# Using body sensor networks for increased safety in bomb disposal missions

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# Using Body Sensor Networks for Increased Safety in Bomb Disposal Missions

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## Abstract

*Bomb disposal manned missions are inherently safety-critical. Wireless Sensor Network (WSN) technology potentially offers an opportunity to increase the safety of the operatives involved in such missions through detailed physiological parameters monitoring and fusion of "health" information.*

*Wearing heavy armour during bomb disposal manned missions may have side effects that, due to reduction of the body's ability to regulate core temperature in the enclosed environment of the suit, lead to uncompensable heat stress and thus impair the technician's physical or mental ability. Experimental trials have shown no obvious relationship between temperature of any single skin site and the core temperature nor between single point temperature and subjective thermal sensation (usually associated with comfort). Also, core temperature alone may not yield indicators of danger sufficiently early.*

*This paper proposes to integrate a body network of temperature sensors into the bomb disposal suit. The paper describes an in-network sensor data fusion and modelling approach that estimates the overall thermal sensation for the suit wearer, in real time, based on the multi-point temperature data. The case is made for performing the modelling in-network on the basis of reducing communications with the remote mission control point and to better support actuation of an in-suit cooling system. It is also argued that thermal sensation indicators are more useful to present at an on-line remote monitoring station than individual temperatures. The appropriateness of the developed Body Sensor Network (BSN) application is supported by experimental validation.*

## 1 Introduction

A range of body sensor network (BSN) systems have been proposed in the literature for monitoring the human body for timely detection of health-related problems. BSN developers have targeted a variety of environments, including emergency response [5, 18], hospital [4, 11] and physiotherapy environments [6]. Added to these, several other general purpose body monitoring devices [10, 1, 7] have also been proposed. A common element of much of the work on BSNs is the focus on integrating accurate single-point physiological parameter measurements (such as heart rate or blood oxygenation) into larger monitoring and assessment systems. The challenges hence identified by the BSN community are largely to do with secure communication of the sensed parameters to remote units, portability of the measurement systems, devising the supporting infrastructure for concurrently monitoring a number of subjects and, in some measure, miniaturisation of the supporting sensing and communication platforms (this will be further supported in section 2).

In contrast, the work proposed here explores the potential benefits of deployed BSNs, in terms of:

- providing detailed physiological measurement, hence providing better insight into what is happening to the human body when exposed to uncomfortable and potentially hazardous environments (such as heavy protective armour) and extreme environmental conditions,
- supporting on-line and real-time extraction of accurate human thermal sensation estimates based on multiple sensor measurements,
- reporting of useful information rather than data to a remote station, thus enabling rapid assessment of hazardous situations,
- allowing the provision of thermal remedial measures through control and actuation of systems commonly integrated with armoured suits.

The appropriateness and usefulness of deployed BSNs catering for the above four points is demonstrated here through a motivating application described below.

**Figure 1. Explosive Ordinance Disposal (EOD) Suit**

Bomb disposal missions provide armour designers, disposal technicians, and mission controllers with a number of challenges, due to the extreme conditions and strain generated by both wearing the armour and the typical bomb disposal sites and scenarios. A typical scenario of a 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. It may be necessary to climb stairs, crawl through passageways, or even lay down in order to reach the bomb's location.

The suit itself consists of three main sections (helmet, jacket, and trousers), with more than one layer composing each, and a total weight of approximately 40kg. The suit forms a practically blast-impenetrable environment for the technician wearing it, this being the primary concern in the design of such suits. The combined outcome of weight and specialist protective materials is that wearing the suit is potentially injurious to the wearer through side-effects, as further discussed in section 3. (The environment where the suit is used, such as the hot climate of the Middle East, adds to the negative effect of the protective suit on the wearer.)

