John Kemp

Investigating into the use of advance sensing technologies for protection suits.
Published Report (PDF)
(Refereed)

Kemp, J. (2007) *Investigating into the use of advance sensing technologies for protection suits*. Report no. COGENT.001 Coventry: Coventry University

COGENT
computing

Investigation into the Use of Advanced Sensing Technologies for Protection Suits

John Kemp
kempj@coventry.ac.uk

The goal of the project presented here is to develop a wearable wireless sensing system suitable for deployment in manned bomb disposal missions. The system will be capable of making in-network autonomous decisions related to the actuation of the cooling system within the suit, to increase the comfort of the wearer. In addition, it will allow an external observer to remotely monitor the health and comfort of the operative.

Results are presented from a series of experimental runs performed using a prototype sensing system. The need for timely application of in-suit cooling is shown, as well as the importance of monitoring the overall health of the wearer of the suit.

This is a preliminary report based on the first year of work.

Technical report number COGENT.001
Cogent Computing Applied Research Centre

Published on 23/10/2007

Coventry University

Contents

List of Figures

List of Tables

Chapter 1

Introduction and Research Motivation

The monitoring of hazardous environments, along with the people working within them, is an area which lends itself to applications involving 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 technicians work in an environment that can potentially be very dangerous and to counteract this they are required to wear large suits of protective clothing, as shown in figure 1.1. During these missions, operatives often experience high, uncomfortable, and potentially dangerous temperatures due to the size and weight of the clothing. This means that a cooling system within the suit is required in order to prevent dangerous temperatures being reached during a mission. The immediate method of control for such a system would be a manual one, however this may mean that the technician will not be able to focus solely on the task at hand, instead being required to administer the cooling system. Current cooling systems used in the suits in question are indeed provided with this type of manual control and thus are subject to the mentioned problem. Additionally they are battery powered and the manual control arrangement does not enable the most efficient use of the available power.

Figure 1.1: Explosive Ordinance Disposal (EOD) Suit

The goal of this project is to develop a wearable wireless sensing system suitable for deployment in manned bomb disposal missions. The system will be capable of making in-network autonomous decisions related to the actuation of the cooling system within the suit, to increase the comfort of the wearer. In addition, it will allow an external observer to remotely monitor the health and comfort of the operative. In pursuing the goal, the following research questions must be answered:

- Which physiological parameters must be measured in order to effectively allow this monitoring?
- Which parameters are required for the resulting control action to be effective in providing actuation towards a specified level of comfort for the wearer?
- Which parameters can be used to refine this control?
- Can the system be implemented in a way that is not intrusive to the wearer's tasks?
- How should the autonomous decision-making engine be designed to fulfill the requirements of safety-critical applications?

Answering the questions presented above requires delving into several areas of research: body sensing systems; modelling systems; autonomous decision-making systems; remote monitoring.

This report presents the work and achievements during the first year of the project (September 2006 - September 2007). The report is structured as follows. Chapter 2 presents an overview of the literature in the area of Body Sensor Networks, concentrating on prototype and commercial applications of body sensing and the relevance of these techniques to this project. Chapter 3 covers the design of the prototype system, including a discussion on the constraints and system requirements. Chapter 4 discusses some of the sensing parameters selected for inclusion in the prototype system. Chapter 5 details the hardware and software components of the prototype system (as created to date) and notes some of the directions planned for the near future. Chapter 6 presents the results of a series of experiments carried out with the prototype system and discusses the findings. Chapter 7 draws together the points made in the previous chapters and discusses the future directions of the work.

Chapter 2

Background and Literature Review

The areas that this project is centered around are those of sensor networks in general and body sensor networks specifically. These are areas which are currently undergoing a substantial level of research, particularly from a wireless sensor networks perspective, with a number of hardware and software platforms under active development and a number of commercial products currently available. Much of the current research in wireless sensor networks is centered on topics such as routing algorithms (at the low level) and information extraction (at the high level), while body sensor network research is centered on applications such as medical monitoring in hospitals and other controlled environments.

This section summarises findings within three general areas of the body sensor network literature: critical mission applications (involving monitoring of subjects in dangerous or hostile environments), patient care applications, and a review of the hardware platforms used in a variety of reported body sensing applications.

2.1 Critical Mission Applications

An example of a commercial product designed for the purpose of monitoring personnel carrying out missions in dangerous environments is the VivoResponder by VivoMetrics [1] (shown in figure 2.1). It is based upon an earlier product called the LifeShirt. The VivoResponder is supplied in three parts: a lightweight chest strap with embedded sensors; a data receiver; 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 skin temperature, and it is machine washable.

Figure 2.1: VivoResponder by VivoMetrics

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

The system is aimed at personnel engaged in:

- firefighting and hazmat (hazardous materials) training or emergency response
- industrial clean-ups using protective gear
- biohazard-related occupational work

The device has several interesting aspects that relate to this project. The first is the method of attachment to the subject. A chest strap (with additional shoulder strap) will ensure that the device will not be dislodged during use, as well as providing a measure of comfort to the wearer. These two factors are important for a wearable sensor system due to its close contact with the body. If the system is dislodged then any sensor readings from that point are likely to be useless, whilst if the device is uncomfortable it will distract the wearer from their task or simply not be worn. A second relevant aspect is the sensor load of the device. The device is designed for monitoring, in a similar class of applications to the system presented here and thus has a similar set of sensors. Skin temperature monitoring will play an important part in this project as the basis of it is the monitoring of a subject's temperature and comfort levels, while the other parameters measured by the VivoResponder device are also being considered or are already in the process of being integrated (see section 4.3 for a discussion of posture assessment).

2.2 Patient Care Applications

In this section, a survey of various body sensing projects reported in the literature is presented, with particular emphasis on those within the domain of patient care. Patient care applications are similar in nature to the application developed in this project in that they require the monitoring of a subject to ensure that no parameters stray outside of a safe range. There are two basic types of patient care application which may be relevant to this work:

- those designed to focus on a particular physiological parameter that the patient in question will be affected by (such as heart activity for example in a person susceptible to abnormal rhythms)
- those designed to provide general monitoring solutions for patient status within a hospital, or similar environment.

In the following sections, four projects will be surveyed, as follows: CodeBlue, ActiS, MITes and BSN Node.

2.2.1 CodeBlue

The CodeBlue project [2] worked towards the development of a prototype medical monitoring system. The project was held within the Division of Engineering and Applied Sciences at Harvard University in 2005, and integrated a set of medical sensors with the Mica2, MicaZ and Telos motes. The sensors fitted included a pulse oximeter, a two-lead electrocardiogram (EKG), and a motion-analysis board incorporating an accelerometer, gyroscope and EMG unit (which measures electrical activity in skeletal muscles). A custom mote design, named Pluto, for wearable applications was also developed. The Boston Medical Center, Brigham and Women's Hospital, the Spaulding Rehabilitation Hospital, and Johns Hopkins University were collaborators and stake holders in the project, interested in making use of the system commercially.

The system was, by and large, built within off the shelf components as detailed below.

An off-the-shelf pulse oximeter interface board was used: the Micro Power Pulse Oximeter board produced by BCI Medical. This board measures 39mm x 20mm and draws 6.6mA at 3V. It can measure heart rates in the range of 30 - 254bpm and SpO2 (blood oxygen saturation) values between 0 and 99%. The pulse oximeter board is shown in Figure 2.2.

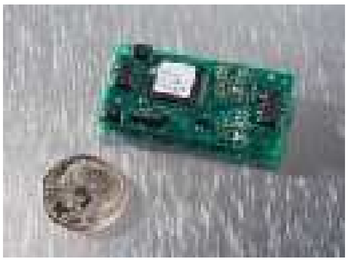


Figure 2.2: BCI Micro Power Pulse Oximeter

This board was interfaced with the Mica2/MicaZ motes via a custom produced board incorporating a 51-pin connector for interfacing with the MicaZ's on-board connector, two headers for the BCI board, and a DB9 connector for the finger sensor that the BCI board will take readings from. The startup time before readings are reported is approximately 20 seconds. (Given that pulse oximetry is aimed for inclusion in the project here, section 2.4.2 of this report provides a more detailed presentation on pulse oximetry and other available pulse oximeters).

The Electrocardiograph (EKG) in this prototype used EKG leads sampled via an ADC on the mote at a rate of 120Hz. This method of monitoring the electrical activity of the heart involves measuring the differential across a pair of electrodes attached to appropriate places on the subject, while a third electrode is used to identify the bias in the electrical potential of the patient's skin. This measurement method provides more information than simply the heart rate of the subject and can be used to detect abnormal rhythms, which is an important aspect in general medical monitoring systems.

The motion analysis board used a 3-axis accelerometer, a gyroscope and an electromyograph (EMG) unit. The gyroscope measures angular velocity and this is combined with the accelerometer data to give an accurate determination of limb position. Surface electrodes capture data for the EMG, which provides a measure of the electrical activity in the skeletal muscles. The RMS (Root Mean Square, a statistical measure of the magnitude of a series of values) of this value is roughly proportional to the force exerted by the monitored muscles. The motion analysis board was interfaced to a Telos mote and the particular sensors it incorporates are:

- an STMicroelectronics LIS3L02AQ 2g/6g 3-axis accelerometer
- an Analog Devices ADXRS300 single-axis gyroscope
- a Motion Lab Systems Inc. MP1A.20.A0DM.60 EMG unit

Signals from these sensors are interfaced via five of the Telos' ADC ports. The accelerometers and gyroscope are sampled at 100Hz, while the EMG is sampled at 1KHz. The intention was for the next revision of the system to include three gyroscopes in a triaxial configuration.

The three types of sensing used for the CodeBlue prototype have potential applications in the project presented in this report. Pulse oximetry is useful for obtaining a simple measure of pulse rate which can potentially indicate stress levels, both physical and mental, along with the level of blood oxygen saturation which can indicate whether the oxygen level in the breathed air is sufficient. Both of these conditions have relevance to the project as a bomb disposal technician is likely to be under a lot of stress during a mission, and the suit may restrict air circulation leading to reduced oxygen levels in the breathed air. Heart monitoring is essential in our system as in a healthy individual it primarily indicates the physical strain the subject is under. Furthermore, it can potentially be used to monitor the stress level of the subject as well as detect any abnormalities in the heart rhythm. However the attachment of the necessary leads is not likely to be practical in our system, therefore alternative sensing solutions are to be found. Additionally any heart conditions causing abnormal rhythms should be known due to previous testing of the subject, either prompted by complaints or in routine checks. Motion is an important parameter to sense in our project as it can indicate the posture of a subject. Posture may be used to refine the prediction models for heat loss/gain and further help determine the best timing for the application of cooling. Particularly when the subject is moving, it may be possible to reduce the cooling level as air will be circulated to some extent within the suit by the movement.

2.2.2 ActiS

Jovanov *et al.* [3] proposed a wireless BAN (Body Area Network) built with off the shelf components. The system architecture is discussed generally by Jovanov *et al.*, with the focus placed on an activity sensor named ActiS. The ActiS sensor incorporates two accelerometers and a one-channel bio amplifier. When used as a heart monitor this allows the ActiS sensor to monitor both heart activity and the position of the upper trunk. ActiS may also alternately be used to monitor the position and activity of the arms and legs.

Initially the ActiS sensor system was based on both a custom platform and a custom wireless protocol due to the lack of commercially available platforms suitable in terms of the application's needs for processing power, power consumption, and standard software support. The constraints placed on processing power and power consumption by small embedded systems are a common problem when designing a wireless sensor network. The platform of choice needs to have sufficient processing power to carry out the data acquisition, filtering and, where required, fusion, while consuming little power in order to have as long a life as possible, or stay within the limits of available power harvesting systems. The latter requirement, that of standard software support, is important in a wireless sensing system, particularly in the prototype stages, as it allows interoperability with other devices that may be used either as part of the system or in the testing or validation stages to confirm correct and expected operation of the system under design. The prototype revision presented by Jovanov *et al.* used a ZigBee protocol stack which is based on the IEEE 802.15.4 standard and has become a popular protocol for low power wireless devices. Further, the platform was moved to the Telos mote, which supports a ZigBee radio stack.

The architecture developed by Jovanov *et al.* consists of three basic levels of components.

1. Intelligent sensors monitoring the subject
2. A personal server; potentially a PDA, cell phone, or home computer
3. Remote health care servers and related services to support system operation (systems owned by a carer or physician, along with weather and emergency services, are examples of such servers)

The diagram in figure 2.3, reprinted from the work by Jovanov *et al.* [3], shows a view of this system architecture.

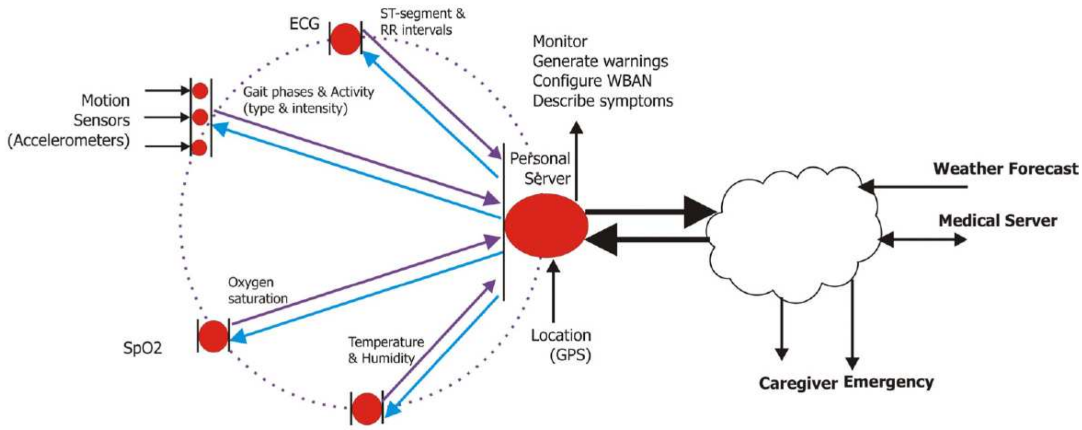


Figure 2.3: ActiS sensor system architecture [3]

The sensor level could consist of any number of sensors. The following list was suggested by Jovanov *et al.* as a relatively complete example set: an ECG (electrocardiogram) sensor for monitoring heart activity; an EMG (electromyography) sensor for monitoring muscle activity; an EEG (electroencephalography) sensor for monitoring brain electrical activity; a blood pressure sensor; a tilt sensor for monitoring trunk position; a breathing sensor for monitoring respiration; movement sensors used to estimate user's activity; a "smart sock" sensor or a sensor equipped shoe insole used to delineate phases of individual steps. It is suggested that multiple sensors may share a single processing node, which may incorporate sufficient processing power to allow local processing of the incoming data. Note that this view is adopted in the project here too.

The personal server level performs tasks related to initialising and setting up of the sensor nodes, along with the collection and processing of data from them. This is used to provide a user with audio and visual indicators of the current health state, as well as communicating securely with health care providers.

The remote services consist of links to health care providers who will collect data from the monitored patients and integrate it with the appropriate records as well as issuing recommendations and alarms if needed. Large-scale processing of the data will also be performed to allow health care providers and researchers to analyse the conditions of the monitored patients, for instance to recommend a regime for hip replacement patients.

The ActiS sensor itself consists of a Telos mote by Moteiv [4], pictured in figure 2.4, along with a custom module named the ISPM (Intelligent Signal Processing Module). The ISPM incorporates two dual-axis accelerometers (Analog Digital ADXL202s) to cover all 3 axes and a one-channel bio amplifier along with a low-power microcontroller (the Texas Instruments MSP430F1232). The bio amplifier could be used to collect EMG or ECG readings from a patient. The microcontroller provides signal conditioning and other low-level processing before the readings are transmitted to the Telos mote via a hardware UART. The Telos mote was chosen due to its size and software support in addition to its built-in sensors which may be used for detecting ambient conditions. It also includes a ZigBee compliant radio and antenna.

Figure 2.4: ActiS sensor

The focus of the project described by Jovanov *et al.* was detecting electrical bio-signals and the movement of a patient, which are important in monitoring a large number of patients including the elderly and those undergoing a physiotherapy regime. The parameters considered by Jovanov *et al.* are not of prime importance in the project described in this report as they do not directly relate to the need, or lack thereof, for cooling though they may be important secondary indicators of the health of the subject. The platform used, the Telos mote, is not suitable for the purposes of this project as it does not have the processing power required for full in-network data collection and modelling, in addition to being relatively bulky compared to other platforms. The on-board sensors considered by Jovanov *et al.* are also not required in our application. The architecture presented is a sensible method of operating that is, in some aspects, adequate for this project with the sensors feeding data to a local processing point which will further forward some data to a remote monitoring point.

2.2.3 MITes

Tapia *et al.* [5] developed wireless sensing devices called MITes designed to studying behaviour. These devices had several advantages over their competitors at the time (such as the Berkeley Motes), as follows:

- The cost of MITes with accelerometers included was less than 1/3 of the cost of the least expensive commercial mote, even when the mote included no sensors (this held even when the MITes were manufactured in small quantities).
- The MITes were smaller than the other commercial motes as they did not require additional sensor boards or battery packs. This also makes them easier to setup and install in a real deployment scenario.
- As the MITes had a transmit/receive range of approximately 30m indoors and 220m outdoors, it was possible to directly transmit to a single point given the short distances between the nodes in the sce-

narios considered by Tapia *et al*. This resulted in less overhead for routing in the network protocols and fewer points of failure compared to more complex schemes involving multi-hop routing.

- The radio frequency used (in the 2.4GHz band) allowed a small on-board antenna only 3cm in size, preventing the need for external an antenna that would add size and possible fragility to the system.

The processing and communication tasks for the MITes wireless sensors are carried out by an nRF24E1 chip manufactured by Nordic VLSI Semiconductors. This chip integrates a radio transceiver, an 16MHz 8051 based microcontroller, a 9 channel 12-bit ADC, and miscellaneous peripherals including 3 timers (UARTs, SPI, PWM) and 11 general IO pins. The radio transceiver operates in the 2.4GHz band and offers data rates up to 1Mbps. 125 channels are provided for multi-channel communication. The chip offers features to support low power operation, such as a sleep mode and transmitting readings in bursts.

The use of an integrated microcontroller and radio chip led to a smaller size than would otherwise be possible, as well as reducing costs. 4K of EEPROM program memory and ADXL202/210 accelerometers are also included. The whole device is powered by a single CR2032 coin battery.

The MITes are intended to be devices that may be attached to a point of interest and then forgotten, requiring no additional setup or maintenance. The main purpose is to monitor physical objects that a person may interact with in order to determine usage patterns and other related information. An additional design, termed mobile MITes, were produced in order to allow monitoring of the motion of human subjects. These monitored motion on all three axes (compared with the two axes in the basic MITes devices) and had a greater range of measurable acceleration. At 30.5mm x 25.4mm x 6.4mm and a weight of 8.1g, including the battery, they were considered to be the smallest, lightest and least expensive wireless 3-axis accelerometer sensors available at the time and as such could be attached on a wide variety of places on a subject without restricting movement or becoming uncomfortable. The complete system is shown in figure 2.5.

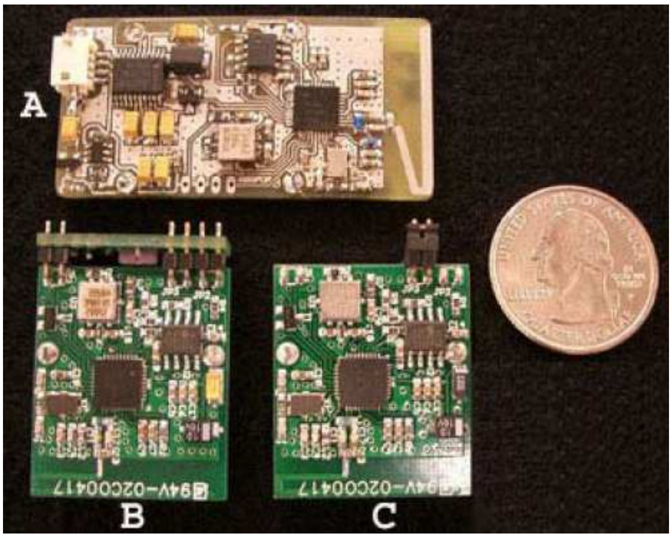


Figure 2.5: MITes device [5]
(A) receiver, (B) wearable accelerometer (3 axis, 10g), and (C) stick-on state-change sensor (2 axis, 2g)

The device presented is a good example of engineering for a specific purpose, and shows that where expansion is not required, the size and weight of a wireless sensing device can be significantly decreased. The obvious disadvantage in terms of its use for research in a wider context is very little flexibility with respect to any change in requirements. The aim for the instrumentation system under development in this project is to have devices as small as possible to both allow easy attachment to the subject or Explosive Ordnance Disposal (EOD) suit and not to cause discomfort where the weight of the suit acts to press the devices against the wearer. As such, the type of device presented by Tapia *et al.* is a good example of how this can be achieved. Tapia *et al.* have shown that significant miniaturisation is possible once the requirements have been fixed.

2.2.4 BSN Node

Lo and Yang [6] report the design and implementation of a wireless sensing node for use in a body sensor network. Their approach incorporates a stackable design to allow a variety of sensor types to be attached, given appropriate carrier boards. The connector providing this capability offers various interface options including I^2C, UART and analogue, along with power and ground lines. The design of the node is shown in figure 2.6.

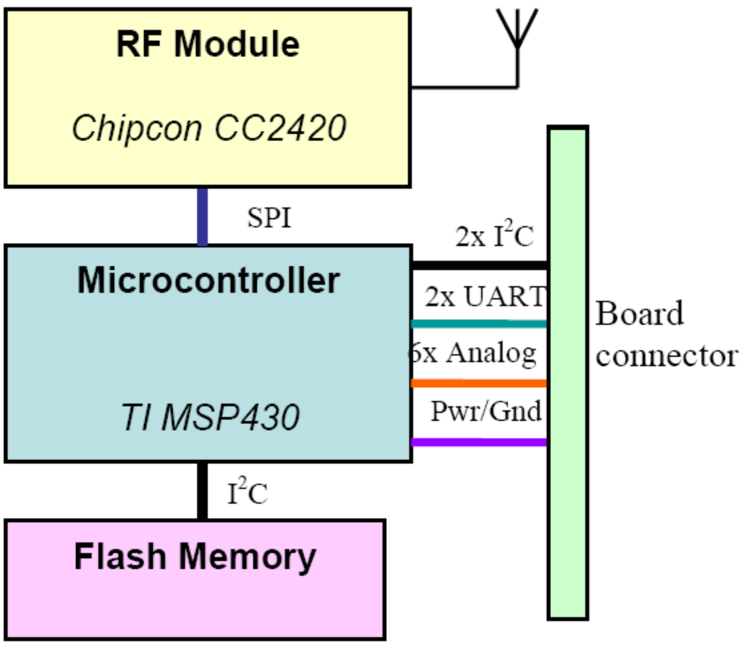


Figure 2.6: BSN Node architecture [6]

The radio is the ZigBee compliant Chipcon CC2420 which provides up to 250kbps throughput at up to 50m range. It also offers hardware AES-128 encryption and decryption for security purposes. The processor is a Texas Instruments MSP430F149 microcontroller, a 16-bit chip offering 60KB of flash memory, 2KB of RAM, and 12-bit ADCs. This chip can operate at voltages down to 1.8V and consumes a maximum of 3mW when active and 15µW while sleeping. The total power consumption of the device is from 0.01mA when active, increasing up to 1.3mA when performing computationally intensive operations. Provided on the device is 512KB of flash memory to supplement that provided by the microcontroller. Up to 1.5 hours of ECG data (at 100 samples per second) can be stored uncompressed, or up to 13 hours with compression applied. The node size is 26mm, allowing it to be used in body sensing applications while being unobtrusive. The node uses TinyOS as the operating system, which allows a modular approach to software building with module sizes as small as 200 bytes.

Various sensor boards have been developed for this platform, including 3- and 2-lead ECG sensors, and an SpO2 sensor. An integrated sensing device was also developed measuring 3.1x4.6cm and consisting of an ECG sensor, a 2-axis accelerometer, a temperature sensor, and a rechargeable battery. Lo and Yang consider this to be smaller than any commercially available ECG monitoring system, with the added advantage that it is capable of full context aware sensing due to the accelerometer and temperature sensors. These can be used to extract additional information about the current status, or context, of the readings (in this case aiding interpretation of the ECG sensor readings, but potentially it can aid any other attached sensors). An example here is the case of a patient undergoing physical exercise. Where only the ECG was available an external observer would see an increase in heart activity but would be unable to determine the reason unless there was prior knowledge of the subject's activities available. With the additional context sensors, the accelerometer data would show in increase in movement which would allow the observer to deduce a reason for the change in heart rate. Conversely, if the heart rate increased without the context sensors showing a detectable cause then this could mean that medical assistance is required.

