Vital Signs Monitoring and Patient Tracking Over a Wireless Network

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Patients at a disaster scene can greatly benefit from technologies that continuously monitor their vital status and track their location until they are admitted to a hospital. We have designed and developed a real-time patient monitoring system that integrates vital signs sensors, location sensors, ad hoc networking, electronic patient records, and web portal technology to allow remote monitoring of patient status. This system will facilitate communication among providers at the disaster scene, medical professionals at local hospitals, public health personnel, and specialists available for consultation from distant facilities.

INTRODUCTION

Steady advances in wireless networking, medical sensors, and interoperability software create exciting possibilities for improving the way we provide emergency care in prehospital situations. The Advanced Health and Disaster Aid Network (AID-N) being developed at APL explores and showcases how these advances in technology can be used to assist victims and responders in times of emergency. This article covers a subset of the technologies in the AID-N.

The Department of Homeland Security (DHS) defines a *disaster* as any incident that challenges the resources of the local community. The overwhelming number of patients requiring urgent care at a disaster site is a significant challenge for responders. Triaging, monitoring, and tracking patients at a disaster scene are critical tasks in the rescue process. Unfortunately,

current methodologies for these tasks are often inefficient for mass casualty situations. Below, we address some major deficiencies with these methodologies.

When first responders on the scene of a mass casualty incident become overwhelmed with the number of patients to be tracked, they may request secondary aid from other local units or neighboring jurisdictions. However, there is often a significant time delay before aid arrives; it is not unusual for first responders to wait up to an hour for secondary aid. During this waiting period, patients cannot be monitored and tracked efficiently by the understaffed crew. To alleviate this problem, responders need resources that allow them to track and monitor a large number of patients until additional help arrives. Furthermore, different jurisdictions need to be able to access disaster information from

neighboring jurisdictions so they can work together effectively.

One proposed solution has recently been pushed by DHS and the Association of Public Safety Communications Offices: to enable all first responder disciplines (EMS, fire, and police) to use interoperable communications equipment (e.g., handheld radios) to exchange disaster information. Today, communications equipment in each discipline operates on its own radio frequencies, which makes communications among first responders nearly impossible. The need for the proposed communication system is undoubted. However, if the radio frequencies become crowded with too many users, the communications systems could fail. In these situations, valuable patient information cannot be shared and effective patient care becomes a problem. It is essential that the communication technology be scalable to the high usage demands of mass casualty disasters.

Another current methodology is to monitor patients using paper-based triage tags (Fig. 1), which are color-coded to designate the severity of the patients' injuries. 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. Patients are classified as black if they are deceased or expected to die. These tags have many obvious problems. First, it is difficult for responders to update the color designation easily. In addition, they provide little room for manually recording the patients' vital signs and chief complaints, which are essential pieces of information. Finally, reading the tags can be difficult because patient information recorded under time pressure is often illegible.

For all of these reasons, current methodologies in emergency response are error-prone and burdensome for the medics. APL has designed and developed technology-based solutions to alleviate these problems. These technologies facilitate collaborative patient care in emergency response and relieve the workload of each responder. As a result, our solutions could significantly increase the quality and quantity of patient care and more efficiently deliver patients to the hospital. Our technology-based solutions include the following components:

- Electronic triage tags with sensors
- A wireless ad hoc mesh network
- Prehospital patient care software
- A secure web portal
- A handheld PDA

In this article, we briefly describe these components, discuss the methodologies behind them, and detail their implementation.