One of the UK manufacturers of such suits, having identified the problem of the suit wearer becoming uncomfortably hot and, in the worst case, suffering heat exhaustion, have attempted to address it by installing an in-suit cooling system. The system is 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. Whilst theoretically the cooling could alleviate the heat stress in some measure, mission trials have shown both:

- the inefficient use of the battery power (hence inefficient cooling provision and limited remedial effects) by mission technicians, and,
- the need for remote monitoring of the mission technicians.

The authors have developed a prototype system which both satisfies the need for remote monitoring and allows for future integration of a cooling automation component to ensure effective, need-based cooling.

This paper presents the authors' work towards the software support and communications aspects of the prototype system, particularly the inference of thermal sensation of the wearer of the protective suit and the communication of the sensation levels to a remote monitoring station.

The paper is structured as follows: Section 2 reviews related work. This is followed by a discussion of the key aspects of the protective suit and its effect on the wearer. The design of the proposed system is described in section 4, along with the model used to estimate thermal sensation from multi-site, sensed temperature (section 5). Experimental results are presented in section 6, which is then followed by the conclusions.

## 2 Related work

With respect to the instrumentation design and implementation, the work reported in this paper is most closely aligned 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 most present BSN approaches is patient care. Such systems are either designed to focus on capturing the evolution of particular physiological parameters and ensuring that alarms are generated when parameters stray outside a safe range [8], or aimed to provide general monitoring solutions for patient status within a hospital or similar environment [4]. 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.

The authors' work shares some of the design space of BSNs 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, sample applications of BSNs are reviewed together with their supporting architectures.

### 2.1 Emergency response and disaster management

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 [18]. 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.

Another system for first responders is the patient monitoring system presented by [5], which was developed as part of the CodeBlue project [15]. Unlike the VivoResponder, this system is designed for monitoring patients at an emergency scene, and provides the facility to monitor a patient's vital signs and location, as well as medical record storage and triage status tracking. Several additional devices were added to the Mica2 platform which supports this application: location sensors, a pulse oximeter, a blood pressure sensor, and an electronic triage tag. The electronic triage tag replaces the paper equivalent commonly in use. (A paper triage tag is also provided as backup if the electronic tag fails.) The mote continuously transmits patient information to a tablet device which the first responder carries in a weatherproof casing. Mote packages are distributed to patients as required once the scene is reached.

### 2.2 Continuous monitoring solutions for patient care

The CodeBlue project [15, 11] aims to provide an architecture and system implementation for continuously monitoring patients in a hospital environment. Two of the devices produced during the course of this project were a mote-based EKG and pulse oximeter, with the goal of integrating them into one device. Fulford-Jones *et al.* [4] present the EKG unit, which is built onto a Mica2 mote. It is designed for continuously monitoring patients in a hospital intensive care unit. Standard "portable" EKG systems require power from an electrical outlet and are moved around on a cart which must be taken with the patient, whereas this system aims to be lightweight and unobtrusive. The EKG data is collected by the mote and transmitted to a monitoring device such as a PC or PDA. The pulse oximeter is based on the same hardware platform and aims to provide similar benefits in terms of portability.

Working towards similar monitoring aims as the above, Jovanov *et al.* [6] present a sensor node named ActiS that is designed to be used as part of a wireless body area network. This node incorporates a bio-amplifier and two accelerometers, allowing the monitoring of heart activity as well as the position and activity of body segments. The main focus is the node's use for monitoring the activity of physiotherapy patients outside of the laboratory. The proposed system speeds up the set-up process compared to is classical monitoring counterpart solution and has the alternative advantage that it may be left attached to a patient for a prolonged period (meaning that the set-up phase is not necessary before every physiotherapy session).

### 2.3 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.* [16], 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 but has limited generality.

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 [10] and Jovanov *et al.* [7]. 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 $I^2C$ bus are also available. Gao *et al.* [5] 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.* [19] 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.

The system proposed in this paper uses off-the-shelf components, although integration into custom chips is foreseen as an avenue to be explored in the future.