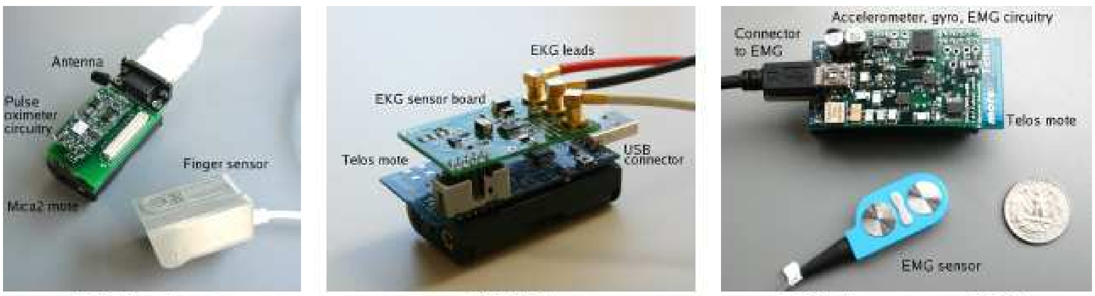
Like the work presented by Tapia *et al.* [5], this device shows that wireless body sensing devices can be very small. Unlike the other device, the BSN Node allows alternative sensors to be attached, enabling the use of this single platform throughout a system requiring multiple types of sensor. The various types of sensor made available on the BSN Node have been discussed in relation to previous works in this section. The specific important difference here is that the BSN Node is a custom-created system which is small and allows attachment of external sensor boards. This may be an important consideration in the system under development here in both its experimentation and EOD suit instrumentation roles as different areas of the body will require different sensors and using a single sensor platform supporting these would allow for faster development and easier replacement in case of malfunction. However, the BSN node microcontroller is severely underpowered by today's standards, but is sufficient for the task required of it in the application described by Lo and Yang, and the use of an OS specifically designed for embedded applications allows the power available to be fully utilised.

2.3 Body Sensing Network Platforms

There have been a variety of platforms used by researchers in the area of body sensing networks. These range from very small very low power devices with minimal processing and storage capabilities to embedded computers with processing power and available storage approximately equivalent to a modern

PDA or multi-function cell phone. The drive for companies to develop ever more powerful commercial hardware has resulted in significant advances in the available embedded hardware, with devices such as the Gumstix [7] Verdex range providing processor speeds of up to 600MHz and up to 128MB of RAM in a device only 80x20mm in size. These advances give current research a huge advantage over the related research carried out even a few years ago, with smaller more powerful devices able to perform a wider range of tasks while being less intrusive than their predecessors. This section provides an overview of the platforms utilised in a sample group of research from the literature, focusing on the hardware capabilities provided by each platform.

A platform that has been widely used in previous years in this area is the Mica series of motes, specifically the Mica2 and MicaZ. These have been used in projects such as CodeBlue [2] for example, where a variety of sensor boards were developed for sensing bodily parameters, and for research such as that by Gao *et al.* [8], where an expansion board was added to monitor a patient's vital signs during an emergency response. The Mica2 motes are a hardware platform developed by the University of California, Berkeley and sold by Crossbow Technologies Inc [9]. The processor is an Atmel ATmega128L and provides 128KB of program flash memory and 512KB of flash memory for the purpose of storing measurements. A UART is provided for serial communication along with an 8 channel 10-bit ADC and DIO, I^2C and SPI interfaces. A 916MHz radio is used for wireless communication, which can transmit at up to 38.4Kbaud with an outdoor range of up to 500ft quoted. Two AA batteries are used for power. The unit measures 58mm x 32mm x 7mm and weighs 18g (both measurements made without a battery pack). An expansion connector is provided to allow for connection of various expansion boards, with both commercially produced and custom boards being used by various researchers. The MicaZ motes are of very similar design, offering the same microcontroller, memory and interfaces, except that the wireless communication functionality is fulfilled by a ZigBee compatible radio offering speeds of up to 250kbps. Figure 2.7 shows the Mica2 motes with expansion boards as used in the CodeBlue project [2].



(a) Pulse oximeter (b) EKG (c) Motion capture and EMG

Figure 2.7: Mica2 motes as used for the CodeBlue project [2]

Another common platform is the Telos mote, sold by Moteiv Corporation [4]. This is used by Jovanov *et al.* [3] as a basis for the ActiS sensor for measuring bio-signals and motion-based context information. The Telos mote is based around a 8MHz Texas Instruments MSP430 microcontroller which provides 2KB of RAM and 60KB of ROM. Communication is achieved via USB or a ZigBee compatible radio, featuring hardware encryption and a range of 125m outdoors. An expansion connector is provided and humidity, temperature and light sensors are provided onboard. The mote is 32mm x 65.5mm x 13mm (excluding the battery pack). Figure 2.8 shows a basic Telos mote without additional expansion boards or a battery pack.

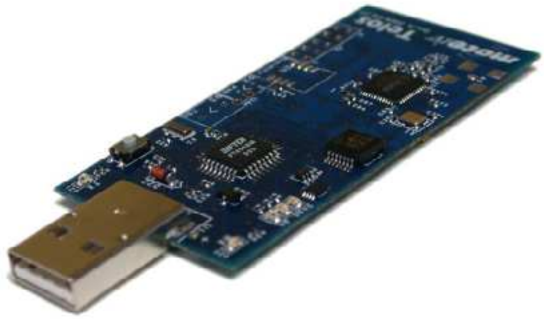


Figure 2.8: Telos mote

A third platform that has seen a rise in usage recently is that manufactured by Gumstix Inc [7], as used in work by Keoh *et al.* [10] and a team at Carnegie Mellon University (Embedded Systems Design Project in 2007 [11]). These devices offer more processing power and memory (both RAM and flash) than most previous platforms thanks to advances partially pioneered by manufacturers of PDAs and cell phones. An example Gumstix device is the Verdex XM4-bt, which offers a 400MHz PXA270 ARM processor, 64MB of RAM, 16MB of flash memory, an integrated Bluetooth radio, and exposed data lines for USB and a CCD camera. Three different expansion connectors are provided on the board to allow a variety of expansion boards to be connected. There are no onboard sensors provided, though these can be easily connected via an expansion board through the available I^2C or GPIO lines. The Verdex range also includes a device with a 600MHz processor and 128MB of RAM, though this does not have a Bluetooth radio. Figure 2.9 shows a Verdex XM4-bt motherboard viewed from the top and the bottom.

Figure 2.9: Verdex XM4-bt motherboard, both sides

These hardware platforms, while representative of the commonly used off-the-shelf units that are available, do not encompass the entire range of platforms used for body sensor networks. Of note are platforms developed for particular applications, which often provide a microcontroller and quantity of memory equivalent to that provided by the Mica2 or Telos motes, along with features required for the specific application. Examples of this are the BSN Node presented by Lo and Yang [6] (see section 2.2.4) and the MITes devices presented by Tapia *et al.* [5] (see section 2.2.3).

2.4 Sensing Parameters

There are a wide variety of physiological and environmental parameters that can be measured by a system such as the one proposed to be developed in this project, each with varying degrees of relevance to the goals of the system. While parameters such as a subject's skin temperature are fairly well researched and obviously relevant to a system intended to provide cooling, other parameters such as CO_2 levels also play a role in determining the health of the subject and allow for a much fuller view of the effects of the subject's environment in general and the worn EOD suit in particular.

This chapter provides an overview of several parameters that have been considered for measurement, covering the meaning and safe limits of each, along with the limitations of the respective sensing methods, their appropriateness, and the possible benefits gained by their inclusion in the system.

2.4.1 Temperature

There are three basic types of temperature reading that are of interest to this project: subject skin temperature, subject core temperature, and ambient temperature. Skin temperature is valuable as an indicator of the overall temperature of a subject as well as forming the basis for the calculation of thermal comfort levels. Core temperature is primarily a health related measurement as there is a narrow range of core temperatures that can be safely sustained by humans. Ambient temperature may be combined with skin temperature readings in order to determine the rate of heat loss in a subject. The following sections provide a more detailed presentation of these parameters.

Skin Temperature

There are seven points spread about the body that are commonly monitored for medical and research purposes when skin temperature data is required, often with the intention of deriving a mean body temperature. These seven points (shown in figure 2.10) are: the calf, thigh, chest, forearm, back, abdomen and forehead [12]. This set of points can be supplemented by backup sensors covering the same points as well as additional sensors for a more complete coverage or for research on specific locations of interest.

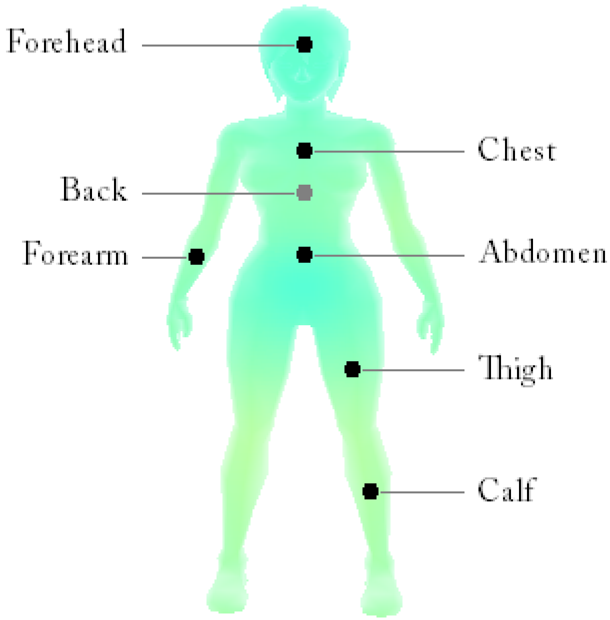


Figure 2.10: Locations for monitoring skin temperature

Skin temperature is an important measure when considering a subject's overall state of health and comfort. One piece of information that can be obtained from skin temperature data is the general health of the subject, as abnormally high or low overall temperatures can indicate poor health from internal causes such as infection, or external causes such as extreme environmental conditions. The skin temperature is not an accurate guide to core temperature however as it depends greatly on the ambient temperature, local air circulation (which is affected by clothing), and blood circulation.

Skin temperatures do not always provide a reliable measure of core body temperature, particularly when the core temperature is undergoing change. The body uses the skin to lose or gain heat as required, which may impact the readings of skin temperature. Additionally, clothing and medication can affect these readings. Despite this, the average of the skin temperature across the body is often used as an estimate of core temperature where a more direct measurement is not available (see for example the algorithms for determining thermal sensation developed by Zhang [13]). As skin temperature is widely variable and affected by so many factors it is impossible to provide a definitive range of safe and dangerous temperatures, though the table of core temperatures (Table 2.1) provides a general guide for areas that approximately follow core temperature such as the mouth, armpit and anus.

In addition to health related motivations, skin temperature can be used to estimate a subject's thermal comfort levels (as presented by Zhang [13]) as the readings directly correspond to the sensations that will be relayed by the subject's nervous system. A detailed exposition on comfort modelling is given in section 2.5.

The use of skin temperature in determining both health and comfort of a subject mean that it is a very valuable parameter to be monitored with the instrumentation system under design in this project and will be the first to be fully integrated into the prototype.

Core Temperature

Under normal healthy conditions, the core body temperature in a human varies between 36.5°C and 37.5°C. The armpit will measure between 36.25°C and 37.5°C. The temperature in the mouth will read between 0.25°C and 1.5°C higher than this and the rectum will read an additional 0.9°C higher still. Core temperature is not constant throughout a person's life, instead it varies with age. The variability of core temperature during the early stages of life is much greater than later on, and comparatively slight causes may result in wide divergences. These age-based variations should not be significant enough to present problems establishing a safe range for a subject's core body temperature as any such range, will have a built-in "safe" region rather than a simple binary "dangerous or not dangerous" decision.

The lower limit of temperatures that can be endured varies from person to person, but the upper limit is more well defined. Temperatures of 45°C and up cannot be survived for very long and at 50°C the muscles become rigid, which will render it impossible to do anything, including breathe, even if the temperature increase has been survived up to that point. A short guide to the effects of elevated core body temperatures is shown below, derived from a list presented on Wikipedia [14]. Note that the specific temperatures will vary from person to person.

Temperature	Effect
37°C (98.6°F)	Normal body temperature. This varies between about 36.1 and 37.5°C (96.8-99.5°F).
38°C (100.4°F)	Sweating, feeling very uncomfortable, slightly hungry.
39°C (102.2°F)	(Pyrexia, or fever) Severe sweating, flushed and very red. Fast heart rate and breathlessness. There may be accompanying exhaustion. Children and epileptics may be very likely to get convulsions at this point.
40°C (104°F)	Fainting, dehydration, weakness, vomiting, headache and dizziness may occur as well as profuse sweating.
41°C (105.8°F)	(Medical emergency) Fainting, vomiting, severe headache, dizziness, confusion, hallucinations, delirium and drowsiness can occur. There may also be palpitations and breathlessness.
42°C (107.6°F)	Subject may turn pale or remain flushed and red. They may become comatose or be in severe delirium. Vomiting and convulsions can occur. Blood pressure may be high or low and heart rate will be very fast.
43°C (109.4°F)	Normally death, or there may be serious brain damage, continuous convulsions and shock. Cardio-respiratory collapse will occur.
44°C (111.2°F)	Almost certainly death will occur; however, patients have been known to survive up to 46°C (114.8°F).

Table 2.1: Effects of raised core temperature in humans (derived from Wikipedia [14])

Obviously, in general, it is undesirable for a person's core body temperature to rise above 38°C as after this point discomfort turns into real danger. The comfortable range will be approximately centered around the value presented at the top of table 2.1, depending on the particular individual, as both higher and lower temperatures cause ill effects.

Ambient Temperature

Comfortable office temperatures are usually defined to be between 20°C and 26°C at 50% humidity and with air velocities below 0.25m/s.

The following table shows the Humidex scale, presented on the CCOHS website [15], which is used by some organisations to determine whether certain ambient temperature and humidity combinations would be comfortable or dangerous.

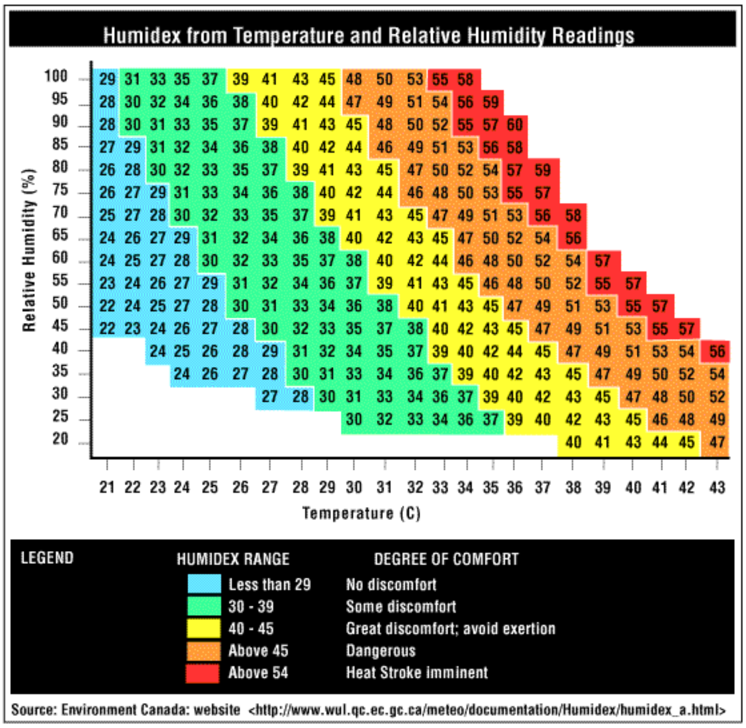


Figure 2.11: Humidex scale lookup table

While the Humidex scale may be useful in some situations, such as an office environment, monitoring this comfort measure is not applicable to the system studied in this project as the environment within the suit cannot be compared to cool office conditions. The Humidex scale, however, does provide another way of checking the point at which the temperature and humidity, in conjunction with each other, may become dangerous.

One further factor to consider is that a higher degree of humidity may represent increased perspiration and thus an increased cooling ability. However if the humidity increases too much it will prevent evaporation of sweat, decreasing the cooling ability of the wearer. This means that a level of humidity must be found where sufficient evaporation may occur from the skin, to remove heat, while not becoming humid to the point of preventing this evaporation.

Relationship Between Body Temperature and Performance in Humans

There is a body of literature discussing the effects of core body temperature on mental performance and related attributes in humans. While such research was performed over a large period of time by different researchers using differing methods, the findings confirm each other with no major contradictions apparent.

An important attribute of someone working in an area such as bomb disposal is that of reaction time; the ability to react to events in a fast and constructive manner could make a large difference in the outcome of a mission. This means that any external condition that works to increase reaction times should be avoided where possible, while conditions reducing reaction times should be welcomed where they do not cause other potentially dangerous effects. Kleitman *et al.* [16] show that an increase in body temperature of up to 1.5°F (approximately 0.8°C) provided an improvement in reaction time of between 7 and 20% depending upon the individual and the particular activity being performed. This is a significant improvement in some cases and a definite advantage where reaction times are important. Wright *et al. [17]* had differing results, with only the slowest 10% of reaction times being improved by temperature. While this result is not as encouraging as that found by Kleitman *et al.* it does demonstrate that temperature has a marked effect on reaction times. The largest improvements in reaction time according to Kleitman *et al.* were those where the subject was required to make a choice in the process of reacting to an event, such as responding to a red light but not a green one, with the presented theory being that in cases where a simple reaction was required with no decision-making process involved the subject would tend to let their mind wander, while they would have to pay a greater level of attention where choice is involved. This would imply that the process which improves reaction times in response to temperature also causes a greater level of concentration where the subject is already concentrating on a task. Whatever the exact process involved, this applies greatly to the example of a bomb disposal technician who would both be concentrating on the task at hand and would be likely to be presented with situations which require an element of choice in the response.

A second important ability required of a bomb disposal technician is recalling information or previous events to inform current actions. Wright *et al.* [17] performed research into the effects of body temperature on recall memory and found that when body temperature was highest, recall memory was improved in all cases. Holland *et al.* [18] also investigated this effect and produced different results. They found that neither long-term nor short-term memory was affected by body temperature changes, while the speed in solving both logic problems and performing two-digit subtractions was improved, though this effect was not seen in women. Accuracy in both cases was unaffected. They also point out that “increases in body core temperature to near 39°C produce no immediate effects that would be a serious hazard to a trained diver or other trained person carrying out menially *[physically]* demanding tasks”, which may be taken as closely applying to a bomb disposal technician. Improved recall memory, as well as improved speed in logical and mathematical puzzles, are an obvious benefit to someone carrying out a task which requires them to remember items brought up in their training, as well as situations where they are required to disarm an explosive device which may have been constructed in an improvised fashion and thus require some level of ingenuity and study to succeed.

An additional finding by Holland *et al.* was that alertness and irritability, both self-assessed by the subjects in their experimentation, were affected by body temperature. Alertness appeared to decrease with an increase in temperature, while irritability increased. These factors may be a major negative factor for a task requiring concentration, though the decision as to whether they outweigh the advantages presented above cannot be made on a general basis, instead relying on the particular situation at hand.

The research presented above was given in terms of natural changes in body temperature over the course of the day and night cycle. This project will be dealing with changes in body temperature due to external influences which the body cannot completely compensate for, which may result in differences between the findings presented above and the findings through experimentation performed in the context of this project.

2.4.2 Pulse Oximetry

Pulse oximetry is the process of reading a subject's pulse rate and blood oxygen saturation. It is usually accomplished non-invasively by shining an infra-red and a near-infra-red light source into a finger, or sometimes an earlobe or toe, and measuring the difference in levels of absorption between the two sources. As the oxygenated haemoglobin in the blood absorbs one wavelength of light more than the other, more absorption means the presence of more oxygenated haemoglobin and hence a higher saturation of oxygen in the blood. De-oxygenated haemoglobin has different absorption characteristics. The level of oxygen is thus read by means of determining the level of light absorption and comparing this between the two light sources. This data can also be used to read the pulse rate of the subject. Sudden changes in the reading levels relate to more blood or blood with more oxygen being pumped into the reading area, and therefore a pulse rate can be extracted from these changes.

There are a number of shortcomings to this method when used to measure the oxygen saturation of the blood. Firstly, as suggested by the name of the parameter, oxygen saturation is only a measure of oxygenation, not ventilation, and it does not indicate the levels of any other substances in the blood. This means that it will not provide the same level of information as a laboratory-based blood gases check, giving no indication of carbon dioxide levels, blood pH, or sodium bicarbonate levels for instance. If the metabolism of oxygen, that is the body's use of the available oxygen, is to be measured it can instead be done by monitoring expired CO_2. Falsely low readings of blood oxygen levels may result from a number of effects, such as:

- hypoperfusion (reduced blood flow) in the extremity used for monitoring, often due to that part of the body being cold
- incorrect sensor application causing light to not pass correctly through the body part being monitored
- highly calloused skin reducing the level of light passing through
- movement (such as shivering)

Falsely high or falsely low readings will occur when haemoglobin is bound to something other than oxygen. Both carbon monoxide and cyanide poisoning will give falsely high readings for example. For more information, Wikipedia's article on Pulse Oximetry [19] is readily available.

A pulse oximeter's readings are not usually affected by products such as nail polish or other tissues within the measured area as a base reading is established that the future readings are compared against. This has the effect of cancelling out the part of the reading that does not change, compensating for fixed interference such as the mentioned nail polish or tissues. For the purposes of this project, issues related to the subject being cold are not likely to pose problems, with high temperatures being far more likely. There are a variety of methods for compensating for spurious readings resulting from conditions such as subject movement, such as those discussed by Yan *et al.* [20] and Rusch *et al.* [21]. Carbon monoxide and cyanide should also not be present in the suit during any regular operation, and so for the purposes of this project they will not be considered to be a significant risk unless significant evidence is found to show otherwise. Overall pulse oximetry will allow a fuller view of the effects of the suit and it appears to be a suitable method for measuring the subject's pulse rate and blood oxygen level in the system presented here.

2.4.3 Carbon Dioxide Levels

Carbon dioxide content in normal air is usually between approximately 0.03% and 0.06%. In exhaled air this increases to approximately 4.5%.

In concentrations of over 2% it can cause a feeling of heaviness in the chest and more rapid/deeper breathing. In concentrations of over 5% it is immediately dangerous to a person's health and exposure to these levels for more than 30 minutes causes acute hypercapnia (excess carbon dioxide levels in the blood), while levels between 7 and 10% can cause unconsciousness within minutes.

Non-lethal concentrations of carbon dioxide can cause drowsiness, headaches and lower performance levels.

The current maximum that is considered safe during an 8-hour work day is 0.5%, and workplace levels are limited to this in the US by the OSHA (Occupational Safety and Health Administration) [22]. The NIOSH (National Institute for Occupational Safety and Health) [23] consider indoor levels above 1% to be an indicator of inadequate ventilation, and ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) [24] recommend that this level is not exceeded in any space. The NIOSH also limit exposures of up to 10 minutes to 3% and the level considered immediately harmful is set at 4%.

A danger when measuring CO_2 is to assume two things: that CO_2 and oxygen concentrations are directly related to each other, and that CO_2 is only dangerous due to the displacement of oxygen. In most cases, increased levels of carbon dioxide will indicate a reduced level of oxygen in the air due to the displacement of the oxygen by the carbon dioxide. This is not always true however, particularly in cases where the mix of gases may be different to normal air. If this is the case then higher levels of other gases may displace more oxygen than expected, or lower levels of other gases may mean there is more oxygen available despite the increased carbon dioxide levels. When carbon dioxide is present in large concentrations the danger is not only a result of the displacement of oxygen in the air. Large concentrations of CO_2 can reduce haemoglobin's ability to bind with oxygen, thus providing additional starvation beyond that attributable to the lowered oxygen levels.

Though this will likely not occur within the suit in a normal environment, if both carbon dioxide and oxygen levels are low then this can cause additional problems and pose threats to the wearer's health. Normally a lack of oxygen will be related to increased carbon dioxide levels, and it is this relationship that the human body uses to determine if sufficient oxygen levels are present. This, however, means that if both oxygen and carbon dioxide levels are low, in the presence of another absorbed gas, then the checking process will still assume that the low carbon dioxide levels mean that there is sufficient oxygen available. This means that there will be no urge to breathe more deeply or quickly to obtain more oxygen, and the error will eventually cause unconsciousness. This is mainly a problem in occupations such as diving where artificial gas mixtures are used, which may lead to abnormal levels of both carbon dioxide and oxygen. Due to the links to diving, this problem is termed “shallow water blackout” [25].