OVERVIEW

Our electronic triage tags with sensors continuously monitor the vital signs and locations of patients until
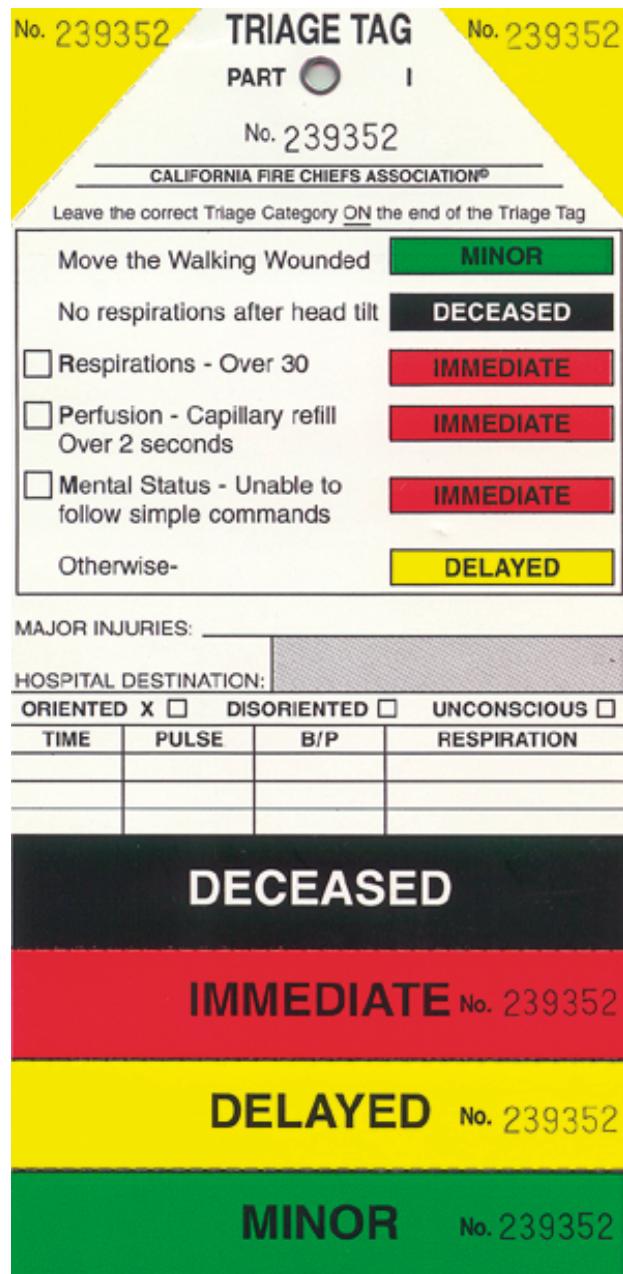
Figure 1. Current paper-based triage tag.

they are admitted to a hospital. We call this technology VitalMote. VitalMote enables medics to efficiently track the location of large numbers of patients. Furthermore, it gives medics immediate notifications of any changes in patient status, such as respiratory failure or cardiac arrest. These sensors solve the problems with paper tags mentioned above. They can also dramatically improve the time-consuming process of manually recording vital signs onto hard-copy prehospital care reports and then converting the reports into electronic format.

The wireless ad hoc mesh network transmits patient information to a central station and guarantees connectivity between patients and providers, even in mass

casualty incidents. The advantages of using a mesh network are reliability and the ability to support vast networks, such as one that would be created in a disaster when a large number of patients would be tagged with VitalMotes. This technology would help reduce the amount of information that needs to be communicated verbally with current radio communications devices.

The prehospital patient care software with algorithms continuously monitors patients' vital signs and alerts first responders of critical changes. This software will help alleviate the current problem of first responders becoming overwhelmed by the large number of patients during mass-casualty disasters.

The secure web portal allows authenticated users to collaborate and share real-time patient information and will also facilitate communication across different responder disciplines and jurisdictions.

The handheld PDA is used by paramedics to collect and report valuable patient information, which is then transmitted in real time to the AID-N server. This device will help solve the problem of current paper-based triage tags having little room to record, and as a result being illegible. This device is called the Surveillance and Incident Reporting PDA (SIRP).

METHODOLOGY

During health emergencies there is little tolerance for system errors and poor usability designs. Through the use of standards-based software and best-of-breed hardware, our goal is to deliver a system that is scalable, reliable, and user-friendly.

Our patient monitoring and tracking system, Vital-Mote, builds upon the CodeBlue project from Harvard University.[1] CodeBlue is a distributed wireless sensor network for sensing and transmitting vital signs and geolocation data. Figure 2 illustrates the current prototypes. A wearable computer commonly known as "smart dust" or a "mote" is attached to the patient's wrist and forms an ad hoc wireless network with a portable tablet PC. We have integrated several peripheral devices with the mote, including location sensors for both indoor and outdoor use, a pulse oximeter, a blood pressure sensor, and an electronic triage tag. The electronic triage tag replaces the paper triage tag and allows the medic to set the triage color with the push of a button. The mote also has onboard memory for storing patient medical records.

