged even while caregivers are busy triaging or treating other patients. Such a system would identify emergency problems earlier. For example, trauma patients who initially seem stable may have internal bleeding that does not manifest itself immediately. A trend toward tachycardia detected by the SpO_2 sensor and derived from the ECG waveform may help detect this condition sooner, alert the nearest available caregiver of an impending problem, and locate emergency equipment.

In this ideal system, a triage caregiver would place a small wearable array of physiological sensors on each patient. Just a few years ago, such a system would have required tethering each patient to several bulky, expensive monitors, and deployment would have required running cables for power to each monitor. Further, to aggregate the data at a central computer would have required additional cabling for communications.

The SMART (Scalable Medical Alert and Response Technology) System takes advantage of advances in computer and communications technologies to provide caregivers with an affordable, scalable option for dealing with disaster situations. Small wearable computers have become available recently at low prices: Personal Digital Assistants (PDAs) are in common use. With miniaturization of sensors, small, inexpensive, off-the-shelf vital signs monitors are becoming available. Advances in location tracking systems, both for outdoor and for indoor use, have made it practical and economical to monitor locations of both people and equipment. Wireless communication systems have become less expensive, more reliable, and more easily deployed.

To develop the SMART system, we decided to seek to initially deploy and test it in a traditional, non-disaster patient care setting. This was intended to provide two benefits from the point of view of disaster preparedness: First, the system could be refined and debugged in such a setting, and second, if the same personnel were to be called upon to use it in a disaster, they would already be familiar with it from its non-disaster-setting use. Based on those desired benefits, our initial deployment and testing will be carried out in the Emergency Department, Brigham and Women's Hospital, an academic hospital located in Boston. The focus is on patients in the waiting area of the ED, with intermediate severity of symptoms of interest, based on triage, who are not able to be seen right away. In recent years, a variety of systems have been built to monitor patients wirelessly. These systems include CodeBlue [1], Telcordia T2 [2], Welch Allyn's Micropaq Monitor[3], and WIISARD [4]. SMART focuses on monitoring and analyzing data from patients, and tracking patients, caregivers and equipment to provide alarms and logistical support.

2. Architecture

The SMART System is designed to be easily deployed, to monitor large numbers of patients, to track equipment, and to interact with caregivers. Deployment is facilitated by using wearable patient monitoring and location tracking devices that are connected to a PDA, and by using wireless communications between the patient PDA and a central computer, and between this central computer and caregivers. The central computer is known as "SMART Central."

If the area to be covered is relatively small, patient devices can communicate directly to a wireless access point attached to the central computer. For larger areas, where patients are located beyond the range of the wireless access point attached to the central computer, a method is needed to “forward” the information collected from these patients to the central computer. One possibility is the deployment of additional wireless access points which are linked to the central computer via wired Ethernet. Another possibility is to set up long-range 802.11 links or wireless Ethernet bridges between remote access points and the central computer. Another approach is to employ *ad hoc* wireless routing to forward data to the central computer. This area of research, being addressed by other research groups, such as the Monet Research Group at UIUC [5] and the PDOS group at MIT [6] is not a focus of our activities.

To monitor a large number of patients, the SMART System needs to be scalable. We address this need in a number of ways. By using sensors directly connected to PDAs, we avoid issues related to interference among wireless sensors on multiple patients. In forwarding data from sensors to the central computer, the PDAs may need to contend for access to the wireless network. Contention can be minimized by using the processing power of the PDA to forward only significant data to the central computer. Limiting the communications from the PDAs can also help to conserve their batteries. On receipt of a significant message from a PDA, the central computer or a caregiver can request additional information from that PDA.

We can also achieve scalability with respect to central computer processing power by adding more computers to “SMART Central.” This is feasible because the processing done for each patient is independent of the processing done for other patients. While the software monitoring of patients’ vital signs may be distributed over several computers, caregivers are still able to access information on any patient on the same display.

Ultrasound tags that are carried by both patients and caregivers transmit information that is captured by receivers located in the ceiling of different areas. Patient data such as ECG signals, SpO_2 readings, and location information flow into SMART Central. The signals are first processed in the Streaming Data Manager (SDM). Then the Decision Support Module (DSM) uses patient-specific thresholds to detect alarm conditions. These alarms are forwarded to the Logistics Support Module, which then locates needed equipment and alerts an appropriate caregiver who is near the patient.

