A Soldier Health Monitoring System for Military Applications

Hock Beng Lim[1], Di Ma[1], Bang Wang[1], Zbigniew Kalbarczyk[2], Ravishankar K. Iyer[2], Kenneth L. Watkin[3]
[1] Intelligent Systems Center, Nanyang Technological University
[2] Center for Reliable and High Performance Computing, University of Illinois at Urbana-Champaign
[3] Center for Health, Aging and Disability, University of Illinois at Urbana-Champaign

Abstract – With recent advances in technology, various wearable sensors have been developed for the monitoring of human physiological parameters. A Body Sensor Network (BSN) consisting of such physiological and biomedical sensor nodes placed on, near or within a human body can be used for real-time health monitoring. In this paper, we describe an on-going effort to develop a system consisting of interconnected BSNs for real-time health monitoring of soldiers. We discuss the background and an application scenario for this project. We describe the preliminary prototype of the system and present a blast source localization application.

I. Introduction

In recent years, there have been tremendous advances in the development of wireless sensor networks (WSNs) technologies. A WSN usually comprises of a large number of low-cost, low-power and tiny sensor nodes, each consisting of sensors, microcontroller, memory and radio transceiver. There are many applications of WSNs, including battlefield surveillance, environmental monitoring, health monitoring, smart spaces, industrial diagnostics, etc [1].

As a member of the WSN family, a *body sensor network* (BSN) [2][3] is composed of various physiological and biomedical sensor nodes that are placed on, near or within a human body to monitor parameters such as core temperature, heart rate, EEG, ECG, etc. Body sensor networks can enable continuous health monitoring and provide real-time emergency alerting to save lives.

There are several previous works on the development and implementation of practical body sensor networks. Several prototype BSNs, including their hardware integration, software architecture and communication protocols are discussed in [4][5][6]. Some other research efforts have been devoted to the design and evaluation of communication and networking protocols [7][8][9]. In [7], the middleware design which is used to shield lower layer differences for upper layer applications is presented. In [8], a new media access control (MAC) protocol which applies cross-layer design principle and integrates the physical layer (PHY) into the protocol design is described. In [9], several security protocols are proposed to ensure transmission security for hierarchical body sensor networks.

In most of these BSN research projects, a civilian application scenario is often assumed; for example, using BSN to support long-term healthcare monitoring for the elderly and chronic patients, to provide quick health check and triage for clinic outpatients, etc. In addition to civilian applications, BSN can also be used in military scenarios, such as using BSN to monitor soldiers' health status and to provide alerts of health emergency during trainings and in the battlefields. In fact, military applications of BSN pose even more stringent requirements than civilian applications. These requirements include high mobility, strict reliability, fast response, tight security, low energy consumption, etc.

In the rest of this paper, we introduce our on-going effort to develop a system consisting of interconnected BSNs for real-time health monitoring of soldiers. This system is intended to be used for real-time monitoring and reporting of soldiers' health information including physiological and cognitive status. We discuss the background and an application scenario for this project. Then, we describe a preliminary prototype implementation of the BSN component of the system, including its hardware platform, system architecture and network protocol stack. We also present an application of the system for blast source localization.

II. Background and Application Scenario

Sudden death or fatal injury is not uncommon among soldiers during both training and battlefield action. To provide real-time health monitoring, we envision that each soldier should be equipped with a comprehensive health monitoring system. A key component of such a system is a BSN that integrates various physiological and biomedical sensors. For example, Fig 1 shows that accelerometer, temperature, EEG, and SpO2 sensors can be embedded within an advanced combat helmet worn by each soldier [10][11]. Such a system enables the continuous monitoring of health status of soldiers. If some abnormalities are detected, alert signals can be generated for the soldier concerned.

