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Increasing Safety of Bomb Disposal Missions: A Body Sensor Network Approach

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Abstract—During manned bomb disposal missions, the combination of the protective suit's weight (37kg), physical activity, high ambient temperatures, and restricted airflow can cause the operative's temperature to rise to dangerous levels during missions, impairing their physical and mental ability. This work proposes to use Body Sensor Networks (BSNs) to increase the safety of operatives in such missions through detailed physiological monitoring, fusion of health information, and remote alerts. Previous trials conducted by the authors have shown no correlation between the suit wearer's temperature at any single skin site and their core temperature, nor between single point temperature variations and subjective thermal sensation.

This paper reports on the development of a wearable, wireless, networked sensing system suitable for integration within the suit and deployment in manned missions. A sensor fusion and modelling approach is proposed that estimates the overall thermal sensation of the suit wearer, in real-time, based on the multipoint temperature data. Zhang's thermal sensation model was used in this work. Modelling is performed locally to enable cooling system actuation, provide local feedback, and accommodate application specific constraints. Experimentation with the prototype confirms the importance of: multi-site skin measurement; timely cooling actuation; and monitoring the operative's thermal state. Evaluation of Zhang's model highlights the need for a bespoke model to account for suit and mission specific factors. The deployed BSN has been evaluated through experimental trials using a number of subjects in mission-like conditions and has been shown to be appropriate for the target application.

I. INTRODUCTION

A range of body sensor network (BSN) systems have been proposed in the literature for monitoring the human body towards timely detection of health-related problems. BSN developers have targeted a variety of environments, including emergency response [1], [2], hospital [3], [4] and physiotherapy environments [5]. Added to these, several other general purpose body monitoring devices [6], [7], [8] have also been proposed. A common element of much of the work on BSNs is the focus on integrating accurate single-point physiological 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.

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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 subjected to hot, enclosed environments (such as, in the application at hand, heavy protective armour) and extreme ambient temperatures,
- supporting on-line, 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,
- supporting automated control of cooling systems commonly integrated with armoured suits.

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

A. Motivating application and problem statement

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 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 to fulfil the mission. The operative typically makes use of a signal jammer during parts of the mission.

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 stress, 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. A separate fan cycles air 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

Figure 1. Explosive Ordinance Disposal (EOD) Suit

Figure 2. Conceptual design of prototype system

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. In effect, whilst theoretically the cooling could alleviate the heat stress in some measure, mission trials, as reported by the suits manufacturer have shown both:

- the inefficient use of the battery power (hence inefficient cooling provision and limited remedial effects) by mission operatives, and,
- the need for remote monitoring of the mission operatives, in order to advise / enforce the use of cooling and assess dangerous situations.

To address the above problems, together with the imminent need to reduce the risks of such missions, this work proposes embedding into the suit a body sensor network based instrument, that, primarily, aims to:

- sense the temperature of the skin of various parts on the body, in order to assess overall thermal sensation, and relay health information to the operative and mission control, and,
- adjust the cooling dynamically to both remove the need for human intervention, and also to prolong battery life to cover a whole mission.

A secondary goal of this work is to provide the manufacturer with instrumentation that will allow them to design test strategies leading to better understanding of how the suit material and design choices are affecting the wearer's thermal sensation during use. With this in view, the prototype presented here has been designed such as to allow easy integration of additional in-suit sensors, such as accelerometers to monitor posture, heart rate monitors, skin wettedness monitors, and CO_2 sensing within the helmet. The prototype system developed both satisfies the need for remote monitoring and allows for future integration of a cooling automation component to ensure effective, need-based cooling. A conceptual view of the prototype system is shown in figure 2. The system will need to sense, model, make decisions, and act locally whilst also transmitting to a remote monitoring point data and information for real-time visualisation thus enabling human feedback in terms of both current and future missions.

In summary, it is apparent from the problem statement that 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, beyond
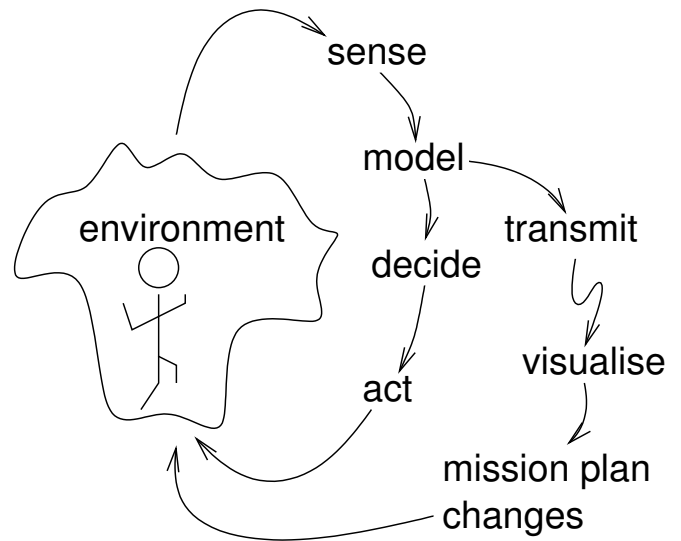
the one at hand, in detecting hazards, providing feedback to remote observers and other critical tasks that can increase the safety and benefit the overall working conditions of people operating in these environments.

B. Paper structure

The paper is structured as follows: Section II examines related work, focusing in particular on BSNs and research relating to instrumenting first responders (such as police, fire services etc). This is followed, in section III, by a discussion of the key physiological issues raised by the protective suit environment and their effect on the wearer. The system design for the instrumentation system is described in section IV, followed by a section reporting the in-network modelling aspects of the prototype: the Kalman filter model and the model used to estimate thermal sensation from multi-site, sensed temperature (section V). The implementation of the prototype is reported on in section VI. Experimental results and the prototype evaluation are presented in section VII. Finally the paper concludes with observations based on the work so far and outlines future work.

II. RELATED WORK - BODY SENSOR NETWORKS

The underlying philosophy behind the work here is that a multi-disciplinary approach is essential to develop a real-world system that meets the application requirements. Hence the work draws from physiological research towards establishing measures and conditions for defining human safety under thermal stress. Related works drawn upon are reviewed in sections III and V. At the same time, 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, reviewed below.

As previously mentioned, 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 [9], or aimed to provide general monitoring solutions for patient status within a hospital or similar environment [3]. In comparison, the work presented here is concerned with increased safety and comfort of human subjects in constrained environments through integrating into untethered wearable systems 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 and inference of application specific information.

The work described here 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, which is reviewed first below. Further, sample applications of BSNs are reviewed together with their supporting architectures and common platforms. Prior work relating to EOD suits is also summarised.

A. 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 [2]. VivoResponder is based upon an earlier product called the LifeShirt and is aimed at personnel engaged in: firefighting; hazardous materials training; emergency response; industrial clean-ups using protective gear; or bio-hazard-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 Gao et al. [1], which was developed as part of the CodeBlue project [10]. 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 mote 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. 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 emergency scene is reached.

B. Continuous monitoring solutions for patient care

The CodeBlue project [10], [4] 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 ECG and pulse oximeter, with the goal of integrating them into one device. Fulford-Jones et al. [3] present the ECG unit, which is built onto a Mica2 mote. It is designed for continuously monitoring patients in a hospital intensive care unit. Standard "portable" ECG 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 ECG 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. [5] 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 its classical monitoring counterpart solution and has the advantage that it may be left attached to a patient for a prolonged period.

C. Body Sensor Networks—Platforms

BSN 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 a 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. [11], 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

onto one chip, but has limited generality, as it cannot easily be enhanced with new components (such as a different radio device to cater for different communication needs).

A 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 (often including 16- or even 8-bit processors) would likely be considered severely under-powered in other systems and have small amounts of memory (in the order of tens or hundreds of kilobytes). For instance, the Texas Instruments MSP430 micro-controller has been used for several systems including those developed by Lo and Yang [6] and Jovanov *et al.* [8]. This is a 16-bit RISC 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 [1], [12] expand upon commercial devices such as the MicaZ motes developed at the University of California, Berkeley. 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^{2}C bus are also available. Gao *et al.* [1] developed their patient monitoring and tagging system, mentioned previously, around the MicaZ mote, adding various sensors and supporting devices. Walker *et al.* [12] 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, the specific details of which are given in section VI, although integration into custom chips is foreseen as an avenue to be explored in the future.

III. THE SUIT ENVIRONMENT - A PHYSIOLOGICAL PERSPECTIVE

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. This condition is known as Uncompensable Heat Stress (UHS).

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].