As shown in Fig. 2, the mote continuously transmits patient information to the first responder's tablet device. The transmission uses the TinyOS Active Messages protocol, which is based on the IEEE 802.15.4 standard.[2] The mote was originally developed at the University of California, Berkeley, in the late 1990s. Since then, it has gained significant interest from academia and industry for its ability to provide low-power, cost-effective, and reliable wireless networks for monitoring applications.
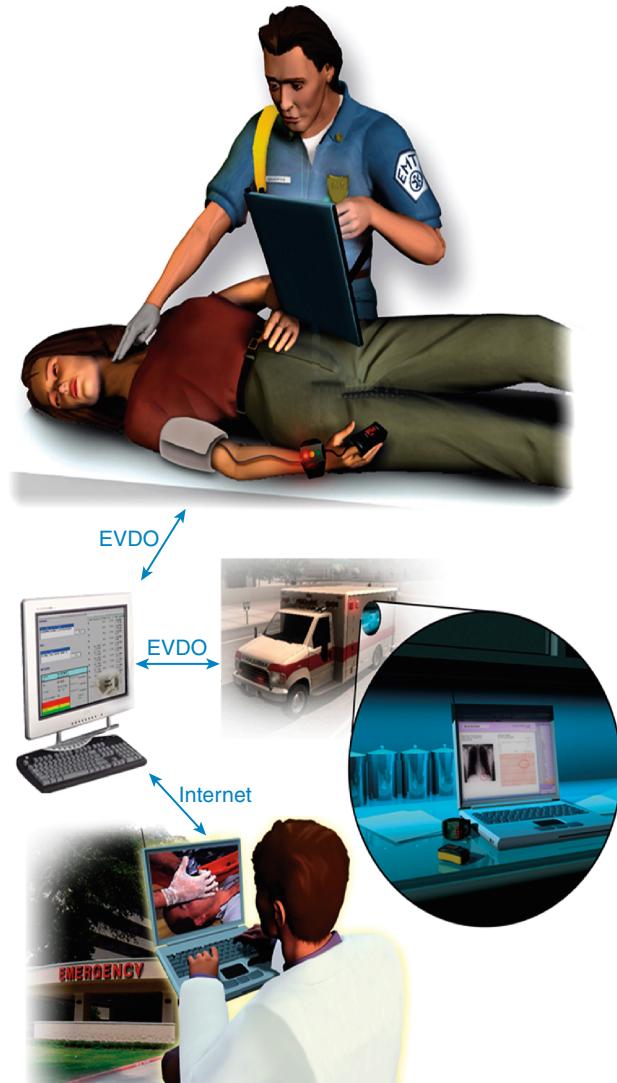
Figure 2. Patient information flow.

Our mote prototype uses the MICAZ platform from Crossbow Technology. It is powered by two AA batteries and consumes roughly 20 mA when active, resulting in a battery lifetime of 5–6 days of continuous operation. It uses a single-chip radio with a maximum data rate of 76.8 kbps and a practical indoor range of approximately 20–30 m.

The system is designed to require little setup time. A medic carries many mote packages and distributes them to the patients. Each mote is preattached with a paper triage tag, which acts as backup if the electronic triage tag fails. When the patient is first triaged, the medic straps the mote wristband on the patient, places the finger sensor on the patient's finger, and sets the electronic triage tag to the patient's triage category. The blood pressure sensor is an optional module, which the medic may put on select patients who need the additional level of monitoring. The mote automatically starts transmitting data to the medic's tablet PC. The tablet

PC is harnessed to the first responder in a weatherproof and anti-glare casing.

We integrated these wearable sensors with a prehospital patient care software package (MICHAELS) created by the OPTIMUS Corporation. MICHAELS runs on the first responder's tablet PC. We modified MICHAELS to automatically record and analyze the patient's vital signs and alert the first responder of abnormal changes. MICHAELS also transmits patient information in real time to a central server that hosts the medical record database. MICHAELS can write the patient's medical record onto the mote, allowing the information to be stored locally with the patient. When the patient boards the ambulance, the medic onboard can load the information from the patient's mote back to the MICHAELS software.

The tablet PC requires a network connection to communicate with the central server. To achieve this connectivity we have used Verizon's EVDO coverage in the Washington, DC, Metropolitan Area. Our tablet PCs use EVDO wireless cards to attain broadband cellular Internet connectivity from anywhere in the region.

We have also built a web portal to connect with the patient record database and make the real-time patient information accessible to users from Internet browsers. This tool will be used by different participants in the emergency response team, such as emergency department personnel, who need this information to prepare for the incoming patient, or public health personnel, who need to understand the situation and assess the additional resource requirements.

