INSTRUMENTING BOMB DISPOSAL SUITS WITH WIRELESS SENSOR NETWORKS

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Abstract: Bomb disposal suits contain a large amount of padding and armour to protect the wearer's vital organs in the case of explosion. The combination of the heavy (roughly 40kg) suit, physical exertion, and the environment in which these suits are worn can cause the wearer's temperature to rise to uncomfortable and potentially dangerous levels during missions. This paper reports on the development of a wearable wireless sensing system suitable for deployment in such manned bomb disposal missions. In its final form, the system will be capable of making in-network autonomous decisions related to the actuation of cooling within the suit, in order to increase the comfort of the wearer. In addition, it will allow an external observer to remotely monitor the health and comfort of the operative. Laboratory experiments with the instrumented suit show how skin temperature varies differently for different skin sites, motivating the need for multiple, distributed sensing. The need for timely application of in-suit cooling is also shown, as well as the importance of monitoring the overall health of the wearer of the suit.

1 INTRODUCTION

The monitoring of hazardous environments, along with the people working within them, is an area which lends itself to the use of wireless and body sensor networks (WSNs and BSNs). The field is rich with potential WSN applications in detecting hazards, providing feedback to remote observers and other critical tasks that can increase the safety and benefit the overall working conditions of people operating in these environments. This paper reports the work towards the development of a wireless body sensor network for the protective suits worn in bomb disposal missions.

A typical bomb disposal mission will initially involve investigating the site using a remote controlled robot, and if possible, disarming the bomb remotely. Sometimes, however, it is necessary for a human bomb disposal expert to disarm the device. For this, the expert will put on a protective suit and helmet (as shown in figure 1), pick up a tool box of equipment, and walk the 100 or so metres to the site. To reach the bomb's location, it may be necessary to climb stairs, crawl through passageways, or even lie down.


Figure 1: Explosive Ordinance Disposal (EOD)Suit.

The environment where the suit is used, such as the hot climate of the Middle East, plays an important role in the design of the protective suit. One of the UK manufacturers of such suits has identified the problem of the suit wearer becoming uncomfortably hot and, in the worst case, suffering heat exhaustion. They have attempted to address this by installing an in-suit cooling system based on a dry-ice pack and a fan that cycles air through the pack and blows cooled air onto the wearer's back and into the helmet. The cooling system has a variable control thus both allowing the airflow to be adjusted for comfort and also allowing the life of the batteries that power the fan to be extended, as they would only provide sufficient power for part of the mission otherwise. The problem with this cooling approach, though, is that the bomb disposal expert has other critical concerns during the mission and either does not bother to put the fan on or tends to set it to maximum airflow from the beginning of the mission.

To address the above problems, this work proposes embedding into the suit a body sensor network that aims to:

- sense the temperature of the skin of various parts of the body, in order to assess overall comfort, and
- adjust the cooling dynamically to both remove the need for human intervention, and also to prolong battery life.

The prolonging of battery life is intended to provide cooling over the whole mission duration (compared to the partial coverage provided currently) rather than increasing the mission duration itself.

A secondary goal of this work is to help the manufacturer better understand how the suit material and design choices are affecting the wearer's thermal comfort during use. Finally, the prototype presented here has been designed such as to allow easy integration of additional sensors, such as accelerometers to monitor posture, heart rate monitors, and CO_2 sensing within the helmet.

The paper is organised as follows: Section 2 examines related work, focusing in particular on body sensor networks and research relating to instrumenting first responders (such as police, fire services etc). Section 3 describes the system design and architecture developed for the prototype system produced to date. Section 4 contains an evaluation of the prototype. Finally the paper concludes with some observations based on the work so far and outlines future work.