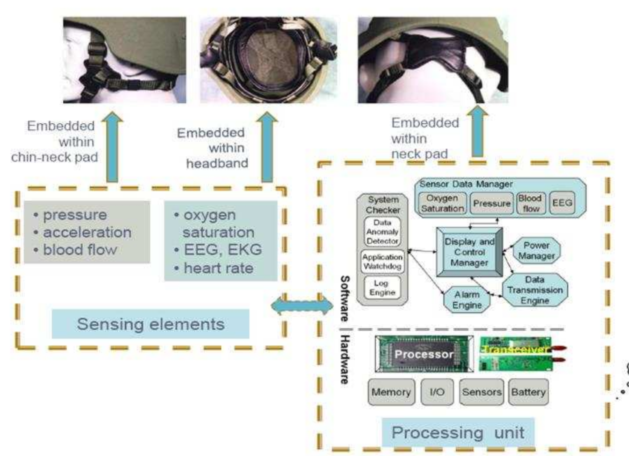

Fig 1: Advanced helmet for health monitoring

978-0-7695-4065-8/10 $26.00 © 2010 IEEE
DOI 10.1109/BSN.2010.58

We consider the scenario where a group or platoon of soldiers is required to perform various trainings or operations in a large area without existing network infrastructure. In this situation, we assume that each soldier is equipped with a radio transceiver so that the entire group of soldiers can communicate via an ad hoc wireless mesh network. Selected soldiers are also equipped with long-range radio transceivers to communicate with the command center. The reliable interconnection of these individual BSNs in the highly mobile and harsh environment is a major challenge.

In this project, we consider the application scenario whereby a group of soldiers may be exposed to bomb blasts. A bomb blast may cause deaths as well as traumatic brain injuries (TBI). The BSN equipped by each soldier should be able to measure the EEG signals as well as other physiological parameters to determine the life signs and injury status for the soldier. Normally, soldiers closer to the center of blast will be injured more severely than soldiers farther away. Thus, it is important to access the blast impact on soldiers, in particular on traumatic brain injuries [10][11]. The assessment on blast impact would require external environmental sensors for measuring blast pressure. Thus, this work actually addresses the integration of personal health monitoring (via BSN) with the detection of external events (such as blast impact assessment), which is a very important area of research for the BSN community.

III. PROTOTYPE DESIGN AND IMPLEMENTATION

In this section, we discuss our preliminary implementation of the prototype system.

A. Hardware Platform

Off-the-shelf sensor nodes often have limited I/O ports and computational power. In this project, we develop our own sensor nodes based on the MSP430FG4618 microprocessor and Chipcon-2500 RF (radio frequency) transceiver. The MSP430 microprocessor has been used in many sensor node platforms for its low power consumption. Although the Chipcon-2500 RF transceiver is not IEEE 802.14.5 compliant, it enables us to achieve fast prototyping of the system. Fig 2 shows the hardware platform in the form of a development board.

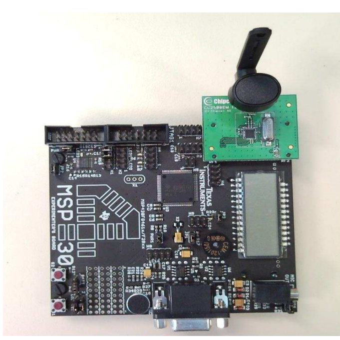

Fig 2: Hardware platform

In this preliminary system, an EEG simulator has been used to simulate the EEG signals of a human being. The EEG simulator can store EEG signals corresponding to various physiological conditions captured from real humans. The simulator that we used simulates the EEG signals of a person who suffered from brain seizures. The EEG electrode locations and names are specified by the "International 10-20" system ensuring consistency in the naming convention. In most clinical applications, 19 recording electrodes along with 2 reference electrodes are used. In this work, only 4 electrodes are used for monitoring abnormal activity [10][11].

Besides the EEG simulator, we also use accelerometers and SpO2 sensors. The accelerometers provide information on the sudden acceleration of a solider subject to an external force (e.g. a bomb blast in the battlefield). One benefit of pulse oximetry is that oxygen saturation (SpO_2) can be measured noninvasively. This is important because studies have shown that cerebral oxygen desaturation is associated with cognitive decline. Another added benefit of most pulse oximetry systems is the ability to calculate the heart rate from the same signals used to calculate oxygen saturation levels in the individual.

B. Protocol Stack

We use a proprietary protocol stack provided by Texas Instruments (TI) to build a network prototype. The protocol stack, known as SimpliciTI, is especially designed for low-power, low-data rate RF networks. The protocol only requires 4k flash memory and 512 bytes RAM, thus it is suitable for sensor nodes with limited hardware resources. However, the protocol only supports an extended star topology. Although most wireless sensor networks often use a mesh topology, the limitation of this protocol does not prohibit us from carrying out experiments using the prototype system.

