Advanced sensing technologies for protection suits

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***Abstract*—NP Aerospace's latest version of their bomb disposal suit, the "Mark IV Explosive Ordinance Disposal (EOD) suit", is one of the most sophisticated ever. However the company have identified an unsolved problem that occurs generally with heavy enclosed armour of this kind: the potential for Uncompensable Heat Stress or UHS. When we exercise, our body heats up and we sweat; the sweat evaporates and this evaporation cools the skin. In an enclosed environment (like the EOD suit for example), however, the air becomes humid, evaporation stops, and this leads to heat stress. Heat stress can impair judgement and, if left untreated, can be fatal. Researchers at Cogent Computing Applied research Centre have been developing a prototype body wireless sensor network (BSN) that is integrated into clothing underneath the armour that will monitor body temperatures at multiple sites, heart rate and posture. The system makes use of mixed wired/wireless technology to achieve detailed monitoring of personnel and innovative information extraction and processing to infer the wearer's thermal sensation and overall comfort. A remote visualiser allows for continuous monitoring and alarm generation at mission control. The full end-to-end system has been deployed and thoroughly tested in "mission like" environments.**

***Index Terms*—body sensor network, first responders**

I. PROBLEM STATEMENT AND PROJECT GOALS

The monitoring of hazardous environments, along with the people working within them, is an area which lends itself to applications of wireless and body sensor networks. The field is rich with potential applications in detecting hazards, providing feedback to observers and other critical tasks that can increase the safety and overall working conditions of people operating in these environments.

Bomb disposal suits contain a large amount of padding and armour to protect the wearer's vital organs in the case of explosion. The combination of the heavy (roughly 40kg) suit, physical exertion, and the environment in which these suits are worn can cause the wearer's temperature to rise to uncomfortable and potentially dangerous levels during missions. Current cooling systems used in NP Aerospace's "Mark IV Explosive Ordinance Disposal (EOD) suits" are provided with manual control. However, it has been observed through mission deployments that the cooling is rarely efficiently used by operatives for several reasons:

- it is distracting to operate;
- operatives either activate the cooling too late to avoid heat stress or too early, thus exhausting the battery well before the end of a normal mission.

To address the above problems, the project showcased here aims to design, implement, and embed into the suit a body sensor and actuation network that will:

- sense the temperature of the skin at specific sites and the orientation of torso and limbs, thus producing an assessment of the subject's thermal sensation,
- combine the detailed temperature profiles with other physiological parameters such as heart rate and the subject's posture (activity patterns) in a predictive model of the subject's comfort state, and,
- proactively actuate the cooling system within the suit in order to maintain acceptable comfort levels for the subject and prolong cooling battery life.

A secondary goal of this project is to aid the suit manufacturer in better understanding how the suit material and design choices are affecting the wearer's thermal comfort during use.

To date, a prototype system has been developed which both satisfies the need for remote monitoring and allows for future integration of a cooling automation component to ensure effective, need-based cooling. 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 have all been positively assessed and experimental validation has taken place. A modelling engine (based on a Bayesian Network) is being developed, which will allow the assessment of thermal comfort in real-time using gathered sensor data. Posture will feature as a factor in the predictive component of the modelling engine in order to allow the effects of changing airflow to be accounted for. The thermal comfort model will be used to control the actuation of cooling. To date, a real-time posture assessment prototype based on integrated accelerometers has also been successfully developed and deployed. The prototype is able to correctly classify 8 human postures, at a rate of 60 assessments per second and relay the posture information remotely to the external observer/mission control point. Work is on-going towards the development of the multi-modal modelling engine and predictive actuation module.

The Explosive Ordinance Disposal suit is shown in Figure 1.

This is a 3 year project which started in September 2006 and is funded as an EPSRC CASE Studentship, through the Integrated Products Manufacturing KTN.

