ARTEMIS: A Vision for Remote Triage and Emergency Management Information Integration

Susan P. McGrath, Eliot Grigg, Suzanne Wendelken, George Blike, Michael De Rosa, Aaron Fiske and Robert Gray

***Abstract*- This paper describes the design of an automated triage and emergency management information system. The prototype system is capable of monitoring and assessing physiological parameters of individuals, transmitting pertinent medical data to and from multiple echelons of medical service, and providing filtered data for command and control applications. The system employs wireless networking, portable computing devices, and reliable messaging technology as a framework for information analysis, information movement, and decision support capabilities. The embedded medical model and physiological status assessment are based on input from humans and a pulse oximetry device. The physiological status determination methodology follows NATO defined guidelines for remote triage and is implemented using an approach based on fuzzy logic. The approach described can be used in both military and civilian settings.**

***Index Terms*- Combat casualty care, physiological monitoring, remote triage**

I. INTRODUCTION

Increasing patient survivability by moving information and resources closer to casualties in the field is a major objective of casualty care research. The goal of the Automated Remote Triage and Emergency Management Information System (ARTEMIS) project is to integrate advances in communications and analysis technologies into a remote triage system that can expedite and improve care of the wounded. In this paper we provide the details of the ARTEMIS military prototype which can be used to monitor soldiers in the battlefield, however this approach can also be used to monitor first responders and casualties in the civilian domain.

Battlefield Casualties

The overarching premise of the military version of the ARTEMIS system is that the survivability of our soldiers and mission success can be improved by expanding the flow of medical information on the battlefield and throughout the chain of command. Our aim is to provide a degree of medical situational awareness at all levels of command that has never existed before. In our view, the most critical stage of this process begins by monitoring individual soldiers and providing relevant information to the medic—the first line of care in the battlefield. Our primary target population is the 25% of soldiers killed in action who die between 5 minutes and 6 hours of injury [1]. These soldiers live long enough to be rescued but die quickly enough to be affected by the suboptimal nature of the current system. In addition to improving the outcomes of injured soldiers, we believe that a more effective flow of medical information will help to prevent injuries. Of all of the casualties that medics attempt to rescue, 25% of them are already dead before the medic arrives, and the process of accessing the soldier puts the medic at risk. Ten percent of casualties in the battlefield are injured while attempting to rescue a previously injured comrade, and if a medic is part of that 10%, the soldiers he is responsible for and their mission are likely to be jeopardized [1]. While some casualties are unavoidable, we believe that these specific types of injuries can be reduced and outcomes improved with a more effective analysis and distribution of medical information on the battlefield.

Extending the Reach of the Medic

ARTEMIS is designed to support the medic's role by:

- Assisting with remote monitoring and triage processes
- Providing focused information to allow the medic to concentrate on higher-level issues

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- Providing distributed situational awareness that allows more informed, effective use of resources
- Delivering treatment protocols to the medic

Augmenting the abilities of medics will minimize the number of casualties, improve the outcomes of unavoidable casualties, and, as a result, improve mission success.

State of the Art

Ruggedized laptops are currently used in the battlefield, but their utility is limited by their size and weight, so they generally remain at higher echelons of the theatre. Handheld computers are being used by soldiers in the field to a limited extent for certain purposes (e.g. targeting), but they are not standard issue. Soldiers' access to information is limited to vertical communication on the battlefield via the soldier with a radio. For example, in order to report a casualty, a medic must verbally relay a message to someone who communicates the message over the radio. The message is then passed up multiple levels of command before an evacuation decision is made. The medic's treatment options are limited to: waiting for evacuation, providing intravenous fluids, applying dressings, performing surgical control, and implementing fracture stabilization. There is no way for a medic to determine if a soldier is dead without a direct, physical examination. Triage is performed one patient at a time after the medic physically assesses each individual. All of these physical assessments take time, tend to occur in the order of physical proximity rather than medical need, and put the medic at risk. Today, a medic experiences the following sequence of events when dealing with a new casualty. Text in red indicates times when the medic is potentially at risk:

