KEY TECHNICAL CHALLENGES AND CURRENT IMPLEMENTATIONS OF BODY SENSOR NETWORKS

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ABSTRACT - Preventative care and chronic disease management to reduce institutionalisation is a national priority for most western countries. This paper outlines some of the key technical challenges related to pervasive health monitoring with Body Sensor Networks (BSNs). Issues concerning the development of a common architecture with context aware sensing is discussed. In order to achieve unobtrusive pervasive sensing that links physiological/metabolic parameters and lifestyle patterns for improved well-being monitoring, and early detection of changes in disease, we demonstrate the basic structure and our experience of the UbiMon platform for continuous monitoring of patients under their natural physiological conditions.

Keywords: *BSN, context awareness, pervasive sensing, multi-sensor fusion*

1 INTRODUCTION

The last decade has witnessed a rapid surge of interest in new sensing and monitoring devices for healthcare. One key development in this area is implantable *in vivo* monitoring and intervention devices. While the problem of long-term stability and biocompatibility is being addressed, several promising clinical prototypes are starting to emerge. For example, in the case of managing patients with acute diabetes, the blood glucose level can be monitored continuously *in vivo*, which controls the insulin delivery from an implanted reservoir. For the treatment of epilepsy and other debilitating neurological disorders, there are already on the market implantable, multiprogrammable brain stimulators which save the patient from surgical operations of removing brain tissue. In cardiology, the value of implantable cardioverter-defibrillator (ICD) has increasingly been recognized for the effective prevention of sudden cardiac death (SCD). In Europe 900,000 patients die suddenly each year and about ninety percent of these deaths are caused by an arrhythmogenic event. Disturbingly, many arrhythmogenic deaths could be prevented if ICD implantation had been made available when the risk of SCD was identified. It is possible to envisage a large percentage of the population having permanent implants which would provide continuous monitoring of the most important physiological parameters for identifying the precursors of major adverse cardiac events including sudden death. Such technological development echoes the social, industrial, and clinical perspectives of future healthcare delivery.

Technological developments of sensing and monitoring devices is reshaping the general practice in clinical medicine. Although extensive measurement of biomechanical and biochemical information is available in almost all UK hospitals, the diagnostic and monitoring utility is generally limited to the brief time points and perhaps unrepresentative physiological states such as supine and sedated, or artificially introduced exercise tests. Transient abnormalities, in this case, cannot always be captured. For example, many cardiac diseases are associated with episodic rather than continuous abnormalities such as transient surges in blood pressure, paroxysmal arrhythmias or induced or spontaneous episodes of myocardial ischaemia. These abnormalities are important but their timing cannot be predicted and much time and effort is wasted in trying to capture an “episode” with controlled monitoring. Important and even life threatening disorders can go undetected because they occur only infrequently and may never be recorded objectively. High risk patients such as those with end-stage ischaemic heart disease or end-stage myocardial failure often develop life threatening episodes of myocardial ischaemia or ventricular arrhythmia. These episodes, if reliably detected would lead to better targeting of potentially life saving but expensive therapies. With the emergence of miniaturised mechanical, electrical, biochemical and genetic sensors, there is likely to be a rapid expansion of biosensor development over the next ten years with corresponding reduction in size and cost. This will facilitate continuous wireless monitoring, initially of at-risk patients but eventually screening an increasing proportion of the population for abnormal conditions.

With the current advances in monitoring devices, several key technologies are essential to the future development of pervasive healthcare systems. They include:

- Biosensor design and MEMS integration
- Miniaturised power source and power scavenging
- Ultra-low power RF data paths
- Context awareness and multi-sensory data fusion
- Autonomic sensing, and secure, light-weight protocol

The purpose of Body Sensor Networks (BSN) is to provide an integrated hardware and software platform for facilitating the future development of pervasive monitoring systems.