In relation to the EOD suit, when the helmet is worn with the rest of the suit it creates an enclosed environment in which carbon dioxide could potentially build up. This means that CO_2 levels in the suit, particularly the helmet, could be an important parameter for measurement in the system being developed. This parameter will considered for the experimentation application of the system, as well as in guiding the development of the prototype monitoring system.

2.5 Comfort Modelling

The comfort model being investigated for the purposes of this project was developed by Zhang [13] at the University of California, Berkeley. It is designed to take skin temperature, and optionally core temperature, readings as input and use these to provide an estimation of comfort both globally across the body and locally to particular body segments. The scale of comfort used ranges from -4 to 4 degrees and is based on a scale used for self-assessment during experimentation. The model accounts for both static and changing temperatures which can cause wildly different comfort levels due to the body’s tendency to overshoot in terms of reaction to a changing temperature.

For the purposes of calculating thermal sensation, each body segment is given a weight which determines its contribution towards the final sensation level. Equation 2.1 shows the method of calculating overall sensation, which is simply the weighted average of the local sensation for each body segment.

$$Overall\ Sensation = \frac{\sum weight_i\, S_{local,i}}{\sum weight_i} \tag{2.1}$$

Overall comfort is defined by a set of rules which effectively assign a weight of 0 or 1 to each location’s local comfort level. These are given below.

1. Overall comfort is the average of the two minimum local comfort votes unless Rule 2 applies.
2. If the following criteria are met then overall comfort is the average of the two minimum votes and the maximum comfort vote.
    - the second lowest local comfort vote is greater than -2.5
    - the subject has some control over his/her thermal environment or the thermal conditions are transient

If both hands or both feet comprise the two most uncomfortable body parts then the second lowest hand or foot comfort value is ignored and third lowest local comfort vote is used in its place in both rules.

The initial equation for determining local sensation in static conditions is shown in equation 2.2. This is a logistic function based on the difference between the local skin temperature and its set point (the point at which the local sensation is 0, or neutral). A constant $C1$, which is different for each body segment, defines how big a change in sensation a change in temperature causes. The output range will be between -4 and 4.

$$\textit{Local Sensation} = 4\left(\frac{2}{1+e^{-C1(T_{skin,local}-T_{skin,local,set})}}-1\right) \tag{2.2}$$

This equation is modified by a term representing the difference between the overall thermal state of the body and the local thermal state, resulting in the equation given in 2.3. A constant K1, which is different for each body part, determines the contribution of the overall thermal state to the sensation of the segment in question.

$$\textit{Local Sensation} = 4\left(\frac{2}{1+e^{-C1(T_{skin,local}-T_{skin,local,set})-K1[(T_{skin,local}-T_{skin,local,set})-(\overline{T}_{skin}-\overline{T}_{skin,set})]}}-1\right) \tag{2.3}$$

This equation is once again modified by terms representing the changes in local sensation in dynamic conditions, where the body's reaction has a tendency to overshoot. These additional terms are shown in equation 2.4, and the final result is simply the sum of these and equation 2.3.

$$C2_i\frac{dT_{skin,local}}{dt}+C3_i\frac{dT_{core}}{dt} \tag{2.4}$$

Local comfort is defined as in equation 2.5 below, where all constants $C\cdot$ are defined separately for each body segment, and S_o and S_l are the overall and local sensation level respectively.

$$\textit{Local Comfort} = \left(\frac{C1+C2S_o}{e^{5(S_l+\textit{Offset})}+1}+C4+C5S_o\right)(S_l+C3S_o)+C6+C71|S_o^-|+C72|S_o^+| \tag{2.5}$$

Shown in figures 2.12 and 2.13 are two graphs showing how the level of comfort for a body segment changes in relation to the difference between the temperature of the segment and the segment's set point. The set point is the temperature that the segment expects to be at and can vary with time and changing temperatures. Figure 2.12 shows the comfort levels of the back segment while the figure 2.13 shows the comfort levels of the breathing zone, that is the area in contact with the air that is being breathed which is commonly measured at the cheek. It should be emphasised that these graphs demonstrate comfort levels in static conditions, if the temperature conditions are not static then the relationship between temperature and comfort will be very different.

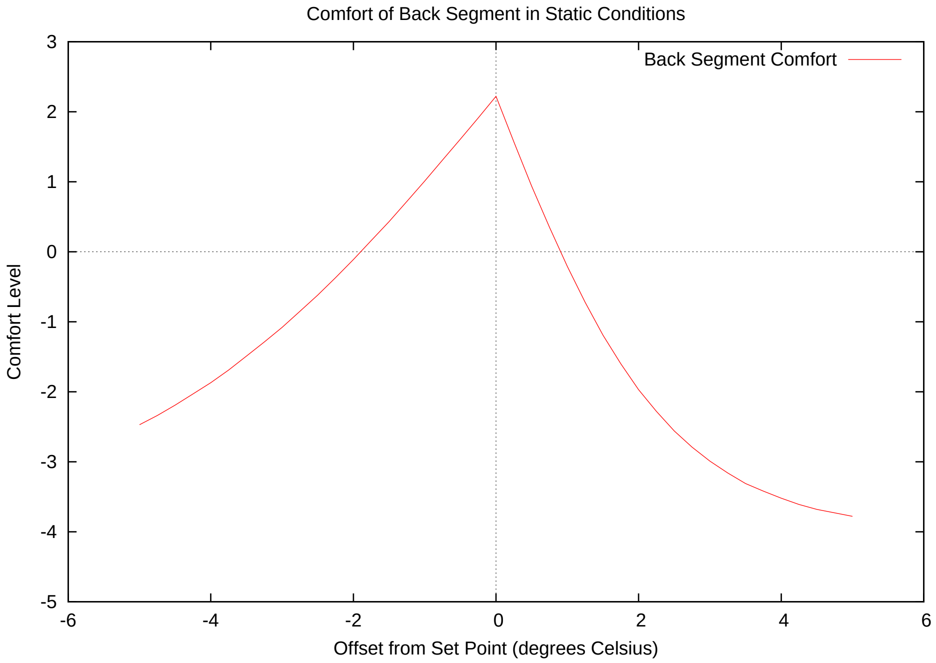


Figure 2.12: Comfort of back segment in static conditions

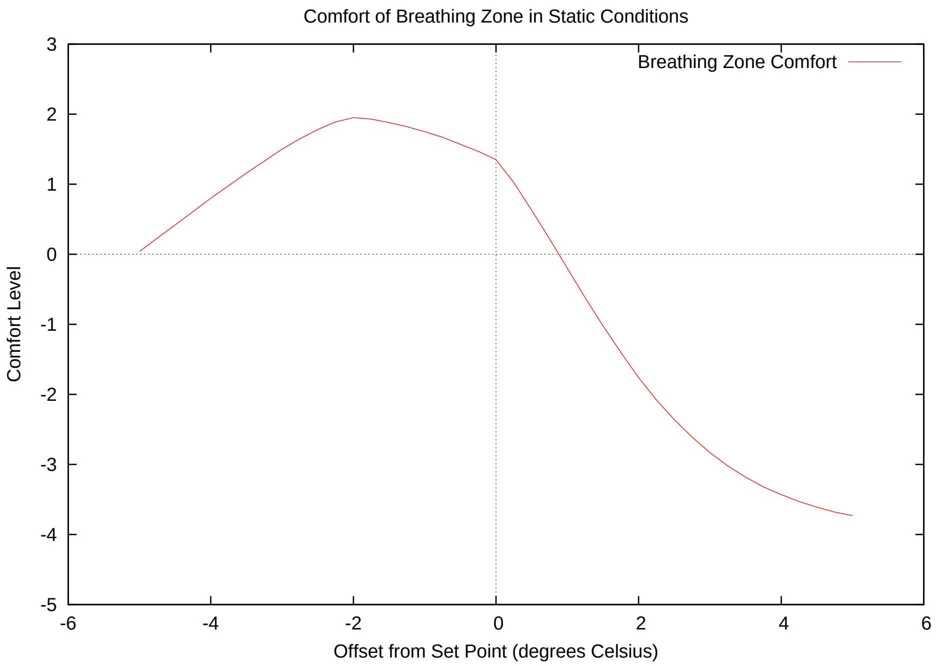


Figure 2.13: Comfort of breathing zone in static conditions

Of note are the entirely different shapes of the graphs. The back segment shows the comfort level reducing on each side as you move further from the set point, which is in line with experience where both cold and hot temperature extremes are uncomfortable. The breathing zone comfort levels are similar, but show a larger band of comfortable temperatures below the set point as well as peaking at a lower temperature than the set point. These types of differences are an important consideration when it comes to predicting the effect that the activation of cooling will have on a subject.

The process of integrating this engine with the prototype system is discussed in section 4.7.

Chapter 3

Design of the Suit Instrumentation System

The instrumentation system to be developed in this project has a diverse range of requirements in order for it to be effective in the intended application, as well as allowing it to function as an aid to experimentation and research. There are three main roles that the system will be required to fulfill towards the project goal. These roles are introduced in section 3.1 below and discussed in greater detail through this chapter, sections 3.2 to 3.5 specifically. Sections 3.6 to 3.12 discuss the components that the system will be composed of.

3.1 The Application

With respect to the application, the prototype system is expected to develop along two separate branches, each with its own requirements and constraints. The first of these applications is the prototype system for installation within an EOD suit that is capable of monitoring a bomb disposal technician on a mission, providing cooling at appropriate times, and allowing remote monitoring within and outside of the danger area. In the nearer term, another aspect working towards this application is that of developing the prototype as an aid that will guide the design of the suit instrumentation system in terms of the sensor load and appropriate mounting points. The second application of the system is its use as an experimentation aid for the purpose of refining our knowledge of the effects of the suit on the wearer, along with research into the issues surrounding body sensor networks not necessarily directly related to the use of EOD suits. It is expected that as part of this role the system will also be capable of serving in a more general body sensing role where required for experimentation outside of the direct scope of this project. These two main applications share several characteristics and may largely be developed as different aspects of a single prototype system, with some components being added or removed as appropriate.

Example of the types of difference required in the prototype between different roles are:

- In an experimental or general body sensing role, the system will be required to support a large number of different types of sensor. In the suit instrumentation role it will only be required to support the sensors that this research has deemed to be necessary.

- In the suit instrumentation role, methods of communicating between nodes (and the monitoring point) will have to be found which do not rely on radio signals as these may be jammed. In the other roles this is not an issue and any supported method may be used.

An EOD suit of the type worked with in this project was presented in figure 1.1 in chapter 1. Figure 3.1 shows the intended data flow within the system as a whole. Note that the sensor locations are for illustration purposes and are not representative of actual appropriate locations (which are shown in figure 2.10).

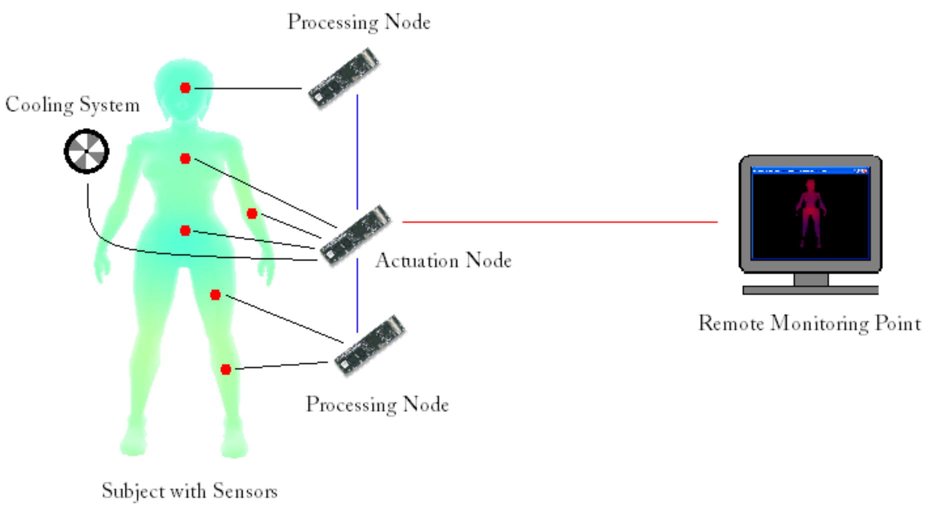


Figure 3.1: System data flow

The sensor readings are gathered by processing nodes (including the actuation node). These nodes perform initial processing of the data, including modelling where possible, after which the results are passed to the actuation node. This node performs the remainder of the data modelling required, and the resulting information is used by the decision-making engine to determine whether the cooling system should be activated. The information is also transmitted to the remote monitoring point.

3.2 The Development Prototype

The system requirements are shared into function requirements and technical requirements, as detailed below.

3.2.1 Functional Requirements

The most basic requirement for both applications discussed above is the system's ability to collect data. This may be data about a human subject or the environment around the subject, and in some cases it may be both. This data will also require some form of processing in order to transform it into useful information, both to be displayed to a remote observer and to allow the system to make autonomous decisions where appropriate (Section 3.8 of this report discusses the difference between data and information).

The system is required to be capable of sending the data collected and the information generated to a remote monitoring point. In the case of the monitoring application this will allow remote observation of the human subject and the instrumentation system itself for safety and mission analysis purposes. While in the case of the research and design aid it will allow logging and real time display during experimentation.

While information is being communicated to a remote monitoring point, it may also need to be logged locally by nodes within the suit. The applications considered here will all require this in cases where communication with the monitoring point may be lost temporarily (or even permanently). The local data logging will also provide a single point of download for all the relevant data collected after the experimentation or mission, including data which may not have been necessary to communicate to the monitoring point.

3.2.2 Technical Requirements

The collection of data requires the querying of sensors by the nodes they are attached to, whether via a wired connection such as and I^2C bus or a wireless connection such as a Bluetooth or ZigBee compliant radio. There are a variety of well known communication standards which may be used and the nodes will be required to support the standards used by the particular sensors attached to them. The processing of this data, including modelling and decision-making, will require a high level of computational ability, as well as sufficient programming support in the form of libraries or facilities provided by the OS.

Wireless communication is further required for communicating readings to a remote monitoring point. This removes the dependence on cables between the subject and the observation system which may otherwise impede experimentation by restricting the natural movements of the subject and adding additional weight to the instrumentation system, potentially affecting the results. Additionally, a wired system would restrict the wearer to being within a certain distance of the monitoring point which could be a problem in experimentation if considerable movement is required and would be impossible in the case of EOD suit instrumentation. Wireless communication between the instrumentation system and the observation system is hence a prime requirement with the possible exception of the restricted range between the subject and the observer, most wireless devices offer sufficient range to allow for substantial freedom of movement.

Storing data locally requires some form of storage device on the nodes. This may be temporary storage such as RAM or more permanent storage such as flash memory, with the latter being capable of storing the data in the case of the device losing power. The storage of data also leads to the requirement for a method of retrieving this data after the experimentation or mission is complete to allow further analysis, either of the readings themselves or of the parts of the system that generated them.

In summary, the system is required to:

- collect data from a subject and/or their environment
- process the collected data
- make autonomous decisions based on the data
- transmit data to a remote point
- log data locally

To achieve these goals, the system will require:

- a method of interfacing to sensors
- sufficient processing capability
- a form of wireless communication
- local storage

3.3 The Continuous Monitoring In-Suit Instrumentation System

In the role of a continuous monitoring in-suit instrumentation system, the system requirements mostly involve robustness and ease of setup and use. Considerable mechanical stresses will be placed on the system during its functional life. To this end the system must be mechanically robust. This means that, where possible, knocks or scrapes encountered during routine operation should not cause malfunctions. There are a variety of sources of potential damage to the system due in part to the weight of the suit pressing on components of the system as well as the additional armour plating which may cause impacts while the wearer moves. This type of resilience usually requires a combination of strong packaging and some form of padding of critical or vulnerable components to absorb impacts as much as possible.

Similarly, the system must be electrically robust:

- Radio frequency signals nearby should have as little impact on operation as possible. This is especially important as signal jammers are often carried by bomb disposal technicians to prevent remote detonation of explosive devices. Problems in this area can be increased by aspects of the system such as lengths of cabling to connect various components together which can act as antennas, picking up radio signals and interfering with the original signals carried by the cable.
- The number of exposed metal parts should be as small as possible in order to reduce the chances of accidental contact with other equipment which may be carrying a voltage. This also helps reduce the system's susceptibility to stray static charges.

The method of packaging as mentioned previously is likely to reduce the vulnerability of the system in terms of the latter requirement, while the former may be reduced by using established good practices in designing the equipment's circuit boards and ensuring cable runs are as short as possible. The signal jammers carried by the technicians, mentioned in the first point above, may unfortunately result in a true wireless solution to communication being infeasible. This can be solved within the suit by a variety of methods such as induction loop type communications across suit segment boundaries. Communication with an external monitoring point will be more problematic in this scenario, though there are technologies available which will not be affected by radio frequency jamming, such as using lasers to transmit data. Where immediate communication of data to a monitoring location is not required, it will be possible to store the collected data locally and download this on request (such as when the wearer has returned to a safe area).

The system must be easy for a non-expert to setup and use. In the role of continuous monitoring in-suit instrumentation system, the system is likely to be used by people with minimal prior experience with this type of technology and who have other priorities as part of their job which require their attention. This means that a system that can simply be switched on and used will be much more acceptable than one which requires more interaction to set up. It also means that automated and possibly even invisible, error detection and graceful recovery will be a requirement. For wireless sensor networks, this is an on-going area of study in the literature and has been investigated by researchers such as Koushanfar *et al.* [26] and Venkatasubramanian *et al.* [27].

The local storage of data mentioned previously will be valuable to medical workers in the case of injury to the bomb disposal technician and as such it should be available in a recognised format that may be interpreted as quickly as possible before, or while, providing medical aid.

3.4 The Instrumentation System as a Suit Design and Prototyping Aid

In the role of a suit design and prototyping aid, the system requirements focus more on adaptability to different purposes as needed and the ability to attach a wider range of sensor types to the basic platform. The primary purpose of the system in terms of experimentation is to discover the optimum sensor load with regard to both the number and type of sensors required. This means that a variety of sensor types will be attached to the system at various points in its lifetime, each with its own physical method of attachment and its own protocol for data communication. The most common interfaces provided by sensors are serial, I^2C, and analogue output, with slightly less common examples including Bluetooth, USB, and SPI (Serial Peripheral Interface, a serial communication link much like I^2C).

The system will also be used to gather data on the effects of the EOD suit on the wearer in order to refine the data models used and aid the improvement of the design of the suit or modifying aspects of mission structure to benefit the wearer. This requirement again means that as an experimentation aid the system must provide more interface options and support more types of sensor than required in the final suit-installed monitoring system.

3.5 The Instrumentation System as a Body Sensor Network Research Aid

In the role of a body sensor network research aid, the requirements on the system are very similar to those in the suit design and prototyping aid role. The same level of adaptability is required so that various types of sensors may be attached during the course of different experiments.The primary purpose here is to allow the investigation of sensor positioning beyond that required for the suit instrumentation system, as well as collecting additional physiological data in a wider context. This aspect of the system may be of particular use in other related projects, where having a system available for experimentation without undergoing a lengthy design phase will allow the research to proceed much faster. This role is likely to require a variety of different software modules to be loaded onto the nodes to perform different tasks, so a method of quickly distributing this to the nodes will be required.

3.6 Overview of the System Data Flow

Functionally, the system envisioned can be divided into several logical blocks or components that pass data and information between each other in order to accomplish the overall system operation. The diagram in figure 3.2 shows these blocks along with the route that data and information will take.

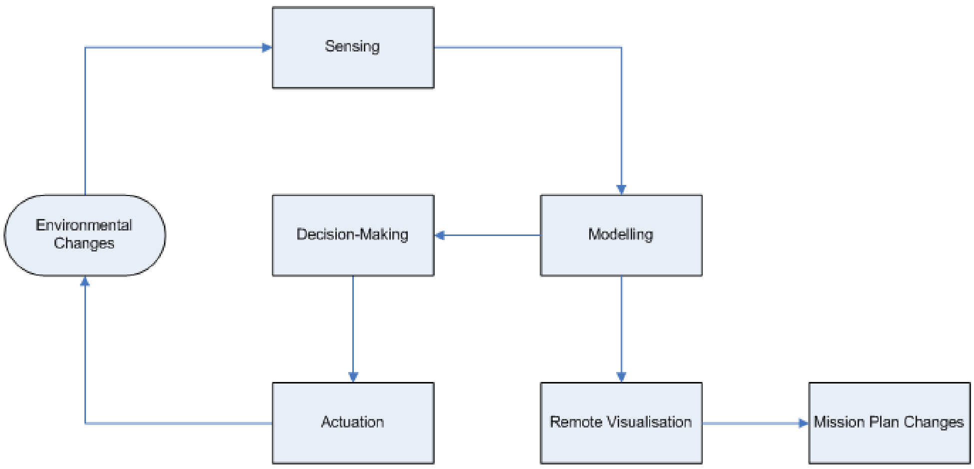


Figure 3.2: Prototype system data flow

The data flow seen here involves two distinct routes. Shared across both routes are the Body Sensing and Modelling components of the system, which are responsible for gathering the data and transforming it into a useful form for the remainder of the system. The data flow via the Decision-making and Hardware Actuation components supports the autonomous functionality of the system, while the alternative route incorporates the Remote Monitoring component which would include an interface for external observers to monitor both the system and the subject. The following sections describe each of these blocks in greater detail.

3.7 Sensing Component

The body sensing component of the application is arguably the most important as it provides the data that all the other parts of the system rely on for their operation. There are a wide variety of sensing parameters that could be considered for inclusion in the system. Measurable physiological parameters include skin temperature, core temperature, exhaled CO_2 levels, pulse rate, blood oxygen saturation, heart rate and posture assessment. Other parameters include ambient temperature and CO_2 levels within the suit. Each parameter has its own potential uses and most, if not all of those listed, will be considered for inclusion at some point during the system development process.

The physical attachment of sensors to the body is an important consideration and here again there are a wide variety of options, from direct attachment to the subject's skin (for example pulse oximetry sensors) to devices that may be woven into clothing (such as activity monitoring) to contactless sensors (such as infra-red temperature probes). The options available for each particular type of sensor are limited primarily by the sensing devices themselves, for instance most temperature sensors require contact with the object they are measuring the temperature of. Further constraints are imposed by the level of obstruction they present for the subject, which is an important consideration in an application such as this. A final point to consider is the practicality of mounting the sensors in the confined space available within an EOD suit. Large sensors or those requiring additional supporting equipment (such as a CO_2 sensor which requires air to be pumped over it) may simply not be capable of being fitted within the suit.

3.8 Modelling Component

The modelling component of the system has the purpose of converting raw incoming data streams into useful information for the automated actuation system and remote monitoring. The distinction made between data and information here is an important one: data are the raw readings generated by the sensors and represent specific details about real conditions, while information is the result of processing one or more sets of data and extracting an abstracted and/or globalised view of the conditions being monitored as well as consequences of changes in the data. Information is the key to effective decision-making as the decision-maker (whether human or software) does not have the burden of interpreting streams of numbers and instead has available a view of events that is relevant to their needs. Figure 3.3 represents this concept visually. Processing data into information can take various forms, from the processing of sets of data in relation to each other, often called data fusion and discussed in works such as Koushanfar *et al.* [28], to generating notifications and alarms. Data fusion is an important aspect of this project as the processing of several data sets in relation to each other can both reveal information that would otherwise be unobtainable and also allows erroneous readings to the autonomously detected and potentially corrected.

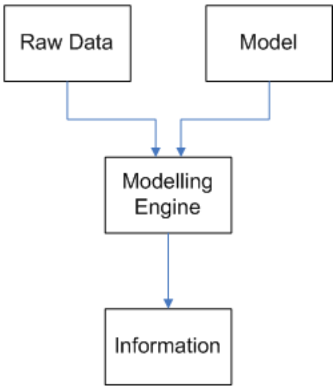


Figure 3.3: Modelling component data flow

A small body of work on data modelling related to physiological parameters (such as comfort and motion sensing) has been presented in the literature. Data modelling is a component that is often overlooked or not considered to be necessary within the requirements of a project, such as in work presented by Jovanov *et al.* [29] and Malan *et al.* [30], where the acquired data itself is the important output of the system. However in a system such as this one where a number of different types of sensors will be used, possibly with many instances of the same sensor type, this component is crucial. The amount of data acquired is likely to overload an observer if delivered raw, while any automated decision-making components (discussed below) will be unable to function effectively.

