A Pervasive, Real-time Electronic Triage System with Noninvasive, Biomedical Sensors

Tia Gao, Tammara Massey, Leo Selavo, Matt Welsh, David Crawford, Alexander Alm, William Bishop, Daniel Bernstein, Logan Hauenstein, James Jeng, Ajun Chanmugam, David White, and Majid Sarrafzadeh

***Abstract*—In mass casualty incidents, an enormous amount of data, including patients' vital signs, patients' location, location and availability of transport vehicles, and the capacity of care facilities must be gathered and monitored efficiently. Today, these pieces of critical information is manually collected on clip boards and communicated over radios. During large scale disasters, providers quickly become overwhelmed with the large number of patients, limited resources, and insufficient information. To facilitate patient care, resource allocation, and real-time communication, the Advanced Health and Disaster Aid Network (AID-N) electronic triage system facilitates the seamless collection and dissemination of data from the incident site to key members of the distributed emergency response community. Here we present the iterative design of electronic triage tags on lightweight, embedded systems with limited memory and computational power and demonstrate how they improve communications during a real-world mass casualty drill. These electronic triage tags use noninvasive, biomedical sensors to continuously monitor the vital signs of a patient and deliver pertinent information to first responders. The real-time collection of data through a mesh network in a mass casualty drill was shown to approximately triple the number of times patients that were triaged compared with the traditional paper triage system.**

***Index Terms*—Biomedical monitoring, emergency services, human factors, multisensor systems.**

Manuscript received October 22, 2006. This work was supported by the U.S. National Library of Medicine under Grant N01-LM-3-3516.

Tia Gao, Logan Hauenstein, William Bishop, David White are with the Johns Hopkins University Applied Physics Lab, Laurel, MD 20723 USA (phone: 240-228-3475; fax: 301-762-8230; e-mail: tgao3@jhu.edu; email: william.bishop@jhuapl.edu; email: logan.hauenstein@jhuapl.edu, email: martin.sikes@jhuapl.edu; email: david. white@jhuapl.edu).

Tammara Massey and Majid Sarrafzadeh are with the University of California, Los Angeles, CA 20723 USA (e-mail: tmassey@ucla.edu; email:majid@cs.ucla.edu).

Matt Welsh is with Harvard University, Cambridge, MA (email:mdw@harvard.edu)

Leo Selavo is with the University of Virginia, Charlottesville, VA 22904 USA (e-mail: selavo@cs.virginia.edu).

David Crawford is with the University of Maryland, College Park, MD, USA. (email:)

Alexander Alm is with the Vanderbilt University, Nashville, TN 37235 USA (e-mail: alexander.m.alm@vanderbilt.edu).

Daniel Bernstein is with the St. Joseph's Medical Center, Towson, MD 21204 USA (e-mail: jhurugby@hotmail.com).

I. Introduction

EMERGENCY medical situations require responders to effectively care for patients with limited resources and medical infrastructure, often under intense time pressure. At disaster, a critical first step in the response process is the rapid and accurate triage of the patients. Triage information from the field is communicated to multiple parties of the response team and must be continuously updated to reflect the ongoing response. This information triggers a sequence of events to occur in coordination of response, including the request for ambulances and personnel, notification of receiving care facilities, and prioritization of patients for transport and treatment. Patient triage acuities vital signs and locations steadily evolve and must be tracked continuously to ensure proper resource allocation and patient care. Unfortunately, the current response process use paper triage tags that cannot ensure for efficient triage, monitoring or location of patients during mass casualty situations.

At the scene, responders perform triage by attaching a paper tag or colored ribbon to each patient to indicate acuity level and then call their triage officers to report their counts. Triage officers collect data from responders in their team onto a clip board, and in turn report the aggregate information to the incident commander. The commander tallies the patient numbers, and then requests for the necessary number of ambulances and hospital.

Paper tags employ color codes to determine the severity of the patients' injury. Patients classified as red are considered to need the most immediate attention, followed by patients classified as yellow. Patients classified as green are the least severely injured and patients classified as black are either deceased or expected to die despite immediate medical care.

These tags have obvious limitations in patient monitoring. They also provide little room for manually recording essential information during treatment, such as the patients' vital signs and chief complaints. Furthermore, reading the tags can be difficult because the patient information, recorded under time pressured situations, is often illegible. Paper tags also have limited visual feedback and do not aid in locating a particular patient in a sea of patients tagged with the same color. When a large number of patients need to be tallied by the commander, the manual count of each triage level is prone to human error. Critical minutes are wasted between the time a patient is triaged and the time that information is verbally reported to the officers. The status indicated by the paper tag cannot be quickly upgraded or downgraded when a patient's condition changes. Further prioritization between patients categorized with the same color triage tags is done in an ad hoc manner or not at all.

Upon completion of initial triage, patients are moved from the triage area to a specified treatment/waiting area to await transportation to a hospital. Secondary triage allows for an in-depth reassessment of the patient's condition and collects information such as the patient's demographics (age, gender), allergies, medications, chief complaint, and a description of the injury. This information is necessary for proper patient treatment and appropriate transportation to a hospital capable of treating the patient's condition. During secondary triage, the vital signs of the patient, such as the heart rate, blood pressure, and respiration rate, are also assessed. If transportation to a hospital is delayed, patients must be reassessed every five to fifteen minutes. The constant reassessment is problematic in mass casualty situations because it prevents responders from collecting other useful information about the patient and focusing on patients who need additional aid.

In this chaotic environment, insufficient information is often provided to EMS officers regarding the developing needs of the ongoing response. Patients who are mobile can often depart the scene without being authorized to do so. When patients contaminated with hazardous materials depart before they are decontaminated, public facilities and receiving hospitals become at risk for secondary exposure. Such missteps create an organizational nightmare for the EMS officers responsible for the scene. During chaotic environments, patients often wait for extended periods before ambulatory transport arrive. An extended wait time hastens the unnecessary deterioration of patients' conditions. In addition, secondary injuries such as hypoxemia, hypotension, and cardiac tamponade may arise. To address these problems, current emergency response protocols require paramedics to periodically re-triage patients [12]. Every 5, 10, or 15 minutes, patients with red, yellow, or green priorities are re-triaged, respectively. However, this important protocol is time consuming and not very practical for many emergency situations [23].

To resolve some of these challenges, AID-N has a designed decentralized electronic triage and sensing system that contains low power embedded devices. The physiological characteristics of each patient is efficiently monitored and tracked through a fault tolerant communication infrastructure. Patient information is automatically distributed to response members on computing platforms tailored to fit individual workflow needs. Laptop displays patient information on a wide screen and is suitable for use by treatment officers localized to a particular treatment area. PDA with GPS serves as a portable platform for field medics on the move. The PDA contains an integrated camera and barcode scanner that allows users to rapidly collect information at the scene. A web site allows authenticated uses to log on and review critical information from the field. The main benefits of the AID-N electronic triage include:

1) continuous monitoring of triage levels, physiological status, and location of the patients
2) automated distribution of patient data in real-time to response team members both on and off the disaster site.