1.1 Biosensor Design and MEMS Integration

Recent advances in biological, chemical, electrical and mechanical sensor technologies have led to a wide range of wearable and implantable sensors suitable for continuous monitoring. For instance, Khurana *et al.* proposed a chemical glucose sensor for diabetic monitoring (1). Ziaie and Najafi introduced an implantable blood pressure sensor cuff for tonometric blood pressure measurement (2). IMEC (Interuniversity Micro-Electronics Centre) has developed a Si-based DNA sensor that can directly detect hybridization without any fluorescent labelling (3). Lakard *et al.* presents miniaturised pH biosensors based on electrochemically modified electrodes (4). Grimes and Kouzoudis introduced the use of implantable magnetoelastic sensors for remote sensing of temperature, glucose etc (5). The reliability of biosensor is often relied on the interface between the sensor and tissue or blood, especially for implantable sensor, biocompatibility is the major issue to be considered in the sensor design. Sensor array was used by Kim *et al.* (6) to ensure the reliability of the sensors. Vadgama has recently introduced the use of polymeric barrier membranes for the enzyme-based electrochemical sensors (7).

Parallel advances in the MEMS (Micro-Electromechanical Systems) technology has facilitated the development of physiological sensors, such as the micro-needle array for drug delivery and glucose measurement (8) and the piezoresistive shear stress sensor (9). Context awareness sensors include 3D accelerometers and gyroscopes (10). In addition, technological advancement in photonics has enabled the realisation of unobtrusive optical biosensor, such as the optical glucose sensor (11).

1.2 Miniaturised Power Source and Power Scavenging

Power source is one of the key elements for pervasive sensing. It often dominates the size and lifetime of the sensors. Thus far, battery remains the main source of energy for sensor nodes. Typical Lithium based batteries can deliver 1400-3600J/cc, allowing sensor nodes to operate for an extended period of time (months to years depending on the duty cycles) (12). Hydrocarbon based fuel cells can provide about 6 times more power than lithium batteries, for example, methanol has an energy density of 17.6kJ/cc (13). With the advancement of micro fuel cell technology, fuel cell can replace batteries for future wearable devices (13). Recent research has also proposed the use of bio-fuel cells where glucose or dehydrogenase enzymes are shown to be able to provide power for implantable sensors (10,14).

In order to provide a constant energy supply, power scavenging is an actively pursued research topic. A number of power scavenging sources have currently been proposed, which include motion, vibration, air flow, temperature difference, ambient electromagnetic fields, light and infra-red radiation. For instance, Mitcheson *et al.* recently developed a vibration based generator designed for wearable/implantable devices, which is capable of delivering 2uJ/cycle (15). A thermal micro power generator with a size of $3x3x1.5cm^3$ has been developed by IMEC, which can convert thermal energy to 4uW power at 5^oC temperature difference on the thermopile (3).

1.2 Low Power Wireless Data Paths

Compared to other components, the wireless communication link is the most power demanding part of the BSN. Reducing the power consumption of the RF transceiver could significantly cut down the power consumption and prolong the lifetime of the sensor node. For wireless communications, the FCC (Federal Communications Commission) has currently allocated the frequency range of 402-405MHz for medical implant communication services (MICS), and the frequency ranges of 608-614MHz, 1395-1400MHz and 1427-1432MHz for medical telemetry (16). Thus far, extensive research has been conducted in the design of low power RF transceivers. For instance, Otis *et al.* proposed a 400uW receive and 1.6mW transmit transceiver for wireless sensor network applications (17). The use of ultra wide band for wearable sensors has also been proposed (18). The newly emerging ultra-wide band technology offers short-range wireless communication with a theoretical data rate up to 1Gbps but with low power consumptions (19).