The closest relevant example to the scope of this project, found in the literature, is the case of comfort modelling (see section 2.5). Zhang [13] provides a solid basis for extracting local and global comfort estimates from skin, and optionally core, temperature readings. The model is designed to operate in both stable and transient conditions allowing a wide range of applicability. Using algorithms such as those developed by Zhang, estimates of the local and global comfort of the subject can be extracted and thus used for display to an observer as well as being fed to the decision-making component in order to inform decisions regarding the actuation of the cooling system. Another piece of information that can be extracted at this stage is knowledge of the movement and posture of the subject, which can be used in providing a better interpretation of the temperature data gathered, as well as being relayed to the external observer. Audible or visual feedback to the subject may be made available (such as via LEDs or a sound system), in which case it will be utilised by this component to alert the subject to potentially dangerous conditions.

3.9 Decision-Making Component

Due to the nature of the system under development, decision-making is a very important aspect, in terms of both the actual decision and its timing. At its most simple level, the system must know when to activate the cooling systems and when to hold off. The latter is just as important as the former, as rapidly switching the cooling unit on and off is likely to drain the batteries faster than simply leaving the unit on. Additionally, rapid switching is likely to cause considerable distraction to the wearer of the suit which could be dangerous in a situation where concentration is required. The decision-making burden could be placed on a mission observer, however this may cause similar problems to the current system where cooling is activated when not needed or not activated when needed and additionally would likely provide slower reactions to events than an automatic system. Moreover, air is drawn by the cooling system from the external environment and where it is not separately cooled its temperature is not changed. This may mean in some situations this may mean that activating the cooling system will not in fact produce any cooling effect.

Inputs to this component will be supplied by the data modelling component situated before it in the chain. The inputs are likely to include the subject's body temperature (such as core temperature and average skin temperature) and comfort levels. In addition to using these inputs to determine the correct time at which to actuate the cooling system, this component will also be responsible for predicting the effect that the cooling system will have at any particular moment and for a short time into the future, which will allow it to avoid situations where the cooling system is rapidly switched on and off, potentially providing distraction to the wearer of the EOD suit as well as draining the battery further.

Decision-making is often seen as a area that is best served by artificial intelligence (AI) techniques, as discussed by Georgeff and Ingrand [31] for instance who present a system called PRS (Procedural Reasoning System) aimed at decision-making in embedded applications. This system was the basis for the development of a number of other derived systems. While AI based systems can indeed produce good results, an AI approach may be considered too heavyweight for an embedded system such as one in the project presented here where a more lightweight system would execute faster and require less memory, allowing more power and storage to be made available for predicting the results of actions and other such activities. Whilst this is true of some AI systems, if the components of the system are sufficiently well-defined it is possible to produce a smaller, more lightweight AI system. The components of most expert systems are: a database containing the current knowledge of the world (to the extent that is relevant to the system); a set of goals that are to be achieved; a set of plans that instruct the system in the appropriate way to respond to situations; and a list of plans that have been selected for execution at the current time. The flow of data within the AI system proposed by Georgeff and Ingrand (shown in figure 3.4) is commonly used and suitable for a variety of different systems.

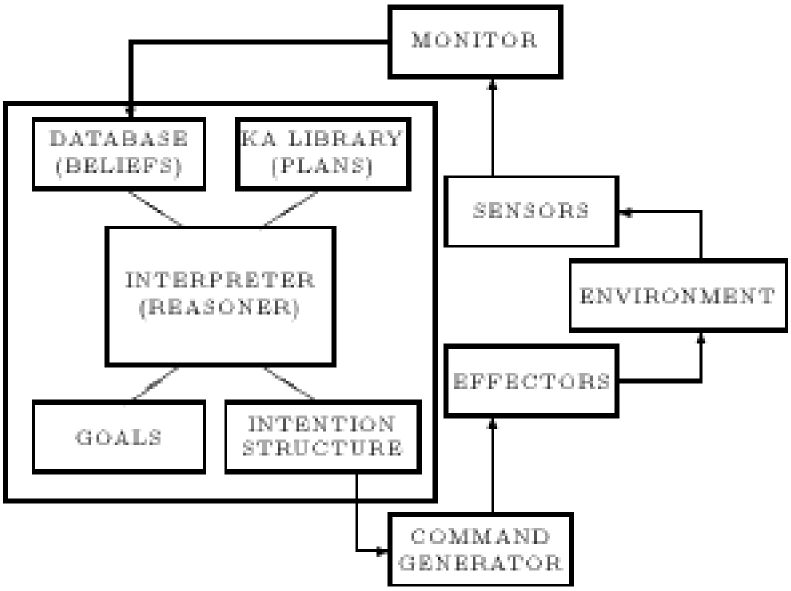


Figure 3.4: PRS System Data Flow [31]

This diagram would map to the prototype system here in the following way:

Prototype System	PRS System
Sensing component	Sensors
Modelling component	Monitor
Decision-making component	Beliefs, Plans, Interpreter, Goals, Intention Structure, Command Generator
Hardware actuation component	Effectors

Table 3.1: Mapping between PRS system data flow and prototype system components

More research in this area must be conducted before the suitability of the system proposed by Georgeff and Ingrand, or one of the later systems based on this, can be determined. In particular, it must be established whether an AI type of approach will provide the system here with any real benefit.

3.10 Hardware Actuation Component

This component provides the interface to the cooling hardware in the suit and thus is, along with the remote monitoring component, one of the major outputs of the system. In the current cooling system cold air is supplied to the subject's back region by a fan with air input either from the environment, or optionally from a dry ice unit (where additional cooling is desired). Another fan supplies air near the neck/chin directed into the helmet for the dual purpose of cooling the head and ensuring that the breathing air is circulated. The interface provided by the cooling unit currently utilises a manually controlled variable resistor to adjust the fan speed and a separate switch to activate and deactivate the fan. These components can be replaced with an actuation circuit which can in turn be controlled by a node in the sensing network.

The input to this component will be simple, with an indication of whether the cooling units should be activated or deactivated, along with the desired power level.

3.11 Remote Monitoring Component

The remote monitoring component of this system allows an external observer, or observers, to monitor both the instrumentation system and the bomb disposal technician during a mission. This component serves several important purposes. The instrumentation system needs to be monitored for correct operation during a mission or experimentation run, with problems such as suspect readings being flagged for the attention of an observer. The current status of the subject also needs to be monitored to ensure that he or she continues to be safe, hence the system has to have the ability to alert the observer if this ceases to be the case. This component will also allow additional observers to determine in real time the effects of the suit or the wearer, and monitor the effect a variety of physiological conditions have on the subject, and also the success of the mission. This immediate feedback could in some cases be more valuable than stored data as it can be directly linked to what is actually happening at the time the readings are taken. Unfortunately the information supplied cannot be used by an observer to effect immediate changes in the mission plan as bomb disposal technicians working with the British Army for example do not wear communication devices, and for the duration of the mission they have control over operations. There is a limited time they are permitted to be engaged with the disarming of the device without a break however, so the information could allow changes to be considered once the technician returns to the safe area.

In the suit instrumentation application specifically, additional information can be supplied to medical workers if injury occurs during a mission due to either the detonation of a bomb or some form of accident. This information could be valuable for a medical team in determining the best course of action in making sure the subject is stable and while delivering treatment.

Part of the envisaged prototype system is an application for visualising data collected by the sensors so that both the human subject and the system itself can be monitored. The visualisation software is expected to support the dual roles of the sensing system:

- monitoring the wearer of a protection suit during a mission
- providing a basis for experimentation and research under controlled conditions

To this end, two sets of requirements upon the software had to be considered for its development. On the one hand, the end-product of the project is required to be both easy to use and robust due to the intended operating environment. It will be used by people who are not experts in the field of body sensing, which means that complex visualisations requiring considerable background knowledge of the area will not be fit for the purpose. It will also require effective handling of error conditions, with either well explained, or automatic, recovery procedures or at the very least an obvious indicator that the information displayed may not be accurate. On the other hand, the intention for the system to be used as an experimentation aid requires it to be adaptable and have an open architecture, potentially supporting more complex visualisations and greater detail in error reporting.

There are several ways to solve this potential conflict between requirements, including the production of two versions of the software, generated from the same code base via conditional compilation. These options have not yet been fully investigated.

3.11.1 General Requirements

The visualisation application under development has two main roles: a real-time monitoring tool for an instrumentation system, and a basis for experimentation in the area of body sensor networks, including specifically a role as a test-bed for the instrumented suit during design cycles and trials.

These two roles share the requirement for the ability to read information from a sensor network and display it in an intuitive manner. While the role as a monitoring tool will require the ability to display data in real time, this will not always be necessary for the experimentation role and would rate primarily as a usability benefit and a way for an observer to note interesting data points prior to the actual analysis of the gathered information. This is because often in this role the data from the sensors will be recorded and then analysed at a later date, possibly by a separate program specifically written to carry out the processing required for the particular experiment undertaken.

Data Input

Depending on the particular purpose the visualiser is put to, input from a variety of sources will be required. The most important of these is input from the remote sensing devices in use, which will usually be transmitted via some form of network, for example Ethernet or a Bluetooth PicoNet. The ability to read from stored records, such as files containing data from previous experimental runs, may also be required in cases where, for example, a visualisation is to be replayed. This data may be stored on the current PC's hard disk or an attached shared network drive.

Because of the wide variety of networks in use for different applications, and the different protocols associated with each type, it is envisaged that the visualiser will provide a general abstracted method of reading data from a network. This will allow support for additional network types to be added as required without requiring major source code revisions or multiple versions of the software. Consequently support for Ethernet and Bluetooth PicoNets, for example, should be provided via the same abstracted method as support for communication via a PC's serial port.

The same can be said for the process of reading data from storage. While a standard format for data storage will be proposed, the end-user could have additional data files in a large variety of formats which may be not all be anticipated at the time the software is created. Databases may also be used in some instances to store retrieved data. This means that an abstracted method for reading from stored data should be provided so that additional file formats may be added with minimal effort. A method involving using a descriptor file to describe the format of the data files would mean that certain formats could potentially be added “in the field” as required, which would be a distinct advantage over distributing an updated application.

Information Extraction

During the use of the visualiser, some processing of data may be required. While the system presented here aims to integrate the data modelling and decision-making functionality into the network nodes, this may not be the best solution during the early stages of development. Additionally, if the visualiser is to be used with other networks they may not perform this processing within the network, instead taking the more traditional route of having the processing performed at a central location (in this case the PC the visualiser is running on). This means that the option to perform such processing must be left available in the visualiser. (Section 3.8 covered the modelling of data in more detail). The two main types of processing that are likely to be required are that of data fusion, where multiple streams of data are processed in relation to each other in order to reveal additional meaning, and the generation of alarms or event notifications.

Incoming data streams should not necessarily be considered in isolation, in some cases it needs to be combined in order to result in useful information. This is especially important considering that “information”, where generated appropriately, is much easier to interpret by a user of the system than raw “data”. As an example directly related to the parameters being sensed in this project, in order to determine if someone is losing or gaining heat it is necessary to know both their skin temperature and the temperature of the surrounding environment, one or other of the data streams, individually, is insufficient.

The concept of notifications, alarms, and triggers is a common one. The idea is to notify the user of a condition that they may not have noticed if their attention is occupied elsewhere. In some cases the display of an entire stream, or set of streams, of data may be usefully hidden in favour of a notification of condition changes. As an example, carbon dioxide levels within the suit is not a parameter that is likely to change suddenly or unexpectedly which means that constantly displaying it will not provide any positive benefit. Instead it may be appropriate to only inform the user when it is becomes close to a defined threshold, and/or display the percentage change in value.

Data Display

Display of the incoming data is possibly the most important feature of the visualiser as the intended purpose of the application as a whole is to allow the intuitive display of sensor data, and information generated from it. To this end, both 3D and 2D display of the data may be required, potentially along with dialogs using the standard user interfaces for the host operating system as expected by the user.

The visualisation of data in 3D allows a much wider range of possibilities than a purely 2D solution.

For instance, mapping skin temperature values across a human subject's body is most effective in 3D using a model-based representation of the subject. Alternatively, some information is best presented two-dimensionally. For instance, a subject's heart rate or blood pressure is traditionally shown numerically alongside a sliding scale and is very easily read in this format, particularly for someone who has experience with previous monitoring equipment showing this data. In the case of dialogs that require user input, it is most beneficial from a usability viewpoint to make use of the standard look and feel of the interface provided by the host operating system. The user will usually be most familiar interacting with applications of this type, and there are a substantial number of documented cases where software had the effect of disorientating the user and causing them to use the facilities provided less effectively due to attempting to follow an interface style different to the host system.

Data Storage

Often in experimentation data needs to be stored for later use. This may be for replaying an experiment using the visualiser in order to concentrate on an interesting set of readings observed during the original experimentation, or for running a different analysis tool against the data to extract further information from it. Often researchers have tools, either general purpose (such as a graphing application) or custom written, to process data from a set of experiments, and the visualiser should support their use wherever possible.

3.11.2 Requirements Specific to this Application

The application being considered here is that of a protection suit monitoring system with a focus on user comfort and health, as well as an experimentation oriented system to support the development of the monitoring system.

Data Input

In the prototype system, data will be supplied from sensors mounted within the EOD suit or upon the subject wearing the suit. The prototype system will make use of Bluetooth to transmit information to the PC running the visualiser. Bluetooth communication functionality is integrated into the Gumstix Connex devices that will be used as the basis of the prototype. There are two options for the PC in terms of receiving this transmitted data: a Bluetooth dongle plugged into the PC to directly receive the data; an additional Bluetooth enabled node to receive the data and forward it to the PC via another communication method, such as Ethernet or USBNet (Ethernet emulation over USB). The method that is currently in use for the prototype is the second, with USBNet as the communication method. This means that the visualiser must support Ethernet connections to receive data. In the final system the data will be provided via a network that is currently of an unknown type.

Data Processing

The level of data processing required within the visualisation software is not expected to be intensive in this application. Modelling is expected to be performed within the sensor system, with the processed results being relayed to the application in a usable format. The exception is during the early stages of the project, where the modelling will be performed within the visualiser in order to allow for easier debugging of the code.

Data Display

There are a variety of parameters that may be visualised in the prototype, requiring two of the three methods of display mentioned earlier. Skin temperature data, for example, may be best visualised on a 3D model as the source (a human body) is three-dimensional and displaying the data in this way allows us to more easily identify what is being shown and how it relates to reality. Parameters such as heart rate, on the other hand, are commonly shown in a 2D format (often as a line showing measured electrical activity) along with a numeric reading. This is a format that makes sense for that particular parameter, and due to the high recognition it is one that should be sustained. I cannot see an immediate need for standard operating system user interface dialogs outside of the ones general to the application, such as load/save or options dialogs.

Data Storage

While storing the incoming data to disk will not necessarily be a requirement in the final product (though it will certainly be a useful feature and may become a solid requirement), it will be useful in the prototype stages as it will allow the data to be further analysed by other means, for example to check the application is showing it correctly, and will allow replaying of experiments.

3.12 Functional System Diagram

Figure 3.5 shows the data flow within the system with respect to the hardware and software components. The instrumentation system comprises the components of the system that are contained within the EOD suit, while the remote system represents an external computer system such as a PC connected to the sensor network. The sensor nodes will be small devices with minimal processing power, responsible for filtering and limited processing of the data. Multiple sensor nodes will communicate with each processing node to relay readings. The processing nodes will have more computational power than the sensor nodes and will be responsible for supporting the data modelling component of the system (see section 3.8). One processing node, termed the “master node” from this point on, will have additional responsibility, encompassing the decision-making (see section 3.9) and actuation (see section 3.10) components of the system, which will enable it to provide control over the cooling system within the suit. The other processing nodes will forward their information to the master node for final processing to allow decision-making and actuation to take place. Information will also be forwarded to a remote system for visualisation.

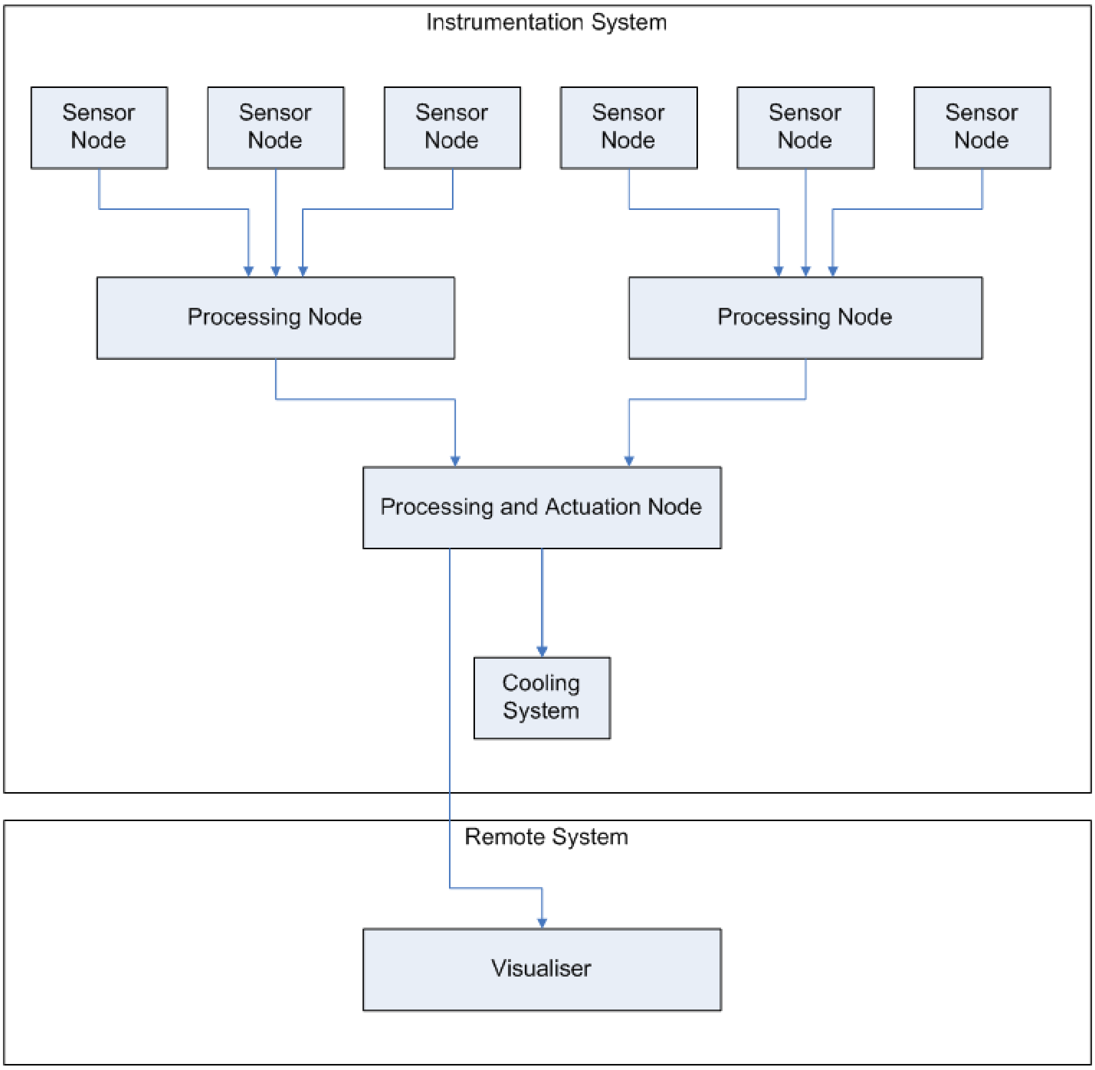


Figure 3.5: System data flow with respect to hardware and software

Figure 3.6 shows the components forming a sensor node. The onboard sensors supply collected data to a microcontroller, which performs any necessary processing, such as filtering or error-detection. This data is then supplied to a host system on request. The use of an onboard microcontroller means that the sensor boards will be capable of operating independently of a host system. This microcontroller based arrangement also allows greater flexibility in reporting identifying parameters (such as the type of the onboard sensors and the location of the board) to the host system should it require this knowledge. If the host system were to directly communicate with each of the sensors in the system, it would be required to know their functional details prior to operation, whereas a microcontroller based arrangement method means that all the information may be gathered at run-time as required. Each sensor board may also store additional calibration information for the sensors, allowing their readings to be corrected before the data is exposed to the host.

Figure 3.7 shows the components of a processing node, of which there will be several within the system. Communication with sensor nodes feeds into both the error detection and data modelling components. The error detection component is tasked with detecting the presence of errors that the sensor nodes themselves did not detect, which is likely to involve comparing readings from different sensor nodes with each other or other more sophisticated fault detection and isolation methods. The data modelling component is responsible for performing modelling of the incoming readings where possible. As the node will only have access to its own subset of sensor nodes, a data modelling component requiring knowledge of the readings from all the nodes will not be feasible to run at this point. Once the data modelling process has taken place, the information is passed onto the network communication component to transmit to the master node. Future work might involve inter-processing node communication for the purpose of data modelling.

Figure 3.8 shows the components of a combined processing and actuation node. The system will contain only one of these nodes. Data and information will be transmitted to this node from the processing nodes as well as any attached sensor nodes. The error detection and data modelling components will function as described for the processing nodes (except that the data modelling stage will have access to data from the whole network at this point), and the network communication component of the processing nodes is replaced with a remote communication component that will allow information to be transmitted to a remote monitoring point. The new components in this node are the decision-making and hardware actuation components.

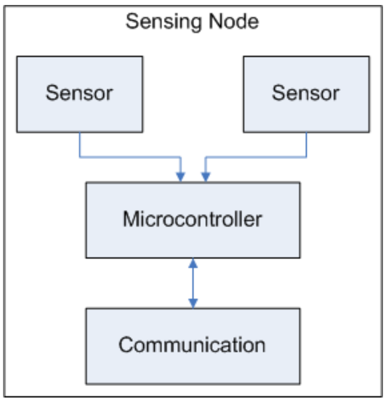


Figure 3.6: Sensor node components

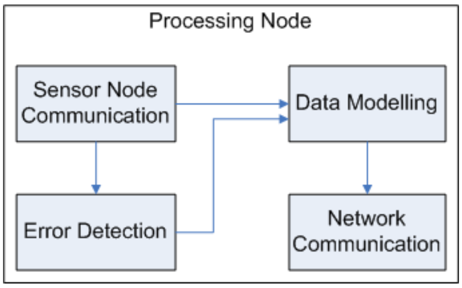


Figure 3.7: Processing node components

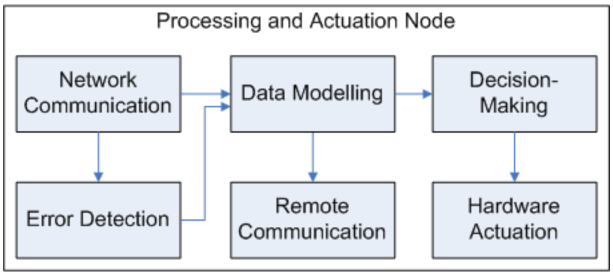


Figure 3.8: Actuation node components

The figures above have shown the overall data flow of the system. For a view of this flow that is more focused on the communication between the various devices, see figure 3.1 (block diagram), or figure 3.5 (a representation based on the physical devices).

Chapter 4

Experimental Prototype

This chapter discusses the development, current status, and future research directions for the prototype instrumentation system. The first half of the chapter, sections 4.1 to 4.5, cover the hardware aspects of the system, while sections 4.6 onwards cover the software aspects.

4.1 The Hardware Platform

There are a variety of available embedded platforms for sensing and control applications as discussed in section 2.3. The hardware choice decisions in this project were based on the following criteria:

Processing Power

Due to the requirement for autonomous operation during a mission, sensor data will have to be processed in real-time, including modelling, prediction, and decision-making. The processing will be performed in addition to receiving and transmitting data and information. Sufficient processing power must therefore be available for this to occur.

External Interfaces

There are a wide range of different types of sensor available with interfaces such as I^2C, UART, and analogue voltage levels, and the chosen platform must provide suitable interfaces for multiple types of sensor to be connected. Specifically, single-chip sensing devices tend to use an I^2C bus for communication or provide a voltage level as an output, while sensors which are provided with a signal processing board often use a UART for communication with a host device. Once the instrumentation system is finalised the interface requirements can be defined exactly, but until that point there needs to be a certain level of adaptability.

Ease of Software Development

The development of new software implies repeated deployment for testing. Hence, software deployment should be made as easy as possible. Additionally, support for familiar languages as used on other systems will dramatically shorten the initial development time as the developer will not be required to learn a new language. One major factor in deploying new software, or a new version of existing software, is the ability to transfer it to the device without interrupting operation. Some platforms require the device to be powered down and programmed via a special programming board. This will not necessarily be possible in all scenarios, such as when the device is fixed within an enclosure or in use. This is not as large a factor as it would be in, for instance, a long-term field monitoring application, but it should still be considered as it allows much easier testing during development.