Using the SimpliciTI protocol, three types of sensor nodes can be configured; namely, AP (access point), RE (range extender) and ED (end device). The AP serves as a data hub and it is connected to a host server. The RE serves as an extension device to extend the range of a star topology network. Each ED is an individual sensor node for collecting various sensor data and transmitting them back to the AP. The AP will then send the received data to the host server for data storage, processing and analysis. Fig 3 shows the system architecture.

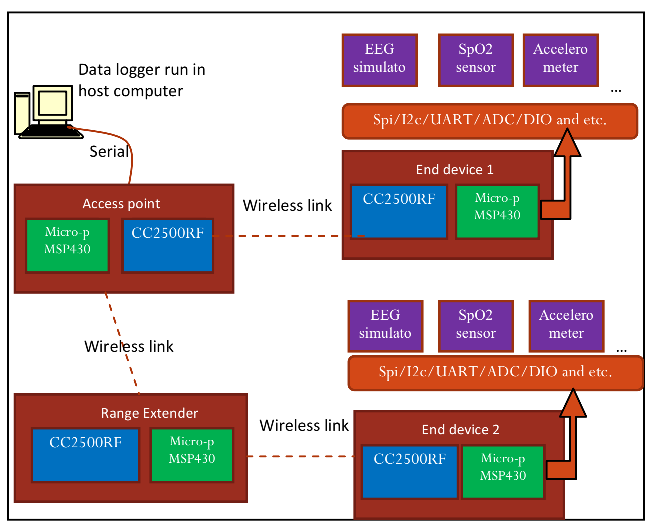

Fig 3: System architecture

IV. APPLICATION : BLAST SOURCE LOCALIZATION

For the blast impact assessment, we propose a blast source localization algorithm. The idea of the algorithm is to make use of the acceleration experienced by each soldier due to the blast to estimate the location of the blast. For now, we are unable to carry out field tests involving real blasts since these require a facility to conduct blasts and animals for the experiments. Thus, the proposed algorithm is validated through a simulation study.

A. Problem Formulation

Suppose all soldiers in the battlefield are equipped with BSNs and they form a connected network. A soldier's coordinate are denoted by (x_i, y_i) where i is the index of the soldier. At time t, some soldiers in the network experience a sudden acceleration a_i due to a blast at an unknown position (x_b, y_b) in the battlefield. The acceleration information, the coordinates and the weight of a solider are then relayed back to the host server. A source localization algorithm estimates the blast location (x_b, y_b) by using these data. The impact of the blast on each soldier can then be assessed.

B. Blast Model

Suppose the force at the blast point (x_b, y_b) is F_b and the blast wave propagates out omni-directionally. We assume the blast force has an exponential decay relationship with the distance, namely the magnitude of the blast force along the direction of the blast wave propagation decays exponentially with the distance from the blast point (x_b, y_b). Let d represents the distance between the blast point and a random point near the blast point. The blast force at this random point is then given by:

$$f(d) = F_b \cdot e^{-\lambda d} + N_\sigma \qquad [1]$$

where λ is the decay rate, N_σ is a Gaussian random variable with zero mean and standard deviation σ used to model the random effect of blast wave propagation. Fig 4 shows the force of the blast wave decay with the distance exponentially.

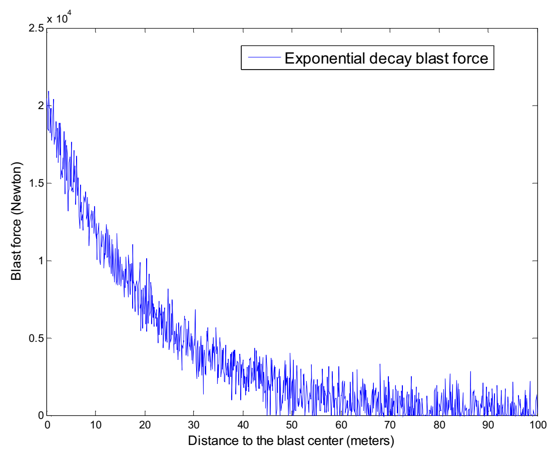

Fig 4: Exponential decay blast force. The decay rate is set to 0.05, the initial force F_b is set to 2×10^4 Newton.