1.3 Context Awareness and Multi-Sensory Data Fusion

Existing research has highlighted the importance of context aware sensing particularly for BSN due to the potential sources of error at sensor nodes and motion artefacts. In addition to analysing the physiological parameters of the patient, the context information is also required for understanding the physiological status under which the adverse events are triggered. A number of inferencing mechanisms have been proposed for context aware sensing applications. For example, Tapia *et al* proposed the use of Naïve Bayesian classifier for activity recognition (20). Kautz *et al.* introduced the use of hierarchical hidden semi-Markov models (HHSMMs) for tracking daily activities (21). Laerhoven and Cakmakci described an integrated approach with SOM and K nearest neighbour for classifying different activities (22). For arrhythmia detection, Lagerholm *et al.* proposed an integrated method for clustering QRS complexes by the use of self-organising maps (SOM) (23). Simelius *et al.* introduced a SOM based spatiotemporal analysis for detecting abnormal ventricular activation (24). Gao *et al.* proposed a neural network classifier based on a Bayesian framework for identifying arrhythmias (25). Traditional sensor fusion techniques mainly rely on the inferencing capability of the classifier. In this case, classifiers are designed to yield optimal results based on fusing all the sensor readings regardless of their relevance to the classification results. Thiemjarus *et al.* proposed a feature selection technique for identifying relevant features or sensors for determining the optimal setup of the sensors in terms of location and channel selection (26).

1.4 Automatic Sensing, and Secure, Light-weight Protocol

As patient information is wirelessly transmitted between sensors, security and reliability are paramount in the design of BSNs. Several protocol designs have been experimented for wearable medical device applications. For instance, a HTTP based protocol is proposed by Dokovsky *et al.* for transmitting sensor data to remote health care provider via the mobile phone network (27). A TinyOS based protocol with EEC (Elliptic Curve Cryptograpthy) key encryption has recently been used by Lorincz *et al.* for transmitting the physiological data between sensors (28). The newly formalised Zigbee protocol and IEEE 802.15.4 standard for wireless sensor networks have incorporated a security layer in the protocol design. Hardware encryption has been adopted in several commercially available IEEE802.15.4 compliant chipsets, such as the Chipcon CC2420 (29) and Ember EM2420 (30). It is expected that issues related to self-management, self-healing, and self-organisation based on light-weight network protocols will be the key research topics for BSN in future research.

2. PERVASIVE MONITORING

In parallel to the development of sensing and monitoring devices, several research platforms are emerging. One approach is to incorporate physiological sensors into the garment by linking sensors to a wearable processing device, such as the knitted bioclothes developed by the EU Project Wealthy (31). Similarly, the EU project, MyHeart aims to provide continuous monitoring of vital signs for cardiac patients. The concept of an intelligent biomedical cloth (IBC) is proposed where biosensors are embedded inside clothes for measuring physiological signals and to provide immediate diagnosis and trend analysis (32). Although embedding the sensors into the garment could provide a convenient wearable system for the patient, the design is not flexible for the addition or relocation of sensors. In addition, different sizes of clothes have to be designed for different persons, which can introduce a significant cost burden. An alternative approach is to use on body sensors such as the Human++ research programme at IMEC (3) and the EU funded project Healthy Aims. Liska *et al* proposed a Bluetooth based wearable ECG server integrated with a GPS (Global Positioning System) sensor, which can report the location of the patient when an emergency event is detected (33). Other systems include CardioNet (34) and MIThril for remote heart monitoring (35).

2.1 Body Sensor Networks

Thus far, most hardware platforms for pervasive healthcare applications are proprietary designed. The lack of interoperability and standards has prohibited a common approach towards the development of pervasive sensing applications. The BSN architecture from Imperial College was developed in response to the significant research activities in this area. The basic concept of BSN is illustrated in Fig.1 where wireless sensors are either worn by or implanted into the patient, and the sensor data is gathered by a local processing unit, such as a PDA before it is further processed or transmitted to the central monitoring server. With regard to the BSN concept, the hardware platform, BSN node, is designed and developed. Despite providing the wireless communication and local processing capability, the BSN is designed to ease the integration of different sensors, such as ECG, SpO2, and other context awareness sensors. In addition, by adopting the IEEE 802.15.4 standard, interoperability is assured between different sensor platforms.

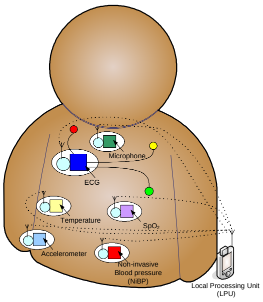


Fig. 1. The basic design of the body sensor network.