Figure 1. Explosive Ordinance Disposal (EOD) Suit

II. System design and architecture

The main part of the prototype system is designed following a sense-model-decide-act architecture as shown in figure 2. The environment within the suit is sensed in terms of temperature and subject's posture; the sensed temperature is integrated into a model representing the thermal state of the wearer; additional aspects for the state estimation are the posture and heart rate; 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, inferred posture information and heart rate values. From this visualisation, the operator can assess how different parts of the mission, or different actions being taken by the suit wearer are affecting their thermal state and hence assess the wearer's fitness for the mission. (It is expected that such information, collected during field trials and real missions, might lead to changes to future mission planning or to changes in the design of the suit.) In summary, the prototype system can be seen as being composed of two control loops: one giving rapid feedback to autonomously adjust cooling; the other, longer term one, providing support for an iterative design process in terms of both the mission use and construction of the suit.

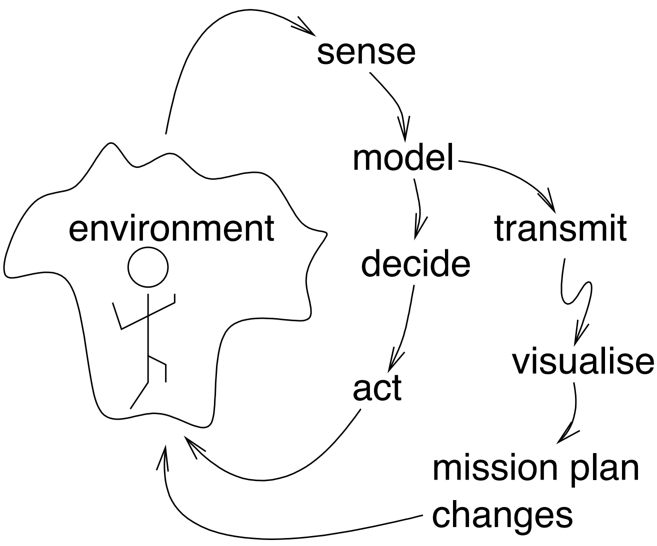

Figure 2. Conceptual design of prototype system

A. Integrated prototype description

The prototype design to-date consists of a number of hardware components, including a remote monitoring station, two processing nodes, one actuation node, 12 temperature sensors, 9 inertial sensors for posture measurement, and the cooling system. The connection between these components is shown in figure 3. The processing nodes, actuation nodes, and remote monitoring point form a wireless network. Each processing node is wired to several sensor packages via an I2C bus. Although it would be possible to integrate all sensor packages used in this prototype into a single processing / actuation node, using separate processing nodes allows the helmet, jacket, and trousers to be kept separate with no wires running between them. This is essential for ensuring that the product remains easy to use and transparent to the wearer.

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

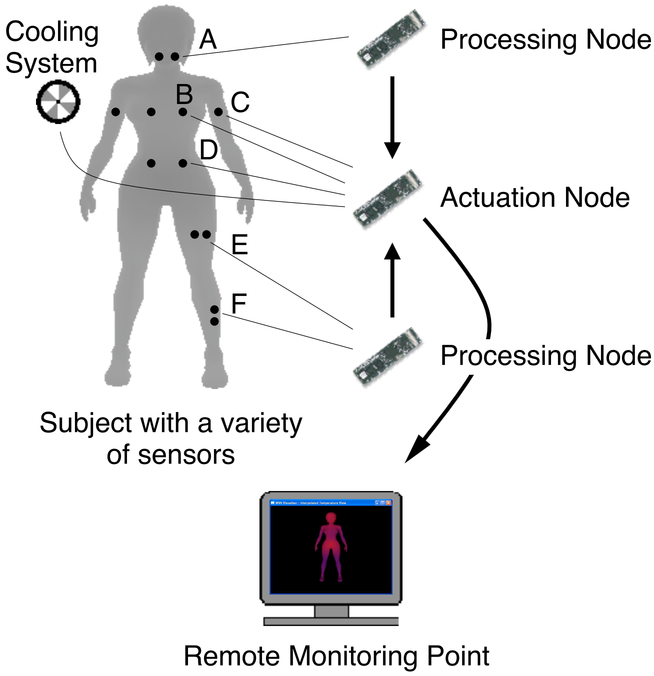

Figure 3. Prototype system hardware components and sensor positioning (A – neck, B – chest, C – bicep, D – abdomen, E – thigh, F – calf).