2 RELATED WORK

The work reported in this paper is most closely aligned with respect to the instrumentation design and implementation with the field of Body Sensor Networks. This is a sub-area of Wireless Sensor Networks that makes use of a combination of wireless and miniaturised sensor technologies to monitor the human body. The scope of present BSN approaches is patient care. Such systems are either designed to focus on capturing the evolution of a particular physiological parameter and ensuring that alarms are generated when parameters stray outside a safe range (Keoh et al., 2007), or aimed to provide general monitoring solutions for patient status within a hospital or similar environment (Shnayder et al., 2005). In comparison, the work presented here is concerned with increased safety and comfort of human subjects in constrained environments through integrating sensing, actuation, and autonomous decision making. In this context, wireless sensor technology is used as an enabler for the necessary detailed measurement of physiological parameters. 5A This work shares some of the design space of BSN in terms of the type of physiological parameters sensed and the wearability requirements of the implemented system. On the other hand, given that the application is within the safety critical domain, the work here also shares some common characteristics with the area of instrumenting and monitoring first responders. In this section, samples of BSN platforms are reviewed together with commercial instances of first responder monitoring and prior, motivating, physiological findings about the EOD suit.

2.1 Body Sensor Networks—Platforms

BSN based systems are often more constrained than ordinary embedded systems. These constraints are mainly in terms of power, size and weight. Power is restricted because mains AC power is not available. Furthermore, size and weight restrictions limit the battery supplies that can be used. Size and weight must be limited because large and heavy devices would be cumbersome, uncomfortable, and in applications such as the one described here, an unnecessary distraction.

In response to the above, some of the BSN systems designed and implemented by research groups integrate within the nodes an appropriate central processing unit, memory and radio transceiver as a single custom chip. An example here is the MITes platform (for monitoring movement of human subjects) developed by (Tapia et al., 2004), which is based around the Nordic VLSI Semiconductors nRF24E1 chip. This chip integrates a radio transceiver and an Intel 8051 based processor core that runs at 16MHz and provides a nine channel 12-bit ADC and various other interfaces, such as SPI (serial peripheral interface) and GPIO (general purpose I/O). This approach is efficient in terms of size and weight due to the integration of several functions into one chip, but has limited generality as it can not be easily adapted for new applications.

Another, more popular design option is to use off-the-shelf components. There is a trade off made between processing and storage capabilities and the size and power consumption of the devices. This means that the devices selected would likely be considered severely under-powered in other systems (often including 16- or even 8-bit processors) and have small amounts of memory (in the order of tens or hundreds of kilobytes). For instance, the Texas Instruments MSP430F149 micro-controller has been used for several systems including those developed by (Lo and

Yang, 2005) and (Jovanov et al., 2001). This is a 16-bit processor running at 8MHz incorporating 60KB of flash memory and 2KB of RAM and provides interfacing opportunities via 48 GPIO lines and a 12-bit ADC. The system developed by Lo and Yang used ECG sensors, accelerometers, and a temperature sensor to monitor patient health. The system developed by Jovanov et al., was used for monitoring the elderly and those undergoing physiotherapy.

Other systems expand upon commercial devices such as the Mica2 and MicaZ motes developed at the University of California, Berkeley, or Intel's Imote platform. This approach often has a disadvantage in that the basic platform is generic, and may not directly provide the facilities required for the specific BSN project. Such commercial platforms are also often larger and heavier than custom developed platforms as they are required to be general purpose in order to achieve any commercial success. The MicaZ mote uses the Atmega128L, an 8-bit processor running at 8MHz and featuring 128KB of flash memory to which an additional 512KB is added externally on the mote itself. A 10-bit ADC, UART and I2C bus are also available. (Gao et al., 2005) developed a system based around the this mote, adding various sensors and supporting devices to allow patient tagging and monitoring in an emergency response environment. (Walker et al., 2006) present a blood pressure monitoring system based on the MicaZ platform. In that work, a commercial blood pressure monitoring device is connected to the MicaZ via a serial interface.

2.2 Instrumenting First Responders

The best fit example of a commercial product designed for the purpose of monitoring personnel carrying out missions in dangerous environments is the VivoResponder by (Vivometrics, 2007). VivoResponder is based upon an earlier product called the LifeShirt and is aimed at personnel engaged in firefighting and hazardous materials training or emergency response, industrial clean-ups using protective gear, and biohazard-related occupational work. The VivoResponder is supplied in three parts: a lightweight, machine washable chest strap with embedded sensors; a data receiver; and, VivoCommand software for monitoring and data analysis. The sensors embedded in the chest strap monitor the subject's breathing rate, heart rate, activity level, posture, and single point skin temperature.

