Ensuring Robustness and Reliability in a Safety Critical Monitoring System

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ABSTRACT

The work reported here explores and assesses the benefits of deployed BSNs for bomb disposal mission critical monitoring, in terms of: providing detailed physiological profiles of operatives; 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; and providing alerts to both operatives and remote monitors. BSNs deployed in this manner must be both robust and reliable in order to fulfil the safety critical requirements of the application. The paper describes and evaluates a fully functional prototype instrumentation system which complies with these requirements.

Keywords: body sensor networks, critical missions, reliability, robustness

1 INTRODUCTION 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 (which weighs approximately 40Kg) and the typical bomb disposal sites and scenarios. A typical mission is conducted in 45 minute stages and involves strenuous activities. The operative makes use of a signal jammer during parts of the mission and presently has no means of communicating with the remote station.

One of the UK manufacturers of armoured suits (shown in Figure 1), 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 a manually controlled in-suit cooling system. 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 cooling by mission operatives, and the need for remote monitoring in order to advise / enforce the use of cooling and assess dangerous situations.

Figure 1: Explosive Ordinance Disposal (EOD) Suit with instrumentation

The work here aims to address the above problems and resolve the imminent need to reduce the risks of such missions, by embedding into the suit a body sensor network (BSN) based instrument that primarily aims to: sense the skin temperature of various body segments in order to assess overall thermal sensation; sense a variaty of other physiological parameters such as heart rate, blood oxygenation (SpO2) and CO_2 levels in the suit's helmet; relay health information and alerts to the operative and mission control; and, adjust the cooling dynamically to both remove the need for human intervention and also to prolong its battery life to cover a whole mission.

A secondary goal 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 and health during use.

In order to support these goals, the system proposed is required to ensure that the data gathered, stored, used for decision making and alerts generation, and presented to remote observers is timely, accurate and reliable. This implies the use of a variety of fault management techniques at several levels in the system chain in order to: ensure data accuracy, compensate for faulty sensors or communications breakdowns, and prioritise vital information transmission to the remote monitor.

The philosophy behind the work is that a multidisciplinary 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, and utilises BSN technologies towards fulfilling the aims. The underlying physiological effects (such as heat stress) that are encountered in applications such as this have been considered here as reported by Thake [8], and methods of determining human thermal sensation and comfort were adopted from [10].

With regard to BSN technologies, although an area wealthy in research and achievement, their present scope is mostly patient care. Such systems are either focused on aiding first responders in monitoring patients and performing triage [3], [5], or aimed to provide general monitoring solutions for patient status within a hospital or similar environment [6], [1], or have been developed for the purpose of instrumenting and monitoring first responders and other personnel in safety critical situations [9]. Hence advance beyond the BSN state of the art was needed to resolve this application.

A variety of options for developing the system platform to support applications such as the above have been explored in the literature: integration of CPU, memory and radio into a custom chip [7], use of off-the-shelf components [4], and expanding on commerical platforms [2]. The system presented here uses a commercial platform with the addition of an in-house expansion board and several sensor types.

The paper is structured as follows: Section 2 gives an overview of the design and implementation of the system hardware and software components, Section 3 presents the evaluation and experimental results and Section 4 concludes the paper.

2 SYSTEM DESIGN AND IMPLEMENTATION

For the work here, the system design has been driven by a mixture of constraints: suit related (such as the need to avoid running wires between the garment components, and overall wearability of the instrument), application related (such as the intermittent use of signal jammers during a mission, and physical obstructions in the environment), safety critical concerns (such as the need for alerting of unsafe conditions and the in-suit actuation of cooling), and the scope of the instrument (such as its dual use as a field deployable system as well its use in laboratory trials).

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 separate nodes for jacket, trousers, and helmet use wireless communication to ease robing and disrobing.

A unifying aspect of the safety requirements, including the need for in-suit actuation of cooling and generating alerts for unsafe conditions, is that all components 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, posture, and CO_2 levels, in order to maximise the effectiveness of cooling.