## 3 Suit environment

The combination of elevated metabolic heat production $M$ and restricted avenues for body heat loss (convection $C$, conduction $K$, radiation $R$ and evaporation $E$) when wearing necessarily heavy and bulky protective clothing has a negative effect on the heat balance of the body and results in heat storage. This is a situation where the thermoregulatory system is unable to defend against increases in core body temperature[1]. This condition of uncompensable heat stress (UHS) is associated with significant physical and psychological impairment [2] therefore placing the individual at an increased risk of making an avoidable error and jeopardising the mission. Furthermore as well as the microclimate within the EOD suit, the rate of heat storage will also depend on the ambient conditions and is likely to increase during operations in hot compared to temperate environments. Approaches to attenuate heat strain have the potential to reduce physiological stress and increase safe operating time. Recent developments in this area include the integration of cooling devices and altered equipment configurations. Clearly knowledge of differences between physiological and thermal responses of the operatives across a range of conditions is essential to inform the requirements of an "active" system to optimise the microclimate between the skin and protective clothing to facilitate heat transfer and maintain body temperature. Laboratory based activity simulation protocols have recently been developed to assess the impact of such innovations on UHS [9, 17].

This paper uses a modified version of Zhang's comfort model [22] to estimate thermal sensation from temperature data and compares it to that actually reported by trials participants [17, Section 6]. In brief, participants undertook up to four 16:30 (min:sec) activity cycles consisting of treadmill walking (4 km/h, 3 min), unloading and loading weights from a kit bag ($\approx$ 2 kg each, 2 min), crawling and searching activity (2 min), arm cranking (unloaded, 3 min), seated physical rest (5 min) interspersed with 30 sec intervals between the first three activities. Heart rate (HR; Polar Vantage), rectal temperature ($T_{core}$), skin temperatures ($T_s$; arm, chest, thigh and calf [12]) were monitored throughout. Thermal sensation, reported on a 0 to 8 scale [21] that incorporates verbal anchors from unbearably cold (0) to comfortable (4) to unbearably hot (8) was sought at specified intervals. Wearing an EOD suit dramatically increased physiological strain as indicated by elevated heart rate (figure 2) and gradual increase in core and mean skin temperatures (figure 3) and thermal sensation in all four participants. Such responses are likely to have a negative impact on performance. Continuous monitoring is essential since the rate of rise in core body temperature can abruptly increase when mean skin temperature reaches a similar level (figure 3). Furthermore unpublished data from our laboratory demonstrate that wearing a phase change cooling vest under the EOD suit results in a reduction in chest temperature ($\approx 3^\circ$C) and elevation in upper arm temperature ($\approx 0.5^\circ$C) compared to not wearing a cooling vest. Such data highlight differences between body segments and support the rationale for multi-point temperature sensing to be used when using thermal information to estimate thermal well being of operatives in protective clothing.

[1] The balance between heat gain and heat loss is represented by the heat balance equation: $S = M - (\pm W) \pm (R + C) \pm K - E$ where $S$ is the rate of body heat storage; $M$ is the rate of metabolic heat production; $W$ is the mechanical work [13].

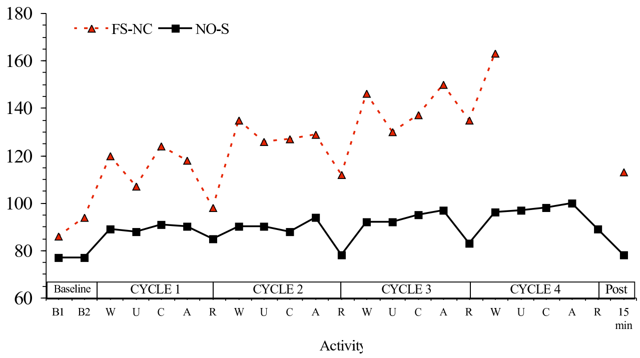


**Figure 2. Typical heart rate response to EOD activity simulation (n=1). FS-NC=full suit, no cooling; NO-S=no suit; W=walking; U=unloading/loading weights; C=crawling and searching; A=arm exercise; R=seated rest. NB. Two of four subjects were not able to complete four activity cycles.**