- Notified of injury – by verbal communication
- Locate injury – visually or by verbal communication
- Physically move to injury
- First assessment – physical
- Triage
- Treatment
- Evacuation
- Ongoing Assessment

Future Soldier / Medic

In the future, projects like Objective Force Warrior will equip every soldier with a wearable computer with a wireless connection. The computing platform allows for a level of information access and transmission never before seen on the battlefield, and we plan to leverage this capability for medical support. ARTEMIS is not intended to affect the medic's treatment options, in fact the system tailors the medical information provided and keeps it relevant to their limited treatment options on the battlefield. However, we provide tools for the medic to determine current state of a soldier without having to put themselves at risk by physically accessing the soldier. In addition, ARTEMIS will allow medics to perform triage remotely, and categorize injured soldiers by urgency. Using ARTEMIS, the medic will experience the following sequence of events when dealing with a new casualty. Text in red indicates times when the medic is potentially at risk; note how much is accomplished before the medic is put at risk:

- Notified of injury – by wearable computer
- Locate injured party– by GPS location and map on computer screen
- Automatic/buddy assessment – access to physiological data
- Remote triage – medic alerted of triage category of multiple casualties simultaneously
- Medic decides which casualty to move to first
- Physically move to injury
- First physical assessment to confirm remote assessment
- Confirm triage
- Treatment
- Evacuation
- Remote Ongoing Assessment

Realizing this vision requires a combination of technologies capable of: (1) extracting information from the soldier, (2) analyzing it to transform raw data into clinically useful information, and (3) ferrying this information around the network in the most efficient way possible. In the next sections we describe how the components of ARTEMIS can help achieve this vision.

II. ARTEMIS DESIGN

The elements of our system fall into two distinct categories: (1) the biomedical and analysis components located on each soldier, and (2) the networking components that connect soldiers and move information. They break down as follows:

Biomedical – On the soldier

- Physiological sensors
- Assessment / triage and alert system
- User interface

Networking – Connecting soldiers

- Mobile messages delivering information
- Ad-hoc wireless routing

The hardware components include a handheld computer system and a single, multifunctional, non-invasive sensor that effectively measures physiological parameters during battle conditions. The assessment and alert system collects, analyzes and interprets physiological data in a meaningful way. The user interfaces enable field and other medical personnel to view medical data and issue treatment protocols. The messaging architecture provides the framework for information filtering, information movement, and decision-support capabilities. The ad hoc wireless routing system transports data among computing devices in both urban and open environments.

Figure 1 depicts the main components of ARTEMIS. Sensors worn by soldiers collect physiological data in a continuous manner. The status assessment software residing on the soldier's computing device collects and analyzes this data. If the system detects abnormalities suggesting an injury, an alert is sent via a wireless connection to the necessary medical personnel (medics, medevac personnel, and medical teams at other echelons). Messaging software routes pertinent information, such as treatment protocols, medical records, reference material, medevac arrangements, and requests for decision support through the wireless network. Requests and queries can be either one-time or persistent, minimizing the workload on medical personnel using the system. A combination of mobile agents and wireless routing protocols ensures reliable and timely delivery of information in limited bandwidth networks.