The overall goal of the AID-N electronic triage system is to more efficiently gather and distribute information on the vital signs and locations of patients in a manner that is extremely fault tolerant. The following sections describe four areas of our triage system: 1) electronic triage tag, 2) wearable sensors, 3) patient monitoring base station laptops 4) 5) documentation PDA.

II. Related Work

The AID-N electronic triage system has been designed and implemented to meet the needs of the next generation of triage systems. Previous research has established standards for initial triage for the categorization of victims according to treatment urgency during explosive events or biological catastrophes [5][8][42]. Also, technology has been combined with triage through the use of barcodes, tag readers, passive RFID tags, hand-held computers, and geolocation to collect data about mass casualty events [6] [15] [10] [24] [26]. Location tracking systems, such as [11], use active RF-ids tags in hospitals, but lack the embedded vital monitoring components of AID-N. The AID-N electronic triage system provides similar functionality as other electronic triage tags [26] [33] [38], but the AID-N electronic triage system use 2.4 GHz Radios (802.15.4) instead of 802.11 and consist of ultra-low power embedded hardware. Previous work by [4] [30] has also developed biomedical sensors, but AID-N specifically built their hardware and software to accommodate triage situations.

Monitoring packs used by responders during routine ambulance runs provide the required updates but can track vital sign trends of a single patient [51][34]. Bedside-monitoring systems used in hospitals can track multiple patients but are not suitable for field use [50]. AID-N presents a low power, wireless electronic triage system with multiple biomedical sensors (EKG, pulse oximetry, non-invasive blood pressure) that yield continuous, automated, real-time patient monitoring. The technical challenges faced by AID-N were the creation of the auxiliary boards to the specification of the paramedics, the creation of lightweight and simple algorithms to fit on the resource constrained embedded systems, the propagation of information across low-data rate radios, and the integration of several disjoint systems together (802.15.4, 802.11, PDA, web services and database).

Compared with the above mentioned projects, the AID-N system has several unique features.

1) Triage System on an 802.15.4 Network: AID-N addresses the challenge of collecting and transmitting vital signs for a disaster application over an 802.15.4 network.

2) Iterative Design of Triage Hardware and Software. Continuous communication with paramedics throughout the design process resulted in a realistic and usable system. All embedded systems created can be used with the standard sensors in any ambulance.

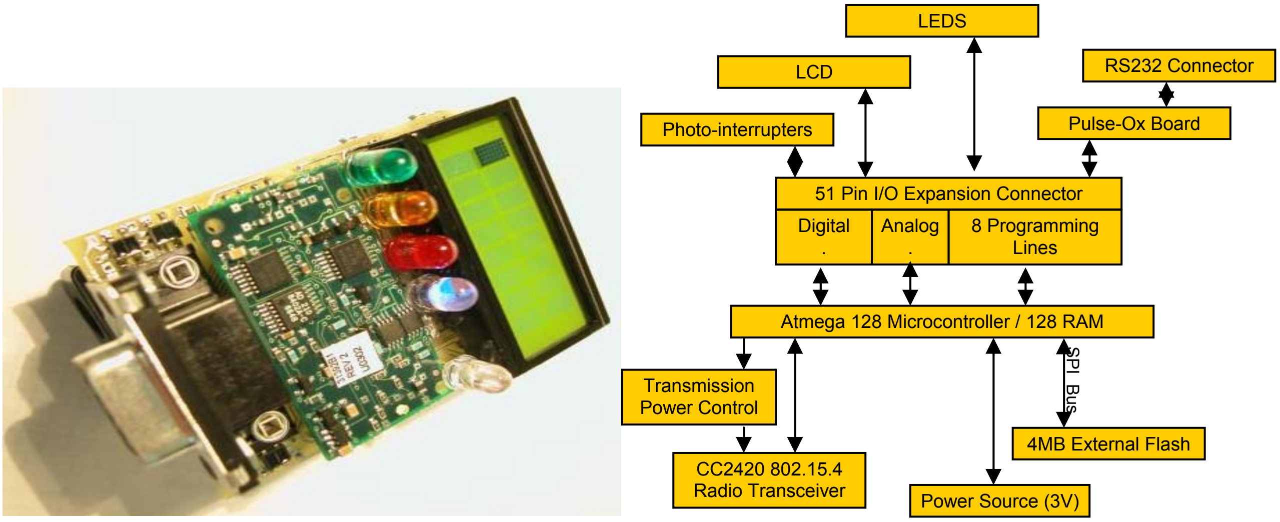

Fig. 1 a) Electronic Triage Tag with pulse-oximeter board attached. b) Architecture of the Electronic Triage Tag (includes MicaZ mote and AID-N custom built Etag board).

3) Flow Mesh Networking Protocol. AID-N used the Flow networking protocol designed specifically for lightweight embedded systems.

III. The AID-N Electronic Triage Architecture

Embedded systems in AID-N transmit data over ad-hoc mesh networks to patient monitoring computers such as laptops at the scene and via Internet links to a central server for access by emergency departments and Public Health. Each device is constructed with inexpensive electronic hardware and operates on software suitable for embedded systems. These systems have limited memory, computational power, energy source, and communications bandwidth. The main challenges in the design of AID-N were the collection and distribution of information using lightweight embedded devices. Several kinds of such low power devices were developed: electronic triage tag (ETag) with integrated pulse oximeter, EKG monitor, and blood pressure (BP) monitor (Table 1).

TABLE I
Power Analysis of Electronic Triage Tags and Noninvasive Biomedical Sensors

Component	Mode	Power (mW)
ETag	n/a	138mW
EKG	Heart Rate Extraction	63mW
EKG	Waveform	93mW
BP Mote	Inflation	3330mW
BP Mote	Standby	240mW

A. Electronic Triage Tags

The hardware in the AID-N electronic triage system provides a low power embedded devices to meet the challenges of efficient triage. The electronic triage tag allows the medic to set the triage color (red/yellow/green/blue) of the patient at the push of a button. It replaces the paper triage tags that are commonly used by medics today. The functionalities of the electronic triage tag are triage, status display, location tracking, pulse oximetry sensing, and alarm signaling. The electronic triage tag's modes of operation can be controlled directly on the device or remotely. The tag runs on a platform that has telemetry capabilities and its triage states are reported to a remote station.