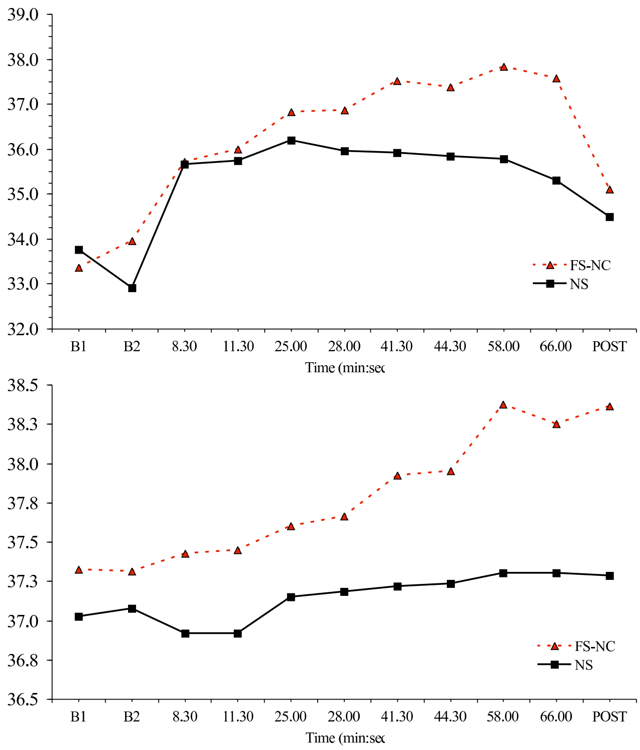


**Figure 3. Core and mean skin temperature responses (n=4; error bars are omitted for clarity). FS-NC=full suit, no cooling; NO-S=no suit.**

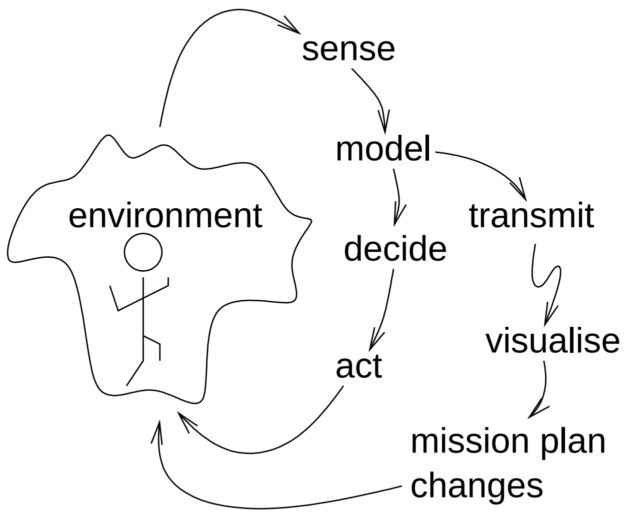


**Figure 4. Conceptual design of prototype system**

## 4 System Design and Implementation

A prototype sensing system is in development to provide a greater data gathering capability than that offered by currently available monitoring systems. This system is designed following the architecture shown in figure 4. The environment within the suit is sensed in terms of temperature; sensed data is integrated into a model representing the thermal state 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. 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, which is the object of discussion here, transmits the thermal sensation information to the remote monitoring point.