Size

Due to the limited space that will be available within the EOD suit, as well as the need to not burden the wearer or restrict their movement, the system needs to be as small as possible. This is a common requirement for most body sensing systems for much the same reasons of space restrictions in mounting and practical restrictions in terms of allowing the wearer the freedom to perform the tasks required of them.

Platform Choice and Suitability Analysis

The platform chosen based on the requirements mentioned above was from the Connex range produced by Gumstix Inc. [7]. These devices are small, low-power embedded computers running Linux and providing a wide range of expansion options, both with off-the-shelf expansion boards and custom-made boards. The specific board used as the basis of the hardware platform here is the Connex 400xm-bt, which offers:

- Intel XScale PXA255 400MHz processor
- 16MB flash memory
- Bluetooth controller and antenna
- 60-pin and 92-pin connectors for expansion boards

This device is more powerful than a large number of other devices previously used for body sensing projects, such as those presented in section 2.3. The processor provides enough processing power to be able to deal with a wide range of tasks, and due to the combination of this power and the use of Linux as the OS there is very little restriction on the languages available for use in software development, with both C and Python being routinely used. The 16MB of flash memory allows for storing larger programs and data files than other platforms (such as the Mica2 motes) would have allowed.

The Bluetooth radio provides a convenient means of establishing a small network between the devices, particularly as the original intention of Bluetooth was to create small PANs (Personal Area Networks) between the devices carried by a person. Bluetooth PANs involve the creation of PicoNets, which are composed of up to 8 devices one of which is designated the master. The device number limitation is not a problem in the intended system as there are not likely to be more than 8 devices contained within the suit. The requirement for a master to arbitrate communication can also be solved in a suitable manner, for instance by designating the device charged with control of the cooling system as the master. Bluetooth transfer rates are limited, but more than adequate for transmitting the quantity of readings expected for this system. As an example, the current experimental system uses six temperature sensors attached to a Gumstix device. Readings from the sensors are transmitted to the remote monitoring system, along with various items of related information such as a timestamp and device id. Each reading is transmitted using 12 bytes, with readings from six sensors transmitted once each second. This means that the bandwidth usage is 72 bytes per second for each Gumstix device, which is well within the capabilities of Bluetooth. This will increase with additional sensors and collaboration between nodes, but it should not exceed the available bandwidth.

To conclude here the advantages of the Gumstix platform are evident in terms of the ease of development of both the hardware and the software of a new system. The Gumstix devices, while small, offer enough power to deal with almost any embedded application. The use of Linux as a base operating system means that a wide variety of existing software can be used or adapted and a range of standard programming languages, such as C or Python, can be used. The large amount of flash memory and RAM also mean that relatively large and complex programs can be stored and run. The platform also provides a range of methods of interfacing to external sensors, such as the I^2C bus which has been extensively exploited in this project and will continue to be in the near future.

The main disadvantages of the platform, however, are in a similar vein to the advantages. The use of Linux as the operating system provides greater ease of development, but also adds processing and storage overheads. The overheads can be reduced in a production system by the elimination of unused components, but will still exist to some degree. Whether this is critical or not is dependent on the application. The reference use efficiency and system lifetime will be investigated in the future.

The Gumstix platform has been used in a variety of embedded computing applications ranging from body monitoring (Gao *et al.* [8]), to the control of autonomous flying machines, as presented by Holland *et al.* [32]. The level of processing power and storage it makes available, along with the wide range of interface options offered and the small size mean that the platform enables a range of applications that are not possible with more traditional limited power sensor nodes.

This project will primarily utilise the following capabilities offered by the Gumstix device:

- Bluetooth communications to transmit data/information between nodes
- I^2C bus interface for the attachment of sensor boards
- Faster processor than other platforms in order to carry out data modelling and decision-making in real time
- Small size to enable convenient mounting on or around a subject

Providing power to wireless sensing devices is a question with a variety of solutions, some currently under research and some commercially available, including power harvesting (as by Paradiso and Starner [33]), “wireless power” (as by Kurs *et al.* [34]), and the more traditional battery packs. The solution in use in the current stage of the prototype is a rechargeable LiPoly (Lithium-ion polymer, an advancement of Lithium-ion [35]) battery pack with a charging circuit integrated into the in-house expansion board. The battery is sufficiently slim to add almost no height to the board stack, as well as adding only 16 grams to the weight, and the charging circuit allows for easy in-situ recharging of an empty battery. Power harvesting, particularly from body heat or movement, will be an area to be investigated for providing power to the system in the future as this will allow operation without the regular replacement or recharging of batteries, and the slight explosion risk associated with their use in a potentially hazardous environment.

Note: For comparison purposes, see section 2.3 for a discussion of alternate hardware platforms.

4.2 Temperature Sensing

4.2.1 Suitability of Parameter For Monitoring in Prototype System

Skin Temperature

As noted in section 2.4.1, there are seven points commonly used for measuring skin temperature: the calf, thigh, chest, forearm, back, abdomen and forehead. Measuring temperature at these points is possible with wearing the prototype system as the available sensors are small and these locations are easily accessible.

Ambient Temperature

Sensors for measuring ambient temperature within the suit could be the same ones used for measuring skin temperature, with the only difference being they would be in contact with the air rather than fixed to the appropriate points on the skin. The measurement points for ambient temperature should be adjacent to the measurement points on the skin as the main reason for measuring ambient temperature is to establish the relative difference between it the temperature of the skin. This difference is what determines how effectively the human body can control its internal temperature as well as being a contributing factor to how comfortable one is.

Core Temperature

The same types of sensor as used for skin and ambient temperature measurement cannot necessarily be used for measuring core temperature. There are two main methods that are used to establish core temperature. These are ingestible pills and the more traditional probes. Both methods measure temperature at only one point.

Core temperature is often traditionally measured via internal probes and there are a variety of places this may be performed, such as the ear, mouth, or anus. The result returned is an estimate based on knowledge of the average difference between the temperature at the chosen location and the core temperature as detailed in section 2.4.1. The major problem with using an internal probe is that they are hard to keep in place if the subject is in motion, and this is only made worse by the confined environment of the suit. Previous experiments involving this type of technology showed that often connecting cables, or the device itself, become snagged or get dislodged, resulting in the probe coming out of position and producing bad readings. The subject is also very much aware of the probe's existence, which may distract from the task at hand. These factors combined, mean that these probes are not a good solution for this application.

The problems related to using internal probes are negated in the case of the ingestible pills as they are simply swallowed and proceed to relay readings from within the body. As well as being more convenient and discreet, they also give a more accurate reading of the true core temperature. This means they are much more useful in the intended usage scenario. They are however more expensive than the probes and will be a single-use device. Consequentially, core temperature will only be monitored during experimentation in the final stages of this project using the ingestible pill.

4.2.2 Types of Temperature Sensor Available

Using the information on sensor devices available from Omega Engineering [36] and Maxim Integrated Products [37] a survey of the types of temperature sensor available off the shelf was performed. The sensors break down into three distinct types:

- Thermocouples
- Thermistors
- IC packaged devices (often with additional functionality)

Thermocouples consist of two strips of different metals joined together. When these strips are heated, the different materials cause a potential difference between the "hot" junction and the "cold" junction (used as a reference). Thermocouples are relatively accurate devices, with accuracies in the range of ±0.25% to ±1% or ±1°C to ±5°C in the sample selection, and also have a fast response to temperature changes, with response times as low as 0.3 seconds. Normal temperature variations, particularly in a mostly closed system such as an EOD suit, are unlikely to occur this rapidly. This means that this speed of response will not be necessary, and though there may be situations in which such fast response may be a benefit, these will be the exception rather than the rule.

Thermistors are resistors which are specifically designed to take advantage of the fact that their resistance varies depending on temperature. Thermistors are not as accurate as thermocouples (with accuracies between ±1% and ±5% in the devices surveyed), nor are they as fast to react to changes (with response times between 1.5 and 2 seconds), but they are sealed units, which can be an advantage in some cases where it may be dangerous or inconvenient to have exposed equipment. Thermocouples can also be constructed to be electrically insulated from the outside. However this also introduces thermal insulation, thus causing them to be slower in reacting to temperature changes and also possibly less accurate.

IC packaged temperature sensors come in two basic types - those with an analogue, usually linear, output (the output of thermocouples and thermistors is not linear, thus requiring additional conversion) and those with a digital serial output. The former have the advantage that a linear output requires less support circuitry than a non-linear one, however they are not as accurate as thermocouples, with accuracies of between ±0.5% and ±1.5% quoted. This disadvantage is offset by a repeatability of to within 0.1°C, which means that identical temperatures on two occasions will produce almost exactly the same output readings. As with the thermocouple and the thermistor talked about previously, support circuitry (such as an ADC) is still required when interfacing with a microprocessor system. The more advanced chips available provide a digital output over a 1, 2, or 3 wire interface, often a well-known one used by other devices that allows them to interface directly to a data bus on those devices. They also have a multi-drop ability, which means that several of them can connect via the same bus and are individually selectable. These two abilities substantially reduce the required support circuitry when interfacing with a microprocessor system. The output can be of 6 to 13 bits, with some devices offering multiple selectable options. The accuracy of these chips is given as between ±0.5% to ±2%, which, while better than the thermistors surveyed, is worse than the thermocouples. By using appropriate techniques with bandgap type devices [38] the accuracy can actually be improved approximately tenfold, to between ±0.05% and ±0.2%, which is substantially better than any other device presented here. The digital output of these devices introduces a delay while the reading is converted internally. This delay is given as 25ms on the devices surveyed, which is faster even than the thermocouples, hence they should be appropriate for use in the system here in terms of measuring skin temperature.

Given the potentially superior accuracy and response time of the digital output sensing chips, along with their multi-drop capability and ability to have different options selected to handle different needs, they would appear to be the best choice for the application.

4.2.3 Choice of Sensor for the Prototype System

Following decisions on the type of device to be used for gathering temperature data (see section 4.2.2), a specific device model was selected from those available. The selection was previously narrowed down to sensing ICs with a digital output, and this was further narrowed to those with an I^2C interface in order to interface most conveniently with the Gumstix Connex platform, and potentially future platforms that may be used (the SBW001 sensor boards described in section 4.5.3 also use the I^2C interface to communicate with the sensors). This led to the selection of the AD7416 chip produced by Analog Devices [39]. This chip has a 10-bit resolution (giving values to within 0.25°C), a 400µs update rate and can sense temperatures in the range of -40°C to 125°C. The base accuracy is to within 3°C, which can be improved to 2°C with a slight reduction in range that would not impact this application. This accuracy is in terms of a constant offset from the actual temperature which can be compensated for with additional calibration, potentially eliminating it entirely. The power requirements are 0.35 - 1.0mA (dependent upon the use of I^2C), which drops to between 0.2µA and 1.5µA when the device is in Shutdown mode.

After an initial order was placed, there was insufficient stock available to satisfy the complete order, so the ADT75A device was selected to complete the order. This is again produced by Analog Devices and is pin- and register-compatible with the AD7416. This chip has an increased 12-bit resolution, with a slower 100ms update rate and an enhanced temperature range down to -55°C. The base accuracy is once again within 3°C, which can again be improved to 2°C with a slight reduction in range. The current requirements are 0.3 - 0.5mA with I^2C inactive, which drops to between 3 and 8µA in shutdown mode. There is some slight additional circuitry required to use this chip but overall it requires no significant change in circuitry and no change to the software making use of it unless improved resolution is required.

The chosen device is shown in figure 4.1, mounted on a carrier circuit board as used in the Medusa2 prototype (see section 4.5.3). The two resistors visible in the image are used to pull up the I^2C data and clock lines as required.

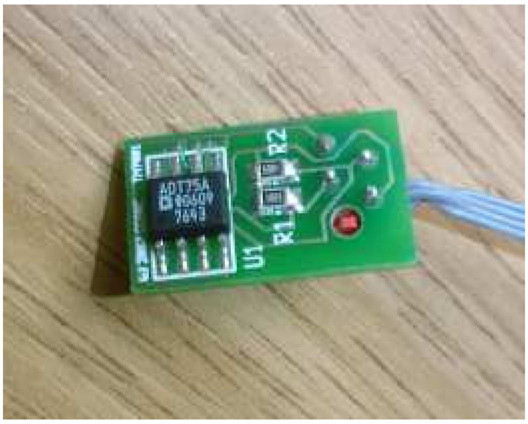


Figure 4.1: Medusa2 temperature probe with ADT75A temperature sensing chip

4.3 Posture Determination Hardware

The tracking of posture is useful in gaining an overall understanding of the events occurring during a mission. Posture information can be integrated with other sensor readings to improve this understanding. For instance, if a subject is experiencing increased heat levels and heart rate while crouching and performing a mentally or physically taxing activity then these can often be reduced simply by standing and relaxing for a moment. If the same readings are encountered while the subject is motionless and not otherwise occupied then they indicate potentially dangerous conditions. In other words, the information regarding posture provides context to other data collected. The methods of processing posture related data are covered in section 4.8, while this section covers the hardware choices for assessing this parameter. Data related to the determination of posture may be collected via several different types of sensor. The sensors discussed here are accelerometers, gyroscopes, and pressure pads.

Accelerometers are mass-produced, generally cheap, and widely available. They monitor the level of acceleration they are undergoing, i.e. the changes in their speed. Often the data from an accelerometer is integrated over time, which means that the accuracy of the resulting information is heavily dependent on the precision of the readings, the range of the forces that are sensed, and the update rate of the readings.

This means that the quality of the sensor has a large bearing on the information obtained, though this has become less of a problem with the improvement of the sensors in recent years. Another problem with accelerometers is that they may simply provide too much information. This is because they track the full movement of whatever they are attached to, right down to small vibrations, so frequent changes in readings will occur. This will mean that transmission of the readings may consume a greater level of power than those from other sensors which have less frequent or slower changes. Accelerometers may be used to detect the orientation of an object due to the influence that gravity has upon the readings obtained. In the absence of other forces, and given appropriate calibration, the readings returned by a three-axis accelerometer may be used to calculate a vector describing the direction of gravity's pull, and therefore the sensor's orientation can be derived.

Gyroscopes are devices designed to return information about their orientation. Compared to accelerometers used for the same purpose, gyroscopes may provide more accurate or easy to use data, as well as requiring less data processing to achieve this. They are, however, an order of magnitude more expensive than accelerometers, and the small gains provided over accelerometers (given that the processing power is available within the prototype system to allow processing of the data) do not justify the additional cost in this case.

A third option for determination of posture is that of pressure sensitive pads, which lend themselves to a different approach for inferring posture to the two presented above. Pressure pads could be used to provide movement tracking by sensing where pressure is being applied rather than what movements are occurring. Pressure readings from several points can be combined and checked against a list matching activated pads to postures. Fusion with accelerometer data could be used to enhance the information obtained using this method. This would allow, for instance, the pressure pads to provide the overall picture of posture while the accelerometers would fill in the finer grained details where required. If the accelerometers were used only when required, in this fashion, it would also prevent the transmission of a constant stream of data, thus preserving battery life to an extent (where batteries are in use).

Initially, in the prototype system, accelerometers will be used in order to gather as much data as possible about the type and level of movement encountered during the use of the suit. These will be mounted at appropriate defined locations in order to detect posture, further investigation upon which will follow. The most effective way of mounting accelerometers appears to be to use at most one per body segment. More may potentially be used towards a goal of redundancy but these will be ignored for the purposes of this discussion. This would allow a range of tracking techniques to be used from full reconstruction and interpretation of the body posture, to pattern matching against the set of readings. In the application here the most important information gained from these readings is the general posture of the subject (such as sitting or standing), the exact position of each segment is not needed. If pattern matching is used as a method of determining current subject posture, especially in relation to the scenario at hand, there are several segments that do not require tracking. The upper and lower arm segment readings are not necessary for the purposes of determining posture. Similarly, readings from the head segment would not have a use in determining body posture in the majority of cases. The remaining segments, namely the torso and upper and lower leg, are the important segments for measuring body posture. These five data points, one for the torso and two per leg, are the points that can be used to determine if the subject is standing, crouching, or bending, along with the type of movement, such as walking, running, or standing still. Table 5.14 in section 5.3 presents a list of potential postures identified during the experimentation described in section 5.3. Section 4.5.3 includes details of the hardware that prototype revision 3 (Medusa2) has available for posture detection and section 4.8 describes the intended method for extracting posture information from the accelerometer data.

4.4 Additional Sensing Options

4.4.1 Pulse Oximetry Monitoring

Use In The Project

During the initial stages of the creation of the prototype system, a pulse oximeter will be useful for gathering information about how the suit, or the environment that the suit is worn in, affects the wearer. During real usage of the suit, the oximeter could provide useful data to accompany other data types being gathered via other sensors, and aid towards the health assessment of the wearer. Lowered SpO2 (blood oxygen saturation) levels could indicate inadequate ventilation within the suit leading to excessive carbon dioxide levels, or indeed health problems. An increased or erratic pulse could indicate increased stress or other such undesirable conditions, which could mean that mistakes could be made in the tasks being performed. This could, in turn, be life-threatening in a real-life situation.

Usually pulse oximetry sensors are attached to a subject's finger. This would not be suitable for the in-suit monitoring application of the system here as it would interfere with the dexterity of the user and potentially endanger him or her. An alternative is to monitor the subject via an ear lobe. This is a much more suitable method in the scenario here. If a communications earpiece is worn then the attachment of the sensor could be arranged to coincide with that in order to reduce the number of trailing cables.

Device Selection

The CodeBlue project [2] used the Micro Power Pulse Oximeter Board from BCI, sold by Smiths Medical [40]. This device is 39 x 20mm and consumes a typical current of 6.6mA at 3.3V. It provides output of SpO2 and pulse readings along with a plethysmogram (a measure of changes in volume of an organ, or of blood flow) and a measure of the pulse signal strength via a serial interface (3.3V CMOS levels). The board is supplied with a finger sensor, though ear sensors are also available. A board with one finger sensor costs $200 (approx. £120), with an ear-based sensor costing an additional $95 (approx. £57). This board is shown in figure 4.2.

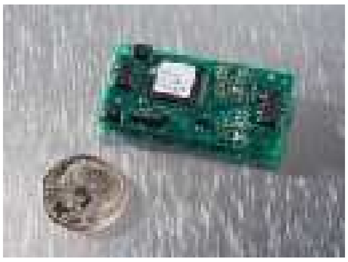


Figure 4.2: BCI Micro Power Pulse Oximeter

This device appeared to be suitable for the prototype system under development as it consumes relatively little power, provides readings via a serial interface, which the Gumstix platform can readily interface to, and has already been used for a similar application with positive results. Unfortunately a unit could not be obtained and an alternative device had to be located. Further enquiries led to Nonin Medical, Inc. [41] who supply a range of pulse oximeter products including several OEM units for integration with other equipment. Of particular interest were the 4100 Bluetooth Oximeter and the OEM III Module, shown in figures 4.3 and 4.4 respectively.

Figure 4.3: Nonin Medical, Inc. 4100 Bluetooth Oximeter

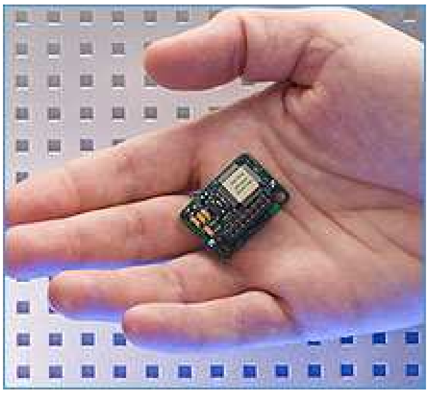


Figure 4.4: Nonin Medical, Inc. OEM III Module

These units are both interesting for different reasons. The 4100 Bluetooth Oximeter does not require a physical interface to a host system as all the readings are relayed via Bluetooth, thus potentially reducing the time required to integrate it with an existing system as well as reducing the amount of wiring required. The sensor is attached to a device which straps onto the subject's wrist, keeping it all close together in the case of the more common finger sensor being used. The OEM III Module is a small board that connects to a sensor and interfaces with a host system via a serial connection. The major advantage of this unit is the small size, allowing it to be easily mounted in restricted spaces or to be mounted with the host device without a large impact on the space requirements. The serial interface is a common standard, particularly for sensors that have dedicated interface boards such as this one, and it should not be difficult to connect to any of the popular body sensing hardware platforms.

4.4.2 Carbon Dioxide Level Detection

Suitability of Parameter For Monitoring in Prototype System

When monitoring a person in a medical environment, it is often useful to measure the quantity of carbon dioxide they exhale. This can provide an indication of the metabolism of oxygen in a subject, something which pulse oximetry, as discussed in section 4.4.1, is unable to do. The problem with measuring this parameter is that commercial measurement equipment is invariably bulky and requires the subject to wear a mask to collect the exhaled gas. These two factors combine to make it impractical to measure the exhaled CO_2 in the suit environment.

Similar to the exhaled carbon dioxide monitoring, equipment to measure the ambient level of CO_2 in the suit, or indeed in any situation, is usually bulky, though the sensor may be mounted almost anywhere in the suit in this particular case. An additional problem brought up by this parameter however is that a lot of sensors require that the air be flowing over them (usually achieved through a pump), in order to provide a good reading, which would require even more equipment along with the additional bulk and weight. This measurement may also only be useful for discovering suit ventilation problems, which is not directly related to the scenario at hand and can be done pre-mission while the suit is stationary and larger external equipment can be attached. It may however still be useful in an experimentation scenario and hence this type of sensor has been considered for inclusion in the system.

Appropriate Available Sensing Equipment for CO_2

There are a multitude of devices available for sensing carbon dioxide levels, all tending to be self-contained units intended for industrial use. Three suppliers of gas sensors designed to be integrated into other equipment (as opposed to the self-contained units more commonly available) were found: Edinburgh Instruments Ltd [42], Vaisala [43], and Draeger Safety Inc [44].

Edinburgh Instruments produce units such as the Gascard II, which measures 100 x 160mm and several variations of which provide a variety of measurement ranges, and the MiniByte sensor. The prices for these devices ranges between £120 for a MiniByte sensor with no interface board, up to £495 for a Gascard II Plus designed to measure concentrations of up to 5000ppm (0.5%) of CO_2.

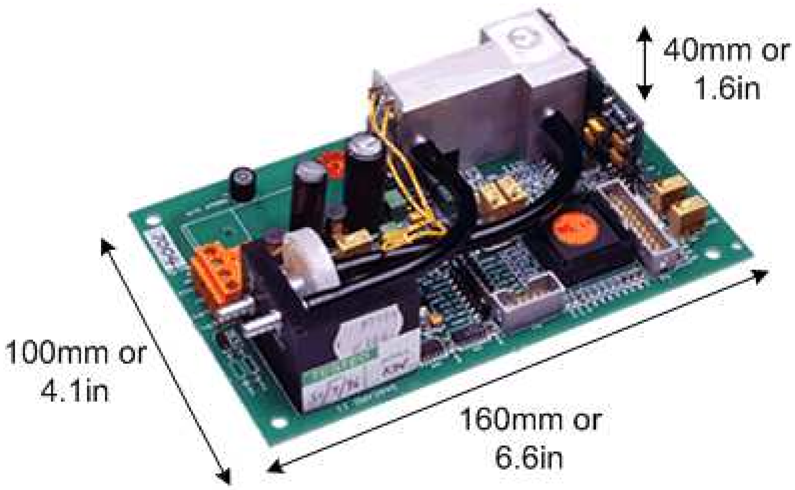


Figure 4.5: Edinburgh Instruments Gascard II CO_2 sensor board

Vaisala produce units such as the GMM20W, which is 74 x 72mm and includes an on-board CO_2 sensor, and the GMM221, which is 78 x 48mm and uses an external probe to take measurements. These have a response time from 20 seconds for the GMM221 to 1 minute for the GMM20W. The GMM221 costs £404.

Figure 4.6: Vaisala GMM220 series CO_2 probe and signal processing board

Draeger provide sensors designed for their own instruments. An example of one of these sensors is the CO_2 sensor from their IR Sensors range. This can be set to measure concentrations of CO_2 from 0 to 25% (with a default setting of 0 – 5%) and provide a response within 50 seconds (10 seconds when pumped) with an accuracy of 5% of the measured value.

Figure 4.7: Draeger IR CO_2 sensor

Unfortunately, none of these devices seem appropriate for this application. The devices produced by Edinburgh Instruments are too large to feasibly be fitted within a suit and the Draeger devices are designed for use in their own equipment. The closest match is the Vaisala units which, while smaller than the ones produced by Edinburgh Instruments, are still overly large for the space within the suit.