However, when encapsulated in the EOD suit and the water vapour pressure gradient between the body and the micro-environment within the suit is reduced, the required rate of evaporative cooling $\dot{E}_{req}$ to balance heat gains and losses is more representative. This rate is defined as,

$$\dot{E}_{req} = \dot{M} - \dot{W} \pm \left(\dot{C} + \dot{R} + \dot{K}\right) \pm \left(\dot{C}_{resp} - \dot{E}_{resp}\right)$$

where $\dot{M}$ is the metabolic rate, $\dot{W}$ represents the rate of heat loss from the generation of external power, $\dot{C}$, $\dot{R}$, and $\dot{K}$ are the rates of convective, radiative and conductive heat transfer, respectively, $\dot{C}_{resp}$ defines convective heat transfer through respiration and $\dot{E}_{resp}$ represents evaporative heat loss with respiration. Furthermore, the rate of heat storage will also depend on the ambient conditions, not only the microclimate within the EOD suit, and is likely to increase more quickly during operations in hot environments compared to temperate ones.

The UHS condition is associated with significant physical and psychological impairment [14] therefore placing the individual at an increased risk of making an avoidable error and jeopardising the mission. 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 [15], [16].

In such trials, in brief, participants undertook up to four 16:30 (min:sec) activity cycles (further described in section VII) consisting of treadmill walking, unloading and loading weights from a kit bag crawling and searching activity, arm cranking, seated physical rest, interspersed with 30 sec intervals between the first three activity cycles. Aspects of hand-eye coordination and psychological performance were also assessed. Heart rate, rectal temperature, and skin temperatures (arm, chest, thigh and calf [17]) were monitored throughout. Thermal sensation, reported on a 0 to 8 scale [18] that incorporates verbal anchors from unbearably cold (0) to comfortable (4) to unbearably hot (8) was sought at specified intervals. Note that throughout the reminder of this paper, the 0 to 8 Young's scale has been normalised to a -4 to 4 scale, with -4 being unbearably cold and 4 unbearably hot.

The trials have indeed demonstrated that wearing an EOD suit dramatically increased physiological strain as indicated by elevated heart rate (up to 60 BPM (beats per minute) more than without the suit; see figure 3) and gradual increase in core and mean skin temperatures (up to 2°C more than without the suit; see figures 4 and 5) and thermal sensation (increasing from a reported score of 0 (neutral) prior to activity to 4 (unbearably hot) after 66 min) in all participants. Such
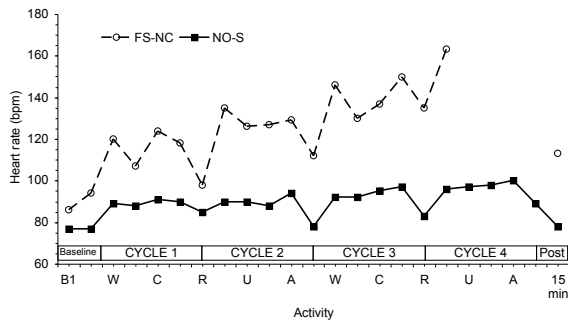
Figure 3. Typical heart rate response to EOD activity simulation (based on a single subject trial). FS-NC=full suit, no cooling; NO-S=no suit; W=walking; U=unloading/loading weights; C=crawling and searching; A=arm exercise; R=seated rest. NB. Two of four subjects were not able to complete four activity cycles.

Figure 6. Skin and rectal temperature over time for a subject wearing the full suit with no cooling. Note how core temperature rises with thigh temperature after the two merge. This experiment needed to be terminated as the subject could not continue.
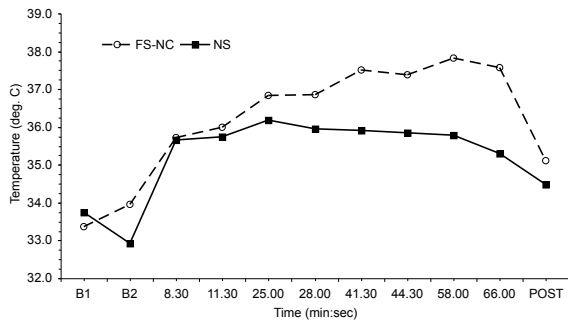

Figure 4. Mean skin temperature responses (averaged over 4 subjects; error bars are omitted for clarity). FS-NC=full suit, no cooling; NS=no suit.
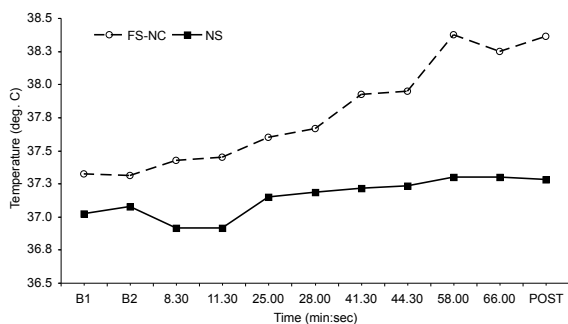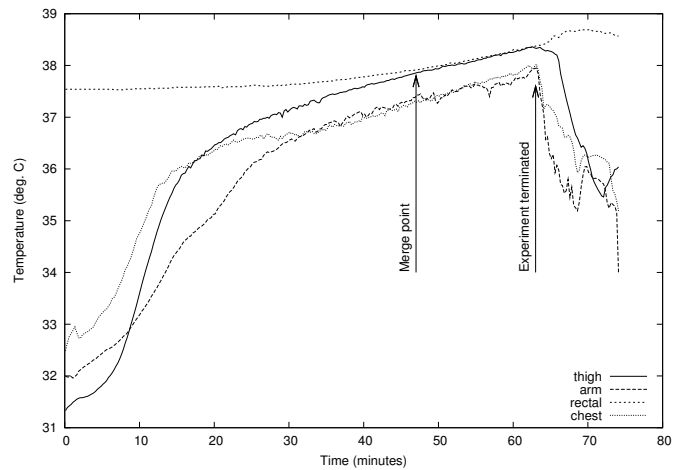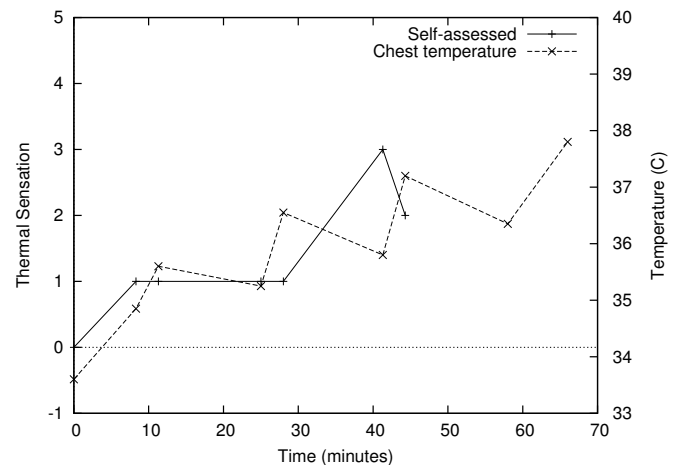

Figure 7. Self-assessed thermal sensation compared with chest skin temperature for subject 1.

Figure 5. Core temperature responses (n=4; error bars are omitted for clarity). FS-NC=full suit, no cooling; NS=no suit.

physiological variations are likely to have a negative impact on performance. Continuous multi-site monitoring is hence essential since the rate of rise in core body temperature can abruptly increase when mean skin temperature reaches a similar level. An example of this effect is shown in figure 6. Any significant increase in core temperature is dangerous and therefore, the merging of skin and core temperatures is a useful early warning indicator of a potential problem. In the example shown in figure 6, the experiment had to be terminated as the subject could not continue.

In a separate experiment with the same activity regime, a dramatic increase in thermal sensation occurred between the 30 and 40 minute mark, as shown in figure 7, corresponding to the subject feeling much hotter than previously. At the same time, the chest temperature (which would normally be the only site monitored in most BSN systems for First Responders) has actually decreased by about one degree. Just after this, the self assessed sensation drops to 2 while the temperature increases. These results reinforce the need to measure temperature at a

number of skin sites and / or the need for measurement of other physiological parameters in order to accurately predict thermal sensation.

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 ($\approx 3°$C) and elevation in upper arm temperature ($\approx 0.5°$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. Also, cooling specific body areas influences thermal sensation even though core temperature remains unchanged [19].

Identifying and attempting to predict potentially hazardous conditions from excessive and repeated exposures has been and an area of high debate for the past 30 years [20]. The arena is still open to new research due to the intricate interactions of a wide variety of physical and physiological phenomena that determine the probability of hyperthermia and UHS. A number of efforts have been directed at defining thermal comfort limits and heat stress indices, however most of this research refers to people within air conditioned spaces rather than the hot enclosed environments generated by protective clothing. Taylor [20] notes that the WBGT (wet bulb globe temperature) index more frequently used by industrial, military and sporting applications to assess thermal comfort has the significant limitation of not considering either variations in skin temperature or skin wettedness. Moreover the usefulness of the WBGT index for clothed subjects has been found to range from inferior to wholly inappropriate when encapsulating ensembles such as the one studied here are worn.