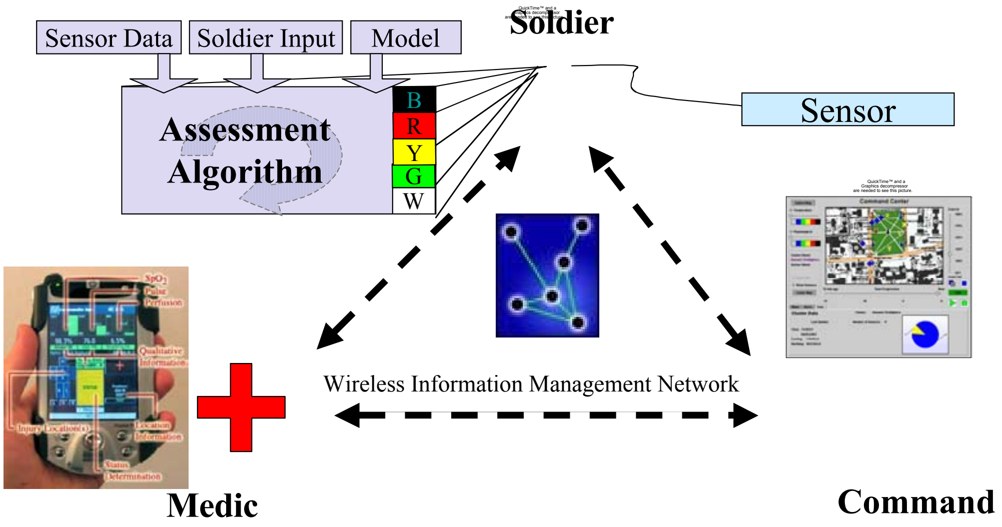


Figure 1: ARTEMIS concept for combat casualty care.

Hardware and Sensors

The focus of the ARTEMIS project is on triage analysis strategies and casualty care information management. Therefore, we chose to employ a commercial sensor from among the many being developed for remote physiologic monitoring. See [4], [5] ,[6] for examples of such sensors.

Our key sensor is a pulse oximeter which collects physiological data, including saturation of oxygen in the blood stream (SpO_2), perfusion index, and pulse rate. These parameters are key diagnostic indicators of patient health. Oxygenation is an indication of how well the lungs are providing oxygen to the blood. Perfusion is the circulation of blood through the vascular bed of tissue and is an indicator of circulatory function.

Our other primary input comes from human sensors. The medic can input the results of his assessment, or a remote assessment can be performed if the injured soldier answers a few, simple questions. One of the more innovative aspects of our system, however, employs the 'Buddy'. In the future, most soldiers will be trained as combat life savers [6]. Equipped with basic first aid skills, a soldier nearby the injured will be able to input basic, qualitative information about the injured soldier's status – about the state of his airway or the presence of major bleeding, for example. The information from this human sensor, the Buddy, will be both sent directly to the medic for his evaluation and incorporated into the software assessment algorithm ultimately determining the soldier's state.

The pulse oximeter currently interfaces to a handheld device. This handheld wireless device transmits processed physiological data to the medic handheld. In the future we hope to integrate this functionality into the military's OFW system, but, as mentioned earlier, we are currently more concerned with the development of the analysis approach.

Assessment and Alert System

Since the 1970's there have been a number of rule based medical expert systems developed to assist medical diagnosis of diseases [7]. Combat care, however, has unique requirements due to the types of injuries sustained during combat and the restraints of limited resources in the field. There has been previous research in combat care and injury models [4], [10] that we have incorporated into the design and implementation of ARTEMIS.

We considered a number of modern artificial intelligence approaches in the development of our software including neural networks, fuzzy logic, and Bayesian probability theory. Ultimately, we decided to use a traditional rule-based system and fuzzy logic due to the practical drawbacks of implementing neural networks and Bayesian statistics [7], [8].