The triage status is entered to the electronic tag by toggling the triage button and displayed by four light emitting diodes (LEDs) that represent the triage colors of the patient. The colors represent the triage priority levels in descending order: red, yellow, green, and blue. The patient can only be on one level at a time and the tag employs a lockout feature to prevent patients from triaging themselves either accidentally or intentionally. A small green LED, on the side of the tag, blinks in sequence with the patient's heartbeat and an amber LED can be turned on if the patient is contaminated. The tag can blink all LEDs to signal that the patient should be taken to the hospital. In addition, providing visual interface in-situ is useful and important, therefore the electronic triage tag has an integrated display [45].

The triage tag hardware and driver software were developed at the University of Virginia (UVA). The device has five programmable LEDs and LCD for information display, up to four buttons for user input, an interface to OEM pulse oximeter daughter board and sensor, four channel photoscanner for reading coded triage card, and an optional RS232 interface to other medical sensor devices (Figure 1). The monochrome LCD screen has text output, two lines with eight characters each, and optional LCD backlight. The LCD screen currently displays the oxygen saturation and the heart rate of the patient. The photoscanner is made from four photo-interrupters and can optically detect up to 15 different code cards. The electronic triage tag uses the MicaZ platform from Crossbow Technology for information processing from the sensors and wireless communications over 2.4GHz ISM radio frequency band [35]. Data on the tag is relayed via a compatible radio and sensor node Tmote Sky from MoteIV, which attaches to a PC via Universal Serial Bus (USB) [49].

The MicaZ and TmoteSky motes have maximum data rates of 250 kbps. The single-chip radio in the MicaZ and TmoteSky, CC2240, operates in the unlicensed 2.4GHz ISM band and is compatible with IEEE 802.15.4 standard. The radio has a practical indoor range of approximately twenty to thirty meters. The TmoteSky and MicaZ motes can be powered by two AA batteries and consume roughly 19.5 to 23 mA or 26 to 28 mA at 3V respectively. The low power consumption results in a battery lifetime of five to six days of continuous operation. The motes are constructed to be inexpensive and light weight. With MEMS manufacturing, we envision the motes to become single-use disposable devices [17].

MicaZ mote's standard whip antennas were substituted with commercial 802.11 rod antennas to increase outdoor range from 23 to 66 meters. Tmote's printed circuit board antennas were substituted with 8.5dB gain external antennas. These antennas are available as a magnetic vehicle mount and can be conveniently placed on ambulances to significantly increase the base station's wireless coverage.

B. Noninvasive Biomedical Sensors

In order to effectively measure patient's physiological conditions, multiple sensor modalities are attached to the mote. The Etag contains integrated pulse oximetry capability for measuring the oxygen saturation and heart rate of the patient (Figure 1). The pulse oximeter board is developed by Smiths Medical and operates with SpO2 accuracy of ±2% variation and heart rate accuracy of ±2 bpm according to specification. Vital sign readings are displayed on the LCD screen. A standard serial port interface connects with multiple types of commercially available oximeter clips: finger clip, finger wrap, ear clip, and foot wrap for infants [32]. When the Etag was connected to a simulator in a controlled lab environment, it showed perfect performance with an accuracy of ± 0% variation . Multiple oximetry clips were tested for performance with motion artifacts. The variation caused by brisk movement was measured for ear clip pulse-ox [$\bar{X}$=± 36% variation, s=.03], finger pulse-ox [$\bar{X}$ = ± 41.8% variation, s=.04], and robust finger pulse-ox [$\bar{X}$ = ± 36.0% variation, s=.04]).

The BP monitor and EKG monitor were developed for patients who need additional levels of monitoring beyond pulse oximetry. The BP mote automatically inflates an upper arm cuff at customizable time intervals to acquire blood pressure readings and transmit the data over the wireless mesh network (Figure 2). This is another modular system that allows various sizes and styles of cuffs to be connected in order to accommodate children and adults. When acquiring BP readings every 5 minutes, the device operates for 10 hours on a four-cell battery pack of 9V lithium batteries [47].

This device builds upon the NIBP module from SunTech Medical, known as the Advantage Mini [47]. The Advantage Mini, a clinical grade NIBP module, delivers systolic, diastolic, and mean arterial pressure. Pulse rate is also sensed, and then used by the base station in vital sign monitoring software to verify pulse data from the pulse oximeter readings. The cuff meets AAMI SP10-1992 standards, delivering pulse rate accuracy of ±3 beats per minute and pressure accuracy of ± 3 mmHg according to the specification.

Fig. 3. Embedded Blood Pressure Prototype in the AID-N Electronic Triage System

The EKG monitor, based upon the sensor board developed at Harvard University, detects 2-lead EKG waveforms, extracts heart rate using a lightweight algorithm [14]. It transmits heart rate measurements and/or waveforms across the mesh network, depending on network bandwidth requirements. The EKG hardware is another modular system that interoperates standard connectors (Figure 3). Different types of EKG leads and associated electrodes can be attached to this module based upon the patient age and size [41] [16].

The heart rate detection algorithm produces reliable results while operating under considerable environmental and human noise, such as noise created by muscle activity and respiration. Furthermore, this algorithm is resilient to common usage errors such as reversing the polarity of the leads and differences in lead placement (e.g. leads placed on the wrist, chest, or abdomen). These features make it practical to deploy our EKG devices for a broad range of care providers, patients, and environments.

Fig. 3. Embedded EKG device prototype to collect a patient's heart beat (seen attached to an EKG waveform simulator)

C. EKG Heartbeat Extraction Algorithm

When several EKG waveforms were transmitted over the network, the heavy network load of the waveforms reduced throughput in the network. Additionally, high noise interference from movement of the patient resulted in an undecipherable waveform to be created while signal processing on the sensor. Therefore, AID-N developed lightweight EKG heartbeat extraction algorithm that extracts the heartbeat of the patient from the EKG waveform and is resilient to noise. The algorithm is based on the SQRS algorithm which can be found on MIT's physionet website and was described by [40] and has been modified to improve performance when tested over the MIT-BIH database of EKG waveforms with different forms of simulated noise superimposed on the underlying signals.

The EKG algorithm first passes the incoming signal through a simple FIR filter with coefficient weights [1.5, 0, -1.5]. Assuming a sampling frequency of 100 Hz, this gives a weighted derivative of the incoming signal with a max gain near 36 Hz achieved with the original FIR filter employed by the SQRS algorithm. This signal is then tested to see if it passes either an upper or lower threshold, both of which are dynamically updated. If the signal passes the upper and lower signals in an alternating fashion within 190 milliseconds of each occurrence, the detection of an R wave is declared. If more than four threshold crossings occur in an alternating fashion within 190 milliseconds of each other, the algorithm waits to see if more occurrences occur within 240 milliseconds of each other to prevent artifacts from being detected as beats.