To summarise, the work towards the development of a sophisticated multi-sensor instrument such as the one proposed here is motivated by:

- clothing manufacturer and field user experience of thermal discomfort when wearing the EOD suit,
- previous experimental studies regarding the thermal effects of the EOD suit, and,
- research findings in the wider area of hazardous conditions for people in hot environments.

The previous two sections have motivated the need for a system to monitor and assess thermal sensation and heat stress indicators, as well as providing a summary of the physiological effects surrounding the use of protective suits using thermal information to estimate thermal well-being of operatives in protective clothing. The following section describes the design requirements for a suit-integrated instrument aimed at monitoring EOD suit wearers.

IV. SYSTEM DESIGN

The system design has been driven by a mixture of constraints largely falling into the following categories:

- Suit related constraints, such as its modular structure and the need to avoid running wires between the various garment components, and the overall wearability of the instrument.

- Application related constraints, such as the intermittent use of signal jammers during a mission, communication distances, and physical obstructions in the environment.
- Safety critical concerns, such as the need for in-suit actuation of cooling and alerting the operative and mission control of unsafe thermal conditions.
- Scope of the instrument, such as its dual use as a field deployable system as well its use in laboratory trials for both physiological research and suit design analysis.

In response to the suit related constraints, the overall design of the system is structured around a mix of wired and wireless communication. Multiple sensing packages are wired to each processing node. The wiring will be incorporated into the fabric of the suit or an undergarment in future. Although wireless communication from each sensor package might seem feasible, this would both increase the size and weight of the sensor packages and require additional batteries or power harvesting devices, hence decreasing the wearability of the system. Since there is a need to sense skin temperature at a number of points, such an approach would be unwieldy.

Wireless communication will allow communication within the components of the instrument given that the instrumentation for jacket, trousers, and helmet needs to be physically separate to ease robing and disrobing. This mix of wired / wireless communication is similar to that of the Xsens Moven inertial tracking system [21]. Hence the system is designed as a four node body sensor network with three tiers of communication: sensor package to processing nodes (wired); node to node within the suit (wireless); and node to base station / remote monitoring unit (wireless).

With regard to application related constraints, there are a number of reasons to expect and allow for intermittent communication, such as the common use of signal jammers during bomb disposal missions, and temporary obstruction of the radio signal as the user moves about. Since the instrument has to serve a safety critical application, it must sustain operation during loss of communication with the remote monitoring unit. Consequently the system must support two modes of wireless communication: one, short range communication, between body worn nodes that can be shielded and thus made less sensitive to signal jammers, and the other, long range communication to the remote monitoring unit (base station). Wireless short range communication that is immune to signal jamming devices is an open problem, however possible options to be explored include near-field communication [22]. Due to the nature of the long-range communication, a single node maintains this link, with this node acting as a data and information concentrator for the rest of the network.

Given that long range communication is likely to be blocked for extensive periods, the system must be able to: cope with this communication loss without overfilling network buffers in order to ensure that no data is lost, and; on reestablishing communication, transmit up-to-date data as well as historical data. The options chosen here was to buffer data when communication channel loss has been sensed. The safety critical aspect of the system, as well as its real-time use, implies the use of a priority protocol.

A unifying aspect of the safety requirements, including the need for in-suit actuation of cooling and alerting the operative of unsafe thermal conditions, is that all require information rather than data. Specifically, operatives are to be alerted when predicted thermal sensation (rather than merely single point temperature) exceeds some threshold. Similarly, cooling actuation should be based on information extracted from the global thermal state of the operative, possibly coupled with heart rate levels and posture, in order to maximise the effectiveness of cooling.

Responding to the above requirement, the prototype developed here processes the acquired data locally, "in-network", at one of the nodes that are worn within the suit, rather than at a remote base station. This enables cooling actuation and alerts to be generated locally, without dependence on the remote monitoring station or the long range communication link. Furthermore, buffering *information* on the evolution of the operative's global state and alerts over time removes the burden on the network to store large amounts of data. Although, temperature sensors generate a relatively small amount of data at a low rate, the system must cater for the addition of several other sensor types, including high data rate sensors such as accelerometers, further justifying both the extraction and buffering of information. A more effective priority protocol can then be designed whereby important event information can be transmitted first on reestablishment of the link. With this design approach, no delays occur in alerting the operative and any delay in informing mission control of an alert is minimised. Note the separation of concerns as a result: the information to operative is dependent on the short range communication only.

Another aspect of the safety requirement is the provision of some level of hardware redundancy, without compromising the system's wearability. Whilst the fault isolation and management requirements for a system such as this have not been fully resolved, steps have been taken towards increased sensing reliability and monitoring of sensor health. For example, redundant temperature sensors are employed to reduce the information cost of sensor failure and also to improve the quality of the data obtained (see section V-A for further discussion).

With respect to the scope of the instrument, although the main motivating use case for the system is in the field, where factors such as communication reliability and range, and timeliness of alerts will be critical, another important use of the system will be in the laboratory, both to study the physiological effects of wearing the suit under different conditions, and to study how suit design changes affect the wearer. Hence, two functional modes need to be supported: one where all detailed sensor data is transmitted and one where only abstracted information is transmitted, such as thermal sensation level, temperature trends, posture and alarms. Setting the functional mode must be done at start up, but it may also be desirable to change mode during a mission at the request of the mission controller. For example, the mission controller may see that the operative is becoming thermally uncomfortable and wishes to obtain temperatures profiles for different parts of the body and consider them in conjunction with other sensed physiological parameters.

A variety of processing algorithms are needed to cater for the multiple functional aspects of the demonstrator: 1) estimating temperature gradients from past data values, 2) threshold comparisons of individual skin site temperatures, average temperature and thermal sensation to generate alarms, 3) sensor fusion to give reliable skin site temperature estimates, 4) prediction of temperature in case of missing or invalid sensor data, 5) modelling to generate thermal sensation estimates, and finally, 6) multi-modal sensor fusion and predictive modelling to generate actuation signals. These requirements highlight the need for powerful processing nodes.

All constraints discussed in this section have been considered in the prototype design although not all have been implemented to date.

V. In-Network Modelling

In this section, two in-network modelling components are described: Kalman filtering, and thermal sensation modelling.

The need for in-network information extraction has been justified in section IV for this particular application, however the rationale for performing such in-network processing is more generally applicable. Commonly the argument raised is based on the relative energy cost of computation versus the energy cost of reliable transmission. Since computation is relatively cheap, it is advantageous to perform some computation in the network prior to transmitting on the basis that this computation reduces the number of bits that need to be transmitted [23]. The Kalman filter is one such computation that can reduce the number of bits transmitted by fusing data from redundant sensors. Thermal sensation estimates can also be transmitted in fewer bits than a detailed thermal profile from a large number of sensors. A sensation estimate removes unnecessary contextual information such as number of sensors, position of sensors and whether redundant sensors have been used.

A. Kalman filtering

There are several reasons for incorporating Kalman filtering [24], [25]: 1) to recover some resolution in the temperature measurement that is lost through A/D conversion; 2) to reduce sensor and measurement noise; and 3) to fuse multiple redundant sensor readings into a single estimate. Skin temperature over time is clearly a non-linear function, however since there are so many factors (both measurable and unmeasurable) affecting it, and since it tends to change relatively slowly, the linear assumption implicit in a Kalman filter is a good compromise. Two possible models were considered for this work: one that assumes that the temperature does not change (and thus any change is noise), and one that assumes that the rate of change of temperature is constant (and thus any change in the rate of change is noise). In the present system, the latter was used, as it provides smoothed estimates of both temperature and rate of change of temperature. Since temperature rate, which is used by the thermal comfort model described in the next section, is typically in the range $\pm 10^{-3}\,^{\circ}\mathrm{C}.s^{-1}$, and since sensor noise and quantisation is several orders of magnitude

larger, time-based filtering is imperative for obtaining accurate thermal sensation estimates.