The prototype components supporting this functionality are presented in figure 5. The processing nodes, actuation nodes, and remote monitoring point form a wireless network. Each processing node is wired to several sensor packages via an $I^2C$ 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 sensor packages are attached to the body following the standard positioning used for skin sensors as used by

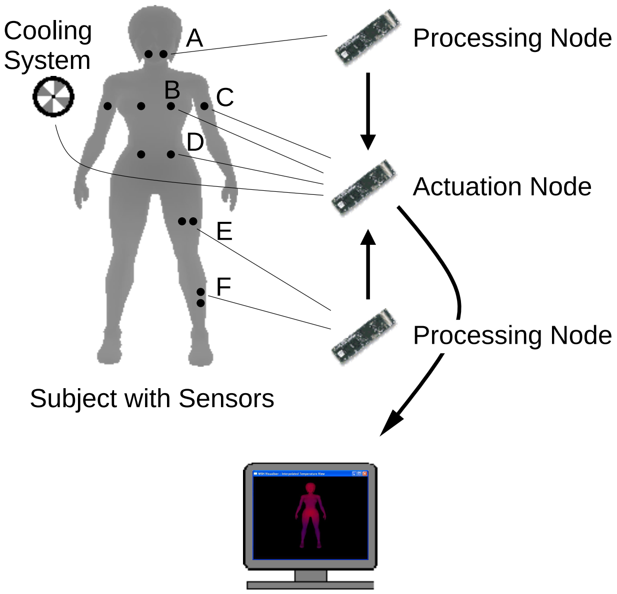


**Figure 5. Prototype system hardware components and sensor positioning.**

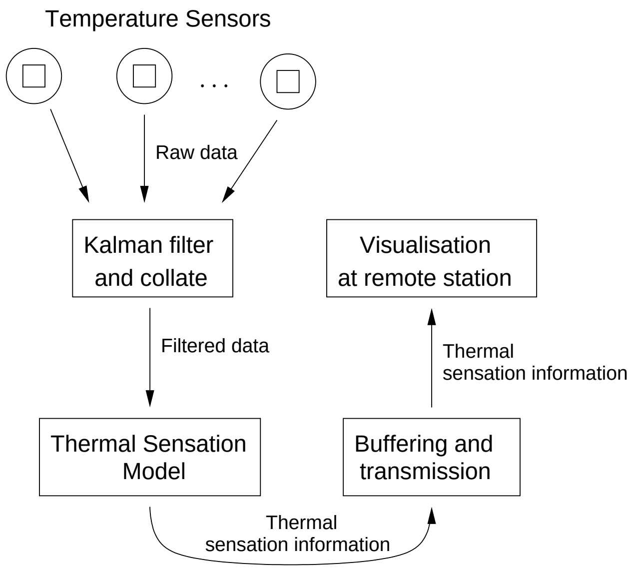


**Figure 6. Information flow for remote monitoring**

Thake and Price [17], which is a subset of the locations described by Shanks [14]. The used skin sites were: A – neck, B – chest, C – bicep, D – abdomen, E – thigh, F – lateral calf muscle, as indicated in figure 5.

The Gumstix Connex 400xm-bt board was selected as the main processing and communication platform (supporting the processing and actuation nodes). The Connex includes an Intel XScale PXA255 400MHz processor, 16MB of flash memory, 64MB of RAM, a Bluetooth controller and antenna (enabling all communications), and 60-pin and 92-pin connectors for expansion boards. There are no onboard sensors provided. The sensor packages connect to the Connex board via an expansion board that was designed inhouse. As shown in figure 5, three Connex boards are used; two as processing nodes and one as an actuation node.

### 4.1 Remote monitoring loop

Remote monitoring is shown conceptually as a feedback loop (in figure 4) that transmits the modelling results (thermal sensation) to a remote monitoring station and displays the information (thermal sensation level), thus allowing human-in-the-loop feedback. The data and information flow for this process (as implemented in the current prototype) is illustrated in figure 6. The first phase is to smooth the raw sensed data from all skin sites using Kalman filtering [20] and to collate all into a skin temperature vector. A thermal sensation model is applied to the resulting vector, which yields an estimate of the thermal sensation for the current point in time. The next phase is to transmit this to the remote station. (Optionally, the skin temperature vector can also be transmitted.) Due to the possibility of a radio jammer being used and to compensate for other factors causing communications link failures (such as obstructions and out of range mobility), it is necessary to first buffer the information, and then, when it is sensed that communications are available, to transmit all buffered information. Given that only the information is being buffered rather than whole ready-to-transmit packets, this approach saves memory and avoids dropped packets due to overflowing communication buffers. The last phase is the information arrival at the remote monitoring station and its conversion to visual form.