The heart rate detection algorithm was tested over 48 EKG recordings in the MIT-BIH arrhythmia database of EKG recordings [36]. Combined noise including abrupt baseline shifts and drift, power line noise, EMG noise and motion artifact noise was superimposed on each recording, and the mean positive predictivity and sensitivity1 was measured and were found to be 97.6%, 91.9% respectively. The types and characteristics of super imposed noise were based on work by [13] and observation of EKG waveforms recorded with the AID-N system.

To determine heart rate, the algorithm calculates the reciprocal of the interval between the times of detected R waves. After five seconds of no detected beats, the algorithm declares a heart rate of zero beats per minute.

D. CodeBlue Mesh Network

The software that runs on the ETags allows the responders to monitor and control multiple ETags simultaneously. The software and sensors are an extension of the CodeBlue project at Harvard University [32]. CodeBlue is a distributed wireless sensor network for sensing and transmitting vital signs and geolocation data. The communication vastly improves coverage and reliability with a virtually unlimited range. The wireless networking software uses Flow Routing2, a mesh networking protocol developed at Harvard University. Each sensor communicates with the networking protocol using the CodeBlue Interface (CBIF) (Figure 4).

This mesh network guarantees connectivity between patients and providers in mass-casualty incidents. AID-N designed the system to be reliable and requires minimal setup. The mesh network allows AID-N to support hundreds of patients with electronic triage tags and medical sensors. The wireless transmission of vital signs reduces the amount of information that is verbally communicated and provides a second source of information to what is occurring on the disaster scene.

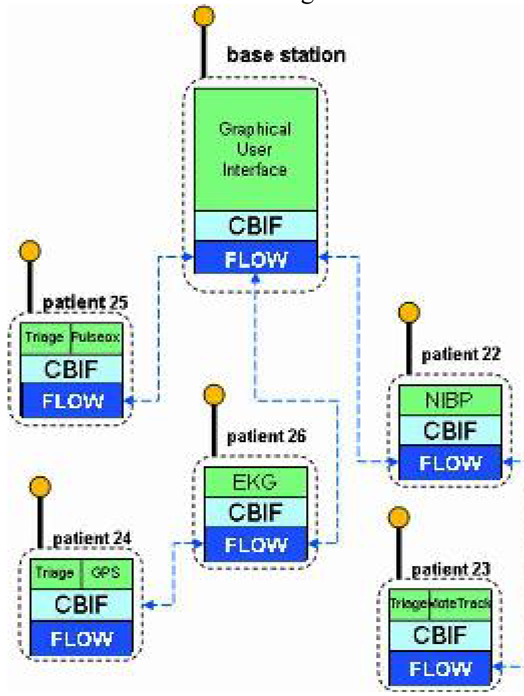

Fig 4. Networking diagram of the triage system showing multi-hop communications.

E. Patient Monitoring GUI and Vital Sign Detection Algorithms

Sensor data travels over the mesh network to a base station that displays the patient information and patient alerts (Figure 5). Upon receiving the data, the graphical user interface (GUI) sorts the patients based upon priority levels and waiting times. The icons and text use universally accessible colors schemes used by paramedics. The status codes are commonly accepted color codes (pink =stable, blue=critical).

The base station laptop's vital signs analysis algorithms are based upon: 1) published detection methods implemented by existing patient monitoring products and 2) feedback from paramedics and physicians [9][43]. Table II shows a list of the monitored patient conditions.

Detection parameters are customized to each patient using several novel techniques.

1) If the patient has a medical record that was previously entered, information from the record is used to adjust the detection thresholds.
2) Thresholds are adjusted upon environmental factors (e.g. altitude and temperature) reported from standalone sensors at the scene.
3) Thresholds are programmatically adjusted upon patients' baseline readings.
4) Paramedics can adjust thresholds on a per patient basis by manually updating thresholds.

Patients' thresholds are transmitted to the remote patient record database for later retrieval. If there is no network connectivity to the remote server, thresholds are stored locally on the electronic triage tag.

[1] Sensitivity is defined as true_positives/(true_positives + false_positives) and gives the percent of declared beats that were truly beats. Sensitivity is defined as true_positives/(true_positives + false_negatives) and gives the percentage of beats that were detected.

[2] Additional details on the Flow Networking protocol can be found in a separate publication under review.

TABLE II
ALERTS RAISED BY VITAL SIGNS ANALYSIS ALGORITHM

Category	Alert
Cardiac	No pulse
	Bradycardia
	Tachycardia
	Onset of change
	Stability
Respiratory	Low oxygen saturation
	Onset of change
Blood Pressure	Systolic pressure
	Diastolic pressure
	Widening pulse pressure
	Narrowing pulse pressure
	Mean arterial pressure
	Change

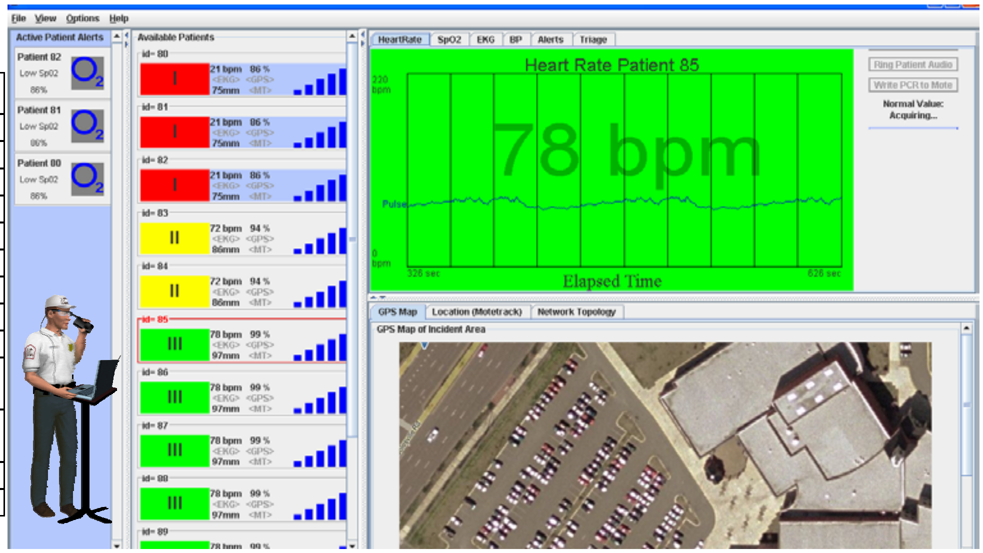

Fig. 5: Graphical user interface of mass casualty patient monitoring station.

F. Web Portal

A web portal, known as the Emergency Response Information Center (ERIC) supports the need for multiple parties to share up-to-date patient information from Internet browsers (Figure 6). Sensor data from the incident site travels to a centralized database server and is then forwarded to a web portal. The web portal tailors information to multiple types of users, including:

1) Emergency department personnel login to the portal to retrieve information about the patients who are being transported to their hospital.