Given a single skin site temperature x_s, a constant rate of change temperature model is comprised of the state space $\mathbf{x} = (x_s, \dot{x}_s)^T$, a transition model $\mathbf{F} = \begin{pmatrix} 1 & \Delta t \\ 0 & 1 \end{pmatrix}$, and some model noise $\mathbf{w}$, such that at time k,

$$\mathbf{x}_k = \mathbf{F}\mathbf{x}_{k-1} + \mathbf{w}_k$$

The vector of sensor measurements for a skin site $\mathbf{z}_k$ is given by

$$\mathbf{z}_k = \mathbf{H}\mathbf{x}_k + \mathbf{v}_k$$

where $\mathbf{H} = \begin{pmatrix} 1 & 0 \\ 1 & 0 \end{pmatrix}$ is the sensor model and $\mathbf{v}$ is noise affecting the sensor. Sensor measurement noise is distributed normally with a zero mean and covariance $\mathbf{R}$. It is assumed that sensor noise is uniform across sensors and uncorrelated between sensors and thus $\mathbf{R} = \sigma_z^2 I$ where σ_z^2 is the variance due to measurement noise in a single sensor. This variance was estimated for the sensors used from measurements made in a water bath with stable temperature. The model noise $\mathbf{w}$ is also distributed normally with a zero mean and covariance $\mathbf{Q}$. In terms of the model, the noise $\mathbf{w}_k$ corresponds to the change in temperature and temperature rate due to the "acceleration" rate of temperature a_k, which is

$$\mathbf{w}_k = \mathbf{G}a_k$$

where $\mathbf{G} = (\Delta t/2, \Delta t)^T$. It is thus possible to derive an expression for the covariance $\mathbf{Q}$ in terms of Δt and the variance in the temperature acceleration σ_a^2. The acceleration rate variance provides a convenient tuning parameter to allow for more or less rapid variations in skin temperature.

Although all sensors report degrees Celsius, some calibration and outlier rejection is required and this is performed prior to filtering. The Kalman filter's sensor model provides a mechanism for fusing sensors that are positioned symmetrically (such as left upper arm and right upper arm). In most other work, temperature measurements are typically taken from a single side on the basis that it is known that temperatures are bilaterally symmetrical in healthy subjects [26], [27]. This fact is used here to compensate for bilateral temperature asymmetry due to other factors, such as differing thermal conductivity between the sensor package and the skin between the two sides. In essence, any temperature asymmetry is treated as noise by the filter.

A key challenge is to support the Kalman filter with minimal computational cost. In the prototype system, Python was used with matrix manipulation done via Numeric, and although this is a relatively inefficient approach, it reduced coding time dramatically and was still able to run in a real-time mode on the platform of choice for this prototype.

The output of the Kalman filter is a series of smoothed estimates of skin temperature at various sites and rate of change of temperature at those sites. The following section describes the use of a model to estimate thermal sensation.

B. Thermal sensation modelling

1) Thermal sensation model: Several models for estimating human thermal sensation exist. Examples are the PMV-PPD, SET* [28] and Zhang's model [29]. Of these, Fanger's Predicted Mean Vote (PMV) model, provided as a index look-up table and most used in human comfort studies, is based on thermoregulation and heat balance theories [30]. According to these theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. In extreme thermal conditions, this regulation is necessary for the body to function properly. In office buildings (for which the PMV model was intended), it is very unlikely that temperatures associated with serious bodily dysfunction will occur, but thermoregulation is still used to maintain a comfortable heat balance [31]. Maintaining this heat balance is the first condition for achieving a neutral thermal sensation. However, Fanger noted that "man's thermoregulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist" [32]. To be able to predict conditions where thermal neutrality would occur, Fanger investigated the body's physiological processes when it is close to neutral and determined that the only physiological processes influencing heat balance in this context were sweat rate and mean skin temperature, and that these processes were a function of activity level. In recent years, however, the model has been questioned with respect to the methodology used by Fanger to derive it. Moreover, more recent laboratory studies have shown great discrepancies from predicted PMV results. As Charles [30] points out, the error in predicted PMV tends to increase where heavy clothing or high activity levels are involved. Given that both heavy clothing and high activity cycles are at the core of the application reported here, in this work, a model provided by Zhang [29] has been evaluated in detail and adopted as a starting point for this component of the prototype reported here. Note that a detailed comparison of different models is beyond the scope of this work; rather, Zhang's model is chosen as a focus due to its apparent suitability for enclosed environments.

Zhang validated the model with a large number of human subject trials and it is solely based on multi-site temperature measurement, fitting within the capabilities of the instrumentation proposed in the work here. 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 the bias of -4 applied to the trials scale as described in section III to unify the self assessed and modelled thermal sensation. This unified scale was used throughout 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 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. 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 $\sum_{i \in B} w_i^{\pm} S_i / \sum_{i \in B} w_i^{\pm}$ where B is the set of body segments. Different weights w_i^{+} or w_i^{-} are used depending on whether thermal sensation S_i is greater or lower than the mean sensation. According to Zhang's model, all w_i^{-} weights are negative, presumably corresponding to an inverted relationship between local and overall sensation.

It should be noted that in order to apply Zhang's model of thermal sensation to the protective suit environment, four skin site measurements were used and these were mapped to the set of body segments required by the model, with corresponding changes in associated weighting.

In the model evaluation studies conducted by the authors here, a perfect match was not expected (and indeed was not obtained, as documented below). The reasoning is twofold: 1) Zhang's model has been developed for stationary subjects whilst the application here refers to highly active regimes, hence affecting the model prediction accuracy, and 2) the effects of the suit on the wearer are expected to contribute significantly to their subjective assessment of the thermal sensation.

Nevertheless, the evaluation of Zhang's model highlights an important point for the work here: the need for a bespoke thermal sensation model to cater for both typical exercise regimes encountered in bomb disposal missions and the effects of the suit. With regard to physical activity influence on thermal sensation, Goto *et al.* [33] noted that "activity level is probably one of the least well-described parameters of all the parameters that affect thermal sensation, comfort and temperature preferences", hence it is expected that work on such a bespoke model will provide novel and useful results.

Finally, thermal sensation is different from measures such as thermal satisfaction (I am satisfied / unsatisfied with the thermal conditions), thermal acceptability (the thermal conditions are acceptable / unacceptable), thermal comfort (I am comfortable / uncomfortable), and thermal preference (I would like to be warmer / cooler). Thermal sensation simply measures the temperature that occupants perceive, whereas other measures also ask occupants to evaluate the appropriateness of that temperature. It is foreseen that, of the alternative measures above, thermal acceptability is going to be of most interest in further studies.

In order to evaluate the appropriateness and accuracy of Zhang's model for this application, a series of experimental trials were conducted with and without the EOD suit. Participants conducted activities representative of those performed during bomb disposal missions. The participants verbally reported overall sensation followed by individual values for the back, chest and arms, groin and legs. Given the activity regime the subjects undergo in our experiments, it is not feasible to collect subjective thermal sensation data more frequently than twice during each activity cycle, once at the end of the arm exercise and once at the end of each activity cycle.

2) Zhang's model evaluation: Both the static and dynamic components of the model have been evaluated and the results for one subject are presented here. Similar divergence between the predictions provided by the model and the subjective thermal sensation have been found for a number of subjects. The evaluation was performed for the static component of the model over a number of subjects in two stages: 1) with a one-hour long bomb-disposal-like activity regime and no suit being worn; 2) the same activity regime but with the full suit being worn.

With regard to stage 1, the difference, for the first 20 minutes, between subjective and predicted thermal sensation (see figure 8) can be attributed to the physical activity, which is not taken into account in Zhang's model (the model specifically refers to stationary subjects). Note that the shape of the predicted and subjective trends is similar after the subject becomes more accustomed to the physical strain.

In comparison, for stage 2, the effect of the weight of the suit has resulted in a dramatic increase in the reported subjective thermal sensation leading to the subjective and predicted thermal sensations being apparently closer in trend (see figure 9). In fact, the final upward trend of the subjective thermal sensation corresponded to the wearer being unable to carry on with the experiment and so the predicted thermal sensation remaining at 2 is misleading and a significant error. Note that whilst the trends in figure 9 are common for subjects wearing the suit for the first time, subjects who are habituated with the suit tend to have predicted thermal sensation values that match the trend of their reported subjective sensation throughout the experiment, taking into account the physical activity induced deviation (see figure 10).