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, and to study how suit design changes affect the wearer. Hence, two functional modes need to be supported: one where all sensor data is transmitted and one where only abstracted information is transmitted, such as thermal sensation level, temperature trends, posture, and alarms. It may be desirable to change mode during a mission. For example, the mission controller may see that the operative is becoming thermally uncomfortable and wish to obtain detailed temperature profiles and consider them in conjunction with other sensed physiological parameters.

2.1 Platform and Sensors

The Gumstix Verdex XM4-bt board was selected as the processing and communication platform. The Verdex includes an Intel XScale PXA270 400MHz processor, 16MB of flash memory, 64MB of RAM, a Bluetooth controller and antenna, and connectors for expansion boards. The sensor packages connect to the Verdex board via an expansion board designed in-house. Three Verdex boards are used; two as acquisition nodes and a third acting as a processing node.

Each acquisition node is wired to several sensor packages via an I^2C bus. The prototype (shown in figure 2) uses twelve sensor packages based on Analog Devices ADT75A temperature sensor ICs. The sensor packages are attached to the body as in the standard positioning used by Thake and Price [8]. The skin sites used are neck, chest, bicep, abdomen, thigh, and lateral calf muscle. (Two sensors are used per site to increase system robustnes.) Heart rate and SpO2 data is supplied by a Nonin Medical pulse oximeter, which communicates with the upper body node via Bluetooth. Helmet CO_2 data is supplied by an Europa Environmental miniature CO_2 sensor, communicating with the helmet node via a serial link. All data is sampled at 1Hz. The collection and processing of posture data is not reported here.

2.2 Communications and System Data Flow

The sensors, acquistion nodes, processing node, and remote monitoring point form a three tier wireless network. Although the system design calls for differentiating the in-suit communication and the long range

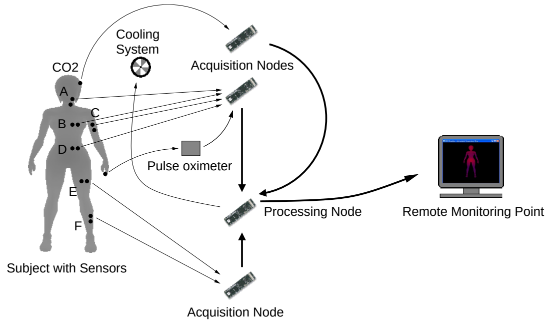

Figure 2: System design and implementation

communication, the implemented prototype makes use of Bluetooth throughout (class 1 on the base station and class 2 on the nodes).

The data acquired by all sensors is procesed within the network to allow generation of alarms and cooling actuation in-suit. Firstly the raw sensed temperature data from all skin site sensor pairs is filtered on a per-node basis. The result is transmitted to the processing node which collates a skin temperature vector. Zhang's thermal sensation model [10] is then applied to the resulting vector, which yields an estimate of the thermal sensation for the current point in time. Thermal sensation together with CO_2, heart rate, SpO2 and average temperature values added to the time stamp form the *information package* to be transmitted to the remote station. A distinction is made between data and information, as information is considered to be more valuable, often being easier to understand. For instance, raw temperature readings from the skin sensors are classed as data, while generated sensation estimates are considered as information. This differentiation, along with the sample age and the potential presence of alerts, forms the basis for transmission prioritisation. The last phase in the system flow is the information/data arrival at the remote monitoring station and its conversion to visual form.

2.3 Alert Mechanism

A key problem with heat stress, particularly in military situations, is that the operative may continue 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. The alert system is based on thresholds (informed from literature and experimentation) for: average and individual segment skin temperatures and thermal sensation, heart rate (HR), SpO2, and helmet CO_2 levels. The abnormal ranges are set as follows: skin temperature < 31°C, skin temperature > 37°C, SpO2 $< 94\%$, HR < 55bpm, HR > 140bpm, and CO_2 in the helmet > 15000ppm. Currently alerts are in the form of an audible and visual alarm at mission control. In future work it is planned to extend the feedback mechanism with visual and haptic alarms for the operative.