2) Incident commanders login to the portal to see summaries of patients triage status and locations at particular disaster scenes. This allows them to make informed requests for additional medical supplies and personnel and to properly allocate available resources. Figure 6 shows a page in the portal for this group of users.

3) Medical specialists, often located at distant facilities, may be called on to give treatment instructions to the medics at the scene. They log in to view real-time medical data of the patient being treated. They can also review the triage colors of patients at the scene to verify that the patients have been triaged correctly.

Effective healthcare requires access to patient data that are generated and stored on heterogeneous database systems. Integration of patient data is a significant challenge faced by the healthcare community. Through the use of well defined web services, we were able to connect two disparate systems, that is, the CodeBlue network of sensors and the AID-N patient management system. Patient information is transmitted over SOAP, a form of XML. The WSDL (Web Service Definition Language) for these web services is published to a community of authorized users. Our solution has flexibility to interoperate with additional systems in the future and does not require the client to use heavyweight software libraries or

Fig. 6. Screenshot of the Emergency Response Information Center (ERIC).[LEFT] Portal for Incident Commander: displays the transportation status and triage summary of all patients (top) and maps of the incident scene (bottom). In the timeline (top) boxes below the horizontal line indicate patient have been transported and boxes above the horizontal line incident patients at the accident scene. [RIGHT] Portal for receiving hospitals: histogram of patient age (top left) and histogram of chief complaints (top right); list of patients at the bottom left, and patient details at the bottom right

locally-housed databases – a practice commonly dictated by other disaster modeling systems. Our system enhances the quality of a disaster response by providing a lightweight and publicly-available web service to the clients. During a mass casualty incident, the web portal greatly simplifies the sharing and consuming of data across various responder disciplines and jurisdictions.

G. Surveillance and Incident Reporting PDA (SIRP)

Paramedics carry a handheld PDA called the Surveillance and Incident Reporting PDA (SIRP). SIRP is a handheld device with software and hardware designed to improve the efficiency of the first responder tasks (Figure 7). During secondary triage, SIRP improves the process of reassessing and matching patients to resources by recording patient status, chief complaints, and treatments in the PDA using drop down lists and geo-location through GPS. SIRP also improves the process of recording patient identification information by scanning and parsing the 2D barcode of patient's driver's licenses. Patient identification information can also be manually inputted for patients without driver's licenses. SIRP also provides an integrated camera as a method for recording patient photos, for identification, capturing photos of patient injuries, and for pictorially documenting events at the scene.

Finally, SIRP allows responders to view real-time readings of patient's vital sign sensors while in the field. Manual information can also be captured onto the field. Incident commanders also can use the PDA to plan the spatial organization of the disaster scene, review locations of responders, patients, and locations on scene, and communicate scene information to other responders.

Figure 7. PDA screenshots of secondary triage and patient identification entry.

IV. An Effective and Usable Triage System

The main contribution of the AID-N electronic triage system is an architecture that allows for more information on the vital signs and location of patients during initial triage. The system reduces the workload of the first responders by reducing secondary triage since a patient's vital status is immediately gathered wirelessly once the device has been activated.

The miniaturized, low-power sensors use universal accessory connectors that detect the physiological conditions of the patient. The AID-N team built upon the CodeBlue mesh networking software developed at Harvard [32]. AID-N added functionality for the electronic triage tags, integrated the blood pressure sensor, and created a heart rate extraction algorithm that minimized the amount of information that is sent across the network for the EKG sensor.

The base devices are small USB compatible devices that receive data from AID-N sensors. We envision the base stations used in every ambulance, every care facility, and every disaster scene. Hence, the medic can track the general locality of the patient based upon which base station is communicating with the ETag. Software alerts providers if a particular patient is walking away from the scene without an official discharge. The base station identifies wandering patients by monitoring the signal strength of ETags.

ETags also allow one to attach extra data such as special circumstances which may necessitate specific ways for handling that patient, more specific categorization of the injury, or identifying information such that this info is immediately known to other first responders or EMS officers

V. Evaluation of Usability Requirements in Triage

In collaboration with emergency response `personnel in the Washington DC Metropolitan area, we practiced a user-centered and iterative design described in human-computer interaction literature [3][39]. As shown in Table 3, our sampled user community consisted of over 50 emergency medicine providers from various ranks, in three counties in the DC Metropolitan area: Arlington County, VA, Montgomery County, MD, and Baltimore County, MD. A detailed description of our iterative design process is presented below. AID-N members rode along on ambulance runs with medics and interviewed twenty-two medical personnel, including three captains, two platoon chiefs, and eight paramedics, in regards to EMT procedure and requirements for a patient tracking

Fig 8: An Iterative Package Design. From left to right, black Mote 21 is the initial prototype with three LED lights. The black mote with five LED lights and buzzer is prototype number two. Prototype number three is a clear mote with a LCD screen to display the oxygen saturation and heart rate. The photo-interrupter cards are displayed in prototype 3. The final prototype is the white mote with the LCD screen and push buttons.

system. Of the twenty-two medical personnel, six individuals took an anonymous survey. The age range of the medical personnel surveyed were from 7 to 25 years (mean=15.0, std = 6.4). A seven-point Likert scale was used with the medics (1 = not important, 7 = very important).

The evaluation of requirements results in a large number of first responders desiring to minimize the amount of paperwork done after a mass casualty event. Also, first responders desired easy location of medics, a bird's eye view of the disaster scene, accurate tracking of patients to treatment centers, and the ability to monitor the patients in the disaster area. Numerous other needs were also ranked. In general, paramedics ranked tasks that directly affected their responsibilities during triage more highly than tasks completed by other members on the team. However, it was universally mentioned that tracking critical patients was a high priority.

The subjects were asked to rank possible AID-N features using a range between 1 and 7. 1 was the least important or least useful; while 7 was the most important or most useful. From the surveys, a feature that received one of the highest marks was the pulse-ox sensor (mean = 2.83, std=1.47), which became the default sensor on our electronic triage tag.

AID-N evaluated the design implications from the preliminary evaluations and incorporated these suggestions into the initial design. As a direct result of the surveys, AID-N built the system to operate for several days with little setup time. Necessary maintenance and training to use the system is minimal. Also, treating patients with a necklace-like sensor raised concern due to the fragility of the neck with spinal cord injuries. Therefore, AID-N also built dual attachments for patients' belts. The system was designed to withstand rough usage. The packaging provided splash-proof insulation for the embedded devices to protect the device against damage.