In spite of the evident inappropriateness of the model for the application discussed here, it serves as a baseline for development of a bespoke model that better fits the application. Moreover, it allows for identification of further parameters that need to be considered in the bespoke model such as posture,
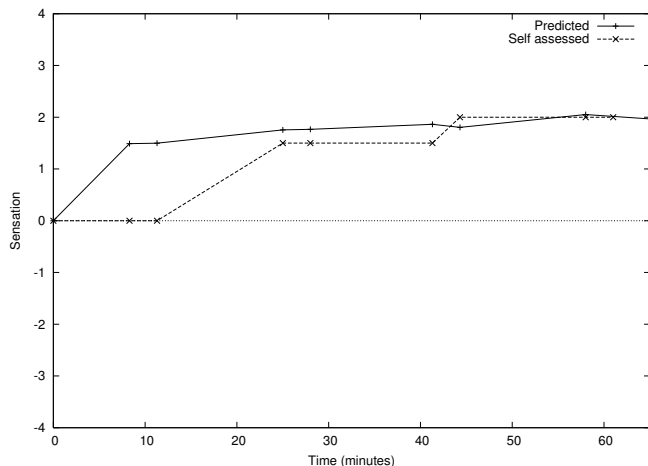
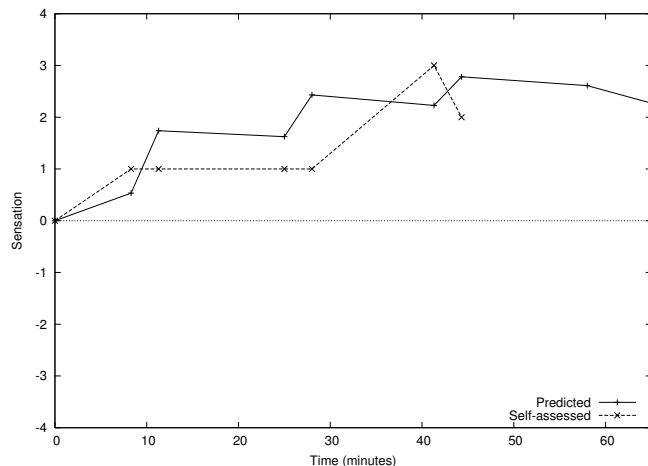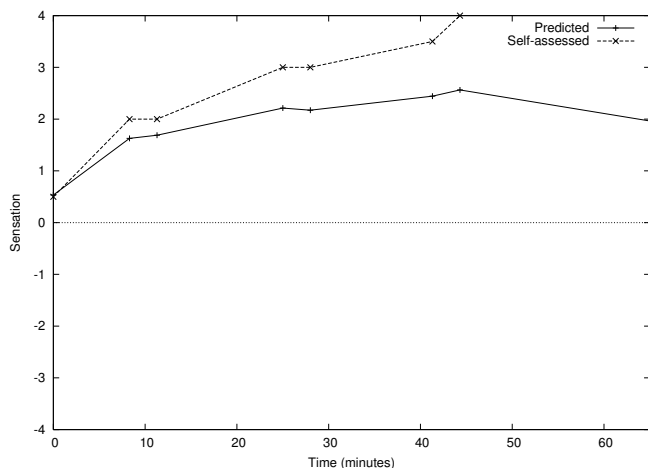Figure 8. Overall thermal sensation over time during the activity regime with no suit.

Figure 9. Overall thermal sensation over time during the activity regime with the full suit and with no cooling.

Figure 10. Overall thermal sensation over time for a habituated subject with the full protective suit and no cooling.
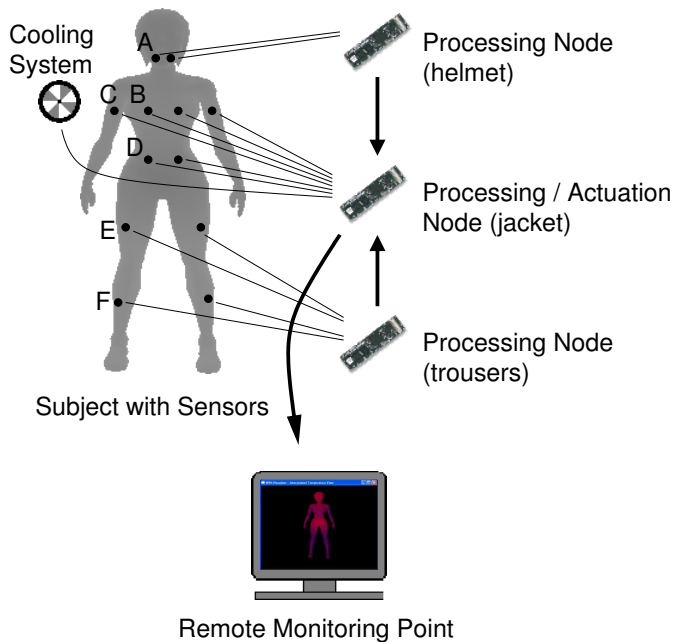

Figure 11. Prototype system hardware components and sensor positioning.

skin wettedness, and heart rate. Consequently the model was deployed as described further in the paper in the prototype presented here. Further analysis of dynamic model predictions as produced by the prototype system is given in section VII.

VI. Prototype implementation

A. Platform and sensors

The Gumstix Connex 400xm-bt board was selected as the main processing and communication platform (supporting the processing and actuation nodes) within the suit. 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 that was designed in-house. As shown in figure 11, three Connex boards are used; two as processing nodes and a third acting as a processing as well as an actuation node. The processing nodes, actuation nodes, and remote monitoring point (acting as a base station) form a wireless network.

Each processing node is wired to several sensor packages via an I^2C bus. Sensor packages are daisy chained along the bus, thus minimising wiring. The prototype system discussed here uses twelve sensor packages based on Analog Devices ADT75A temperature sensor ICs (shown in figure 12). 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 $1/16°C$. Sensors are sampled at a rate of once per second.

The sensor packages are attached to the body following the standard positioning used for skin sensors as used by Thake and Price [16], [17], which is a subset of the locations described by Shanks [34]. The used skin sites were: A – neck, B – chest, C – bicep, D – abdomen, E – thigh, F – lateral calf muscle, as indicated in figure 11.
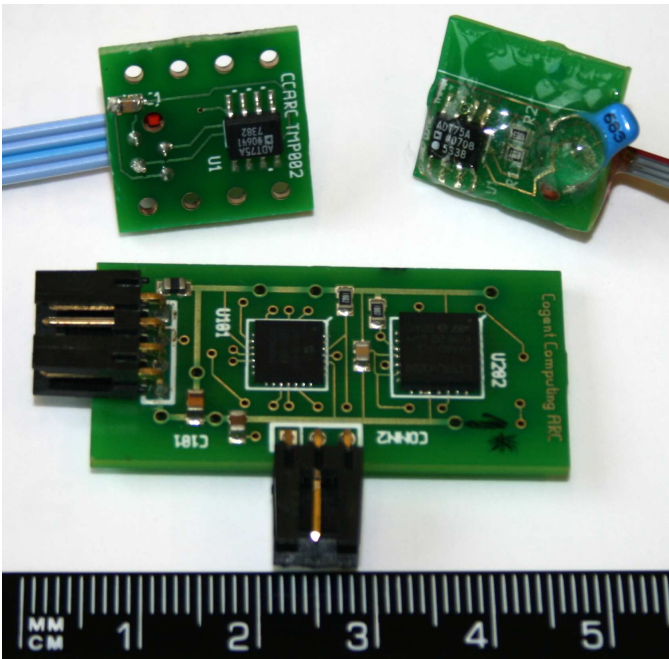
Figure 12. Sensor packages with ADT75A temperature sensor IC prior to waterproofing (top left), after waterproofing (top right) and enhanced version which includes a triaxial accelerometer (below).

B. Waterproofing and calibration

Early experiments demonstrated that sensors need to be waterproofed due to the large amount of perspiration produced by subjects when wearing the suit. To waterproof the sensor package, an epoxy resin was used. The resin layer was reasonably thin and did not introduce a noticeable lag in response to temperature changes. A further benefit of the resin layer is that the package sits more comfortably against the skin. Although sensors are factory calibrated, readings from different sensors in a water bath varied from each other by several degrees indicating the need for further calibration. Therefore, individual sensors were calibrated by placing them in 5 litres of stirred water with an initial temperature of 50°C and comparing with a mercury thermometer while the water cooled to room temperature. Note that the same thermometer was also used to calibrate a wired data logger used for validation in the experimental work reported further in the paper.

Sensor variance σ_z^2 was estimated to be $0.0025°C^2$ based on measured variance between two independent sensors at the same temperature and assuming that the variance for all sensors of this type is the same. Note that this sample variance does not account for errors in the calibration offset, nor errors induced by changes in the sensor over time.

C. Communications

Although the system design calls for differentiating the in-suit communication and the long range communication, the implemented prototype makes use of Bluetooth (class 2) throughout, which has a typical operating range of around 10 metres indoors, and slightly more outdoors, depending on the environment. Class 1 equipment could be used to extend the range at the cost of lower battery life (which for the prototype here is approximately 8 hours of full functionality). An alternative is to use ZigBee, which would reduce the available data rate but allow a longer range.