A snapshot of the remote monitoring visualisation component is shown in figure 7. The main information display panel (in this case using illustrative data) includes a 3D figure showing the interpolated temperature distribution across the subject's skin, the current average skin temperature, and the current thermal sensation level. Other panels show the location and status of the sensors and the history of the incoming data.

## 5 In-Network Thermal Sensation Modelling

In this section, a case is established for performing thermal sensation modelling "in-network" and communicating to mission control this global "well-being" parameter. The argument is raised from two perspectives: first, a network-

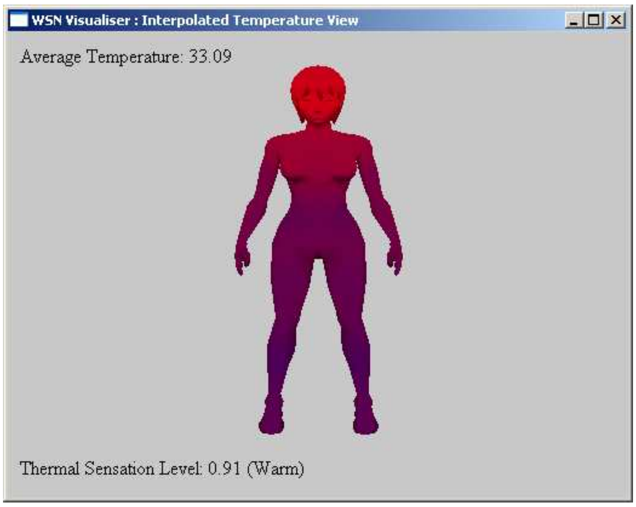


**Figure 7. A snapshot of the remote monitoring visualisation component.**

ing hardware perspective, and second, an information benefit one.

Thermal sensation estimates can be transmitted in fewer bits than a detailed thermal profile from a large number of sensors. Also, a sensation estimate removes unnecessary contextual information such as number of sensors, position of sensors and whether redundant sensors have been used. Due to the nature of embedded, low power devices, reducing the number of bits that need to be transmitted extends their lifetime.

Furthermore, communication with the base station may be intermittent due to radio jammers or other factors as noted previously. Even though buffering may help, the effective bandwidth will be considerably less than that available under optimal conditions. For this reason, it makes sense to perform modelling on-board and to transmit thermal sensation estimates.

Effective visualisation systems need to assist the user with interpreting the data. It has been the authors' experience that it is difficult for a user to assess thermal comfort by looking at individual skin temperatures. Furthermore, skin temperatures tend to change slowly and overall trends are difficult to assess. It has been noticed, for example, that skin temperature of one body segment may be rising while the temperature of another is falling, whilst the overall thermal sensation follows yet another trend.

A final advantage for modelling in-suit is that more effective and efficient cooling might be achieved by using thermal sensation rather than single point temperature measurements as the basis for controlling the cooling system.

The thermal sensation model, used in the current prototype system, is described below.

## 5.1 Thermal sensation model

Several models of human thermal sensation exist. Examples are the PMV-PPD and SET* [3] models. In this work, a model provided by Zhang [22] has been evaluated in detail. Zhang's model was chosen as it has been well researched and validated with a large number of human subject trials. This model takes skin temperature (and optionally core temperature) readings from a subject as input and provides as output an estimation of thermal sensation, both per body segment and globally. Thermal sensation is given in the range $[-4,4]$, with $-4$ being very cold and 4 being very hot. (Note that a bias of $-4$ has been applied to the trials scale described in section 3 to unify the self assessed and modelled thermal sensation. This unified scale was used throughout the remainder of this paper.) The model accounts for both static and dynamic temperature conditions. In Zhang's work, thermal sensation levels are then used to calculate the thermal comfort level, which is not discussed here.