TABLE III DATA SOURCES FOR SOLICITING USER FEEDBACK

Understanding user workflows
Interviews
4 medics (at Fire, Police, and EMS Expo)
Field Studies
60 hrs of ambulance ride-alongs (Arlington [27], Montgomery)
2 site-visits to emergency operations center (Montgomery [46], Baltimore)
2 MCI exercise observations (Baltimore [28], Prince George's [29])
Identifying and ranking user needs
Surveys
6 medics (Arlington County [48])
12 medics (Arlington, Montgomery, and Baltimore [1])
Discovering additional user needs through prototype demonstrations
Interviews
3 medics (2 Arlington County, 3 Baltimore County, 1 Montgomery County)
2 nurses (Suburban Hospital)
5 physicians (3 Suburban, 1 Maryland , 1 military)
3 MCI experts [18][19][20][21][22]
Round-table discussions
10 responders in Baltimore County
15 responders in Arlington County
6 responders in Montgomery County

AID-N evaluated the design implications from the preliminary evaluations and incorporated these suggestions into the initial design. As a direct result of the surveys, AID-N built the system to operate for several days with little setup time. Necessary maintenance and training to use the system is minimal. Also, treating patients with a necklace-like sensor raised concern due to the fragility of the neck with spinal cord injuries. Therefore, AID-N also built dual attachments for patients' belts. The system was designed to withstand rough usage. The packaging provided splash-proof insulation for the embedded devices to protect the device against damage.

The medics ranked assistance with information flow as important as or more important than vital sign monitoring. Therefore, the AID-N system was built to have the information seamlessly flow from the accident to the end location. Our electronic triage system eliminated duplicate paperwork and utilized the suggestion of paramedics to scan patient information, such as the name, address, date of birth, and social security number, directly from the driver's license barcode in order to save time and eliminate data entry errors through the PDA system called SIRP.

These tags must be designed with consideration for colorblind medics. The LED colors are placed in order of priority with a priority number labeled next to it. Therefore, the medic has three modes for identifying the priority level: color, position, and label. An instruction card is on the back of the mote for medics who are called to duty, but are unfamiliar with the devices.

After constructing our initial prototype, we brought our prototypes on ambulance ride-alongs in order to evaluate the system and to get real hands on experience in emergency medicine and medical service. The emergency personnel stressed the importance of designing the system so that it could be deployed quickly and was easy to use. Interviewees stated that in an emergency situation time is critical. Therefore, they would likely revert back to the paper system if the device was easy to deploy. Emergency personnel also mentioned that the visibility of the LED lights would be problematic in the sunlight. Therefore, in our iterative package design, we developed photo-interrupter cards that would change the color of the LED through the reflection of light from the card onto the photo-interrupter (Figure 8). Unfortunately, medics found the cards to be troublesome and disliked the idea of having more than one component to keep track of.

The electronic triage system was tested in a prospective case controlled study in a mass causality disaster drill using two teams of providers (Figure 9). One team of providers used a traditional paper triage system while the other team used electronic triage tags and Internet technologies. Both the groups of responders comprised of 8 members: Incident Commander, Treatment Officer, Transport Officer, Triage Officer, and 3 responders. There were ten patients in each group for a total of twenty patients.

All patients were triaged at the incident and held on scene for 22 minutes, due to a delay in transport. Upon arrival of a transport vehicle, electronic group responders made decision to transport 2 patients, and paper team responders made decision to transport 3 patients. The remaining patients were moved to a temporary triage center.

Although team using the electronic equipment received only ten minutes of training, the electronic group performed triage with the new equipment at a speed that is comparable to the paper group. Time for responders to triage all 10 patients and report the triage information to the incident commander was 8 min 40 sec in the electronic group and 9 min in the paper group. While responders maintained their triage speed when using ETags, the amount of information being collected and communicated dramatically increased. While patients were held at the scene for 22 minutes prior to transport to either a hospital or a temporary treatment center, vital signs of electronic group patients were continuously reported over the mesh network (time between each vital sign recording: mean = 6.5 s, std=2.4). Patients experienced a maximum delay of 3 min 20 sec between two successive vital sign recordings. Vital sign readings for each patient was reported in real-time and archived into a database (average O2sat recordings per patient: 526; average HR recordings per patient: mean = 365). A high risk patient was identified to need an additional level of monitoring beyond the pulse oximeter and monitored mote with a two lead EKG was used on a subject that was identified as a high risk patient who needed the additional level of monitoring beyond the pulse oximeter. 4 min 32 sec of continuous EKG waveform was transmitted and stored.

Patient photos, and triage details (such as chief complaints and injuries) were captured by PDAs. This information was successfully transmitted to the members of the electronic group who were not located at the site of the patients: hospital emergency department, public health official.

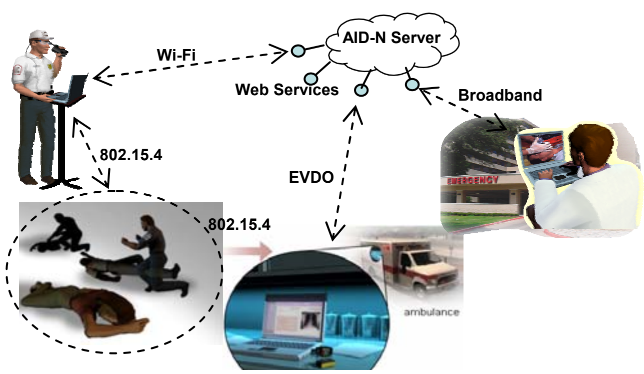

Fig. 9. Investigation of AID-N Technology through a Simulation of a Mass Casualty Drill with Montgomery Fire Department

Immediately following the drill, we conducted small-group interviews with all responders. A series of questions were asked to capture the responder's perception of the successes and problems of the drill, as well as their reactions to the technology such as utility, ease-of-use, and efficiency. Responders commented that the ETags were "as easy to use as they could be" (triage officer). An observed pitfall of the ETag was that the triage status indicator were LEDs and they were difficult to see from a distance under bright sunlight and also when the triage tag flipped over on the patient. In further iterations of the package, we plan to solve this problem by building reflectors in clear areas in the package so that the LED color will be displayed throughput the entire package. Responders' satisfaction was captured through a 5-point Likert scale survey. A series of questions showed our technology to be very well received by the users. For example,

1) "This system was a more efficient way to keep track of triage counts" (mean=4.86, std=.38).
2) "With more training, I would be more likely to endorse this equipment" (mean= 4.25, std=.5).

VI. Challenges and Limitations

Several challenges occurred while implementing and deploying the AID-N triage system. The most significant open challenge is location tracking. Inside auxiliary care centers, the ability to track the location of patients indoors aids medics in quickly locating specific patients whose conditions have deteriorated, or who need to be contacted. AID-N currently locates patients only to the proximity of the base station. A location tracking capability with a resolution of one meter or less is still an open challenge in our current system.