As discussed in section IV, to compensate for communications link failures and fulfil the dual instrument scope, it is necessary to buffer both data and the inferred information. Given that only data and information is buffered rather than formatted, ready-to-transmit packets, this approach saves memory and avoids dropped packets due to overflowing communication buffers. Bluetooth Network Encapsulation Protocol (BNEP) is used to transmit data and the underlying L2CAP protocol ensures reliable transmission. The Gumstix platform has the memory capacity to store all acquired data and information for at least one whole two hour mission.

D. System data flow

The data and information flow for the system is illustrated in figure 13. The first phase is to smooth the raw sensed data from all skin site pairs using Kalman filtering (each pair corresponds to two symmetrically positioned sensors; see section V-A). Filtering is done on a per-node basis and the result is transmitted to the actuation node which collates a skin temperature vector. The actuation node applies a thermal sensation model (see section V-B1) to the resulting vector, which yields an estimate of the thermal sensation for the current point in time. Both the filter and sensation model have been implemented in Python and have proven to be sufficiently lightweight. The next phase is to transmit this to the remote station. The last phase is the information arrival at the remote monitoring station and its conversion to visual form.

E. Alert mechanism

A key problem with heat stress, particularly in military situations, is that the operative may continue to try to work despite discomfort until they are incapacitated or suffer thermal injury. The prototype provides an early warning system that can alert the mission controller that the operative is approaching safety limits. Currently this alert system is based on thresholds for average and individual segments skin temperatures and thermal sensation. The alert is in the form of an audible and visual alarm at mission control, although it is planned to extend the feedback mechanism with visual and haptic alarms for the operative.

F. Remote monitoring

Effective visualisation systems need to assist the mission controller with interpreting the data. It has been the authors' experience that it is difficult to assess thermal comfort by looking at individual skin temperatures. Furthermore, skin temperatures tend to change slowly and overall trends are difficult to assess. In many trials, 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 may be constant. A thermal sensation estimate provides a clear indicator of the thermal comfort and
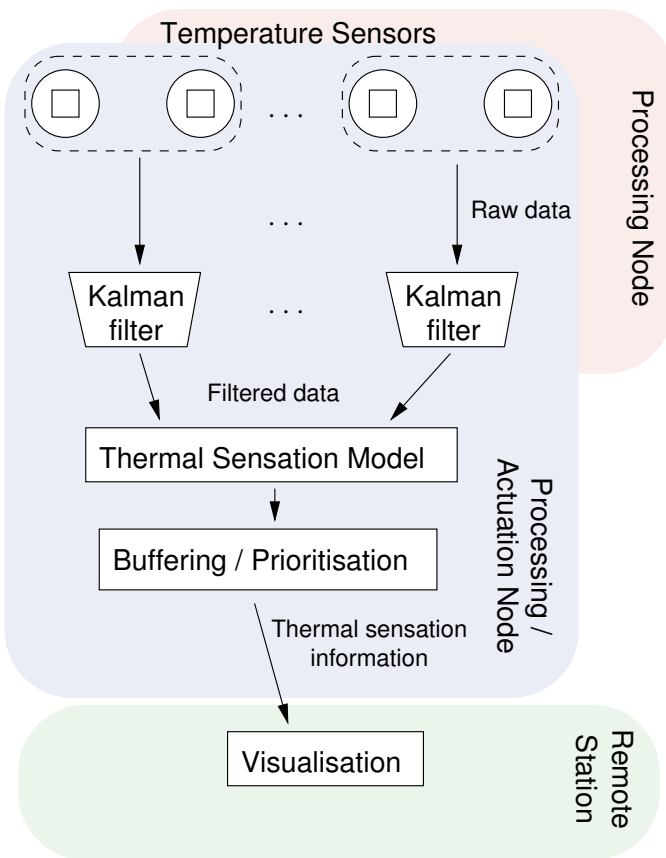
Figure 13. Data and information system flow showing the division of processing across the Processing Nodes, Processing / Actuation node and remote station.

Figure 14. A snapshot of the remote monitoring visualisation component in "information only" mode.

Figure 15. First activity: walking at 4km/h.

this is intended to be the overriding parameter for mission control. Ideally, in the future, this parameter will be fully representative of the thermal state of the operative.

A snapshot of the remote monitoring visualisation component in "information only" mode is shown in figure 14. The main information display panel includes a 2D figure, with individual segment's thermal sensation and temperature mapped on the body at sensing sites. A separate panel displays average temperature, estimated overall sensation, alerts, sensors health status, cooling actuation status, has provision for displaying posture information, and provides time series graphs of average temperatures. There are threshold based alerts for both the overall thermal state of the operative as well as for individual body segments. In "full data mode", the display shows, in addition to the above, time series graphs of all raw sensor values.

VII. EXPERIMENTAL RESULTS AND PROTOTYPE EVALUATION

A. Experimental setup

The prototype instrumentation system was evaluated through laboratory experiments representative of a typical bomb disposal mission situations by having the subject undertake a series of activities and tasks. The experiments begin with sensors being attached to the subject using elasticated straps, fo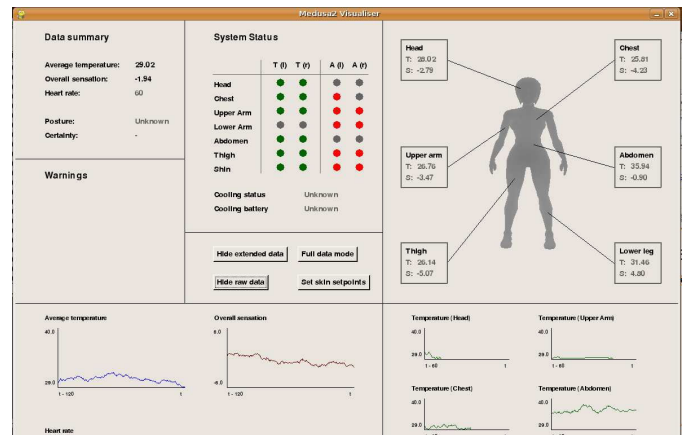llowed by suiting-up. The subject wore the outer shell of the bomb disposal suit including the jacket and trouser segments in addition to armour plating, helmet and boots.

The subject then undertakes an activity regime composed of: (1) walking (3 minutes) (see figure 15); (2) kneeling while putting weights into and out of a rucksack (approximately 2kg, 2 minutes) (see figure 16); (3) crawling (2 minutes); (4) arm exercise (4 minutes); (5) sitting (3 minutes); (6) standing (1 minute). Temperature data is consistently collected both via the prototype wireless system and via a wired-in data logger (accepted, commonly used, off the shelf, laboratory instrumentation for life sciences physiological assessments). Data was gathered during two consecutive activity regime runs as above, in a 5m x 6m draft free room, with an ambient temperature of 21°C. The experiments have been repeated for a variety of subjects, with or without acclimatization, new or not to the suit, more or less fit generally, and so forth.

B. Instrument evaluation against high level user requirements

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

Figure 16. Second activity: kneeling while removing weights from a sack. The wired-in data logger can be seen taped onto the subject's lower back.

Wearability: Instrumentation systems, particularly those used for bomb disposal missions, are expected to have stringent wearability 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.

In previous experimentation, some of the sensor packages have been integrated into clothing, whilst some (neck, thigh, and calf) have been taped to the skin. It was observed that clothing integrated sensors produced less accurate data than ones taped to the skin because contact with the skin surface changed when the subject was moving. While avoiding the problem of inconsistent contact, strapping on sensors, on the other hand, means that they are, all in all, less convenient to apply and remove than clothing integrated sensors. In comparison to using a standard wired data logger, the strapped-based wireless system mounting takes less time and has been found to be more comfortable by experimental subjects.

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 and no out of range readings were recorded. Note that node processing removes out of range values from the data sets further used for transmission and information extraction. In comparison, in the wired data logger measurements, some errors were apparent. The worst case encountered had only 39% yield for a particular sensor but usually the yield was much higher. In general, the number of outliers were significant for the data logger.

Accuracy is a measure of how closely the sensor data obtained corresponds to the underlying physical phenomena being sensed. Following calibration, the instrument produced highly accurate measurements evidenced by comparison with data logger measurements (after exclusion of data logger outliers). Quantisation due to the 12 bit resolution causes some information loss that was offset by sampling frequently and

using the Kalman filter described in section V-A.