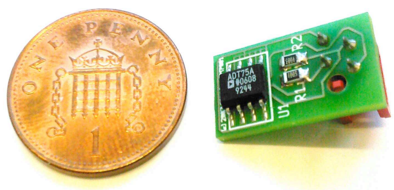

Figure 4. Sensor package, which is based on an ADT75A chip.

B. Sensor packages and sensor positioning

The prototype system uses twelve sensor packages based on Analog Devices ADT75A temperature sensor ICs (shown in figure 4) and nine sensor packages based on the STMicroelectronics LIS3LV02DQ 3-axis accelerometer. The ADT75A

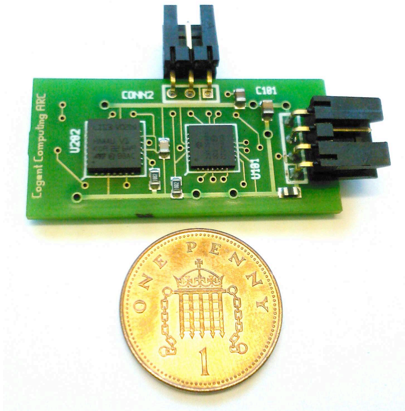

Figure 5. Inertial sensor package, which is comprised of a PIC processor, 3-DOF accelerometer, I2C buffer, and temperature sensor.

has the advantage that it contains the sensor, ADC, and bus interface in a single package. Temperature values are transmitted as 12 bits, which causes rounding to within 1/8°C. The accelerometers have a resolution of 1mg in the ±2g range and its data are acquired by an on-board PIC controller which then supplies it to the I2C bus. The accelorometer and PIC sensor package is shown in figure 5. The sensor packages are connected to only two nodes in the current version: one actuation node and one processing node.

The sensor packages were positioned around various parts of the body. These were: lateral calf muscle, front of thigh (or quadriceps), abdomen, chest, biceps, and neck, as indicated in figure 3 for temperature and lateral calf muscles, front of thighs, chest, upper arms, and lower arms, for accelerometer measurements. Given that temperatures are known to be symmetrical between left and right sides in healthy people, sensors have been placed on a single side. Two sensor packages were used per skin site. This arrangement enables individual data validation.

C. Processing and actuation nodes

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

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

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

2) Functionality: Actuation and processing nodes process temperature sensor data by first removing outliers and then applying a Kalman filter that assumes a near constant rate of change of temperature. The filter provides a smoothed estimate of both the temperature and the rate of change of the temperature for various skin sites. In-network modelling of the thermal sensation is performed by the actuation node. The resulting estimate, along with smoothed skin temperatures are transmitted to the base station.

Data from inertial sensors, based on 3-DOF accelerometers, are converted by the actuation node into inferred posture. The inference engine makes use of a learnt decision tree to convert accelerometer readings from various sites around the body into an estimate of the current posture. In due course, the posture information will be incorporated into the thermal sensation model to further refine the estimate of the wearer's state.

Figure 6 shows the information flow for the instrumentation system.

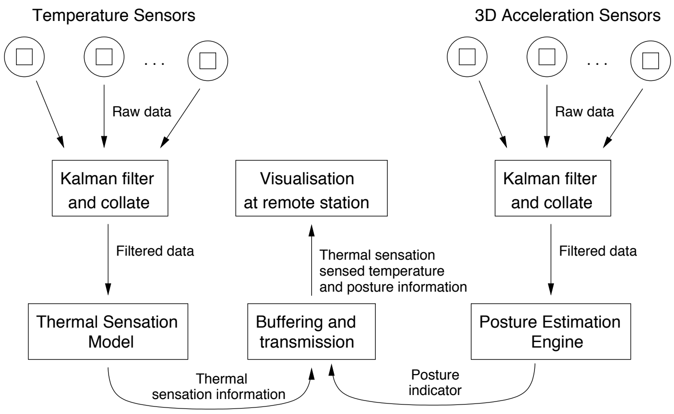

Figure 6. Information flow for the instrumentation system.