Monitoring of the subject's breathing is performed using a method called inductive plethysmography, where breathing patterns are monitored by passing a low voltage electrical current through a series of contact points around the subject's ribcage and abdomen. Monitoring of the subject's heart rate is performed via an ECG.

The VivoCommand software, provided with the device, displays the gathered data from the chest strap in real-time on a remote PC. The parameters are updated every second along with 30-second average trends. The parameters are displayed with colour coding intended to allow quick assessment of the status of up to 25 monitored personnel simultaneously. Baseline readings can be set individually per monitored person.

The work developed here differs in intent: the aim here is to provide a detailed thermal assessment based on sensors integrated into the protective suit and deliver remotely abstracted comfort information.

2.3 Other Work on EOD Suits

Working from a physiological perspective, (Thake and Price, 2007) have investigated the thermal strain of a subject when wearing EOD suits in hot environments. The work looks at quantifying the level of strain by assessing how hot and tired the suit wearer feels whilst wearing various combinations of suit components. An "activity" regime was developed for the assessment based on the types of activities that a bomb disposal technician would undergo during a mission and included walking on a treadmill, unloading and loading weights from a rucksack, crawling and searching activity, arm cranking and cognitive tests. Aspects of hand-eye coordination and psychological performance were also assessed. The investigations have demonstrated a large increase in physiological strain when wearing the EOD suit, though benefits have been shown when the ambient air is cooled for the suit ventilation purpose and lighter-weight trousers are worn.

It is indeed these types of studies, together with the user requests, that prompted the development of the detailed physiological monitoring system presented in this paper. The activity regimes described by Thake and Price were used in the experiments presented in this paper to allow validation of findings.

3 SYSTEM DESIGN AND ARCHITECTURE

The main part of the prototype system is designed following a sense-model-decide-act architecture as shown in figure 2. The environment within the suit is sensed in terms of temperature; sensed data is integrated into a model representing the thermal state

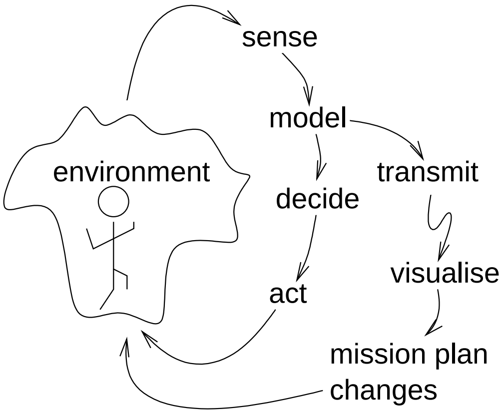


Figure 2: Conceptual design of prototype system.

of the wearer; a decision is made about how to adjust the cooling system based on the thermal state; finally, the determined action is transmitted to the fan speed controller. In addition to this basic architecture, the system also transmits inferred state values for the purpose of remote, on-line, visualisation of the thermal state of the wearer. From this visualisation, the operator can assess how different parts of the mission, or different actions being taken by the suit wearer are affecting their thermal state and hence assess the wearer's fitness for the mission. (It is expected that such information, collected during field trials and real missions, might lead to changes to future mission planning or to changes in the design of the suit.) In summary, the prototype system can be seen as being composed of two control loops: one giving rapid feedback to autonomously adjust cooling; the other, longer term one, providing support for an iterative design process in terms of both the mission use and construction of the suit.

The prototype design consists of a number of hardware components, including a remote monitoring station, two processing nodes, one actuation node, 12 temperature sensors, and the cooling system. The connection between these components is shown in figure 3. The processing nodes, actuation nodes, and remote monitoring point form a wireless network. Each processing node is wired to several sensor packages via an I2C bus. Although it would be possible to integrate all sensor packages used in this prototype into a single processing / actuation node, using separate processing nodes allows the helmet, jacket, and trousers to be kept separate with no wires running between them. This is essential for ensuring that the product remains easy to use and transparent to the wearer.

The system components and their functionality are described in the remainder of this section.