Additional sources for CO_2 sensors are currently being investigated, with a promising candidate being the TGS4160 manufactured by Figaro USA Inc [45]: a small carbon dioxide sensor requiring a minor amount of signal processing circuitry. As there is likely to be only one of these sensors required, the extra circuitry should not present a considerable space.

4.4.3 Heart Monitoring

Technology to monitor a subject's heart rate comes in a variety of forms, including several commercial personal units which may be used without training by people undergoing regular exercise. One form of these devices designed for integration with an external system is that of a thin band which is mounted on the chest with electrodes woven into the back of the strap material. The device provides heart rate readings wirelessly to the host system. This type of device is relatively unobtrusive and easy to mount on a subject, though it is required to be mounted beneath clothing in direct contact with the skin.

Another form of heart monitoring is an ECG, which is more sophisticated than a heart rate monitor and allows detailed analysis of the heart rhythm. This allows the detection of various forms of cardiac arrhythmia, where the heart beats too fast, too slow, or with an irregular rhythm. This method can detect problems that a simpler style of monitoring would not, particularly in the case of an irregular rhythm, which may appear normal due to the averaging involved in calculating a count of beats per minute.

Heart monitoring could be valuable for providing a guide as to how much physical or mental stress a subject is under. Such stress is of particular concern where a heavy protection suit is worn as the heart rate can be severely affected, causing a health risk. The considerable effect of the EOD suit on the heart rate during experiments is documented in sections 5.3.2 and 5.4.2.

4.5 System Prototype Revisions

4.5.1 Prototype 1

The first prototype developed for this project was of a simple design with all system components hard-wired together. The sensor load consisted of eight AD7416 digital temperature sensors, which were the only components added to the base system of a Gumstix Connex / Audiostix2 combination.

Initial testing provided no valid data and showed that the I^2C bus was not being correctly driven. This was temporarily solved by placing a capacitor between ground and the clock line. Tests showed that consistent readings were being obtained from four of the sensors, with occasionally acceptable data from one other. Data from one of the remaining sensors was consistent in average with the others but suffered much larger spikes, while data from the other sensor was entirely inconsistent. Figure 4.8 shows a temperature probe as used in this prototype.

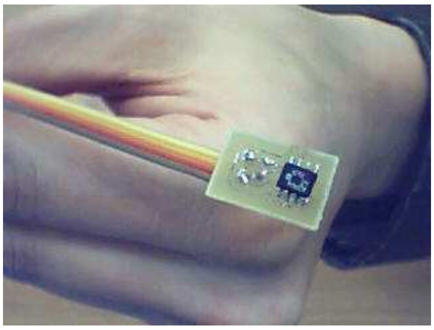


Figure 4.8: Prototype 1 temperature probe

A sample of data obtained via the system during an overnight laboratory test run is shown in figure 4.9, with the readings from three of the sensors visible.

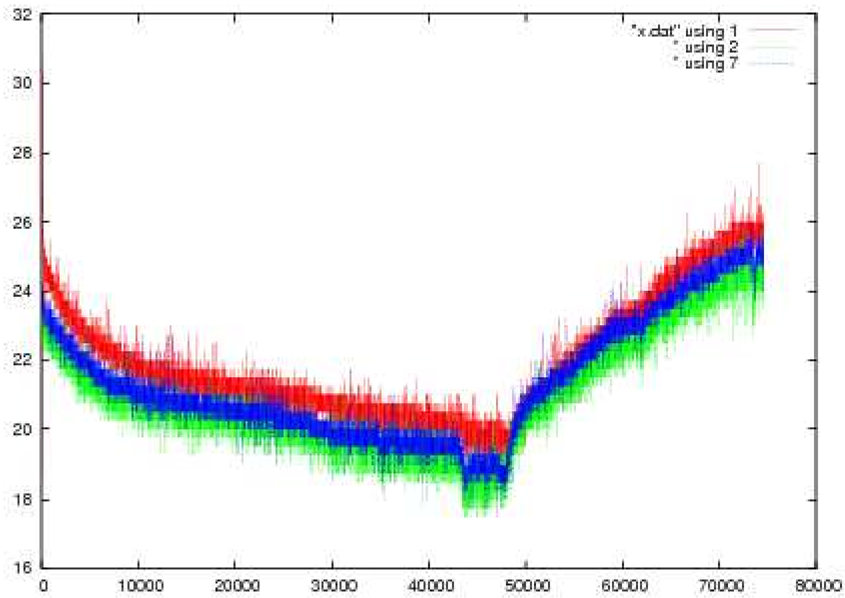


Figure 4.9: Graph of overnight run of Prototype 1

The sensors provided readings consistent between themselves with the exception of an offset from each other due to lack of calibration prior to the test run. More noise than originally expected is present in the readings, causing the readings to deviate by up to approximately 0.5°C from the central reading value.

4.5.2 Prototype 2 - Medusa

The second prototype built upon the first design and featured a more robust method of both connecting sensors to the interface board and connecting the interface board to the Audiostix2 board. An IDC (Insulation Displacement Connector) connection was provided for the sensors to allow them to be replaced, either in the case that they fail, or if different sensor types are required (such as I^2C accelerometers) to be added to the system. In addition, the connection to the Audiostix2 board was made more resilient (the connecting wires on the first prototype had a tendency to break) and there was provision for the interface board to be layered as part of a stack consisting of a Connex, an Audiostix2 expansion board, the interface board, and a battery. This was to enable true standalone wireless operation of the system.

Initially this board suffered the same bus problems as the first prototype, but the addition of an I^2C buffer chip partially solved this (a buffer chip should actually be used at both ends of the bus). Shown in figures 4.10 and 4.11 are photographs of this prototype. Figure 4.10 shows the interface board, while figure 4.11 shows the temperature probes attached via the I^2C bus.

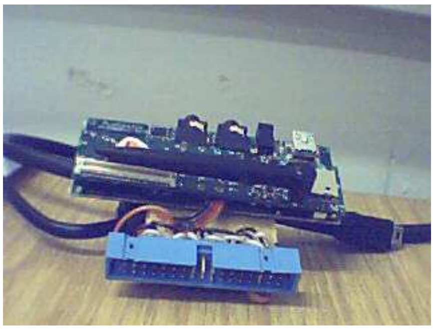


Figure 4.10: Prototype 2 interface board

Figure 4.11: Prototype 2 with sensors

These photographs were taken prior to the addition of the I^2C buffer chip. Eight temperature sensors are shown attached via a length of ribbon cable.

Noise in the readings is still evident during test runs with this prototype, but operation is more consistent compared to the original prototype and the system is more robust as a whole. As an example of achieved robustness and consistent functionality, note that the system was used for two runs of several hours each during a demonstration of sensing technology at a local school (shown in figures 4.12 and 4.13), during the National Science Week 2007.

Figure 4.12: School demonstration: Pupil shown being fitted with temperature sensors

Figure 4.13: School demonstration: Pupil shown testing the insulating effects of a “space blanket”

4.5.3 Prototype 3 - Medusa2

The third, and current, prototype is based on an externally fabricated expansion board, designed in-house. This prototype is more stable than the previous two prototypes, and integrates the previous Audiostix board and interface board into a single board. The current setup uses temperature probes of a similar design to the previous prototype but externally fabricated (in house designed). A new revision intends to use a new sensor board, the SBW001, described below. Figure 4.14 shows the various components of the hardware platform currently comprising the Medusa2 prototype.

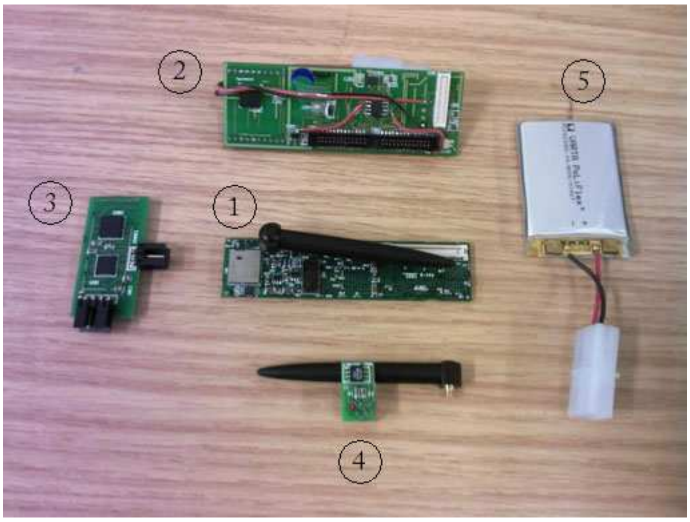


Figure 4.14: Medusa2 hardware components

The boards are marked as follows:

1. Gumstix Connex motherboard, including processor, memory, and Bluetooth radio
2. Internally developed expansion board, offering sensor interfaces and charging circuitry for a battery along with a ZigBee compliant radio (not currently used in this project)
3. SBW001 sensor board containing a microcontroller, accelerometer, and temperature sensor (not pictured)
4. Temperature probe as used prior to the introduction of the SBW001 sensor boards to the system
5. Rechargeable LiPoly battery

SBW001 Sensor Board

These sensor boards were designed in-house and fabricated by an external company. The current revision of the design of this board incorporates an ADT75A temperature sensor by Analog Devices Inc [39] and an LIS3LV02DQ accelerometer by STMicroelectronics [46], along with a PIC24FJ64GA002 microcontroller by Microchip Technology Inc [47]. The two sensors allow the combined monitoring of temperature and acceleration data at any point on a subject's body while the microcontroller makes possible the local filtering and processing of data before it is forwarded to the host system. This arrangement opens a number of openings in terms of implementing error detection and handling along with the removal of processing duties from the main nodes. This may mean that future prototype system revisions may require much less computational power and thus may be made more compact. Additionally, the sensor boards will be capable of identifying their position (if this information has been previously stored) and sensor load to the processing nodes. This provides a better separation of concerns compared to the use of directly connected sensors, where the processing node was required to assume the identification and other duties, unrelated to its intended purpose.

Power and data signals enter the board via one connector while programming of the PIC microcontroller is achieved by a separate dedicated connector. This second connector may be removed in a future revision should the hardware and software design settle and the chips programmed prior to board fabrication.

With the new SBW001 sensor boards, the Medusa2 prototype became more closely aligned with the system architecture presented in section 3.12. Figure 4.15 shows the architecture of the SBW001 sensor board as it relates to figure 3.6. Figure 4.16 shows the top side of the board, with the accelerometer on the left and the PIC microcontroller on the right. The other major components (namely the temperature sensor and I^{2}C buffer) are on the other side of the board.

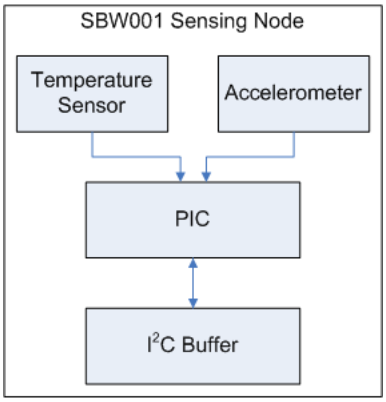


Figure 4.15: Sensing node components

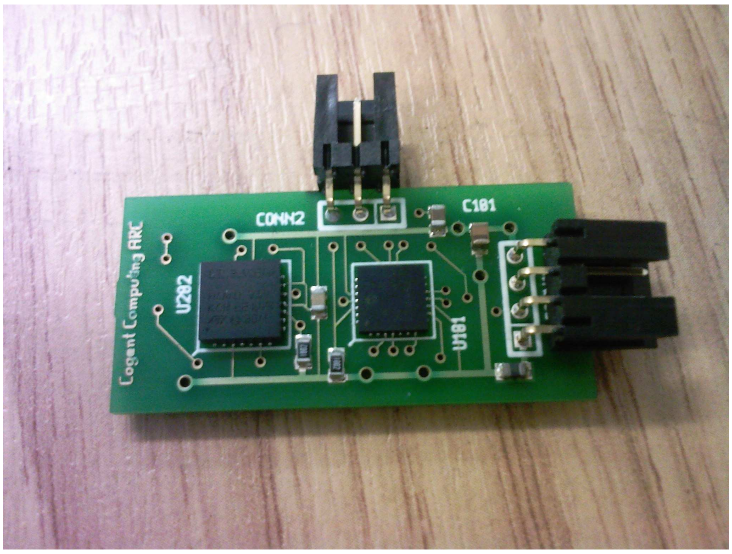


Figure 4.16: SBW001 sensor board

Reliability

The previous two sets of prototype sensing hardware suffered from a variety of reliability issues due to the method of construction. The two types of error encountered in the majority of cases were:

- readings made were inconsistent and fluctuated without actual temperature changes being encountered. This rendered the readings effectively unusable without substantial post-processing.
- sensor malfunctions were relatively common. Sometimes these errors were recovered from but often they resulted in all following readings being corrupted, also most often affecting other sensors.

The current prototype used PCBs designed in-house but fabricated externally. The use of superior fabrication facilities resulted in significant increases in reliability and rendered the readings much more meaningful. Readings became more stable, in-line with expected results, while malfunctions became rare, caused by conditions that would normally be expected to cause such incidents, such as accidental short circuits caused by metal objects or excess moisture. Additionally the system is much more capable of recovering from errors that would have previously caused all future readings to be corrupted until the point that the hardware needed to be reset. The new SBW001 sensor boards are expected to increase reliability further when combined with suitable data processing techniques. Additional improvements can be obtained by providing the hardware with sufficient protection from external influences such as impacts from the EOD suit breastplate while the subject is moving around.

4.6 The Data and Information Visualisation System

4.6.1 The Software Development

Background

The visualiser application was originally created as John Kemp's final year undergraduate honours project. The intention was to attempt to reconstruct the surface that a group of sensor nodes have been placed on, based on their locations, and display this along with basic data about the nodes. This functionality was expanded to allow the display of additional data, such as incoming readings, by manipulation of attributes of the reconstructed surface (e.g. colouring the surface according to recorded temperatures). The visualiser was created with modularity in mind and a variety of additional features have been added over time. Unfortunately, due to some inadequacies in the design it became infeasible to attempt to continue to extend the visualiser to account for new situations. Additionally, the user interface was not suitable for general usage. These factors combined to prompt the decision to perform a rewrite of the application with the requirements given above in mind.

The Original Visualiser

Following are some screenshots from various simulation runs using the original visualiser application. Figure 4.17 shows the visualiser performing a surface reconstruction based on node positions. The specific data shown was gathered manually rather than as part of a WSN localisation experiment. Figure 4.18 shows the visualiser displaying node density by colouring a flat surface beneath them, with brighter areas representing regions with a greater density of nodes. Figure 4.19 shows a much different experiment. Instead of surface reconstruction, the visualiser is taking temperature readings coming in from sensor nodes (in this example a series of sensors attached to a subject) and displaying them on a model of a human body. This is a similar task to that which the visualiser will be carrying out in the final system.

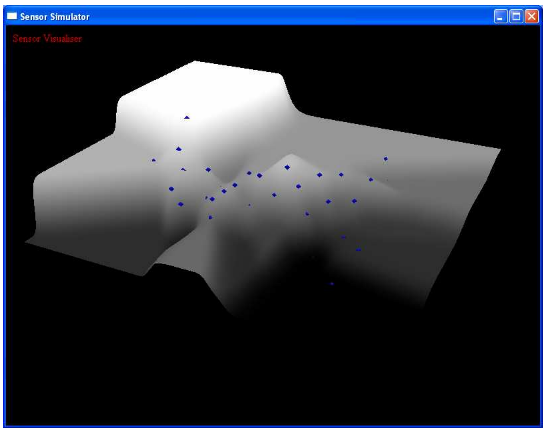


Figure 4.17: Visualisation of terrain

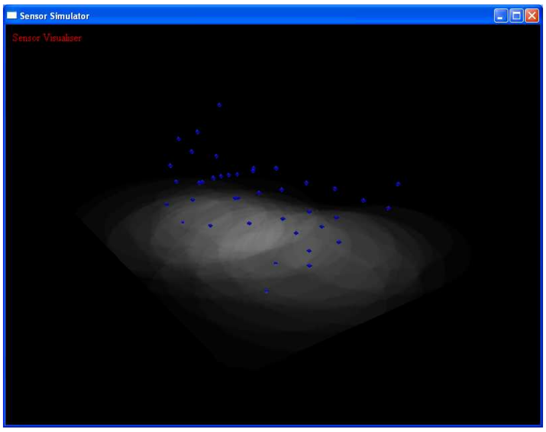


Figure 4.18: Visualisation of node density

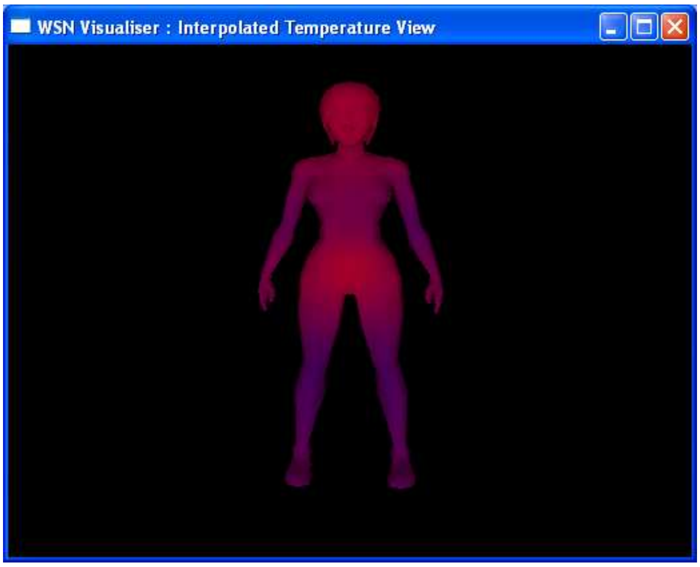


Figure 4.19: Visualisation of human body temperature

Current Progress

The visualiser has undergone development since the original version was created. Additions include the option of multiple windows displaying separate parameter types as well as substantial modifications to allow for flexibility of the visualisation shown. An example of the application running in its current state is shown in figure 4.20. This shows:

- Left: A view of the placement of the sensors with an indication of the reading level given by brightness

- Right: A view of the interpolated temperature distribution across the subject's body. Colours range from blue for colder areas to red for hotter areas
- Bottom: A graph of the current readings from the various sensors mounted on the subject

Figure 4.20: Visualisation using multiple windows

Future Work

Future work on the visualiser is intended to consist of a major reworking of the code base in order to allow additional types of visualisation, enhanced ease of use for an end-user, and easier code maintenance for future developers. The major result of this work will be a much more usable piece of software, which will be shown to adhere to relevant usability guidelines and good practice for data representation. It will also allow for easier modification, for instance to add additional data communication methods.

4.7 The Comfort Modelling Engine

A prototype of the model discussed in section 2.5 was first implemented in the Python programming language in order to judge its suitability for the project. This implementation is now in the process of being ported to C++ in order to integrate with the visualiser. The goal is to move the modelling engine onto the Gumstix devices in order to perform the modelling locally once the engine's effectiveness has been shown. The main problem encountered during implementation of the comfort modelling engine was that the calculations for the overshoot in the body's reaction to temperature changes caused a much larger effect than they should have, often going outside of the -4 to 4 range in values. This was caused because the resolution of the readings meant that rather than a smooth rise you would see from an analogue measuring instrument of sufficient precision there were regular jumps that seem insignificant to an observer but made it appear to the engine that there was a sudden increase or decrease in temperature in almost no time. Methods of allowing for this behaviour while sustaining the real-time operation of the engine are being investigated.

4.8 Posture Determination Methods

The matching of sensor data to particular postures that a subject may be in is an area that has recently been made possible in this project due to the addition of accelerometer data to the temperature data already being gathered. It is possible to determine the orientation of an accelerometer as described in section 4.3.

The intention here is to use the orientation of the various body segments which have accelerometers attached in order to determine the overall posture of the subject. This will be accomplished by matching the information about the segments against a set of data describing the likely orientation of the segments for each documented posture. Using this method, a "certainty" rating can be supplied for the matched posture, as well as suggesting other likely options where the information does not match any known examples. Figure 5.14 in section 5.3 summarises the postures recorded during the experimentation described. These are the most important set of postures as they are the common ones that are likely to be encountered during a mission, though additional postures may be added to the list as needed.

In the future this method may be supplemented with the addition of pressure sensitive pads to the suit. This will enable the accelerometers to be only used when needed, such as when more detailed posture information is required or when the information gained from the pressure pads is inconclusive. Further research into methods to accomplish this are to be investigated.

Chapter 5

Results

5.1 Introduction

During the course of developing the instrumentation system, several experimental runs have been performed in order to determine various attributes of the system, such as robustness; reliability; and instrument repeatability. This section describes the trials that have occurred along with the results obtained from them. To date there have been three separate trials: two took place with personnel from the Cogent Computing Applied Research Center at Coventry University and one took place with additional personnel from the Health and Life Sciences faculty at Coventry University.

5.2 Cogent Computing Lab Trials

This round of experimentation took place on the 5th September 2007 at the IeMRC 2th Annual Conference in Loughborough. Present were Mr John Kemp, Dr Elena Gaura and Dr James Brusey in the role of experimenters, while Mr Daniel Goldsmith was present as the subject.

The hardware used for the experiment was the Medusa2 prototype. In this particular case the sensor load consisted of twelve temperature sensors connected to two Gumstix Connex devices via an in-house produced interface board. The subject wore the outer shell of the bomb disposal suit including both the jacket and trouser segments. The data was gathered during two experimental runs, both consisting of the same routine. The location was indoors, in a large circular relatively empty room approximately 19 meters across and at an average temperature of 25°C.

One of the main goals of these experimental runs was to gauge the reliability of the system as a whole, as well as generating live data that could be analysed to determine the types of faulty readings known to occur from previous experimentation, as well as their likely causes.

5.2.1 The Trial Regime

The subject underwent several types of exercise while wearing various combinations of suit components. The trial regime is summarised in table 5.1.

Activity	Suit on/off	Helmet and breastplate on/off	Fan on/off	Duration
Standing	Off	Off	Off	5 minutes
Step-ups	Off	Off	Off	2 minutes
Standing	Off	Off	Off	3 minutes
Standing	On	Off	Off	5 minutes
Steady Walk	On	Off	Off	4 minutes
Standing	On	Off	Off	7 minutes
Standing	On	On	Off	1.5 minutes
Steady Walk	On	On	Off	5 minutes
Standing	On	On	Off	5 minutes
Standing	On	On	On	3 minutes

Table 5.1: Exercise regime for Cogent Computing Lab trials

It was intended to obtain data for all the combinations of exercise type suit components so that the impact of each could be judged. In particular, the effectiveness of the cooling system was aimed to be assessed. Note that the seven minute duration of the standing phase before the helmet and breastplate were put on includes the time taken to position them on the subject. As the primary goal of this experimental run was to gauge the basic reliability of the system and provide information on the types of error that could occur, the regime did not include the full range of possible activities that a bomb disposal technician might perform, instead focused on general movement.

Figure 5.1 shows the subject during the process of attaching the temperature sensors, which were worked into a t-shirt to speed up the setup process for the experiment, while figure 5.2 shows the subject during the donning of the EOD suit. Figure 5.3 shows the subject wearing the full suit.

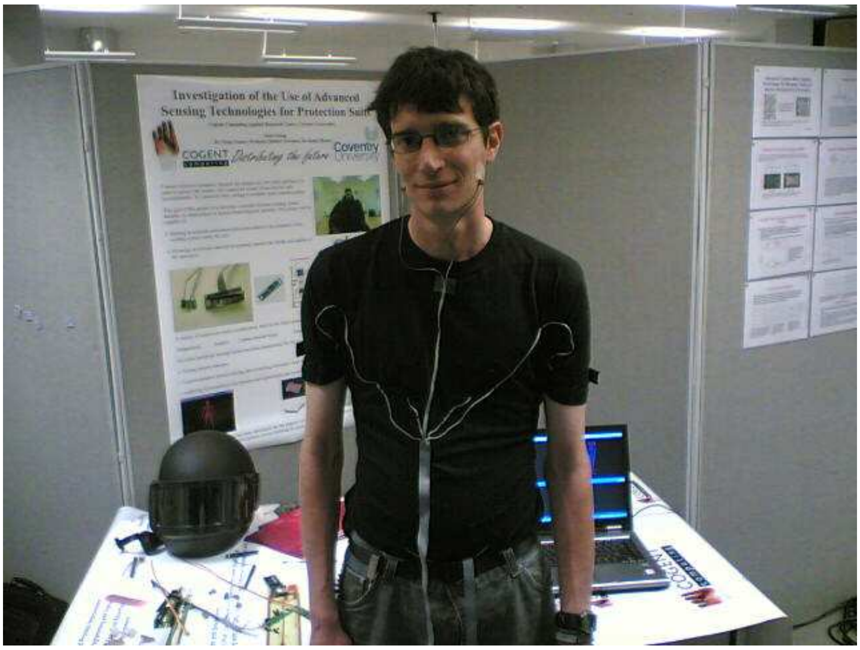


Figure 5.1: Cogent Computing Lab Trial: Sensor attachment

Figure 5.2: Cogent Computing Lab Trial: Subject donning EOD suit

Figure 5.3: Cogent Computing Lab Trial: Subject wearing full EOD suit

A view of the actual sensor positions for this experimentation is shown in figure 5.4.