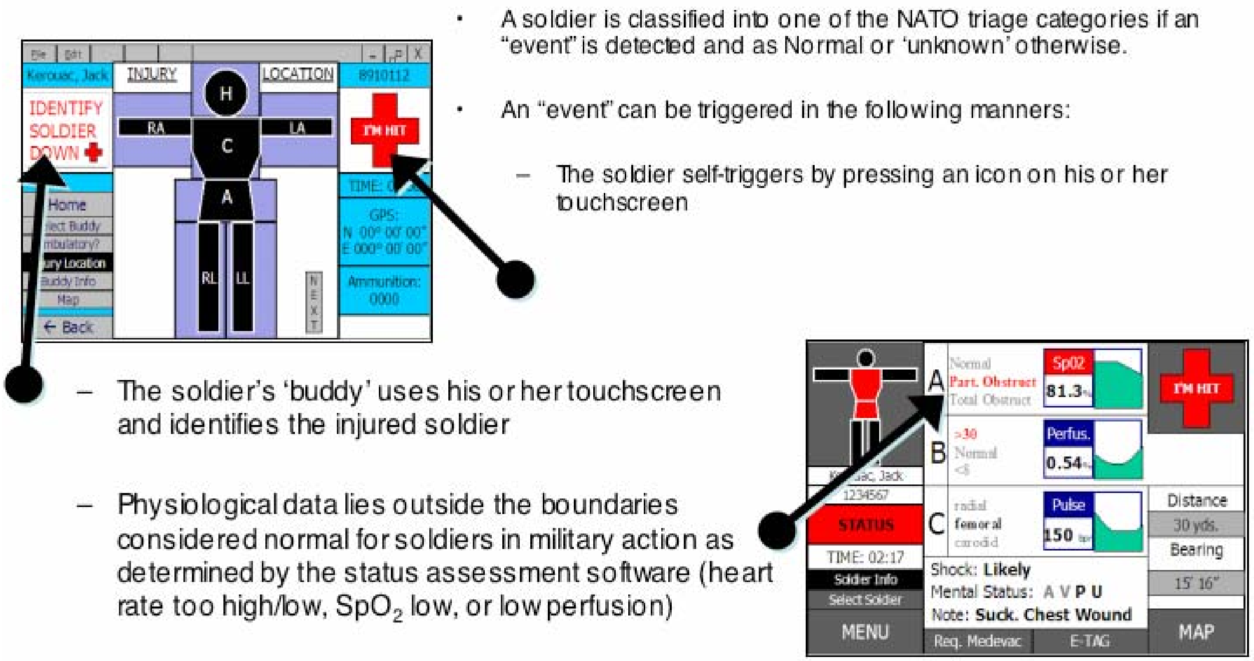
The status assessment software incorporates an interactive medical model currently employed by medics and a rule base developed by a clinician. The algorithm uses these physiological parameters and the medical model to assess the soldier's medical status.

In developing the medical model, we used a simple but effective triage protocol designed by NATO [9]. This protocol prompts the medic to classify injured soldiers based on the location, type, and severity of the injury as well as the soldier's cognitive and ambulatory ability into the categories of: Minimal (able to self-treat and walk to a casualty collection point); Delayed (able to self-treat but not able to walk); Immediate (serious injury requiring immediate treatment); and Expectant (serious injury with immanent death).

In our model, a soldier is classified into one of the four NATO triage categories if an event is detected and as 'normal' or 'unknown' otherwise. An event can be triggered in the following manners:

- The soldier self-triggers (by pressing the "I'm Hit" icon on his or her touchscreen or in the future by voice command)
- The soldier's buddy identifies the injured soldier (by touchscreen or voice)
- The medic identifies the injured soldier on his system
- Physiological data coming from the injured soldier exceeds healthy limits as determined by the status assessment software

These triggering mechanisms are shown from a user interface perspective in Figure 2.



- A soldier is classified into one of the NATO triage categories if an "event" is detected and as Normal or 'unknown' otherwise.
- An "event" can be triggered in the following manners:
  - The soldier self-triggers by pressing an icon on his or her touchscreen
  - The soldier's 'buddy' uses his or her touchscreen and identifies the injured soldier
  - Physiological data lies outside the boundaries considered normal for soldiers in military action as determined by the status assessment software (heart rate too high/low, SpO_2 low, or low perfusion)

Figure 2. Triggering mechanisms for ARTEMIS medical model

In our preliminary studies, we constructed a simulation to develop the decision-making algorithms and to integrate data collection. With the help of an expert clinician, we simulated physiological data and interactive responses using the MILES (Multiple Integrated Laser Engagement System) combat casualty cards that are used to train medics. Because data collected from moving subjects is inherently noisy, we added noise to simulate motion artifacts in the data. Thus, we used a simple but effective limit-based artifact detection algorithm to smooth the data [11].