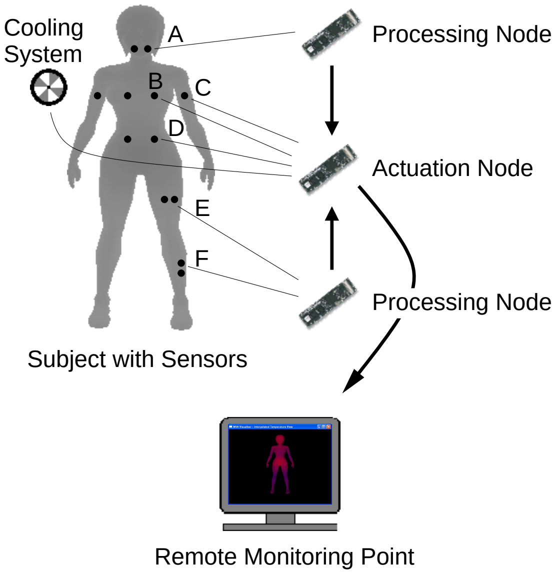


Figure 3: Prototype system hardware components and sensor positioning (A – neck, B – chest, C – bicep, D – abdomen, E – thigh, F – calf).

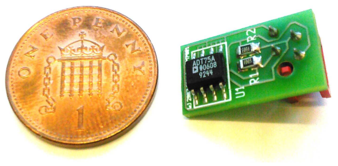


Figure 4: Sensor package, which is based on an ADT75A chip.

3.1 Sensor Packages and Sensor Positioning

The prototype system discussed here uses twelve sensor packages based on Analog Devices ADT75A temperature sensor ICs (shown in figure 4). This device has the advantage that it contains the sensor, ADC, and bus interface in a single package. Temperature values are transmitted as 12 bits, which causes rounding to within 1/8°C. The sensor packages are connected to only two nodes in the current version: one actuation node and one processing node.

The sensor packages were positioned around various parts of the body roughly following the standard positioning used for skin sensors as used by (Thake and Price, 2007), which is a subset of the locations discussed by (Shanks, 1975). These were: lateral calf muscle, front of thigh (or quadruceps), abdomen, chest, biceps, and neck, as indicated in figure 3. Given that temperatures are known to be symmetrical between left and right sides in healthy people (Silberstein et al., 1975), sensors have been placed on a single side. Two sensor packages were used per skin site.

This arrangement enables individual data validation.

3.2 Processing and Actuation Nodes

3.2.1 Construction

There are a variety of available embedded platforms for sensing and control applications. The hardware choice decisions for the prototype system here were based on the available platforms' processing power, external interfaces, ease of software development, and size.

Gumstix Connex 400xm-bt boards were selected as the main processing platform. Although not as popular as Mica2 motes, they are becoming more prevalent (see (Keoh et al., 2007) for an example). These devices offer more processing power and memory (in terms of both RAM and flash) than many similarly sized platforms. The Connex includes an Intel XScale PXA255 400MHz processor, 16MB of flash memory, 64MB of RAM, a Bluetooth controller and antenna, and 60-pin and 92-pin connectors for expansion boards. There are no on-board sensors provided. The sensor packages connect to the Connex board via an expansion board, designed in-house.

The prototype system exploits the following capabilities offered by the Gumstix Connex device: Bluetooth communications to transmit data between nodes; I2C bus interface for the attachment of sensor packages; real-time data modelling and decision-making; and, a small form factor, which enables convenient mounting on or around a subject's body.

3.2.2 Functionality

In the current revision of the prototype, the actuation and processing nodes only transmit data back to the remote monitoring station, upon filtering outlying values. The longer term view is for the processing and actuation nodes to perform in-network modelling of the suit wearer's comfort through collaborative behaviour. Comfort modelling would firstly involve production of a thermal sensation model within the network. This will be followed by integration of supplementary physiological and contextual sensing performed by expanded sensor packages. Work to date in thermal sensation modelling and its integration within the processing and actuation nodes is reported in a separate paper. The actuation node will eventually be used to perform decision making on the basis of the wearer's comfort and act by controlling the fan speed.

WSN Visualiser

Average Temperature: 29.02

Head (Left) : 29.44
Head (Right) : 29.44
Chest (Left) : 31.10
Chest (Right) : 31.06
Left Arm : 27.49
Right Arm : 27.81
Left Leg : 28.01
Right Leg : 28.23

Figure 5: A snapshot of the remote monitoring component.