D. Remote monitoring

The remote monitoring component of this system allows an external observer to monitor both the instrumentation system (to ensure that trustworthy information is being recorded) and the bomb disposal technician during a mission (which is the main function of the instrumentation). The remote monitoring component displays the health and comfort information and provides alerts to the remote observer if physiological parameters fall outside safe ranges or the wearer is shown to be significantly uncomfortable. A snapshot of the remote monitoring component is shown in figure 7 (note that several versions of the graphical user interface have been produced, including the full visualisation of temperature values in real time). Currently the monitor displays skin site temperature data, and a rotating, suggestive, 3-D interpolated model of skin temperatures. Cool to hot zones are displayed dynamically through a range of colours, from blue to red. Furthermore, the display shows the wearer's position (stick man posture indicators as in figure 8) and issues alarms when physiological parameters exceed set values.

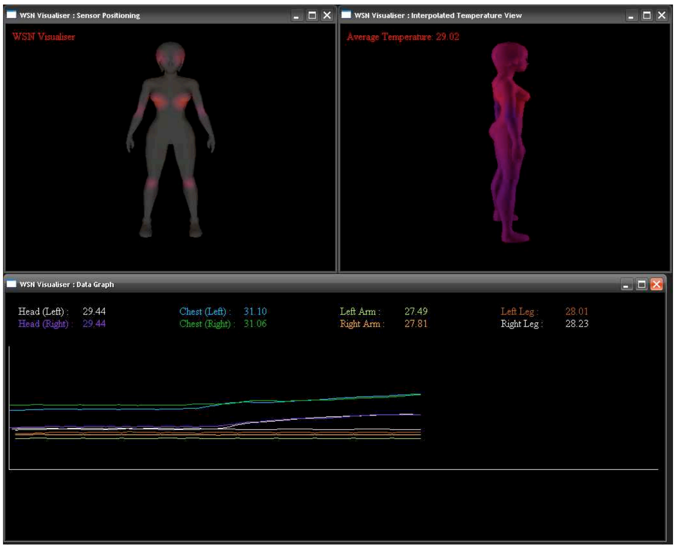

Figure 7. A snapshot of a version of the remote monitoring component.

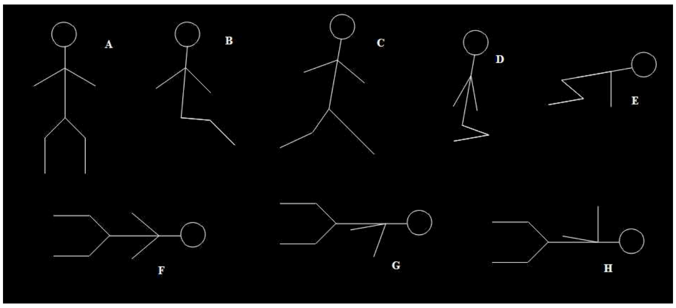

Figure 8. Stick-man posture indicators

III. Conclusions

Added value and novelty : The system proposed has a high innovative value, allowing, for the first time, detailed monitoring of personnel in bomb disposal missions. Moreover, the prototype can act as a design aid/tool within the suit manufacturing processes, allowing for quantitative assessment of wearability for such suits.

Maturity : Presently the work has just passed the “proof-of-concept” stage and has been repeatedly deployed in controlled environments, with the subjects performing bomb disposal protocols at various environmental temperatures (from 20 to 40 degrees Celsius).

Level of integration : The system allows for: sensor data acquisition; various sensed data processing tasks (filtering, outlier identification and rejection; information extraction and inference of abstract values from sensed data; real-time remote data and information visualisation.