The location information can also be used to provide decision support to caregivers in charge of allocating personnel and equipment to patients in need. Figure 1 displays a map of a portion of the Emergency Department at BWH, with the locations of hypothetical patients and caregivers. This kind of map or equivalent location information is displayed in SMART Central and on workstations. Location information is also available on caregiver PDAs.

For the evaluation of SMART within the Emergency Department at Brigham and Women's Hospital and to conform to the hospital's Institutional Review Board requirements, we augmented the system with a SMART Operator. The duty of the SMART Operator, a certified paramedic, is to supervise the monitoring of all SMART patients, confirm alarms produced by the system, and follow up on any communications to the healthcare providers.

3. Technology

The technologies used in SMART consist largely of off-the-shelf components. This serves to make the SMART system affordable, widely available to interested parties, and easy to deploy.

SMART is currently based on HP's iPAQ model 5500, which has an Intel XScale PXA255 processor running at 400 Mhz with 128MB of RAM and 48MB of flash memory, and the Linux operating system. We chose to use this particular model for the PDA for several reasons: (1) MIT's Project Oxygen [7] had used it extensively and we could leverage that project's experience, (2) it had an appropriate amounts of memory, built-in wireless communications, and expandability to include additional CF or PCMCIA cards, and (3) it had a reasonable form factor and a reasonable price. Since the start of the project, other Linux-based PDAs have become available [8].

3.2 Patient Monitoring

Each patient is given a PDA with a sensor box. The sensor box is wired to the PDA and to the vital signs sensors. The vital signs monitored currently are oxygenation level and a single-lead ECG.

Nonin [9] manufactures the SpO_2 sensor that we use. The ECG sensor was developed at MIT, since a low-cost commercially available sensor was not available. The sensor box houses some of the electronics associated with the sensors and provides power to them via two AA batteries.

The e SpO_2 sensor is attached to the ECG sensor board and shares the same serial connection to the PDA as do the ECG sensor. A working prototype is shown in Figure 2.

3.3 Location Systems

The indoor location system is based on ultrasound technology developed by Sonitor Inc. Device ID and amplitude of signals received by units mounted on the ceiling are transmitted to SMART Central, where locations are calculated, displayed, and relayed to the caregiver PDAs.

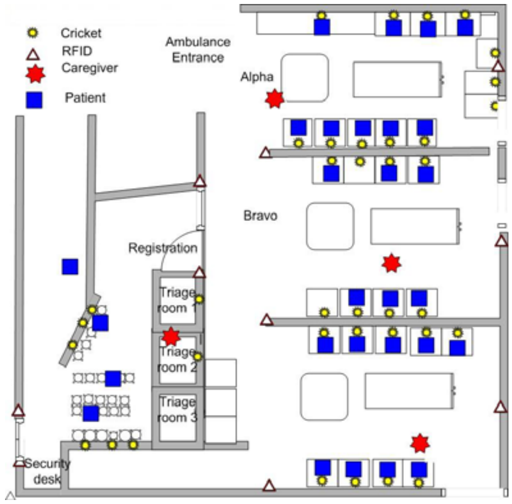

Figure 1. Locations of hypothetical patients and caregivers within a portion of the BWH Emergency Department.

3.4 Networking

Standard wireless networking technology (802.11) is used to connect the patient monitoring PDAs and the caregiver PDAs to wireless access points.

4.5 Decision Support, Logistics Management, and the Caregiver

The heart of the system is SMART Central, which runs on a commodity PC, using the Linux Operating System. SMART Central contains a Streaming Data Manager (SDM), and two decision support components: a patient-specific Decision Support Module (DSM) and a Logistics Support Manager (LSM). The SDM receives the real-time data, processes it, and logs it. The DSM analyzes the data and triggers alarms. The LSM matches alarms to the environment to dispatch relevant information to appropriate caregivers. All data and alarms are logged for later review and analysis.