Effective health care requires access to patient data that are generally stored on heterogeneous database systems. Integration of patient data is a significant challenge faced by the health care community. In our implementation, we are able to connect two disparate systems, that is, the patient record database and the web portal, through the use of well-defined web services. Patient information is transmitted over SOAP, a secure and encrypted form of XML. The WSDL (Web Service Definition Language) for these web services is published to a community of authorized users. This web service-based approach for intersystem communication gives our software the flexibility to operate with third-party software in the future.

IMPLEMENTATION

VitalMote Sensors

VitalMote sensors are portable lightweight electronic triage tags that are designated by paramedics with red/yellow/green/black lights based on the severity of the patient's condition. They provide four functionalities: vital signs monitoring, location tracking, medical record storage, and triage status tracking. We are integrating three types of noninvasive vital signs sensors: a pulse oximeter, a blood pressure sensor, and a three-lead EKG. The pulse oximeter attaches to the patient's finger and measures heart rate (HR) and blood oxygenation (SpO$_2$) level (Fig. 3). A cuff pressure sensor on the patient's upper arm measures systolic and diastolic blood pressure. The EKG leads are packaged in a sticky pad, which can be applied to the patient's chest.

We also integrated two types of location sensing capabilities: a GPS to provide geolocation and an indoor location detection system to provide location where the GPS signal cannot be reached. The GPS sensor allows medics to track patients who are outdoors, e.g., at the scene of the emergency, with an accuracy of 3 m circular error probable (CEP). The indoor location system, based on the MoteTrack project developed at Harvard University, requires the installation of location beacons,[3] which are being placed at a designated auxiliary care center near Washington, DC. Patients are admitted to an auxiliary care center if nearby hospitals have reached their occupancy capacities. At an auxiliary care center, which can often be short on staff and overfilled with patients, the patients' vital signs will continue to be monitored by our system. The ability to track the location of the patients indoors will be a very useful feature for helping

Figure 3. VitalMote with pulse oximeter.

medics quickly find a specific patient whose condition has deteriorated.

With all the peripheral devices turned on, the pulse and oxygenation are reported every second, the GPS location is reported every 5 min, and the blood pressure is reported every 15 min. The battery lifetime of the overall system is approximately 6 h. The blood pressure sensor is the most power-hungry peripheral; when it is not used, the battery life of the overall device increases to 1–2 days.

Vital Signs Monitoring Algorithm

A USB transceiver is plugged into a laptop for vital signs monitoring, map-based patient tracking, and prehospital patient care reporting. Software on the tablet device receives real-time patient data from the mote and processes the data to detect anomalies. If the patient has a previously entered medical record, information from that record is used in the alert detection algorithm. Table 1 shows a partial list of physiological conditions that cause alerts. The algorithm uses additional information such as patient age and height to adjust its thresholds. If additional information is not available, the algorithm uses a set of default values.

**Table 1. Alert detection parameters.**[4–7]

Alert type	Detection parameter
Low SpO$_2$	SpO$_2$ < 90%[a]
Bradycardia	HR < 60 bpm[a]
Tachycardia	HR > 100 bpm[a]
HR change	$|\Delta HR/5\ min| > 19\%$
HR stability	Max. HR variability from past 4 readings > 10%
BP change	Systolic or diastolic change > ±11%

[a]These default values are adjusted based on addition input.

Prehospital Patient Care Software

The tablet PC regularly transmits patient data (vital signs, location, triage color) and alerts for multiple patients to the database via a wireless network. If network connectivity is unavailable, the patient monitor and alert system on the tablet PC continues to operate.