C. Blast Source Localization

Assuming the soldier's own movement is negligible compared to the blast force, the blast force experienced by the soldier i along the direction of the blast wave propagation can be computed as $f_i = m_i \cdot a_i$, where m_i is the mass of the soldier and a_i is the acceleration experienced by the soldier along the blast wave propagation direction. The distance between the soldier i and the blast source can be computed as follows:

$$d_i = -\frac{1}{\lambda}\ln\left(\frac{f_i - N_\sigma}{F_b}\right) \qquad [2]$$

Suppose there are k soldiers experiencing the sudden acceleration. We can construct a k system of non-linear equations.

$$\begin{aligned} (x_1 - x_b)^2 + (y_1 - y_b)^2 &= d_1^2 \\ (x_2 - x_b)^2 + (y_2 - y_b)^2 &= d_2^2 \\ &\vdots \\ (x_k - x_b)^2 + (y_k - y_b)^2 &= d_k^2 \end{aligned} \qquad [3]$$

The system of non-linear equation can be transformed into a system of linear equation of dimension $k-1$ by subtracting the last equation k from all previous $k-1$ equations:

$$\begin{aligned} x_1^2 - x_k^2 - 2(x_1 - x_k)x_b + y_1^2 - y_k^2 - 2(y_1 - y_k)y_b &= d_1^2 - d_k^2 \\ x_2^2 - x_k^2 - 2(x_2 - x_k)x_b + y_2^2 - y_k^2 - 2(y_2 - y_k)y_b &= d_2^2 - d_k^2 \\ &\vdots \\ x_{k-1}^2 - x_k^2 - 2(x_{k-1} - x_k)x_b + y_{k-1}^2 - y_k^2 - 2(y_{k-1} - y_k)y_b &= d_{k-1}^2 - d_k^2 \end{aligned} \qquad [4]$$

The system of linear equation can be further simplified as follows:

$$\underbrace{\begin{bmatrix} 2(x_1 - x_k) & 2(y_1 - y_k) \\ 2(x_2 - x_k) & 2(y_2 - y_k) \\ \vdots & \vdots \\ 2(x_{k-1} - x_k) & 2(y_{k-1} - y_k) \end{bmatrix}}_{A} \cdot \begin{bmatrix} x_b \\ y_b \end{bmatrix} = \underbrace{\begin{bmatrix} x_1^2 - x_k^2 + y_1^2 - y_k^2 + d_k^2 - d_1^2 \\ x_2^2 - x_k^2 + y_2^2 - y_k^2 + d_k^2 - d_2^2 \\ \vdots \\ x_{k-1}^2 - x_k^2 + y_{k-1}^2 - y_k^2 + d_k^2 - d_{k-1}^2 \end{bmatrix}}_{b} \qquad [5]$$

Finally, the blast source location can be computed by solving the over-determined system of linear equations:

$$[x_b, y_b]^T = (A^T A)^{-1} A^T b$$

where A and b are given in the Eq. (5).

D. Simulation Study

We are unable to conduct real blast tests at this stage of the research. Therefore, we use computer-based simulations to validate the blast source localization algorithm. With real blast tests in future, we can improve the blast wave propagation model and the blast source localization algorithm using real data.

Fig 5 shows a scenario where 300 soldiers are randomly located in a deployment area of 1000 meters by 1000 meters.

Three blasts randomly occurred in the field and caused some injuries on the nearby soldiers. The system collects the acceleration information of soldiers who are near the blast and sends the information to the host server via multi-hop relay. The blast source localization algorithm then estimates the location of the blast. The estimated blast source locations are shown in the figure. Note that we also plotted the ranges/coverage such that the blast wave force is half, one-third and one-quarter of the initial blast wave force F_b. Table 1 lists the simulation settings for this blast source localization study.

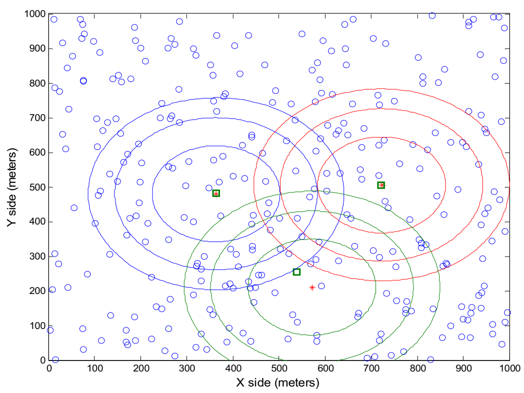

Fig 5: Blast source localization simulation

The red colored stars are the actual locations of the blast sources. The green color boxes are the estimated blast locations from simulations. The blue circles are the soldiers' location. The circles centered at the blast source are the ranges such that the force of the blast wave is half, one-third and one-quarter of the initial force of the blast wave.