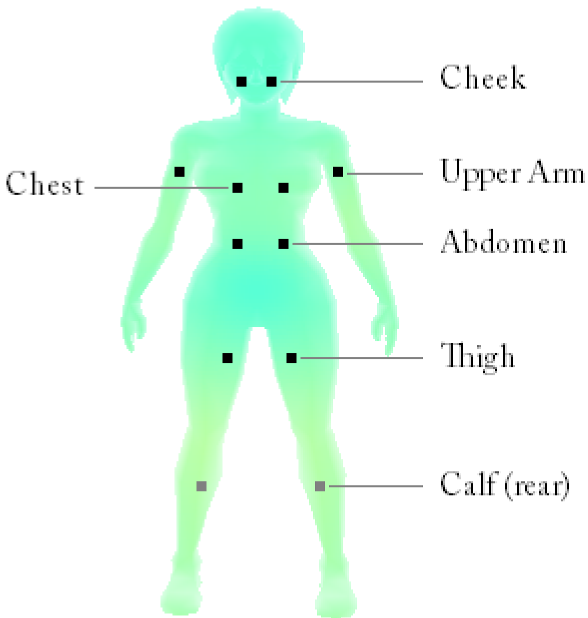


Figure 5.4: Cogent Computing Lab Trial: Sensor positions

5.2.2 Results

Figures 5.5 to 5.7 show the average temperature recorded during the course of the trial, along with data gathered from the abdomen and arm segments. These graphs are representative of the effects of the exercise regime carried out during the experimentation.

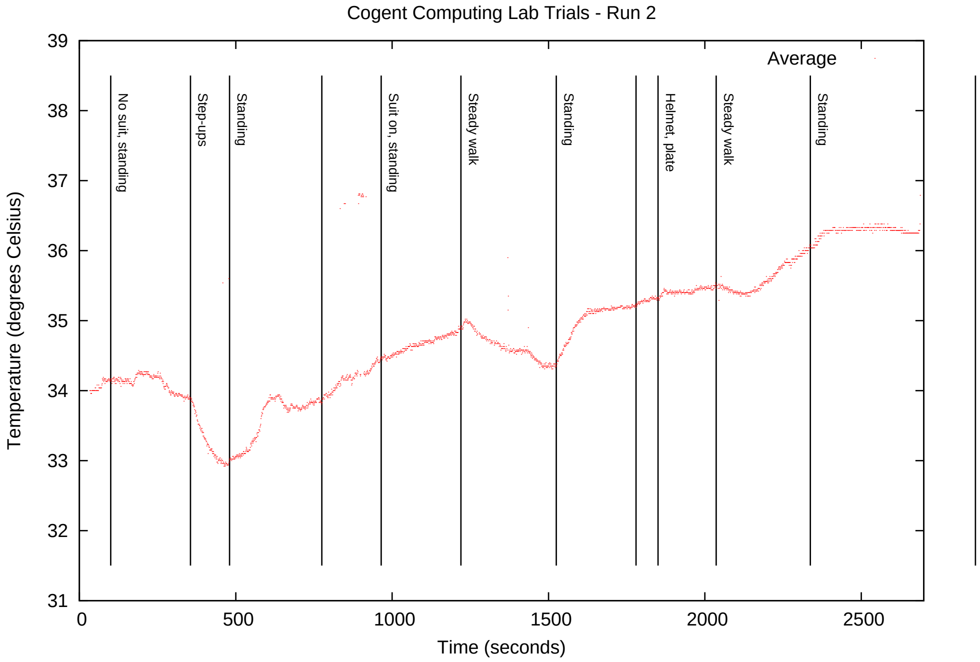


Figure 5.5: Cogent Computing Lab Trial: Average temperature

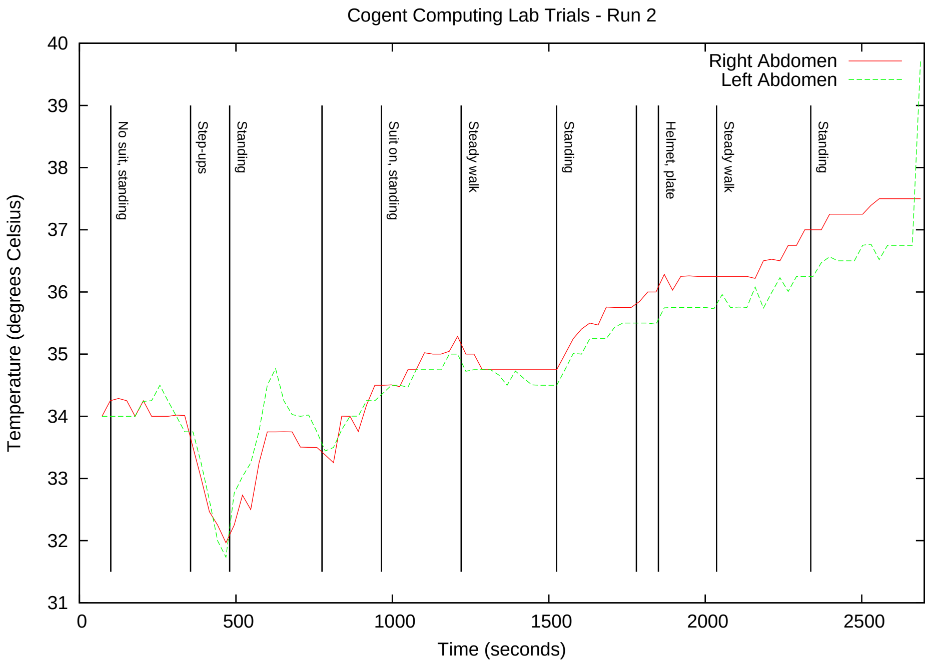


Figure 5.6: Cogent Computing Lab Trial: Abdomen data

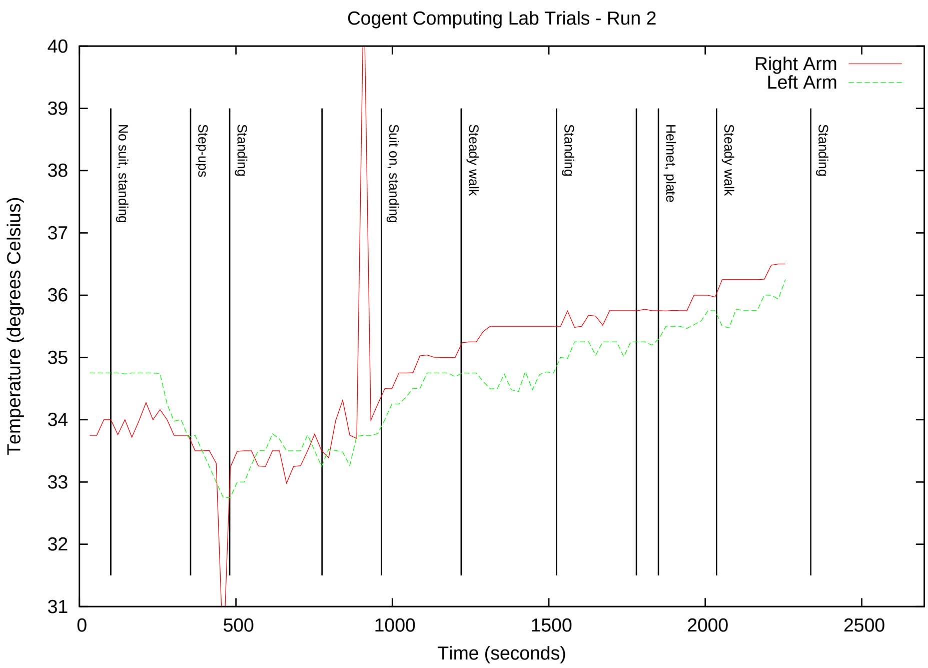


Figure 5.7: Cogent Computing Lab Trial: Arm data

Generally, the results observed followed the sensations reported by the test subject. During post-activity motionless periods the overall temperature level increased, while movement such as walking resulted in overall lower temperature levels. For example, during the first experimental run the ambient temperature measured in the chest region followed this pattern consistently with rises of between 0.5 and 1°C during periods of standing and drops of approximately the same amount during steady movement. This is consistent with the results obtained during the second such run. This may be due to the movement of the subject causing air to be circulated within the suit, as well as causing it to be moved into and out of the suit, which in turn allows temperature levels to be regulated more easily. This effect is also observed, though to a lesser extent, during the period where the helmet was worn. The helmet would act to restrict the movement of air into and out of the suit, an effect which is reflected by the overall rises in temperature during this period. Heat is being generated as normal, however this is being trapped within the suit rather than vented as is the case where no helmet is worn. Of note is that the overall temperatures dropped initially when the subject began walking while wearing the helmet, but this was soon outweighed by a more rapid increase. One explanation for this is that the movement caused air to be circulated within the suit as mentioned previously, however due to the air being trapped within the suit it will have ceased to allow heat transfer away from the subject as it approached the temperature of the subject's skin. This effect causes the helmet to be a critical factor in the free cooling of the subject. It is also worth noting, should the inner suit components be worn, the air exchanges will be further decreased. Moreover, exchanges with ambient air at high temperature is likely to influence the natural cooling observed.

The results in figure 5.5 show that while the suit was not worn and the body was allowed to regulate its temperature naturally in normal environmental conditions, there was no overall rise in the skin temperature after several minutes of steady exercise. While the pattern of cooling during exercise is sustained, presumably again due to greater air flow around the skin, the skin temperature does not rise above its original level while standing. Note that the activity during this experimentation was steady and of relatively low intensity. A more intense regime will likely produce different results.

Whilst wearing the suit, activation of the cooling fans provided no noticeable temperature drop, though the subject did report that he felt cooler during this time. A possible reason for this is that the cooler air was not circulating to the front of the suit where the sensors were situated. The slight drop in temperatures near the end of this period of the experiment may indicate that this trend would have continued to the point of causing a noticeable effect given additional time.

Overall, during the experimentation, the temperatures for each body segment rose steadily, though by varying amounts depending on the particular segment in question. This shows that regardless of the particular activities being performed and the temporary changes they may cause, wearing the protection suit causes skin temperature levels to increase overall. Additionally, the results gained from the use of the fan show that while the immediate sensation caused is that of a cooling effect this effect is not applied evenly, particularly to the front of the body. The average temperature and the readings from each sensor during the experiment were in general within 2°C of each other. As the difference between the lowest and highest average temperature across the experimental run 2 was 3°C, it means that different areas of the body can experience significantly different temperatures.

During the experimentation, one of the temperature probes mounted on the subject's left shin became detached and had to be reattached in order to continue gathering valid data. The effect of sensor detachment can be seen in figure 5.8, which shows the difference between the two sets of shin sensor readings (right shin and left shin) and the average temperature during the experiment, focused on the prior and post fault time slot. There is an obvious negative difference from the period the sensor becomes detached.

Figure 5.8: Cogent Computing Lab Trial: Shin sensor error

This is an example of a fault that can potentially be easily detected given a measure such as the average temperature reading and an appropriate reading correction algorithm. The sharp drop is the primary indicator of the fault as this is not a natural trend for skin temperature.

Figure 5.9 shows the data gathered from the chest segment during the experimentation, highlighting yet another set of reading errors. These errors are very highly concentrated during the period the subject was walking with the suit on and are likely to be caused by the combination of movement and the weight of the suit onto the instrumentation. It is clear that protection of the sensing devices is needed in order to prevent these type of errors occurring. The number of errors became significantly reduced after some time. As the activity of the subject had not changed, this indicates that the condition causing the errors may have been transient and ceased to exist due a small change such as movement of the processing nodes or wiring.

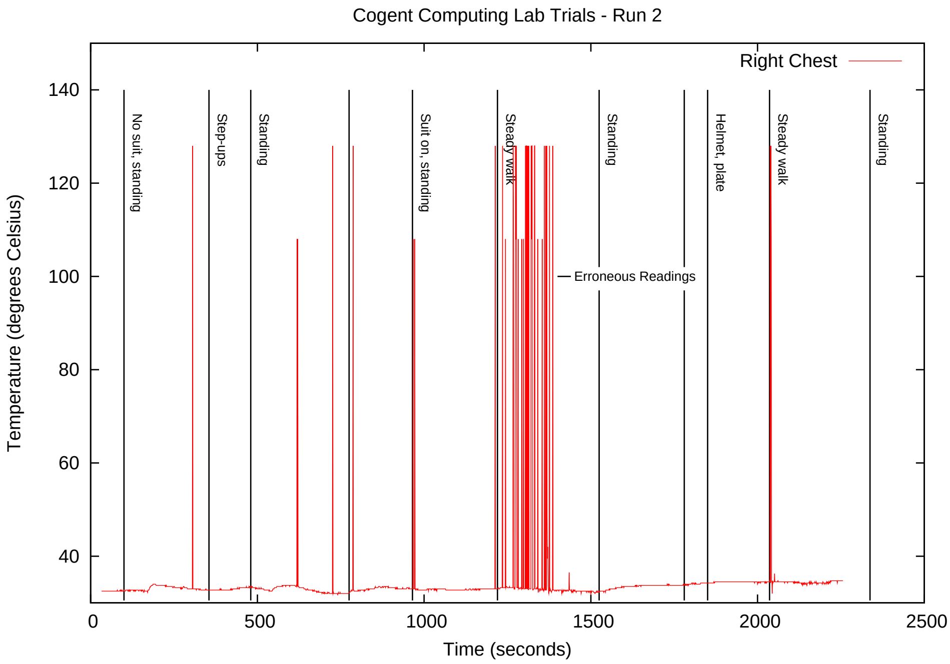


Figure 5.9: Cogent Computing Lab Trial: Chest sensor error values

Of particular note is the fact that erroneous readings often take specific values. Fault robustness can be achieved for such faults through monitoring of these values and automatically flagging them as errors, especially as they do not fall within the normal range of human skin temperature values.

5.3 Health and Life Sciences Lab Trials

This round of experimentation was performed for several purposes. The first aim was the calibration of the temperature sensors used in the prototype when compared against "known good" equipment. The second aim was to identify the types of posture that a subject would assume while performing various activities. This information is for later use in modelling of the accelerometer data. The third aim was to collect additional data on the effect of the suit on subject temperature levels.

The experimentation took place on the 24th September 2007 in facilities owned by the Health and Life Sciences faculty at Coventry University. Mr John Kemp, Dr Elena Gaura and Dr James Brusey were present with the Medusa2 prototype, while Dr Doug Thake and Miss Lindsay Bottoms were in control of the more traditional wired instrumentation systems already in use. Mr Daniel Goldsmith was the experimental subject.

The hardware used for the experiment was the Medusa2 prototype. In this particular case the sensor load consisted of twelve temperature sensors connected to two Gumstix Connex devices via an in-house produced interface board. The subject wore the outer shell of the bomb disposal suit including both the jacket and trouser segments in addition to additional armour plating and the helmet. The data was gathered during two consecutive runs, both consisting of the same routine and taking place in a 5m x 6m room, ventilated to a constant 21°C.

5.3.1 The Exercise Regime

The subject performed several types of physical activity during the experimentation, which are summarised in table 5.2.

Activity	Duration
Walking on treadmill	3 minutes
Kneeling with light manual task	2 minutes
Crawling	2 minutes
Ergometer-based arm exercise	4 minutes
Sitting	3 minutes
Standing	1 minute

Table 5.2: Health and Life Sciences Lab Trial: Exercise regime

These tasks were intended to cover a range of activities similar to those that a bomb disposal technician would encounter during the course of a mission, and to provide more realistic data about expected mission conditions. Figure 5.10 shows the subject on a treadmill simulating the walk to a suspect site, while figure 5.11 shows the subject performing a light manual task simulating a simple bomb disposal task.

Figure 5.10: Health and Life Sciences Lab Trial: Treadmill

Figure 5.11: Health and Life Sciences Lab Trial: Light manual task

5.3.2 Results

Unfortunately the prototype system encountered problems during this trial, hence the results were not greatly meaningful. This experiment however demonstrated the importance of both additional protection for the hardware and improved error detection and recovery algorithms. The results obtained via the wired instrumentation is discussed further here. Figure 5.12 shows the subject's heart rate over the course of the experiment. While the activity regime was performed twice, only the first run has been explicitly labeled on the graph. This is to allow for easier visual comparison as the graph is split into two distinct halves. The overall pattern of change can be seen to be similar in both cases.

Figure 5.12: Health and Life Sciences Lab Trial: Heart Rate

The graph shows an substantial increase in heart rate when the subject was performing the crawling activity. This can be attributed to the weight of the suit causing much greater physical exertion and requiring greater blood flow to important areas of the body such as the muscles. An important point to observe on the above graph is that the heart rate reached values around 180 beats per minute, which is nearing the maximum safe limit for some people. While the danger is not immediate, this level of activity for prolonged periods is problematic. When the activity regime was performed for the second time the heart rate can be seen to be higher overall, which shows that the effects of the suit are sustained (to an extent) even after a period of rest.

Temperature data was also collected during the experiment. Figure 5.13 shows the subject's average skin temperature over the course of the experiment. As with figure 5.12, only the first run has been explicitly labeled on the graph.

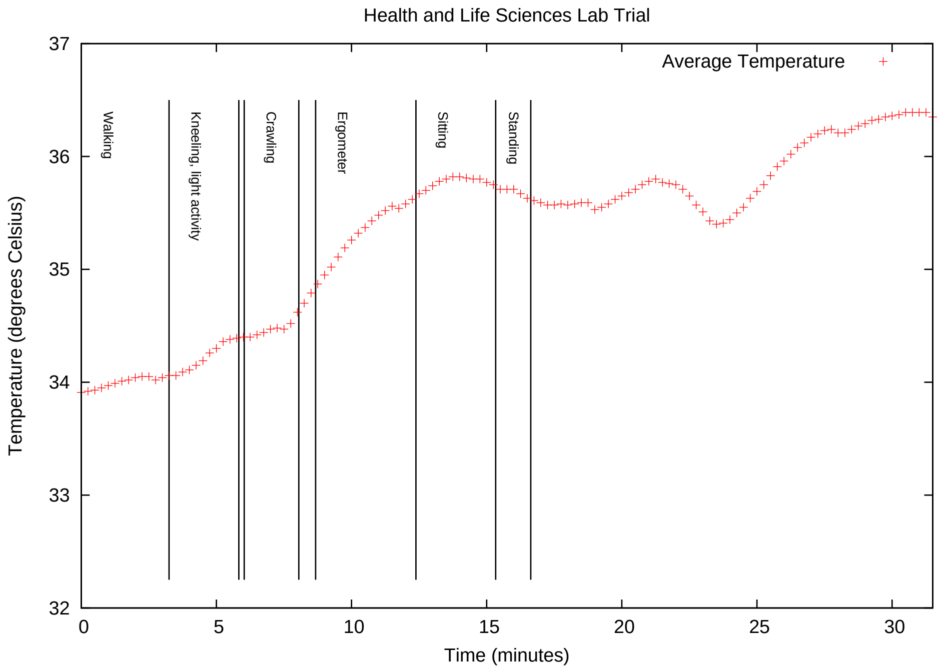


Figure 5.13: Health and Life Sciences Lab Trial: Average Temperature

The average temperature graph shows as expected, a rise overall during the experimentation, with no significant reduction at any time. The temperature did drop (as would be expected) once the EOD suit was removed from the subject. Even at this point, however, the skin temperature did not return to its pre-experiment levels, likely due to the heat being transferred outwards in order to ensure the core temperature did not rise to dangerous levels. The reaction of the body to sudden changes such as the removal of the suit can in fact be dangerous in cases where the body overcompensates for the change or does not react with sufficient speed. In both cases this can cause problems if left unmonitored, (it is known that this can also affect athletes after a period of high exertion).

Figure 5.14 summarises the postures recorded during the experimental run in a simple stick format representing the limbs. Legs are shown in red, the torso in green, and the arms (where relevant) in blue. These observations, as well as confirming initial assumptions as to body posture during these activities, will feed into the development of a pattern matching system for posture identification.

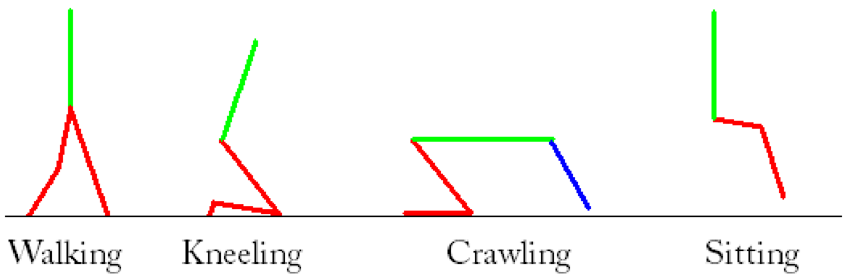


Figure 5.14: Health and Life Sciences Lab Trial: Potential identified postures

5.4 Further Trials

This experimental run was performed as a supplement to the Health and Life Sciences Lab Trials (see section 5.3 on page 85). The experimentation took place on the 26th September 2007 in the Cogent Computing ARC Laboratory at Coventry University. Present were Mr John Kemp and Mr Garry Malone in the role of experimenters, with Mr Louis Macan as the subject.

The hardware used for the experiment was the Medusa2 prototype. As previously, the sensor load consisted of twelve temperature sensors connected to two Gumstix Connex devices via an in-house produced interface board. The subject wore the outer shell of the bomb disposal suit including both the jacket and trouser segments and in the second run additional armour plating and the helmet were added. The data was gathered during two consecutive runs, both consisting of the same routine and taking place in a 4m x 6m room, at room temperature.

5.4.1 The Exercise Regime

The subject performed several types of activity during the experimentation which are summarised in table 5.3.

Activity	Duration
Standing	1 minute
Steady Walk	3 minutes
Light Activity	2.5 minutes
Crawling	2 minutes
Sitting	3 minutes

Table 5.3: Further Trials: Exercise regime

This regime was intended as a reduced version of the regime used in the previous Health and Life Sciences trial and again, covers most of the activity types that a bomb disposal technician is likely to encounter during a mission. The regime was run through twice, once with without the breastplate and helmet and once with them on.

5.4.2 Results

During this experiment heart rate data was collected via a manual method. This was sampled once between each consecutive activity in the regime. Graphs of the heart rate data for the two runs run are shown in figure 5.15. Time on these graphs is shown with the zero point being the activation of the monitoring system. There is no data prior to that shown as this time was taken with donning the suit and ensuring the system was functioning correctly. In the graphs in figure 5.15, interpolation was performed between the data points with the use of splines (which use the data points as the endpoints of curves).

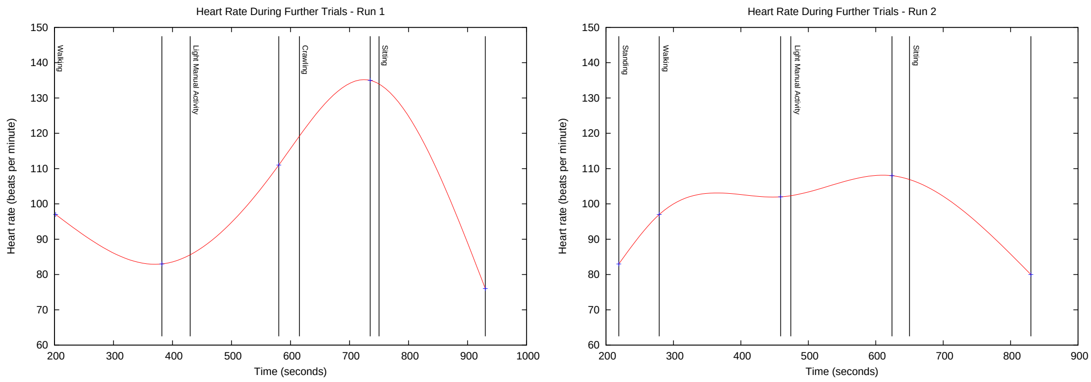


Figure 5.15: Further Trials: Heart rate

The heart rate values follow approximately the same pattern as in the previous experiment: the heart rate increases dramatically during any period of physical activity while wearing the suit, though it drops significantly once the activity stops (with the subject sitting in this case). A noticeable drop is also seen in the first run when walking with no helmet or breastplate. The second run did not include the crawling activity as the subject did not feel they could complete it without causing themself harm. This means the large peak that occurred during this activity in the first run is absent.