3.3 Remote Monitoring

The remote monitoring component of this system allows an external observer to monitor both the instrumentation system (to ensure that trustworthy information is being recorded) and the bomb disposal technician during a mission (which is the main function of the instrumentation). The remote monitoring component displays the health and comfort information and provides alerts to the remote observer if physiological parameters fall outside safe ranges or the wearer is shown to be significantly uncomfortable. A snapshot of the remote monitoring component is shown in figure 5. Currently the remote monitor displays skin site temperature data and a rotating, suggestive, 3-D interpolated model of skin temperatures. Cool to hot zones are displayed dynamically through a range of colours, from blue to red.

4 PROTOTYPE EVALUATION

4.1 Experimental Setup

The prototype instrumentation system was evaluated through laboratory experiments that attempt to reproduce typical bomb disposal mission situations by having the subject undertake a series of activities and tasks, as discussed in section 2.3. The experiments begin with sensors being attached to the subject, followed by suiting-up. The upper body sensors are integrated into the clothing and thus easier to attach, whilst lower body sensors are attached with PVC tape. The subject wore the outer shell of the bomb disposal suit including the jacket and trouser segments in addition to armour plating and the helmet.

Figure 6: First activity: walking at 4km/h.

Figure 7: Second activity: kneeling while removing weights from a sack. The wired-in data logger can be seen taped onto the subject's lower back.

The subject then undertakes an activity regime composed of: (1) walking (3 minutes) (see figure 6); (2) kneeling while putting weights into and out of a rucksack (2 minutes) (see figure 7); (3) crawling (2 minutes); (4) arm exercise (4 minutes); (5) sitting (3 minutes); (6) standing (1 minute). Temperature data is collected both via the prototype wireless system and via a wired-in data logger. Data was gathered during two consecutive runs, both consisting of the same routine and taking place in a 5m x 6m draft free room, with an ambient temperature of 21°C.

4.2 Evaluation Results

The prototype was evaluated according to a number of criteria that follow directly from user requirements. The criteria were: ease of use, data yield, accuracy, robustness, communication range, and information gain.

Ease of Use. Instrumentation systems, particularly those used for bomb disposal missions, are expected to have stringent ease of use requirements as they should be transparent to the user and should not interfere with the mission. Ease of use was assessed here subjectively by comparing the ease of application of the sensor packages with sensor mountings for a wired data logger.

As mentioned previously some of the sensor packages have been integrated into clothing, whilst some (neck, thigh, and calf) have been taped to the skin. It is expected that clothing integrated sensors will be less accurate than ones taped to the skin because contact with the skin surface will change when the subject is moving. While avoiding the problem of inconsistent contact, taping on sensors, on the other hand, means that they are less convenient to apply and remove. In comparison to using a standard wired data logger, the wireless system mounting takes considerably less time and has been found to be more comfortable by experimental subjects. Further revisions of the prototype will have all sensor packages mounted on individual elasticated straps, ensuring both firm contact and comfort.

Data Yield is a measure of the proportion of data captured. Wireless sensing systems are inherently prone to low yields due to both transmission errors and sensor faults. For the system here, during experimentation, no packets were lost in transmission, however 5% of the sensor samples were found to be out of range (95% yield). Most of the out of range values were from particular sensor packages (3.3% from the worst two), with several sensor packages having no out of range values at all. It is likely that the erroneous values were introduced by I2C bus transmission errors. In comparison, there were no errors apparent in the wired data logger values apart from the chest sensor, which produced incorrect values 61% of the time (39% yield for this sensor, 88% over all data logger sensors).

Accuracy is a measure of how closely the sensor data obtained corresponds to the underlying physical phenomena being sensed. As the data logger results in figure 9 show, calibration is needed. Discretisation due to the 12 bit resolution causes some information loss that is offset by sampling frequently. The system is currently being calibrated against a newer data logger instrument.

Robustness is particularly important for this system as the intended usage scenario involves it functioning in an environment where it may be subjected to large mechanical shocks and radio frequency interference (RFI). The activity regime here reproduces shocks roughly equivalent to normal application usage and the prototype functioned correctly throughout all trials. As yet, no RFI testing has been carried out.