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). Robustness has been a significant concern throughout the development of the system. Early prototypes suffered from problems with sweating affecting the system, which have been resolved by waterproofing sensors with epoxy resin. Further problems have been generated by shocks during trials, which may have been related to inadequate protection of the nodes and the amount of stress placed on the Hirose connectors. Strain on the cables leading from nodes to the sensor boards lead in initial prototypes to sensors becoming detached from the skin or connections being broken; a variety of cable types and lengths have been tested, resulting in increased robustness. The weight and configuration of the suit components places supplementary strain on the prototype as a whole and limits the options for the packaging and placement of the network nodes and the Start-up system switch. Improved solutions for field-robust packaging are currently being developed. 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. Compared to the commonly used data logger and thermistors for physiological measurement, the prototype has demonstrated several advantages. First, by being untethered, it allows data gathering to occur in the field, at a sampling frequency greater than 1Hz, compared to 1/15Hz for data loggers. Second, it provides a means for real-time remote monitoring, operative feedback and cooling actuation as opposed to offline data acquisition, which is the only role fulfilled by the wired data logger. Third, it offers the means for real-time graphical visualisation of the measured parameters and the extracted information such as thermal sensation and alerts.

Battery life is 3.7 ($\pm$0.4) hours for the processing nodes and 3.3 ($\pm$0.1) hours for the actuation node.

C. Experimental data analysis

A summary of temperature data obtained from all sensors for a sample subject run is given in the series of graphs in figure 17. Data was recorded during the experimentation using the prototype system. 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 VII-A). 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 three-fold. First, the system under development was compared, in terms of the criteria discussed previously (and particularly here, in terms of its "data acquisition" functional requirement), with a commercially available, wired-in data logger. As reported above, the prototype was an improvement over the data logger in several respects. Second, dynamic thermal sensation estimates produced by the prototype were analysed.

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 3°C over 30 minutes) indicate the need for both operative 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 first responder 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 the chest sensors during crawling (activity 3). Crawling is strenuous with the suit on, so this result is surprising. This however is likely to be due to a redistribution of loading points to which the body is exposed, due to the mass of the suit, that is associated with such a change in posture. This indicates the need for added sensing such as skin wettedness and posture information in order to predict the physiological effects of wearing the suit during such exercise regimes. To address this, a multi-modal sensor board, shown in the bottom part of figure 12 has been designed in house, produced and evaluated. The board integrates 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 various sites on a subject's body. The acceleration data has recently been successfully used for generating posture information, which will allow enhanced, activity based remote visualisation of the subject (thus provide key safety information to mission control) and lead to improved estimates about how the thermal state and thus comfort of the subject is changing. Hence this will improve the timeliness and appropriateness of autonomous cooling decisions.

Considering now the second aim of the data analysis exercise, results provided by the prototype when including the dynamic aspect of Zhang's model are shown in figure 18. In this experiment, a fully suited subject walked on a treadmill for one hour at a speed of 4 km/h. The first problem evident from the graph is that the bounds of [-4,4] are exceeded, particularly for the thigh. Second, a rapid variation in sensation occurs from moment to moment, which is unlikely to correspond to the subject's perception. The former problem stems from what appears to be a flaw in the design of the model, since the dynamic components are neither bounded in themselves nor processed by the logistic function. The latter problem appears to stem from a high sensitivity to variation in the rate of change of temperature. This may reflect Zhang's original method of calculation for this parameter. For both above problems, this
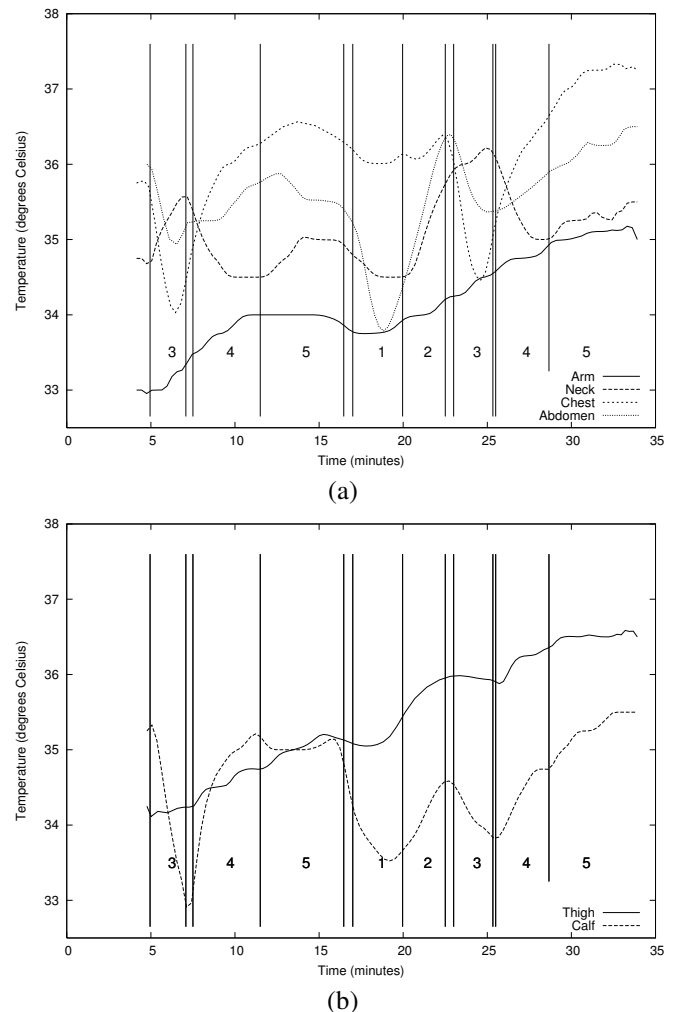

Figure 17. Skin temperature over time for (a) upper, and (b) lower body. The vertical lines in each graph show the start and end of activities. Each activity is represented by a number: (1) walking; (2) kneeling while putting weights into and out of a rucksack; (3) crawling; (4) arm exercise; (5) sitting; and (6) standing.

is a reminder to the reader that the model was developed empirically and had not encountered thermal stresses of the nature explored here.

VIII. CONCLUSIONS AND FUTURE WORK

Wearing heavy armour during bomb disposal missions may induce uncompensable heat stress due to the enclosed nature of these suits. The work presented here has highlighted the need for detailed measurement of skin temperature, the applicability of body sensor network technology to this application domain, and the need for a novel thermal sensation model for EOD suit wearers, based on skin temperature and other physiological parameters. BSN technology is undoubtedly 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.

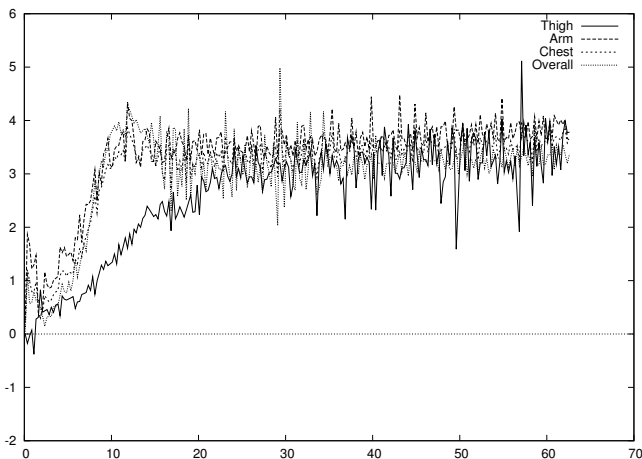Experimental results obtained with a detailed, BSN-based temperature monitoring instrument showed that:

Figure 18. Predicted thermal sensation including dynamic component of Zhang's model.

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 and thus there is value in sampling at several skin sites;

2) skin temperatures exhibit large variations leading potentially to heat exhaustion hence the need for health monitoring of subjects;

3) the hardware and software support for autonomous actuation of the in-suit cooling system is enabled by the prototype; future work will determine how best generate actuation signals in response to changes in temperature to ensure that the wearer is kept comfortable.

The approach taken by the authors further exploited the networked aspect of the prototype by developing a novel in-network information extraction method and communication of real-time thermal sensation to mission control to facilitate both high information yield and timely remedial actions.

Overall, this work has the potential to provide real improvement to both the working conditions of EOD technicians and greater levels of safety.

There is however, large scope for further research and development work before the application at hand is fully resolved. Apart from the general issue of ensuring robustness of hardware and software, there is the issue that the thermal sensation model does not match sufficiently well with user experience. Some possible reasons are:

• there is a tendency for discomfort to grow with time when wearing the suit, possibly due to the subject becoming tired, thus affecting subjective assessment, and this factor is not incorporated into the model,

• 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.

From Zhang's work, it is clear that subjective assessment sometimes appears to predict future state. For example, subjects reported that the same temperature profile felt cooler when they had cool air blown on them. In effect, they were more comfortable not because skin or core temperatures were any lower but because they expected to feel cooler in the future. This leads naturally to the idea that to estimate sensation, it is necessary to predict future temperatures, taking into account factors such as the subject's work rate, and posture.

In future work, it is planned to:

• develop a new or revised model that better accounts for the environmental factors of the EOD suit,

• evaluate the effect of inaccurate placement of sensors,

• develop an autonomous control system for the in-suit cooling system based on multi-modal physiological measurements.