When an anomaly is detected in the patient vital signs, the medic's software application generates an alert in the user interface. Figure 4 shows a list of alerts in
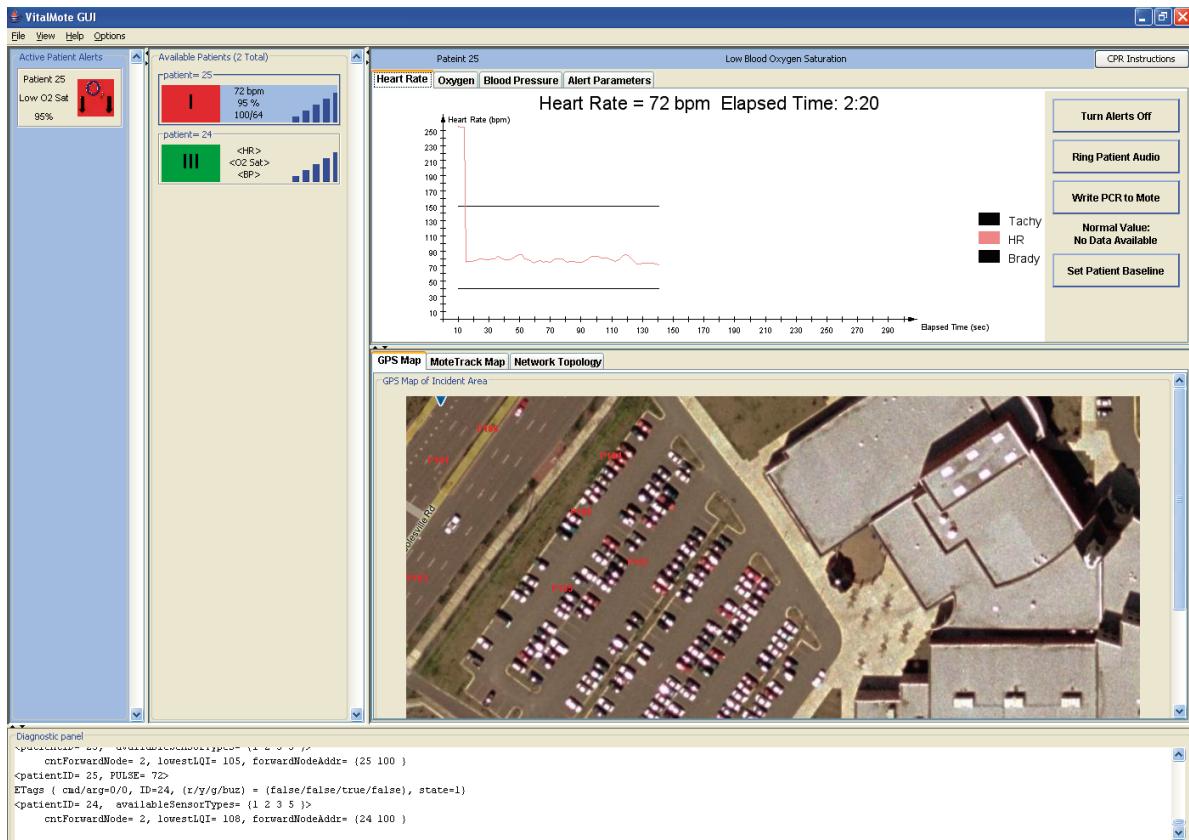
Figure 4. Screenshot of patient monitoring software. The first sidebar on the left shows a list of alerts for all patients, and the second sidebar shows a list of patients sorted by their priority level. The top right panel shows that three types of vital signs readings are available for this patient: heart rate, oxygen saturation, and blood pressure. The top right buttons show functions: Turn Alerts Off, Ring Patient Audio, Write PCR to Mote (transmits patient information to the mote), and Set Patient Baseline (adjusts vital signs analysis thresholds based on patient values).

the GUI (graphical user interface). The medic can also select a "Ring Patient Audio" feature that will sound a buzzer and blink an LED on the mote. All alerts are listed inside the left panel to make multiple alerts easier to manage.

Web-based Information Portal

This web-based information portal is an effective emergency response information system to support the need for multiple parties to share information about patients' status and locations. Our web-based information portal allows different types of users to access patient information in real time. When a user logs in, the information displayed to that particular user is managed by group-level permissions. The portal has three groups of users:

1. Emergency department personnel log in to the portal to retrieve information about the patients who are being transported to their hospital.
2. Incident commanders log in to the portal to see summaries of patients at the disaster scene. Since patients are tracked by the VitalMotes, the incident commanders can review the number of patients for each triage color, allowing them to make informed

requests for additional medical supplies and personnel and to properly allocate available resources (Fig. 5).
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 patients being treated. They can also review the triage colors of patients at the scene to verify that the patients have been triaged correctly.