Communication Range is a measure of how far the subject can roam from the monitoring station without losing communications. In line-of-sight tests, a range of 50 metres was achieved, whilst non-line-of-sight range (through several walls) was about 10 metres. Bluetooth communication will be replaced by ZigBee in the next revision of the prototype.

Information Gain is a measure of the benefit of the system in terms of providing more (or better) information about the subject. The prototype has demonstrated two advantages. First, by being untethered, it allows data gathering to occur in the field. Second, it provides a means for real-time remote monitoring and actuation as opposed to offline data acquisition, which is the only role fulfilled by the wired data logger.

4.3 Data Analysis

A summary of temperature data obtained from all sensors for a sample run is given in the series of graphs in figure 9. Data was recorded during the experimentation using both the prototype system and a wired-in data logger. These graphs show that the two systems agree in terms of the changes in temperature. It is important to note that the shapes of the graphs, not the exact temperatures measured, are compared here as the sensors on the prototype system had not yet been fully calibrated. The graphs show sensed temperatures over a period of time starting from the third activity (crawling) through to the fifth activity (sitting) followed by a repeat from the first (walking on a treadmill) through to the last again (see section 4.1). In the graphs, the start and end times for each activity are indicated by a vertical bar and the activity number (starting with 3) is given in between each set of bars. Note that there were some rest periods between activities, which are left unmarked.

The aim of the experimentation carried out was two-fold. First, the system under development was compared, in terms of the criteria discussed previously, with a commercially available, wired-in data logger. Second, the data obtained from the two systems was compared to check for consistency. The positioning of the sensors, with several locations having more than one sensor, also meant that the data from the system could be compared internally.

While detailed interpretation of the physiological meaning of the data obtained is beyond the scope of this paper, the data gathered is meaningful in the context of the developed application as follows: 1) Large variations in the skin temperature on some of the sites monitored (maximum three degrees C over 30 minutes) indicate the need for both monitoring and accurate cooling actuation; 2) There are uncorrelated skin temperature variations over the sites monitored stressing the need for distributed and detailed measurement (as opposed to single point measurement performed by most developed BSN systems); 3) From the graphs, the relationship between activity and skin temperature at different sites is not an obvious one. (An example here is the sudden dip in temperature which occurs for all chest sensors during crawling (activity 3). Crawling is strenuous with the suit on, so this result is surprising.) This indicates the need for added sensing such as humidity and posture information in order to predict the physiological effects of wearing the suit during such exercise regimes. The next prototype, currently under production contains such enhanced sensor packages.