Extensive experimentation trials are planned to support this work. Moreover concentrated efforts are needed towards improving both the wearability and robustness of the prototype.

IX. Acknowledgements

References

[1] T. Gao, D. Greenspan, M. Welsh, R. R. Juang, and A. Alm, "Vital signs monitoring and patient tracking over a wireless network," in *27th Annual International Conference of the IEEE EMBS*, Shanghai, September 2005, pp. 102–105. [Online]. Available: http://www.eecs.harvard.edu/~mdw/papers/monitoring-embs05.pdf

[2] Vivometrics, "Vivometrics: Better results through non-invasive monitoring," accessed 16-11-2007. [Online]. Available: http://www.vivometrics.com

[3] T. R. Fulford-Jones, G.-Y. Wei, and M. Welsh, "A portable, low-power, wireless two-lead EKG system," in *Proc. 26th IEEE EMBS Annual International Conference*, San Francisco, September 2004.

[4] D. Malan, T. Fulford-Jones, M. Welsh, and S. Moulton, "CodeBlue: An ad hoc sensor network infrastructure for emergency medical care," in *International Workshop on Wearable and Implantable Body Sensor Networks*, April 2004. [Online]. Available: http://www.eecs.harvard.edu/~mdw/papers/codeblue-bsn04.pdf

[5] E. Jovanov, A. Milenkovic, C. Otto, and P. C. de Groen, "A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation," *Journal of NeuroEngineering and Rehabilitation*, vol. 2, no. 6, March 2005. [Online]. Available: http://www.jneuroengrehab.com/content/pdf/1743-0003-2-6.pdf

[6] B. Lo and G.-Z. Yang, "Architecture for body sensor networks," in *Perspective in Pervasive Computing*, October 2005, pp. 23–28. [Online]. Available: http://pubs.doc.ic.ac.uk/architecture-body-sensor/architecture-body-sensor.pdf

[7] H. H. Asada, P. A. Shaltis, A. Reisner, S. Rhee, and R. C. Hutchinson, "Mobile monitoring with wearable photoplethysmographic biosensors," *IEEE Engineering in Medicine and Biology Magazine*, vol. 22, no. 3, pp. 28–40, 2003.

[8] E. Jovanov, D. Raskovic, J. Price, J. Chapman, A. Moore, and A. Krishnamurthy, "Patient monitoring using personal area networks of wireless intelligent sensors," *Biomedical Sciences Instrumentation*, vol. 37, pp. 373–378, 2001.

[9] S. L. Keoh, N. Dulay, E. Lupu, K. Twidle, A. E. Schaeffer-Filho, M. Sloman, S. Heeps, S. Strowes, and J. Sventek, "Self managed cell: A middleware for managing body sensor networks," in *Proc. 4th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous)*, Philadelphia, USA, August 2007. [Online]. Available: http://www.doc.ic.ac.uk/~slk/Publications.html

[10] V. Shnayder, B. Chen, K. Lorincz, T. R. F. Fulford-Jones, and M. Welsh, "Sensor networks for medical care," Division of Engineering and Applied Sciences, Harvard University, Tech. Rep., 2005. [Online]. Available: http://www.eecs.harvard.edu/~mdw/proj/codeblue

[11] E. M. Tapia, N. Marmasse, S. S. Intille, and K. Larson, "Mites: Wireless portable sensors for studying behavior," in *Proc. Extended Abstracts UbiComp 2004: Ubiquitous Computing*, 2004. [Online]. Available: http://web.media.mit.edu/~emunguia/

[12] W. Walker, T. Polk, A. Hande, and D. Bhatia, "Remote blood pressure monitoring using a wireless sensor network," in *Proc. 6th Annual IEEE Emerging Information Technology Conference*, Dallas, Texas, August 2006. [Online]. Available: http://www.utdallas.edu/~axh059000/publications.html

[13] M. N. Sawka and A. J. Young, *ACSM's Advanced Exercise Physiology*. Baltimore, USA: Lippincott Williams and Wilkins, 2006, ch. Physiological systems and their responses to conditions of heat and cold.

[14] S. S. Cheung, T. M. McLellan, and S. Tenaglia, "The thermophysiology of uncompensable heat stress. physiological manipulations and individual characteristics," *Sports Med.*, vol. 29, pp. 329–359, 2000.

[15] J. Kistemaker, E. den Hartog, and C. L. Koerhuis, "Thermal strain and cooling during work in a bomb disposal (EOD) suit," in *TNO Defence, Safety and Security, Soesterberg, The Netherlands. Personal armour systems symposium.*, Royal Armouries Museum, Leeds, United Kingdom, September 2006, pp. 20–22.

[16] C. D. Thake and M. J. Price, "Reducing uncompensable heat stress in a bomb disposal (EOD) suit: a laboratory based assessment," in *Proc. 12th International Conference on Environmental Ergonomics (ICEE 2007)*, Piran, Slovenia, 2007.

[17] N. L. Ramanathan, "A new weighting system for mean surface temperature of the human body," *J App. Physiol.*, vol. 19, pp. 531–533, 1964.

[18] A. J. Young, M. N. Sawka, Y. Epstein, B. Decristofano, and K. B. Pandolf, "Cooling different body surfaces during upper and lower body exercise," *J Appl Physiol*, vol. 63, no. 3, pp. 1218–1223, September 1987. [Online]. Available: http://jap.physiology.org/cgi/content/abstract/63/3/1218

[19] Mündel, Toby, Bunn, J. Sabrina, Hooper, L. Paula, Jones, and A. David, "The effects of face cooling during hyperthermic exercise in man: evidence for an integrated thermal, neuroendocrine and behavioural response," *Experimental Physiology*, vol. 92, no. 1, pp. 187–195, January 2007. [Online]. Available: http://dx.doi.org/10.1113/expphysiol.2006.034934

[20] N. A. Taylor, "Challenges to temperature regulation when working in hot environments," *Industrial Health*, vol. 44, no. 3, pp. 331–344, 2006.

[21] Xsens, "Moven—internal motion capture," 2008. [Online]. Available: http:www.moven.com

[22] T. G. Zimmerman, "Personal area networks: Near-field intrabody communication," *IBM Systems Journal*, vol. 35, no. 3/4, p. 609, 1996.

[23] G. J. Pottie and W. J. Kaiser, "Wireless integrated network sensors," *Commun. ACM*, vol. 43, no. 5, pp. 51–58, 2000.

[24] P. S. Maybeck, *Stochastic models, estimation, and control*, ser. Mathematics in Science and Engineering, 1979, vol. 141.

[25] G. Welch and G. Bishop, "An introduction to the Kalman filter," University of North Carolina at Chapel Hill, Tech. Rep., 1995, [Accessed 3-Dec-2007]. [Online]. Available: http://www.cs.unc.edu/~welch/kalman

[26] H. Freeman, F. E. Linder, and R. F. Nickerson, "The bilateral symmetry of skin temperature," *Journal of Nutrition*, vol. 13, no. 1, pp. 39–49, January 1937.

[27] E. Silberstein, G. Bahra, and J. Kattan, "Thermographically measured normal skin temperature asymmetry in the human male," *Cancer*, vol. 36, no. 4, pp. 1506–1510, Oct 1975.

[28] Energy Systems Research Unit, University of Strathclyde, "Thermal comfort models," accessed 26-Nov-2007. [Online]. Available: http://www.esru.strath.ac.uk/Reference/concepts/thermal_comfort.htm

[29] H. Zhang, "Human thermal sensation and comfort in transient and non-uniform thermal environments," Ph.D. dissertation, University of California, Berkeley, 2003.

[30] K. E. Charles, "Fanger's thermal comfort and draught models," Institute for Research in Construction, Tech. Rep. IRC-RR-162, October 2003. [Online]. Available: http://irc.nrc-cnrc.gc.ca/pubs/rr/rr162/

[31] American Society of Heating Refrigerating and Air Conditioning Engineers (ASHRAE), *ASHRAE Handbook: Fundamentals*. Atlanta, GA: ASHREA, 2001, ch. Thermal comfort, pp. 8.1–8.29.

[32] P. O. Fanger, *Thermal Comfort: Analysis and Applications in Environmental Engineering*. McGraw-Hill, 1970.

[33] G. Tomonobu, J. Toftum, R. d. Dear, and P. O. Fanger, "Thermal sensation and comfort with transient metabolic rates," in *Proc. Indoor Air 2002*, vol. 1, 2002, pp. 1038–1043.

[34] C. A. Shanks, "Mean skin temperature during anaesthesia: An assessment of formulae in the supine surgical patient," *British Journal of Anaesthesia*, vol. 47, no. 8, pp. 871–876, 1975.