Surveillance and Incident Reporting PDA

SIRP is a handheld unit for medical field personnel to collect and report clinical information on sick or injured people during large public events. The device (Fig. 6) contains a wireless transmitter and a patient medical history card reader. SIRP wirelessly transmits data to the AID-N server and to other databases (including a syndromic surveillance database). SIRP allows emergency responders to

- Record the essential information on a patient at the disaster scene, including chief complaint, apparent syndromes, gender, age, current location, and location at the time of injury or onset of illness. SIRP
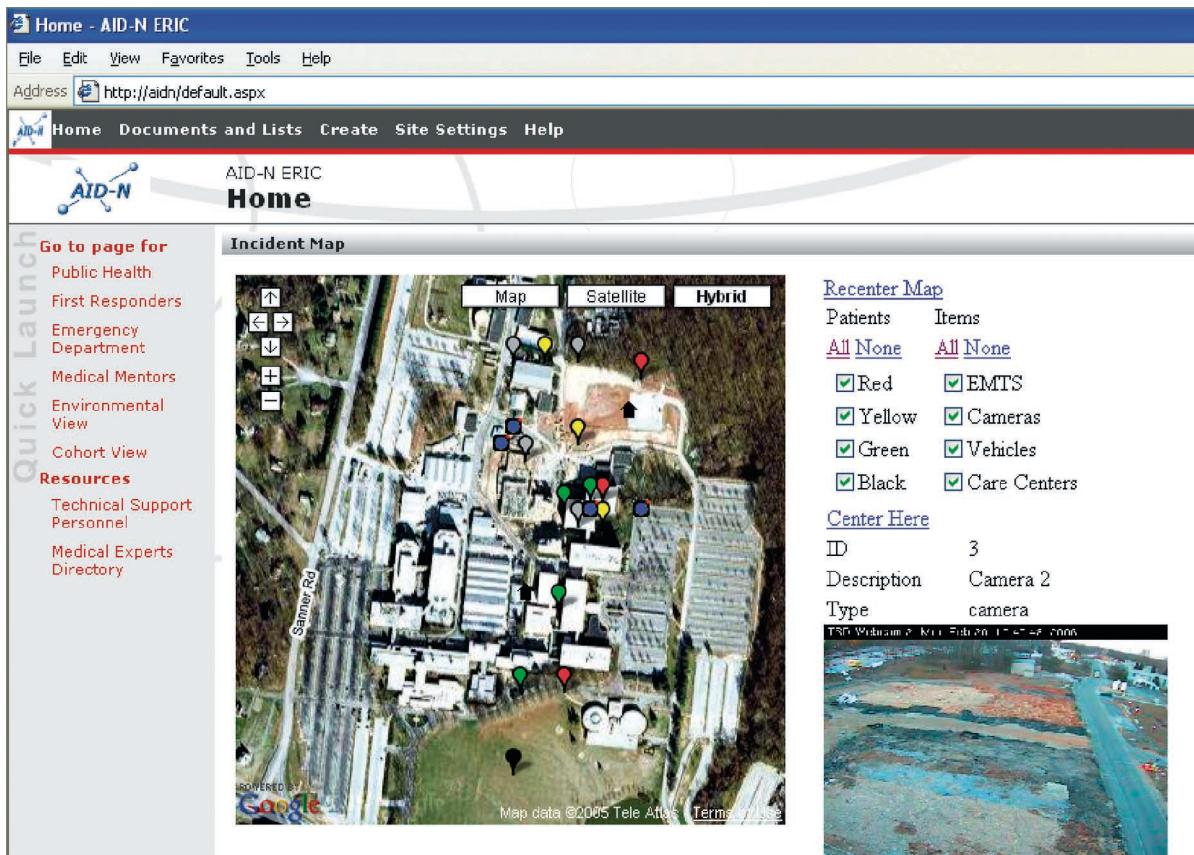
Figure 5. Web page portal for the incident commander showing patient locations. Clicking on one of the flags shows real-time video of that location, as seen in the bottom right of the screen.

Figure 6. SIRP triage screen displayed on the PDA for medical providers.

contains a patient's medical history card reader to help expedite the process.
- Collect other disease information at the event, such as animal sicknesses, apparent environmental hazards, weather conditions, and more.
- Record and review incident information, e.g., hazardous materials, maps of marked areas of the disaster scene, etc.