The SDM receives the SpO_2, ECG, and location data streams. The SpO_2 data stream provides both the patient's oxygenation level and the patient's heart rate. The ECG sensor provides waveform data. The SDM has a computation module for inferring the heart rate from the ECG waveform data. Another SDM module combines the SpO_2 heart rate with the heart rate derived from the ECG waveform data to provide a more robust estimate of the patient's heart rate. For instance, if patient motion causes artifacts in the ECG waveform, the SpO_2 heart rate is likely to be more accurate. If the SpO_2 sensor has fallen off, then the heart rate based on the ECG serves as an alternate source for that information. The SDM provides access to raw data and derived measurements via a simple query mechanism.

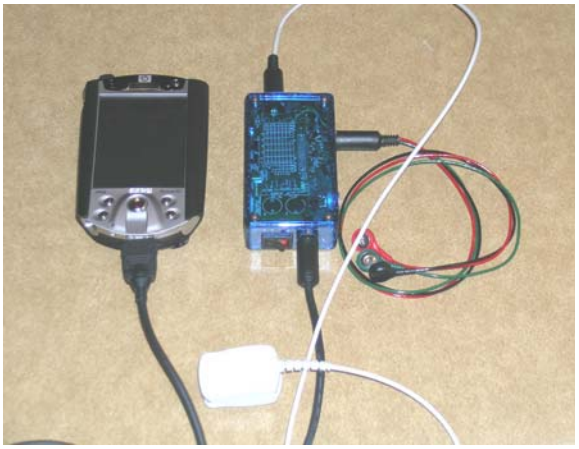

Figure 2. Hardware for SMART patient PDA: SpO_2 and ECG sensors, sensor box, HP iPAQ.

SMART Central's DSM, a client of the SDM, analyzes the streams of data to detect alarm conditions and uses a rule set to generate alarms. Alarms are divided into two categories, technical and medical. Technical alarms may be caused by sensors that have fallen off and loose lead wires. Some example medical alarms are (1) tachycardia (high heart rate), (2) bradycardia (low heart rate), and (3) low oxygenation levels. We also developed algorithms to detect arrhythmias. The intent is to increase the range of conditions we can detect with a minimum number of false alarms.

The LSM is responsible for dispatching alarms to the appropriate personnel or system for notification. Unlike the DSM, which deals with patient-specific data that are independent of the environment, the LSM is highly environment-dependent, and needs to incorporate workflow rules. These rules might indicate that the alarm should be sent to the nearest available and appropriate caregiver. These rules also describe an escalation procedure in case a caregiver does not respond to an alarm. The LSM matches alerts to the appropriate caregiver and sends the alert information to that caregiver’s PDA. A summary of outstanding alerts is also available on the SMART Central display.

Utility modules are used to register patients with the SMART system and to set patient-specific alarm thresholds. There are also modules for combining raw location data into a position estimate for each patient and caregiver. There are modules to review and annotated recorded data.

4. User Interface

There are two classes of user interfaces in SMART: the caregiver’s PDA and the monitoring interface associated with SMART Central. These user interfaces allow the following functions to be performed:

- Alert caregivers to alarm conditions
- Locate patients, caregivers, and equipment
- Access the roster of patients
- Access the vital signs of each patient
- Review the recent alarm conditions and the responsible caregiver
- Register new patients and caregivers

SMART Central provides a basic monitoring interface. This interface displays the list of patients and a map showing the locations of patients, equipment, and caregivers. When a patient is selected from the list, the patient's vital signs readings and ECG waveform are displayed.

The caregiver's PDA has three distinct modes. The first shows a roster of patients. When a caregiver clicks on a patient in the roster, the detailed vital signs are shown, as depicted in Figure 3. The third mode handles alarm conditions : the alarm window identifies the patient with the problem, the degree of severity of the problem, and the nature of the problem. The caregiver then has a choice of indicating to SMART Central that he or she will respond to that problem, by tapping on the "OK" button, or indicating that he or she is busy, via the "BUSY" button, and will not be able to respond to this alert. Of course, SMART Central must deal with the situation where the caregiver does not respond at all. In this case, the re-alerting behavior is governed by the rule set: typically another caregiver will be alerted promptly.