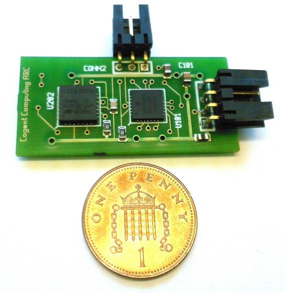


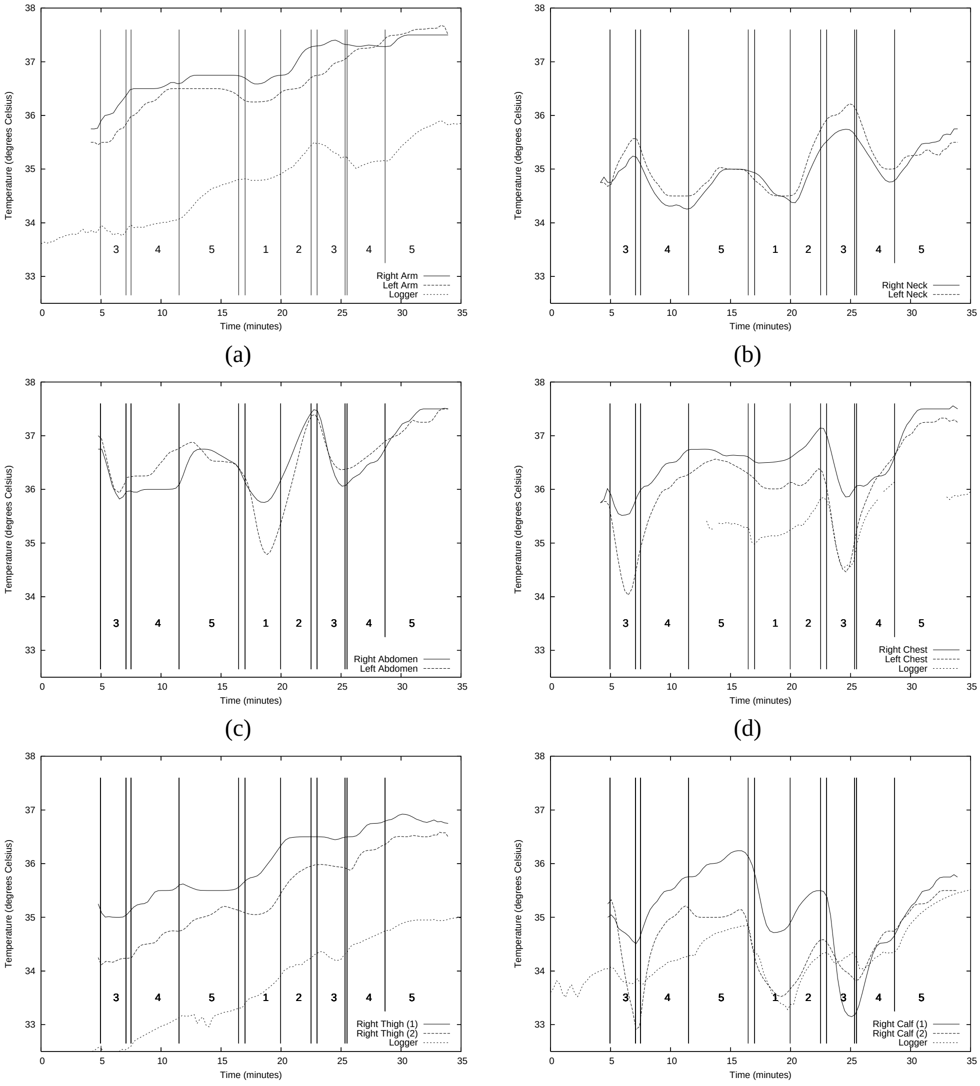
Figure 8: Enhanced sensor package, which is comprised of a PIC processor, 3-DOF accelerometer, I2C buffer, and temperature sensor.

5 CONCLUSIONS AND FUTURE WORK

WSN technology is clearly an enabler for detailed measurement in domains such as the one discussed in this paper, domains which are currently not sufficiently understood and lack the necessary instrumentation to further scientific investigation.

Experimental results obtained with a detailed, WSN-based temperature monitoring instrument showed that 1) under a set of activities typical to a bomb disposal mission, skin temperatures for different parts of the body (arms, thigh, chest, and so forth) vary differently thus there is value in sampling at many points; 2) skin temperatures exhibit large variations leading potentially to heat exhaustion hence the need for health monitoring of subjects; 3) autonomous feedback control of the in-suit cooling system, based on a detailed map of how temperature is changing over time, is enabled by the prototype developed so far but more work is needed to determine how best to respond to changes in temperature to ensure that the wearer is kept comfortable.

In the next revision of the prototype, it is planned



(a) (b)

(c) (d)

(e) (f)

Figure 9: Skin temperature over time for (a) arm, (b) neck, (c) abdomen, (d) chest, (e) thigh, and (f) calf sites. The two leg sensors (thigh and calf positions) were placed on the right leg only. For several skin sites, temperature values were also obtained using a wired-in data logger (denoted “Logger”). The vertical lines in each graph show the start and end of activities. Each activity is represented by a number.

to integrate temperature sensors into a multi-modal sensor board designed in-house, as shown in figure 8. Each board has a temperature sensor and an accelerometer, along with a PIC micro-controller. The two sensors allow the combined monitoring of temperature and acceleration data at any point on a subject’s body. The acceleration data will be used for posture identification in further work, which will allow enhanced, activity based remote visualisation of the subject and lead to improved estimates about how the thermal state and thus comfort of the subject is changing. This will hence improve the timeliness and appropriateness of autonomous cooling decisions.

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