The simulation incorporates the rules of the medical model into a fuzzy logic-based shell. Given data from a soldier and the rule base, this algorithm reaches a fuzzy classification of the soldier's medical status. The triage categories mentioned above were "fuzzified" along with many of the input parameters in order to simulate individual soldier vital sign variability and to incorporate system uncertainty. Performance of the triage algorithm is discussed in [12].

User Interface

The user interfaces for the ARTEMIS system consists of graphical user interfaces (GUIs) that display data relevant to the user's needs in an intuitive and readable manner. Such information includes physiological data, soldier identity information, protocols, and medical records, and interfaces for decision support. The soldier, the Buddy, and the medic each have GUIs tailored to their own needs. The injured soldier may be asked to answer a few, simple questions to determine his mental status, or the Buddy may enter information about the state of his fallen comrade.

An example of a screen from the medic's GUI displaying information about an injured soldier is shown below in Figure 3. The locations and types of injuries are displayed in the soldier icon (top-left). Below that is the triage category, or assessment score, of the soldier (blue box). The buttons on the left allow the medic to access trending information, request a medevac, or fill out an electronic toe tag that is automatically transmitted to all levels of medical care. The "Soldier Info" box in the center displays qualitative input from the Buddy (green boxes: airway, breathing, circulation, major bleeding, and cognitive health), quantitative data from the pulse oximeter on the injured soldier (large white numbers), and trending information about the physiological data (graphs on the right). Finally, on the far-right side of the screen is the medic's own call for help button (red cross), the distance and bearing to the currently selected, injured soldier, and an icon that leads to a map displaying the locations and states of all soldiers in the system.

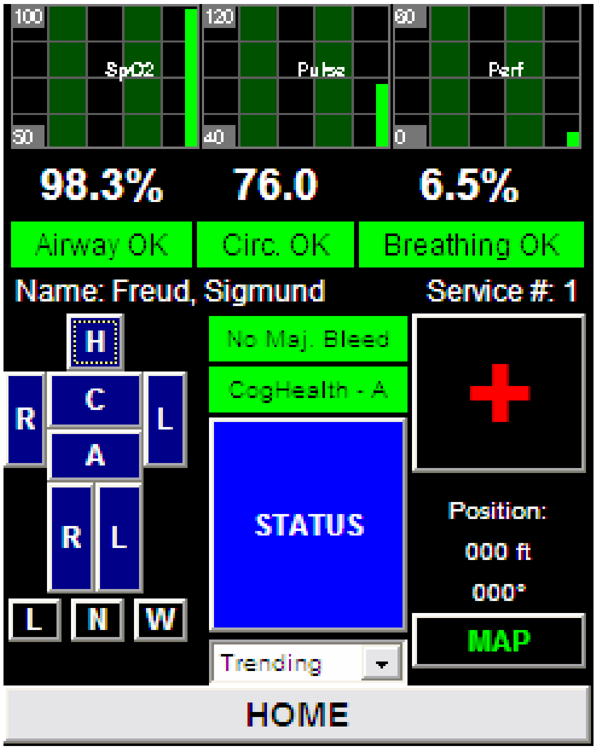


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Figure 3: A sample screen from the medic's display

Reliable Messaging

In a mobile field environment, a wireless communication network provides an efficient means of communication among soldiers. Because of the potential for constant movement of individual and groups of soldiers in the field, the wireless network must maintain a dynamically updated routing system for transmitting messages. A network routing system with this capability will be required for the ARTEMIS system to operate with wireless computing devices. A likely candidate for wireless routing on the ARTEMIS project is the On-demand Multi-cast Routing Protocol (ODMRP), developed by researchers at the University of Southern California [13]. In ODMRP, transmission of routed data is accomplished in an "on-demand" manner. In other words, if no route exists, the transmitted data is concatenated with a "join_request" bearing the sending node's address. The "join_request" floods the network until it reaches the destinations of the transmission. Upon reception of the "join_request", destination nodes reply with a "join_reply", which propagates back to the originating node, which now has a valid route to some multicast group. Through backward-learning, intermediate nodes form a mesh network which can route any data within the local multicast group, and adaptively compensates for link failure and degradation. As there are no explicit group formation messages, ODMRP is highly efficient and highly adaptable in situations with rapidly changing topologies.