Table 1: Simulation parameters

Initial blast force F_b	2×10^4 Newton
Decay rate λ	0.005
Blast propagation standard deviation σ	3000
Mean soldier mass	80 Kg
Solider mass standard deviation	10 Kg

The simulation results indicate that the errors of the source localization are relatively small compared to the blast coverage. The blast source localization error is defined as the absolute distance between the actual blast source and the estimated blast source. In this case, the errors are 6.453, 16.743 and 54.246 meters respectively.

V. CONCLUSION AND FUTURE WORK

In this paper, we discussed the importance for a system for continuous real-time health monitoring of soldiers. We have completed an initial design of the individual sensor nodes and developed a prototype system for data collection. We are planning to integrate more types of sensors into the BSN, including blood pressure sensor, electrocardiogram (ECG) sensor, electrodermal activity (EDA) sensor, etc.

In future, we plan to design a unified yet extensible message exchange protocol to collect and store the sensed data. We will develop an integrated data management system and a web portal to enable various users to easily access the data. We also plan to integrate our system with the Advanced Combat Man System (ACMS), which is the next-generation integrated combat support system for the Singapore military.

REFERENCES

[1] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “Wireless sensor networks: a survey,” Computer Networks, vol. 38, no. 4, pp. 393-422, 2002.

[2] G.Z. Yang, *Body Sensor Networks*, Springer-Verlag, London, 2006.

[3] M. A. Hanson, Harry C. Powell Jr., A. T. Barth, K. Ringgenberg, B. H. Calhoun, J. H. Aylor, and J. Larch, “Body Area Sensor Networks: Challenges and Opportunities,” IEEE Computer, pp. 58-65, Jan. 2009.

[4] K. Lorincz, D. J. Malan, T. R. Fulford-Jones, A. Nawoj, A. Clavel, V. Shnayder, G. Mainland, and M. Welsh, “Sensor Networks for Emergency Response: Challenges and Opportunities,” IEEE Pervasive Computing, vol. 3, no. 4, pp. 16-23, 2004.

[5] A. Milenkovic, C. Otto, and E. Javanov, “Wireless Sensor Networks for Personal Health Monitoring: Issues and An Implementation,” Computer Communications (Elsevier), vol. 29, no. 13/14, pp. 2521-2533, 2006.

[6] T. O’Donovan, J. O’Donoghue, C. Sreenan, D. Sammon, P. O’Reilly, and K. A. O’ Connor, “A Context Aware Wireless Body Area Network (BAN),” Proc. of the 3rd International Conference on Pervasive Computing Technologies for Healthcare, 2009.

[7] A. B. Waluyo, I. Pek, P. Ying, J. Wu, X. Chen, and W-S. Yeoh, “LiteMWBAN: A Lightweight Middleware for Wireless Body Area Network,” Proc. of the 5th International Workshop on Wearable and Implantable Body Sensor Networks (BSN), 2008.

[8] F. Chiti, R. Fantacci, F. Archetti, E. Messina, and D. Toscani, “An Integrated Communications Framework for Context Aware Continuous Monitoring with Body Sensor Networks,” IEEE Journal on Selected Areas in Communications, vol. 27, no. 4, pp. 379-386, 2009.

[9] Y. M. Huang, M. Y. Hsieh, H. C. Chao, S. H. Huang, and J. H. Huang, “Pervasive, Secure Access to a Hierarchical Sensor-based Healthcare Monitoring Architecture in Wireless Heterogeneous Networks,” IEEE Journal on Selected Areas in Communications, vol. 27, no. 4, pp. 1-12, 2009.

[10] A. J. Cheriyan, Z. Kalbarczyk, R. K. Iyer , A. O. Jarvi, T. M. Gallagher, and K. L. Watkin, “Pervasive Embedded Real Time Monitoring of EEG & SpO2,” Proc. of the 3rd International Conference on Pervasive Computing Technologies for Healthcare (PervasiveHealth 2009), pp. 1-4, Apr 2009.

[11] A. J. Cheriyan, A. O. Jarvi, Z. Kalbarczyk, T. M. Gallagher, R. K. Iyer, and K. L. Watkin, “Pervasive Embedded Systems for Detection of Traumatic Brain Injury,” Workshop on Multimedia Aspects in Pervasive Healthcare, IEEE International Conference on Multimedia and Expo (ICME 2009), pp. 1704-1707, Jul 2009.