2.4 Fault Tolerance

The safety critical nature of the application require that hardware and software redundancy and fault management strategies are implemented to increase fault tolerance. The raw temperature sensor values are adjusted to compensate for calibration errors, outliers are rejected, and they are grouped into pairs based on body location. This allows redundant sensors to be used along with Kalman filtering techniques to reduce the information cost of sensor failure and improve the quality of the data obtained. Pulse oximeter data is flagged when artifacts are detected in the signal (for instance when the wearer's finger is moving), and low battery alerts are generated for this sensor. As temperature data is supplied by two separate acquisition nodes and may be received at slightly different times, the processing node performs data processing at a fixed interval and estimates current temperature values based on the previous received value and the rate of change. The long range communications link is monitored for availability (due to the potential use of signal jammers), and the data and information stored is transmitted in an order determined by both its age and importance (samples are defined as "warning", "information" or "data").

3 EVALUATION AND EXPERIMENTAL RESULTS

The system has been evaluated in order to both define the inherent operating parameters and also to ensure that it is capable of operating reliably in non-optimal conditions. A summary of findings is given below.

The processing node's life is approximately 3 hours, while the acquisition nodes offer approximately 4 hours, both on four rechargeable AAA batteries.

The bandwidth of the link between the processing node and base station (which potentially carries the greatest number of data units) is approximately 70KBytes/s. The mean end to end latency is 1.5681 seconds over two hops (with data being held at the processing node and forwarded on at specific intervals). Mean latency across one communications link is 0.0403 second. System startup time is composed of two stages: 1) nodes boot into a useable state, and 2) the Bluetooth network is formed. The former is approximately 35 seconds, while the latter is approximately 5 seconds per link.

Currently, data units within the system are of two types. Type 1 is the most common (containing a timestamp, data mode, sensor id, value, and any flags required), while Type 2 carries additional information related to the skin temperature filtering process and its size is approximately two Type 1 data units. The system transmits 23 Type 1 data units and 6 Type 2 data units to the base station per second in full data mode.

The transmission range is 63.5m outdoors with no obstructions, dropping to 49.4m indoors with no obstructions and 14m through three interior walls and some light machinery. Within a metal stairwell the system was capable of transmitting up 2.5 floors.

The maximum rate of change of skin temperature observed during experimentation is 0.29°C per minute. The normal maximum prediction time for alignment of data is 1 second. The maximum error over this time is then 0.01°C, which is an acceptable error. In the case of a temporary communications failure, the prediction mechanism can continue to predict for as long as is required based on the last valid sample received for each sensor, giving a maximum error of 0.58°C per minute. Testing has shown the error to be usually less than 0.1°C after one minute.

The quantity of data to be stored on the processing node during a communication breakdown is 1107 bytes/s (ignoring warnings, which cannot be predicted). The node has the capacity to store 10 hours worth of data.

All of above operational parameters are within the required ranges for the application here, except for the transmission range. This is required to be at least 100m between the processing node and the base station. Alternative methods (such as ZigBee) are being considered.

4 CONCLUSION

A BSN protype system for monitoring the health of operatives in bomb disposal missions has been implemented and evaluated. The system gathers, processes and transmits data, information and alerts based on temperature, SpO2 and CO_2 levels. The focus of the design was to ensure system robustness and data and information reliability, timeliness and accuracy. These design features have been experimentally evaluated. Node level processing allows fault management to be applied close to fault locations. Filtering and the use of hardware redundancy ensure hat only accurate data becomes part of the information extraction chain whilst predictive algorithms counteract the unreliability of the low range communication link and transient sensor and node failures. Information loss due to failure of the long range link is minimized through storage and priorization of transmitted information and data.

Future work aims to integrate all measured physiological parameters, including heart rate, SpO2, and CO_2 levels into a state model for the operative and further evaluate the prototype in mission like scenarios.

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