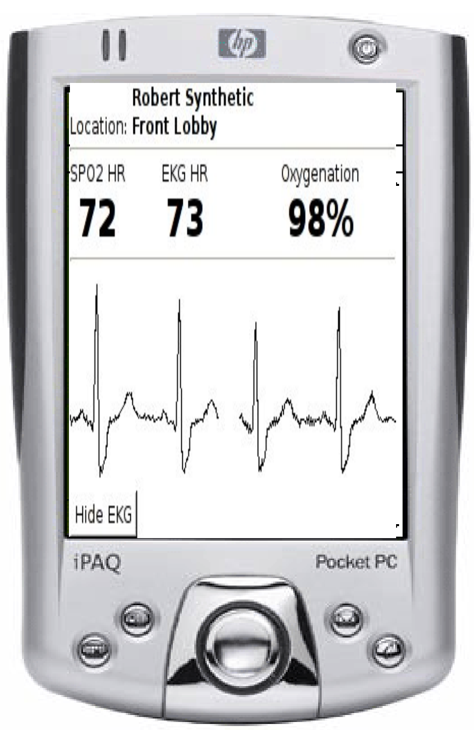

Figure 3. Caregiver's view of a patient.

Figure 4. Caregiver's view of an alarm. Tapping on OK indicates that the caregiver will respond to the alarm.

5. Deployment Status and Future Plans

We have developed a prototype for the patient's PDA and sensors, for the central services that collect and analyze the sensor data, and for the caregiver PDA.

We obtained approval from our Institutional Review Board to implement SMART at the Emergency Department of Brigham and Women's Hospital. Patients who have cardio-respiratory complaints and who are not triaged to be seen immediately (i.e. patients whose Emergency Severity Index [13] is above level 1) are approached by a qualified health care provider to participate in our study. One of the goals was to evaluate the acceptability of the device by patients in the waiting room and by the triage nurses who are responsible for their care. The amount of time that the patient wore the device, his or her perceptions on its usefulness, and other concerns were surveyed. Another important goal was to evaluate the adequacy of alerts generated with input from the signal processing modules: false alarms (stemming from technical or data processing artifacts) were analyzed and the algorithms were periodically tuned to reduce their number without compromise of sensitivity.

We also built a system to implement SMART in the field, by deploying this system in a local ambulance, thus providing vital signs and location (GPS) information to the ED while the patient is in transit. The communication is based on cell phone technology. Beyond this, we have ongoing research in the areas of power management for sensors, wireless communications between the sensors and PDAs, and real time algorithms for analyzing ECG signals. Results from our studies are currently under review in peer reviewed biomedical informatics journals.

References

[1] Malan D, Fulford-Jones T, Welsh M, and Moulton S. CodeBlue: An Ad Hoc Sensor Network Infrastructure for Emergency Medical Care. In Proceedings of the MobiSys 2004 Workshop on Applications of Mobile Embedded Systems (WAMES 2004), Boston, MA, June, 2004.

[2] Chen C-M, Agrawal H, Cochinwala M, Rosenbluth D. Stream Query Processing for Health-care Bio-sensor Applications. Proceedings of the 20th International Conference on Data Engineering (ICDE 04).

[3] Welch Allyn Micropaq Monitor Model Micropaq 404 Monitor (ECG/SpO2) http://www.welchallyn.com/medical/products/catalog/detail_asp?ID=31817

[4] WIISARD http://www.wiisard.org

[5] Xue Y, Nahrstedt K, Providing Fault-Tolerant Ad-hoc Routing Service in Adversarial Environments, *Wireless Personal Communications, Special Issue on Security for Next Generation Communications*, vol. 29, num. 3-4, Kluwer Academic Publishers, 2004.

[6] Biswas S, Morris R. Opportunistic Routing in Multi-Hop Wireless Networks.

[7] MIT Project Oxygen http://oxygen.csail.mit.edu

[8] Linux sets its sights on the PDA market http://www.linuxdevices.com/articles/AT8728350077.html

[9] Nonin Medical, Inc. http://www.nonin.com

[10] TinyOs http://tinyos.net

[11] Nissanka PB, Chakraborty A, Balakrishnan H. Cricket Location-Support System. 6th ACM-MOBICOM, Boston, MA, August 2000. http://cricket.csail.mit.edu

[12] Crossbow Technologies http://www.xbow.com

[13] Tanabe P, Travers D, Gilboy N, Rosenau A, Sierzega G, Rupp V, Martinovich Z, Adams JG. Refining Emergency Severity Index triage criteria. Acad Emerg Med. 2005 Jun;12(6):497-501.