The ODMRP algorithm has the benefit of simplicity, but it generates more broadcast traffic than desired in some situations. Therefore several other algorithms are under consideration for ARTEMIS. These include GPSR (Greedy Perimeter Stateless Routing) [14] and AODV (Ad-hoc On-demand Distance Vector routing), [15]

The routing algorithms described above identify a route between two computers only if a route physically exists. In a dynamic wireless network, there might never be a moment at which there exists a complete route from the source to the target computer. Instead the message must be sent partway through the network, and then sent the rest of the way once the changing connectivity opens up a path to the target. In other words, there must be another layer on top of the basic routing system to handle network disconnections. The goal of this layer is to queue messages as close as possible to the critical disconnection, so that the data can be forwarded as soon as the disconnection goes away [16]. There are several approaches to constructing this layer, and one of the most promising is active messaging [17]. In active messaging, each message specifies its own routing strategy, possibly in the form of procedural code that is attached to the message. The advantage of active messaging is that each application can apply an application-specific routing policy to its own messages. For example, an application might use a routing strategy that replicates high-priority messages at key network points and then sends the copies along different network paths to increase the probability of timely delivery.

In the ARTEMIS prototype, the network traffic routing strategy is straightforward: each message is sent to whichever reachable machine most recently had a connection to the ultimate target machine. The message waits on that machine until the target is once again reachable.

Messages in the current ARTEMIS prototype are encapsulated into mobile agents. A mobile agent is the most general form of mobile code, namely, an executing program that can move at times of its own choosing from one machine to another. A mobile agent often, but not always, displays some of the other characteristics associated with agents, such as autonomy and adaptivity [18]. Mobile agents are used to move computation to more attractive network locations, often to avoid the use of unreliable or low-bandwidth network links. Mobile agents are also used to autonomously filter and transport data from remote locations with the aim of saving bandwidth and increasing the timeliness of the data being delivered. A more extensive discussion of mobile agents and the rationale behind their use can be found in [19].

The specific mobile agent software use in ARTEMIS is D'Agents. D'Agents is a Dartmouth-developed mobile-agent system whose agents can be written in Tcl, Java, and Scheme. D'Agents has extensive navigation services [20] and security mechanisms [21].

III. RELATED WORK

A number of sensors and platforms were developed in the 1990’s under the Defense Advanced Research Projects Agency’s (DARPA) Personal Status Monitor program, including the Georgia Tech Smart Shirt [22]. Characterized as a “wearable motherboard” the Smart Shirt allowed for a variety of physiological sensors to be incorporated into a t-shirt to be easily and comfortably worn by soldiers. Under an SBIR from the Army Research Office, Empirical Technologies developed a wrist-worn sensor to monitor heart and respiration rates [23]. Remote monitoring of vital signs was achieved by the Everest Extreme Expedition in 1999, a joint venture between Yale University and NASA [24]. They were able to study the effects of altitude on the human body by monitoring the climbers’ vital signs and transmitting them back to Yale. A group at Williamson Labs has developed a sensor that remotely detects heart rate and breathing on a soldier in the battlefield using microwave Doppler RADAR [25]. While it requires line-of-sight, it does not require any sensors on the patient.

A number of projects are currently being funded by the Telemedicine and Advanced Technology Research Center (TATRC) to collect casualty data. The Personal Information Carrier (PIC) is an electronic dog tag allowing every soldier to carry their entire medical history around his neck [26]. TATRC also has a large initiative: the Special Medical Augmentation Response Team (SMART) Medical Command Control Communications-Telemedicine (MC3T) [27]. The system is designed to manage and communicate medical information from the medic to higher echelons of the battlefield.