ASSESSMENT OF BENEFITS

The potential benefits of the AID-N project are clear when aspects of the proposed system are compared against aspects of the response system currently in place. Consider a representative scenario in which VitalMote would be used to alert paramedics of sudden cardiac arrest (SCA) victims at a disaster scene. Defibrillating the victim can treat SCA. Each minute that defibrillation is delayed reduces the victim's chance of survival by about 10%.[8]

Assume a disaster situation where one paramedic is monitoring 20 patients in his area with yellow tags. The medic must continuously monitor each patient, so he spends 30 s on each and 15 s traveling among them. All patients are lying down, so a patient whose heart has gone into SCA and passes out would not look noticeably different from other patients who are lying down. Table 2 shows the calculated delay time until treatment of the SCA patient for a control case, where a medic manually monitors the patients, and the VitalMote case, where a medic manually monitors the patients and VitalMote also monitors the patients. VitalMote alerts the medic of the patient who has gone into SCA. Calculations show that VitalMote significantly improved the expected survival.

To ensure the applicability of the AID-N system in the field, the AID-N team has solicited evaluations of the proposed system design from actual EMS field personnel of the Arlington Fire Department, including captains, platoon chiefs, and paramedics with a cumulative 90 years of EMS experience. They were initially questioned on their current practices and the difficulty associated with various tasks when responding to multiple patient incidents. The two tasks that they considered the most difficult were triaging the victims and keeping track of the patients designated as red or most critical. In addition, locating victims and communicating patient information were two tasks which were described as having an appreciable amount of difficulty.

After conducting a demonstration of the device to the EMS personnel, a questionnaire was completed by each participant about the usefulness of the different features of the AID-N. The AID-N system itself was received positively, and much of the input taken from the participants has already been implemented into the most recent design update. The aspects of the system considered most useful were the feature allowing patients to be listed by color, the VitalMote, and the ability to buzz motes to locate them in a crowd of patients. The vital signs alarm monitor, which alerts when vital signs fall out of a certain range, was also rated highly in its usefulness.

From the questionnaires and conversations with various EMS personnel, the applicability and usefulness of the AID-N system in the field have been substantiated to a degree. Minor design changes for the sensor were suggested such as reducing its size and enhancing

Table 2. VitalMote increases patient survival rate.

Case	Control	VitalMote
Worst	15-min delay	45-s delay
	<10% survival rate	>90% survival rate
Average	7-min delay	30-s delay
	≈30% survival rate	>90% survival rate
Best	20-s delay	20-s delay
	>90% survival rate	>90% survival rate

the brightness of the light. These changes are currently being addressed.

CONCLUSION AND FUTURE WORK

The AID-N system has great potential in improving problems in today's emergency response system, especially those associated with mass casualty disasters. While designing our system, we collaborated extensively with medical professionals to identify their greatest needs. The key activities that could be improved using the technology are patient monitoring, patient record generation, and remote patient record review. AID-N has constructed hardware and software prototypes to address these needs and shows promise in improving the efficiency of emergency personnel for these activities.

All technologies have limitations and cannot provide their benefits under all circumstances. When new technology is introduced into the emergency response arena, its limitations as well as its capabilities must be considered. Because of the chaotic nature of emergencies, our system faces the difficulty of operating in situations that challenge instrumentation designed for use in the controlled environment of a clinical situation. For example, the pulse oximeter sensor used by AID-N cannot function on patients with fingernail polish or nail fungus. Furthermore, in cold temperatures and/or high altitudes, the body responds through vasoconstriction in the peripherals; in this case, blood flow to the fingers is restricted and does not register accurately on the pulse oximeter.

We acknowledge that our patient monitoring feature will not be useful in all situations. In a mass-casualty disaster, when the medics must triage many casualties quickly, there will be no time to respond to alerts until all patients have been triaged. The medics whom we interviewed expect our monitoring system to be most useful for patients who have been triaged and are waiting for ambulances. They can then use our system to prioritize the patients who need to be transported to a care facility.

The AID-N system has many benefits over the current paper-based system of triaging and tracking patients, as shown by our hypothetical scenario and opinions of experienced EMS personnel. Our system is currently being prepared to be used in a simulated disaster exercise. This exercise will be conducted in partnership with Suburban Hospital, Johns Hopkins Pediatric Trauma Center, and an auxiliary care center. During this exercise, comparisons between the effectiveness of current disaster response methodologies and the AID-N system will be conducted.

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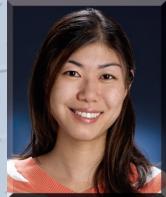
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