AID-N preliminary investigated two types of location sensing capabilities, GPS (Global Positioning System) and Motetrack, an indoor location detection system [31]. The GPS board used SiRFstarIII chipset from SiRF Technology, which acquires signals down to -159 dBm [44]. When operating on a 1000mAh battery, the module draws current of 75mA during active mode and 3.4mA during sleep mode. From our initial test results, the GPS resolution was inaccurate by hundreds of meters indoors. The inaccuracy was due to the lack of base stations to accurately triangularize the signal at the location for our test drill. GPS was not deployed for our test drill with firefighters and paramedics due to its high power draw and inaccurate location readings. MoteTrack was also not deployed in our test drill because of the lengthy set up time required for the beacon motes and the increased network traffic emitting from the beacons to calculate location.

The second most significant challenge was induced by the high data rate of the EKG motes. Due to the limited data rate of the radio on the ultra-small embedded system, running several EKG motes in parallel occasionally caused serious delays in the network. Paramedics want the ability to view multiple EKG waveforms, in addition to the extracted heart rate. Therefore, future work plans to specifically address this problem.

Due to the chaotic nature of emergencies, the system faces the difficulty of operating in situations that challenge instrumentation designed for use in controlled environment or clinical situations. Pulse oximeter readings have limited accuracy in the presence of methemoglobin, carboxyhemoglobin, nail polish, nail fungus, fluorescent light, and motion.

VII. CONCLUSION

We have presented a system that relieves responders from the burden of manually recording vital signs on hardcopy pre-hospital care reports. AID-N electronic triage tag operates under very low power constraints and uses at least eight times less energy than previous triage embedded devices, such as the Airborne Server [2]. Furthermore, the development of a lightweight triage tag, a portable blood pressure cuff, a lightweight EKG heart rate extraction algorithm, and results from a disaster drill are described in detail. We prove that lightweight electronic triage tags allows first responders to retriage patients three times as many times as first responders using paper triage tags.

The current methodologies in emergency response are error-prone and burdensome. The AID-N triage system allows for the rapid gathering of vital signs and location data and the pervasive real-time transmission of this data to a central server. The AID-N system is being carefully designed so that it is usable and compatible with previous systems. All AID-N devices use the accessory connections used in current sensors in emergency medical service vehicles. Instead of sensors being connected to large machines, these sensors now connect to miniature, weather resistant, low power embedded devices.

The ubiquitous collection of vital sign information and location allows one to better understand what exactly occurs during a mass casualty incident and to efficiently plan for such an occasion. The AID-N triage system facilitates collaborative patient care in emergency response and relieves the workload for each responder. As a result, our solution significantly increases the quality and quantity of patient care. Our electronic triage system more efficiently delivers pertinent information to first responders and aids responders in saving the maximum number of lives.

ACKNOWLEDGMENT

This system was developed in continuous feedback and guidance from the user community. We would like to acknowledge technical development support from Dr. Protagoras Cutchis, Dr. Steven Babin, Dr. Brian Feighner, Marvin Sykes, Cassius Sims, Radford Juang, Jeffrey Chavis, Raj Ashar, Judith Theodori, and Pedro Rodriguez at the Johns Hopkins Applied Physics Lab, We would also like to acknowledge project guidance from Cindy Notobartolo, Patricia Hawes, and Dr. Robert Rothstein at Suburban Hospital, Harold Lehmann and Matthew Kim at the Johns Hopkins School of Medicine, Dr. Don Alves and Dr. Jeffrey Michele at the University of Maryland Department of Emergency Health Services, Dr. Azmat Husain at the University of Maryland School of Medicine, Kathy Hurt-Mullen at the Montgomery County Health and Human Services, and Ronald Stickley at Philips Medical Systems. We would also like to thank Gordon Ayoagi and Pamela Montgomery at the Montgomery County Department of Homeland Security for supporting our research in Montgomery County, and EMS personnel in Baltimore MD and Arlington County VA. Finally, we would like to thank Captain Dan Blankfeld and the Montgomery County EMS personnel for donating countless hours in our iterative user reviews and in orchestrating a disaster response drill that may one day become the standard for emergency responders world-wide. The guidance from these individuals was invaluable in developing a usable solution that meet the needs of the emergency response community. Portions of this article have appeared in the Proc. IEEE Engineering in Medicine and Biology Conference and the IEEE EMBS International Summer School and Symposium on Medical Devices and Biosensors.

REFERENCES

[1] AID-N System Evaluation Survey Results http://www.aid-n.org/about/Pub/2006.3.EMS_today_MTF1_survey_results.pdf, March 30, 2006.

[2] Airborne Embedded Device Server Datasheet. Airborne Inc. < http://www.dpactech.com/docs/wireless_products/AB%20 wireless%20device%20server%20module.pdf>

[3] Adler, Paul, and Terry Winograd, Eds. (1992) *Usability: Turning Technologies into Tools*. New York: Oxford University Press.

[4] U. Anliker, J. Ward, P. Lukowicz, G. Troster, F. Dolveck, M. Baer, F. Keita, E. Schenker, F. Catarsi, L. Coluccini, A. Belardinelli, D. Shklarski, M. Alon, E. Hirt, R. Schmid, and M. Vuskovic. AMON: A Wearable Multiparameter Medical Monitoring and Alert System. IEEE Transactions on Information Technology in Biomedicine. Vol. 8, No. 4, December 2004.

[5] M. Benson, K.L. Koenig, and C.H. Schultz. Disaster Triage: START, Then SAVE—A New Method of Dynamic Triage for Victims of a Catastrophic Earthquake. Prehospital and Disaster Medicine. April-June 1996; 11(2).

[6] J. Bouman, R. Schouwerwou, K. Van der Eijk, A. van Leusden, and T. Savelkoul. Computerization of Patient Tracking and Tracing During Mass Casualty Incidents. Eur J Emerg Med 2000; 7(3):211-6.

[7] E. N. Brandt, W. N. Mayer, Mason, J. O. Brown, D. E. Jr., Mahoney, L. E.. "Designing a National Disaster Medical System," Public Health Reports, 1985, 100(5), 455-461.

[8] Burkle, F.M. Mass Casualty Management of a Large-Scale Bioterrorist Event: An Epidemiological Approach That Shapes Triage Decision. Emergency Med Clin N Am 2002; 20:409-36.

[9] Cardiac Arrest Associated With Trauma, Circulation. Circulation. 2005;112(24): IV 146 - IV 149.

[10] P. Chang, Y. Hsu, Y. Tzeng, Y. Sang, I. Hou, and W. Kao. The Development of Intelligent, Triage-Based Mass-Gathering Emergency Medical Service PDA Support Systems. J Nurs Res 2004; 12(3):227.