At the U.S. Army Institute for Surgical Research, work is underway to determine which physiological parameters are indicative of the need for a life-saving intervention [28]. The hope is to revise the existing triage scoring system based upon empirical evidence gathered from med-flight programs.

At the U.S. Army Research Institute of Environmental Medicine (USARIEM) the Warfighter Physiological Status Monitoring (WPSM) program is working on creating a system that both monitors soldier performance before an injury and remotely triages after an injury [29]. Hydration, thermal, and cognitive indices work to prevent injury and maximize soldier performance. A variety of physiological sensors then triage the soldier after an injury is detected.

IV. CONCLUSION

This project represents an initial effort to build a technology based remote triage system. Although we have made progress in addressing many of the issues at hand, there is still work to be done. Our current prototype is hosted on portable computing devices. In future, custom embedded hardware can be used to create a smaller, lighter, and more power efficient platform. A final product will also have to be comfortable, rugged, and “wear and forget”.

We are also in the process of validating the medical model. One approach is to run real physiological data collected from med-flights - such as the database maintained by the U.S. Army Institute of Surgical Research – through the system. To supplement this database, we are implementing a similar collection system at the Dartmouth-Hitchcock Medical Center (DHMC) med-flight program.

Because battle-field injuries are difficult to simulate exactly, we made assumptions about the physiological parameters such as SpO_2 and the plethysmograph which are used in our assessment algorithms. Other studies indicate that the SpO_2 and plethysmograph signal can be used to gather information regarding respiration rate and blood pressure [30], [31]. Using methods presented in such studies, we have designed several experiments that will test our assumptions regarding physiological inputs. One experimental plan will test for correlation between airway obstruction and SpO_2 of post-operative patients who match the demographic of active duty military personnel and whose surgical injuries are similar to battlefield injuries. If there is a correlation, we will test to see if SpO_2 analysis is fast enough to predict airway obstruction in our target population.

Another experiment was proposed that would test for correlation between the respiration rate and frequency composition in the plethysomograph signal of sleep apnea patients who match the demographic of active duty military personnel and are undergoing a sleep disorder study. This data will be used for the same correlation test between SpO_2 and airway obstruction. We are also designing an experiment that tests utility of the plethysmograph in predicting acute hemorrhage.

Finally, further efforts will be made to test the ability of the artifact detection algorithm to handle real-world disturbances such as motion, signal interruption, and sensor adherence given sweating, bleeding, etc. Future simulations include testing the algorithms using pulse oximeter data from post-surgery patients in addition to soldiers during field exercises.

Ultimately, we need to determine the best way to resolve conflicting inputs. What happens when the buddy, the medic, and the sensors don’t agree? We may add more physiological sensor inputs to the medical model with the intent of getting a more accurate triage score or expanding the scope of our project to determining pre-injury status – what the U.S. Army Research Institute of Environmental Medicine calls a “readiness score”.

There are also a number of potential civilian applications that we are exploring in the first responder arena. Response to disasters and other mass-casualty incidents could benefit from our technology by remotely monitoring and triaging either patients or responders or both. Disaster situations have many similarities to battle field conditions, including the need for continuous medical care, unreliable communications, and the management of limited resources.

In closing, the interplay between humans and computers is a delicate balance. Our system is designed to increase the abilities of medics rather than replace them. We are also utilizing humans as sensors in the field rather than relying solely on electronic sensors. Ultimately the limiting factor in the system’s effectiveness is the medic’s ability to treat problems. If, in the worst case scenario, the system fails, the medics will be no worse off than they are today. Keeping them prepared for computer failure is a matter of training.

Wearable computers and networking are being put into play in the battlefield to enhance the soldiers in a number of ways, and we want to leverage that infrastructure for medical purposes. We have identified the sub-optimized flow of medical information in the battle field today, and we believe that increased medical decision support will save lives.

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