The main part of the model is a logistic function based on two main parameters:

- the difference between the local skin temperature and its "set" point (the point at which the local sensation is neutral)
- the difference between the overall skin temperature and overall set point

The local thermal sensation for segment $i$ is defined as,

$$\begin{aligned} L_i &= \left(C1_i^{\pm}\right)\left(T_{s,i} - T_{s,i,set}\right) \\ &+ K1_i\left[\left(T_{s,i} - T_{s,i,set}\right) - \left(\overline{T}_s - \overline{T}_{s,set}\right)\right] \end{aligned}$$

$$S_i = 4\left(\frac{2}{1+e^{-L_i}} - 1\right) + \left(C2_i^{\pm}\right)\frac{dT_{s,i}}{dt} + \left(C3_i^{\pm}\right)\frac{dT_{core}}{dt}$$

where $S_i$ is the local thermal sensation for segment $i$, $T_{s,i}$ is the skin temperature at $i$, $\overline{T}_s$ is the mean skin temperature, and $\overline{T}_{s,set}$ is the set point for the mean skin temperature. A constant $C1^{\pm}$, which is different for each body segment, defines how large a change in sensation results from a change in temperature, while a constant $K1$, which is also different for each body part, determines the contribution of the overall thermal state to the sensation of the segment in question. Constants $C2^{\pm}$ and $C3^{\pm}$ control the contribution of the rate of change of local skin and core temperatures to the local sensation. Note that the model defines slightly different values for $\pm$ constants depending on whether the associated multiplicand is positive or negative.

Estimated overall thermal sensation $S$ is the weighted sum of estimates of local sensations $\sum_{i\in B} w_i S_i$ where $B$ is

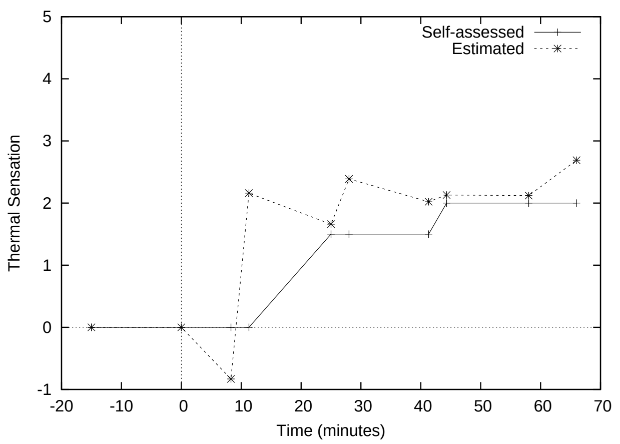


**Figure 8. Self-assessed overall thermal sensation versus estimated for subject 3 with no suit.**

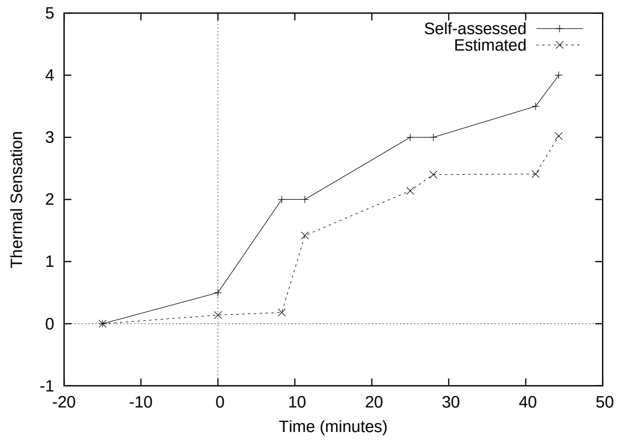


**Figure 9. Self-assessed overall thermal sensation versus estimated for subject 3 with the full protective suit and no cooling.**

the set of body segments and the weights are normalised such that $\sum_{i \in B} w_i = 1$.