[11] Dempsey, Mike. Analyzing the Return of Investment for In-door Positioning Systems. Radianse Inc. White paper. 2004.

[12] FEMA Medical Team Training Manual. Available: http://www.fema.gov.

[13] G.M. Friesen, T.C. Jannett, M. A. Jadallah, S. L. Yates, S.E. Quint, and H. T. Nagle, "A comparison of the noise sensitivity of nine QRS detection algorithms," IEEE Transactions on Biomedical Engineering, vol. 37, no. 1, pp. 85-98, 1990.

[14] T. Fulford-Jones, G. Wei, and M. Welsh. A Portable, Low-Power, Wireless Two-Lead EKG System. In Proceedings of the 26th IEEE EMBS Annual International Conference, San Francisco, September 2004.

[15] J. Hamilton. Automated MCI Patient Tracking: Managing Mass Casualty Chaos Via the Internet. Jems 2003;28(4):52-6

[16] Hawaii Medical, LifeGuard Pre-wired Electrodes, Available: http://www.hawaiimedical.com

[17] J. Hill, R. Szewczyk, A. Woo, S. Hollar, D. Culler, K. Pister. System Architecture Directions for Networked Sensors, In Proceeding of 9th Int'l Conf. Architectural Support for Programming Languages and Operating Systems (ASPLOS 2000), ACM Press, 2000, 93–104.

[18] Interview with Brian Feighner, MD, December, 2006.

[19] Interview with Bob Freeman, operations manager at Montgomery County Emergency Operations Center, Gaithersburg, MD.

[20] Interview with Don Alves, MD, Medical Director of ITLS Maryland, January 23, 2006.

[21] Interview with Jeff Mitchell, MD, Emergency Health Services Professor at the University of Maryland, January 23, 2006.
[22] Interview with Knox Andress, RN, Mass Casualty Incident Response Coordinator of Louisiana Region 7, August 12, 2005.
[23] Interviews with Polk, D., MSW, NREMT-P, Paramedic Program Instructor at the University of Maryland Baltimore County Department of Emergency Health Services.
[24] C. Lauraent, and L. Beaucourt. Instant Electronic Patient Data Input During Emergency Response in Major Disaster Setting. Stud Health Technol Inform 2005; 111:290-3.
[25] .J. Lee, E. Low, Y.Y. Ng, C. Teo, "Disaster Relief and Initial Response to the Earthquake and Tsunami in Meulaboh, Indonesia," Ann Acad Med Singapore, 2005, Oct, 34(9), 586-90.
[26] L. Lenert, D. Palmar, T. Chan, and R. Rao. An Intelligent 802.11Triage Tag for Medical Response to Disasters. AMIA 2005 Symposium. 2005.
[27] Lessons Learned from Ambulance Ride Alongs in Arlington County, http://www.aid-n.org/about/Pub/Arlington_County_Ride_Alongs.pdf, November 2005.
[28] Lessons Learned from Baltimore County Public Safety Mass casualty Table Top Exercise, http://www.aid-n.org/about/Pub/BaltimoreTTX.pdf, February 24 ,2005.
[29] Lessons Learned from Mass Casualty Drill at Maryland Fire and Rescue Institute http://www.aid-n.org/about/Pub/2006.5.MFRI.pdf, May 11, 2006.
[30] Y. Lin, I. Jan, P. Ko, Y. Chen, J. Wong, and G. Jan. A Wireless PDA-Based Physiological Monitoring System for Patient Transport. IEEE Transactions of Information Technology in Biomedicine. Vol. 8, No. 4, December 2004.
[31] K. Lorincz and M. Welsh. MoteTrack: A Robust, Decentral-ized Approach to RF-Based Location Tracking. In Proceed-ings of Personal and Ubiquitous Computing, Special Issue on Location and Context-Awareness, Springer-Verlag, 2006.
[32] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton. 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.
[33] S. McGrath, E. Grigg, S. Wendelken, G. Blike, M. De Rosa, A. Fiske, and R. Gray. ARTEMIS: A Vision for Remote Triage and Emergency Management Information Integration. Dartmouth University. Novermber 2003.
[34] Medtronic Inc. LifePak 12 Monitoring System. Available: http://www.medtronic.com.
[35] MicaZ Datasheet. Crossbow Technology, Inc. < http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/MICAz_Datasheet.pdf> Accessed February 2006.
[36] MIT-BIH Arrhythmia Database Directory. Harvard-MIT Division of Health Sciences and Technology, Biomedical Engineering Center. 1997.
[37] J. Morris, Jr, P. Auerbach, G. Marshall, R. Bluth,; L. Johnson, and D. Trunkey, "The Trauma Score as a Triage Tool in the Prehospital Setting," The Journal of the American Medical Association, September 12, 1986, 256(10), 1319-1325.
[38] T. Morris. Battlefield Medical Information System: Mobile Healthcare Case Study. US Ar,my Medical Research and Materiel Command. <www.himss.org/Content/files/ CHSC-Seminars/Morris092805.ppt>. Accessed March 1, 2006.
[39] Norman, Donald A. and Stephen W. Draper. (1986) *User Centered System Design*. Hillsdale, NJ: Lawrence Erlbaum Associates, 1986
[40] E. Pino, L. Ohno-Machado, E. Wiechmann, D. Curtis. "Real-Time ECG Algorithms for Ambulatory Patient Monitoring." *Proceedings of AMIA 2005 Symposium*
[41] Rochester Electro-Medical Inc, Disposable Electrodes, Available: http://www.rochestermed.com/ElectrodesFrame.htm#DElect.
[42] L. Romig. The "JumpSTART" Rapid Pediatric Triage System. <www.jumpstarttriage.com> Accessed February 2006.
[43] Schwartz GR, Principles and Practice of Emergency Medicine. King of Prussia, PA: Rittenhouse Book Distributors, 1999
[44] SiRF Technology, SiRFstarIII, Available: http://www.sirf.com/products-ss3.html.
[45] L. Selavo, G. Zhou, J.A. Stankovic, "SeeMote: In-Situ Visualization and Logging Device for Wireless Sensor Networks," The Third International Conference on Broadband Communications, Networks and Systems, (BASENETS 2006), San Jose, CA, 2006.
[46] Site visit to Montgomery county EOC and Fire and Police dispatch center.
[47] SunTech Medical, Advantage OEM, Available: http://www.suntechmed.com/HTML/Advantage.htm.
[48] Survey results from Arlington County, http://www.aid-n.org/about/Pub/NeedsMarch06.pdf
[49] Telos Corporation, TmoteSky Datasheet: http://www.moteiv.com.
[50] Visicu. Visicue ICU Solutions. http://www.visicu.com.
[51] Welch Allyn. Mobile Acuity LT Central Monitoring Station. Available: http://www.monitoring.welchallyn.com.