Figure 5.16 shows the subject's average skin temperature during the experimentation, while figures 5.17 to 5.22 show the data collected from each location. Results from the second experimental run are not included for two reasons. First, the subject do not complete the activity regime. Second, there were a large number of data acquisition errors during the second run, possibly due to the extra weight or increased number of physical impacts caused by the addition of the breastplate.

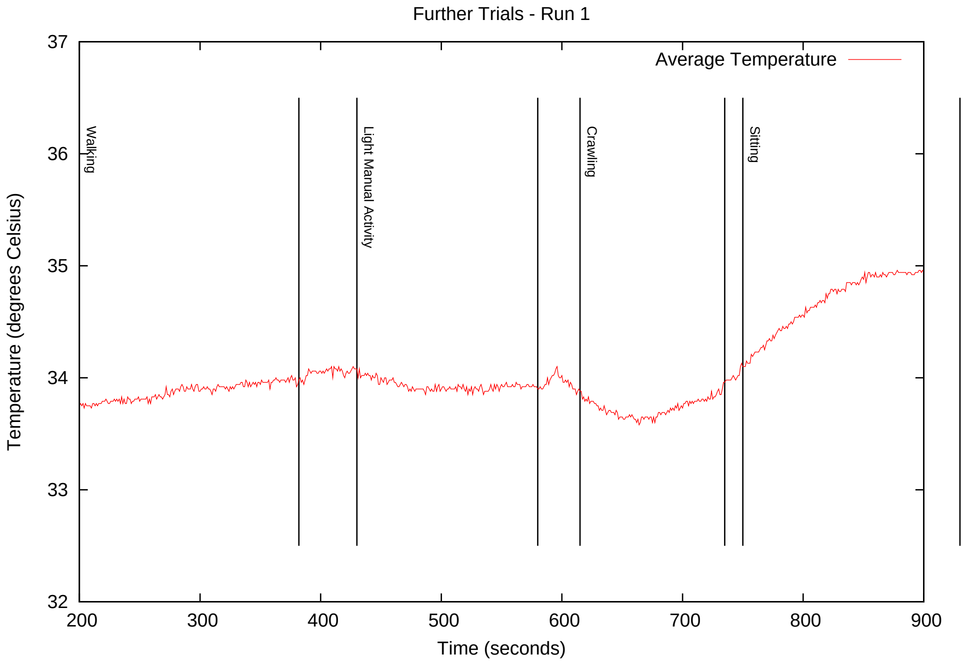


Figure 5.16: Further Trials: Average skin temperature

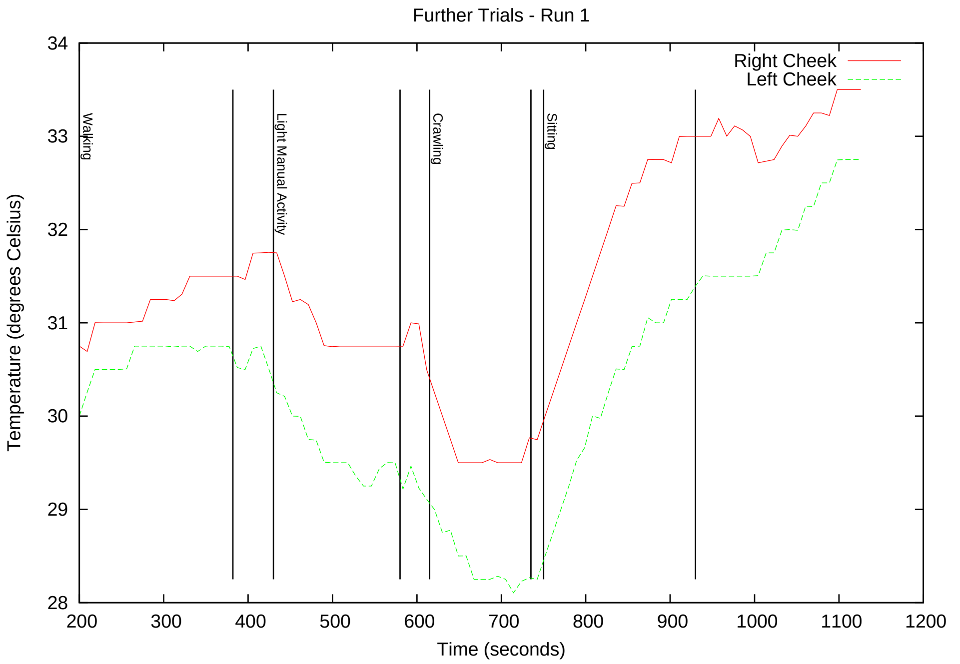


Figure 5.17: Further Trials: Cheek data

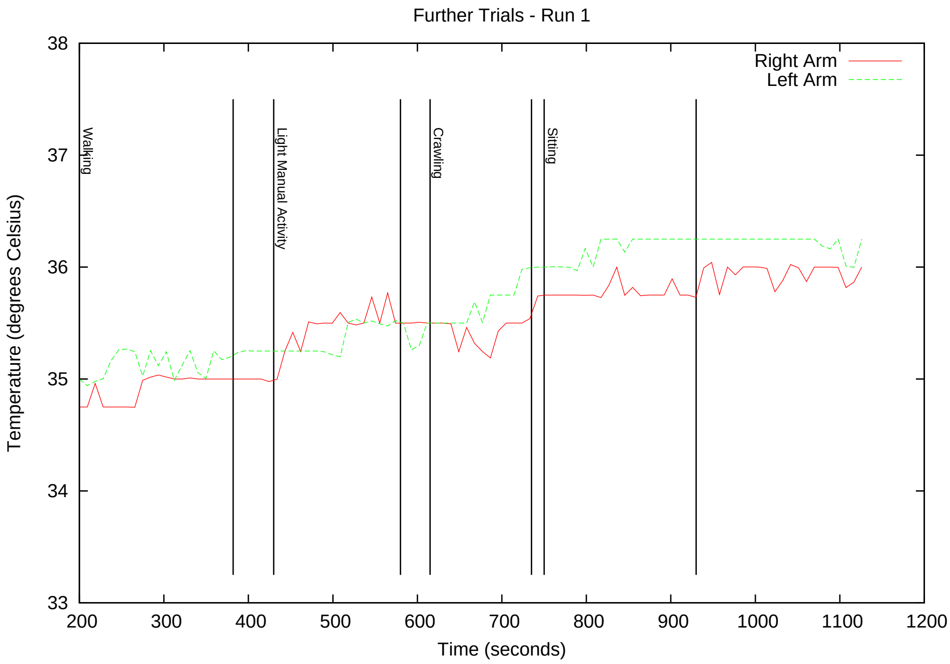


Figure 5.18: Further Trials: Arm data

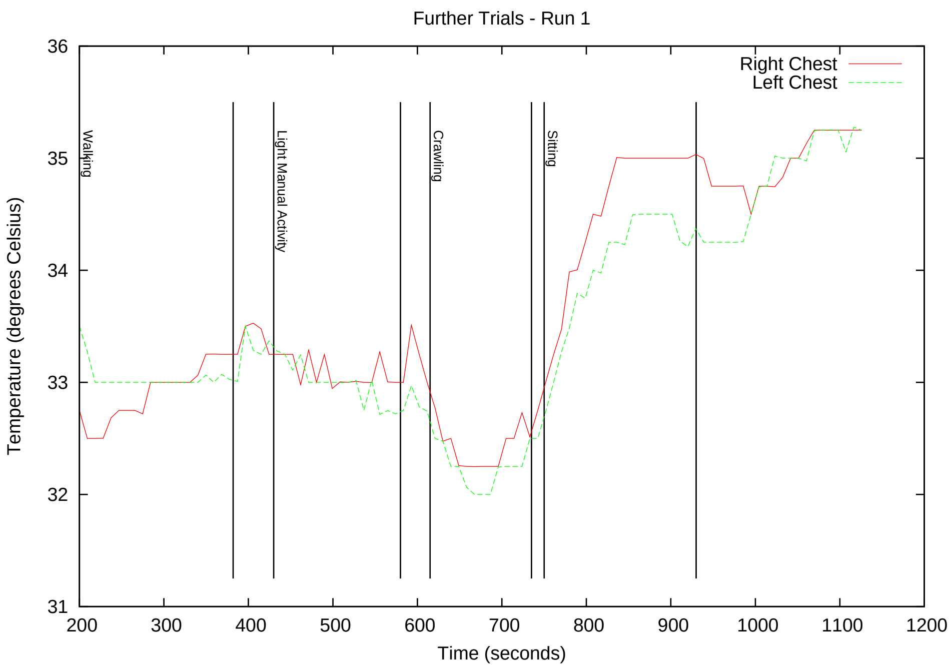


Figure 5.19: Further Trials: Chest data

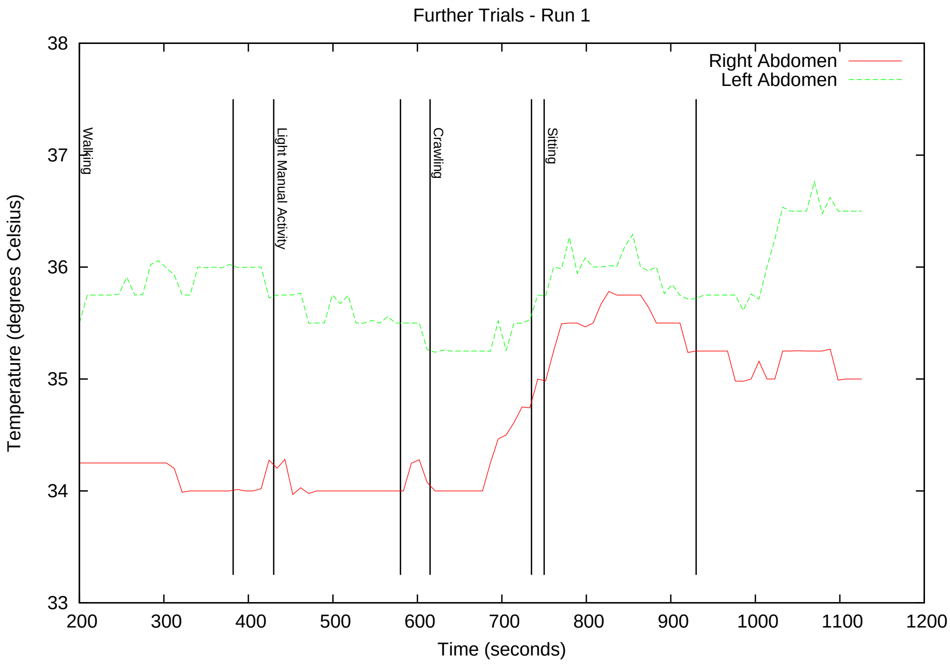


Figure 5.20: Further Trials: Abdomen data

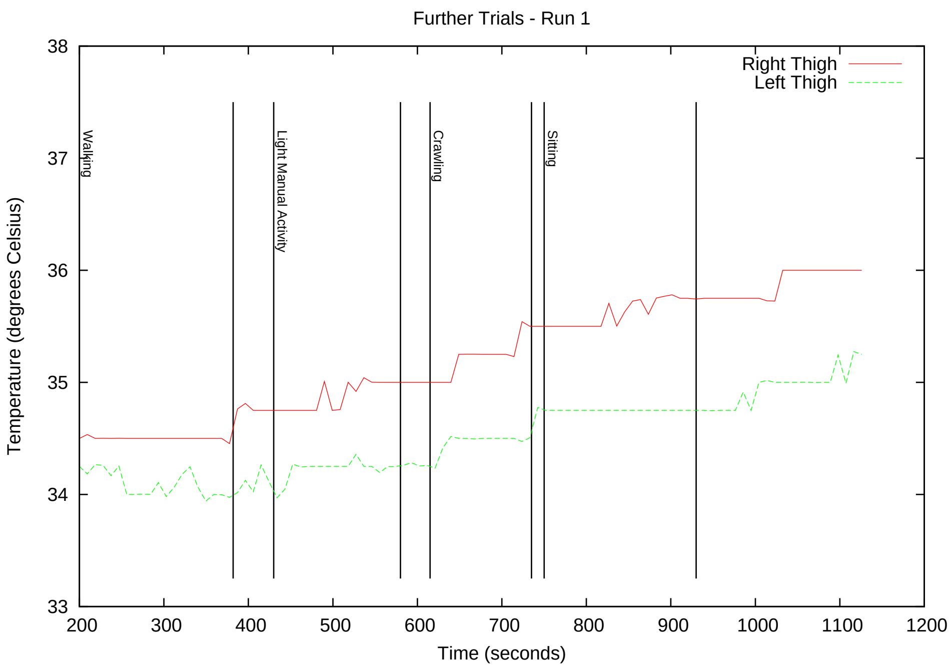


Figure 5.21: Further Trials: Thigh data

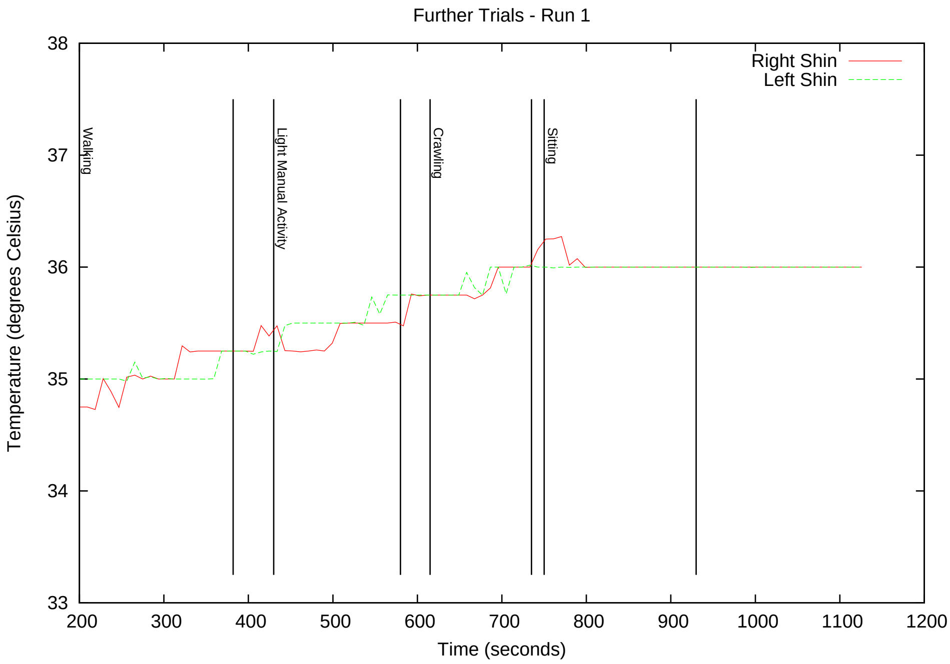


Figure 5.22: Further Trials: Shin data

The difference in readings for the left and right abdomen would appear to be due to a badly attached sensor, this is a type of error that the system will be designed to detect in the future. The results show a general rise in all readings throughout the experimentation. The rise in temperature is relatively slow while the subject is moving, possibly due to the movement causing air to be circulated within the suit. However, when the subject ceased this movement, the rise in temperature immediately became faster for several segments. The suit's inability to allow the built up heat to escape is where the danger lies in situations where protective clothing such as this is worn. Hence there is a need for both a cooling system and an appropriate sensing and actuation system to provide cooling control.

Chapter 6

Conclusions and Further Work

The work so far in this project has demonstrated the feasibility of detailed skin temperature and heart rate measurement in subjects wearing an EOD suit while performing similar tasks to those required of a bomb disposal technician. The data gathered from experimentation shows that, feasibility of the suits have a definite physiological effect on the wearer, producing changes in the values of physiological parameters which would be considered abnormal in many other scenarios. The literature in the area, along with the experimentation presented in this report, further shows that the effects caused by the suit can cause considerable discomfort in a wearer and even become dangerous if uncontrolled.

A hardware platform has been developed for the collection of physiological data. This platform is expandable with a variety of sensor types and supports the in-network processing of the collected data at several levels. A software application has also been developed for the visualisation of information output by the in-suit network. A method of modelling the comfort of a subject has been extracted from the literature, and work has started on the modelling of the posture of a subject using per-body segment accelerometer data.

Several succesful demonstrations of physiological data sensing have been performed, as well as a set of experimental runs, utilising the system as developed so far.

The architecture developed to date for the suit instrumentation system, as well as the systems alternative role as an experimentation system, appears to lead to a sustainable and expandable design with a multitude of options open for exploitation in terms of both the sensor load of the system and the processing of the gathered data.

The future direction of this project is towards advancement of the system with respect to the instrumentation design and furthering its experimentation roles. This will require the integration of additional sensors of various types as well as development of the visualisation tool. The use of new sensor types will be the focus of the project in the near future as the intended experimentation that will be enabled will allow the determination of the optimal sensor load for the various system “roles”, as well as suggesting or confirming the optimum number and positioning of the sensors. Currently the sensor boards available include temperature and acceleration sensors, with the future parameters planned for measurement within the system being heart rate, pulse oximetry (pulse and blood oxygen saturation) and carbon dioxide levels.

The sensing of these parameters at the next stage in the project will primarily determine their usefulness in the final instrumentation system, while also allowing the testing of several locations in order to determine the most appropriate ones leading to consistently useful readings. The visualiser sub-system will also be developed further towards a user-friendly interface and suitability for the experimentation, with particular focus on the ease of use and the types of visualisation provided. Ease of use of the visualiser is an important issue due to its intended use by non-experts; an intuitive interface will allow for a more comfortable user experience while reducing the time required for user training.

Additional work is also needed with respect to the data modelling, including the modelling of comfort and posture information. As mentioned previously, the data collected from the current sensors is not suitable for direct use with the comfort modelling engine proposed, therefore additional work is required towards processing data before the modelling stage. The modelling of the accelerometer data into posture information will also become a possibility. A general approach has been identified towards pursuing the posture information extraction goal. Further research is required to refine this into a specific algorithm and implement it into the system for testing and evaluation.

Bibliography

[1] “Vivometrics : http://www.vivometrics.com.” Website.

[2] V. Shnayder, B. rong Chen, K. Lorincz, T. R. F. Fulford-Jones, and M. Welsh, “Sensor networks for medical care,” tech. rep., Division of Engineering and Applied Sciences, Harvard University, 2005.

[3] 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, March 2005.

[4] “Moteiv Corporation : http://www.moteiv.com/about/contact.php.” Website.

[5] E. M. Tapia, N. Marmasse, S. S. Intille, and K. Larson, “Mites: Wireless portable sensors for studying behavior,” in *Proceedings of Extended Abstracts UbiComp 2004: Ubiquitous Computing*, 2004.

[6] B. Lo and G.-Z. Yang, “Architecture for body sensor networks,” in *Perspective in Pervasive Computing*, pp. 23–28, October 2005.

[7] “Gumstix Inc. : http://www.gumstix.com/.” Website.

[8] 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), pp. 102–105, September 2005.

[9] “Crossbow Technology Inc. : http://www.xbow.com/.” Website.

[10] 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 *Proceedings of the 4th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services (Mobiquitous)*, (Philadelphia, USA), August 2007.

[11] “Carnegie mellon university embedded systems design project 2007 - team 5 : http://www.ece.cmu.edu/ ece549/spring07/team5/.” Website.

[12] S. P. Brown, W. C. Miller, and J. M. Eason, *Exercise Physiology: Basis of Human Movement in Health and Disease*. Lippincott Williams & Wilkins, 2005.

[13] H. Zhang, *Human Thermal Sensation and Comfort in Transient and Non-Uniform Thermal Environments*. PhD thesis, University of California, Berkeley, 2003.

[14] “Thermoregulation (Wikipedia) : http://en.wikipedia.org/wiki/thermoregulation.” Website.

[15] “CCOHS [Humidex Scale] : http://www.ccohs.ca/oshanswers/phys_agents/humidex.html.” Website.

[16] N. Kleitman, S. Titelbaum, and P. Feiveson, “The effect of body temperature on reaction time,” *The American Journal of Physiology*, vol. 121, no. 2, pp. 495–501, 1938.

[17] J. K. P. Wright, J. T. Hull, and C. A. Czeisler, “Relationship between alertness, performance, and body temperature in humans,” *The American Journal of Physiology - Regulatory, Integrative and Comparative Physiology*, vol. 283, pp. 1370–1377, December 2002.

[18] R. L. Holland, J. A. Sayers, W. R. Keatinge, H. M. Davis, and R. Peswani, “Effects of raised body temperature on reasoning, memory, and mood,” *Journal of Applied Physiology*, vol. 59, no. 6, pp. 1823–1827, 1985.

[19] “Pulse Oximetry (Wikipedia) : http://en.wikipedia.org/wiki/pulse_oximetry.” Website.

[20] Y. sheng Yan, C. C. Poon, and Y. ting Zhang, “Reduction of motion artifact in pulse oximetry by smoothed pseudo wigner-ville distribution,” *Journal of NeuroEngineering and Rehabilitation*, vol. 2, no. 3, 2005.

[21] T. Rusch, R. Sankar, and J. Scharf, “Signal processing methods for pulse oximetry,” *Computers in Biology and Medicine*, vol. 26, pp. 143–159, March 1996.

[22] “OSHA : http://www.osha.gov/.” Website.

[23] “NIOSH : http://www.cdc.gov/niosh/.” Website.

[24] “ASHRAE : http://www.ashrae.org/.” Website.

[25] “Shallow Water Blackout (Wikipedia) : http://en.wikipedia.org/wiki/shallow_water_blackout.” Website.

[26] F. Koushanfar, M. Potkonjak, and A. Sangiovanni-Vincentelli, “Fault tolerance techniques for wireless ad hoc sensor networks,” *IEEE Sensors*, vol. 2, pp. 1491–1496, June 2002.

[27] V. Venkatasubramanian, R. Rengaswamy, K. Y. C, and S. N. Kavuri, “A review of process fault detection and diagnosis part i: Quantitative model-based methods,” *Computers and Chemical Engineering*, vol. 27, pp. 293–311, 2003.

[28] F. Koushanfar, S. Slijepcevic, M. Potkonjak, and A. Sangiovanni-Vincentelli, “Error-tolerant multimodal sensor fusion,” in *IEEE CAS Workshop on Wireless Communications and Networking*, (Pasadena, CA), September 2002.

[29] 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.

[30] 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.

[31] M. P. Georgeff and F. F. Ingrand, “Decision-making in an embedded reasoning system,” in *Proceedings of the Eleventh International Joint Conference on Artificial Intelligence*, (Detroit (Michigan)), August 1989.

[32] O. Holland, J. Woods, R. D. Nardi, and A. Clark, “Beyond swarm intelligence: The ultraswarm,” in *IEEE Swarm Intelligence Symposium (SIS2005)*, 2005.

[33] J. Paradiso and T. Starner, “Energy scavenging for mobile and wireless electronics,” *Pervasive Computing, IEEE*, vol. 4, no. 1, pp. 18 – 27, 2005.

[34] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, “Wireless power transfer via strongly coupled magnetic resonances,” *Science*, vol. 317, pp. 83–86, July 2007.

[35] “Lithium-ion Polymer Battery (Wikipedia) : http://en.wikipedia.org/wiki/lithium_polymer.” Website.

[36] “Omega Engineering, inc : http://www.omega.com.” Website.

[37] “Maxim Integrated Products : http://www.maxim-ic.com/.” Website.

[38] “Curve fitting the error of a bandgap-based digital temperature sensor : http://www.maxim-ic.com/appnotes.cfm/an_pk/208.” Website.

[39] “Analog Devices, Inc. : http://www.analog.com/.” Website.

[40] “Smiths Medical : http://www.smithsoem.com/applications/oxiboards.htm.” Website.

[41] “Nonin Medical, Inc. : http://www.nonin.com/.” Website.

[42] “Edinburgh Instruments Ltd : http://www.edinst.com/.” Website.

[43] “Vaisala : http://www.vaisala.com/.” Website.

[44] “Draeger Safety Inc. : http://www.draeger.com/st/internet/us/en/index.jsp.” Website.

[45] “Figaro usa inc : http://www.figarosensor.com/.” Website.

[46] “STMicroelectronics : http://www.st.com/stonline/.” Website.

[47] “Microchip Technology Inc. :http://www.microchip.com/.” Website.

Cogent Computing Applied Research Centre
Coventry University
Priory Street, Coventry CV1 5FB
www.cogentcomputing.org

Coventry University