It should be noted that in order to apply Zhang's model of thermal sensation to the protective suit environment, the set of body segments in the model were reduced to just 4 skin sites, with corresponding changes in associated weighting.

## 6 Results

Sample results showing a comparison of self-assessed (or subjective) thermal sensation and that estimated by the model are shown in figures 8 and 9 with the former showing a trial without the EOD suit and the latter showing a trial with the suit. For all body components (and overall), the self-assessed values with no EOD suit are always lower than estimated by the model. However, when the suit is worn, the model mostly, if not always, underestimates.

Self-assessed thermal sensation does not necessarily follow the same trend as the temperature of any particular skin site. As shown in figure 10, a dramatic increase in thermal sensation occurs between 30 and 40 minutes corresponding to the subject feeling much hotter than previously. At the same time, the chest temperature (which would be the only site conventionally monitored) has actually decreased by about one degree. Just after this, the self assessed sensation drops to 2 while the temperature increases. In conclusion, the results both confirm the need for detailed measurement of temperature at multiple skin sites and also confirm that Zhang's model is a good starting point towards estimating thermal sensation of subjects wearing an EOD suit.

Trials with other subjects, who had previously worn the EOD suit fewer times than subject 3, experienced large changes in skin temperature during the activity regime.

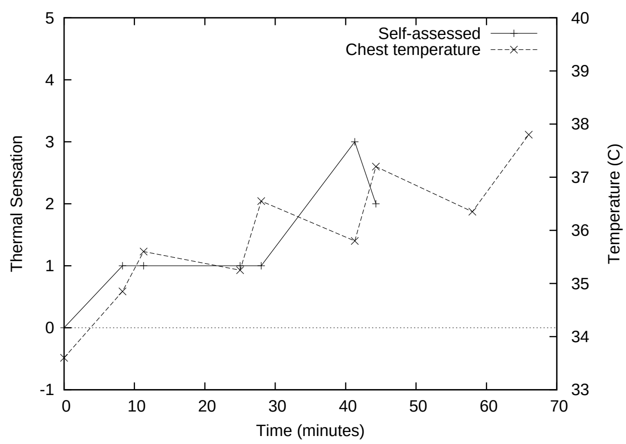


**Figure 10. Self-assessed thermal sensation compared with chest skin temperature for subject 1.**

Subject 3, however, showed much more stable temperatures.

## 7 Conclusions and future work

It is clear that wearing heavy armour during bomb disposal missions may induce uncompensable heat stress due to the enclosed nature of bomb disposal (EOD) suits. The work presented here has positively assessed the need for detailed measurement of skin temperature, the applicability of body sensor network technology to this application domain, and the suitability of modelling thermal sensation based on skin temperature. The approach taken by the authors exploited in-network information extraction and communication of real-time thermal sensation to mission control to facilitate both high yield and timely remedial actions. This work has the potential to provide real improvement to both the working conditions of EOD technicians and greater levels of safety.

As it stands, the model used is not a perfect fit for this application. Some possible reasons are:

- experimentation has shown that there is a tendency for discomfort to grow with time when wearing the suit, possibly due to the subject becoming tired, thus affecting their subjective assessment,
- the model was not specifically designed for estimating thermal sensation while wearing this type of protective clothing,
- thermal sensation is a subjective measure, which may lead to variations in the reporting between subjects.

In future work, it is planned to develop a new or revised model that better accounts for the environmental factors of the EOD suit. Also, it is envisaged to use thermal sensation information as a control parameter for autonomous activation of an in-suit cooling system. Extensive experimentation and trials are planned for January through to March, 2008.

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