2.2 BSN Architecture

Fig. 2 illustrates the basic structure the BSN node. The BSN node uses the Texas Instrument (TI) MSP430 16-bit ultra low power RISC processor with 60KB+256B flash memory, 2KB RAM, 12-bit ADC and 6 analog channels (connecting up to 6 sensors). The wireless module has a throughput of 250kbps with a range over 50m. In addition, 512KB serial flash memory is incorporated in the BSN node for data storage or buffering. The BSN node runs TinyOS by U.C. Berkeley, which is a small, open source and energy efficient embedded operating system. It provides a set of modular software building blocks, of which designers could choose the components they require. The size of these files is typically as small as 200 bytes and thus the overall size is kept to a minimum. The operating system manages both the hardware and the wireless network—taking sensor measurements, making routing decisions, and controlling power dissipation. By using the ultra low power TI microcontroller, the BSN node requires only 0.01mA in active mode and 1.3mA when performing computation intensive calculation like a FFT. With a size of 26*mm*, the BSN node is ideal for developing wearable biosensors. In addition, the stackable design of the BSN node and the available interface channels ease the integration of different sensors with the BSN node. Together with TinyOS, the BSN node can significantly cut down the development cycle for pervasive sensing development.

Fig. 2. A pictorial illustration of the BSN node

2.3 UbiMon

The DTI funded project, UbiMon (Ubiquitous Monitoring Environment for Wearable and Implantable Sensors) project aims to provide a continuous and unobtrusive monitoring system for patient in order to capture transient but life threatening events. Based on the BSN design, the basic framework of the UbiMon is illustrated in Fig. 3. The system consists of five major components, namely the BSN nodes, the local processing unit (LPU), the central server (CS), the patient database (PD) and the workstation (WS).

With the current UbiMon structure, a number of wireless biosensors including 3-leads ECG, 2-leads ECG strip, and SpO2 sensors have been developed (Fig. 4a-c). To facilitate the incorporation of context information, context sensors including accelerometers, temperature and skin conductance sensors are also integrated to the BSN node. Furthermore, a compact flash BSN card is developed for PDAs, where sensor signals can be gathered, displayed and analysed by the PDA, as shown in Fig. 4d.

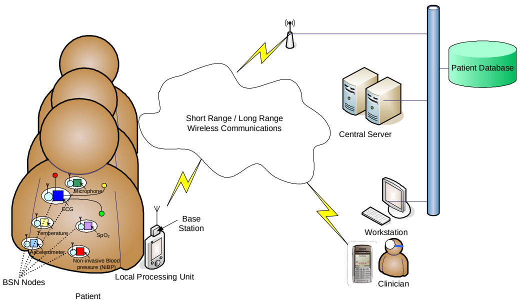
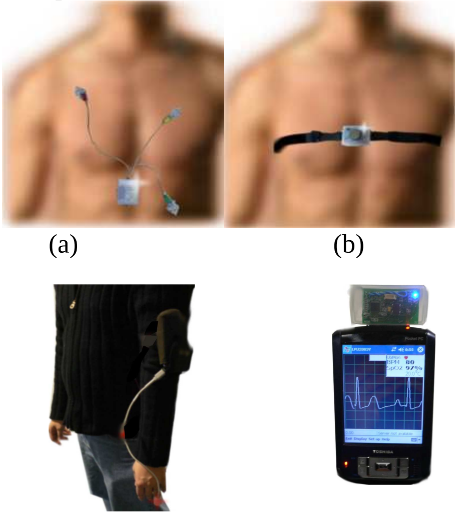


Fig. 3. A schematic illustration of the UbiMon system architecture

Apart from acting as the local processor, the PDA can also serve as the router between the BSN node and the central server, where all sensor data collected will be transmitted through a WiFi/GPRS network for long-term storage and trend analysis. A graphical user interface is developed at the WS for retrieving the sensor data from the database, as illustrated in Fig. 5. To assist patient management, subjects with the highest risk are listed at the top of the patient table, which can be interactively interrogated. In addition, the historical record of the sensor readings can also be playback for any specific episodes.


(a) (b)

(c) (d)

Fig. 4. (a) Wireless 3-leads ECG sensor, (b) ECG strap (center), (c) SpO2 sensor, and the PDA base station

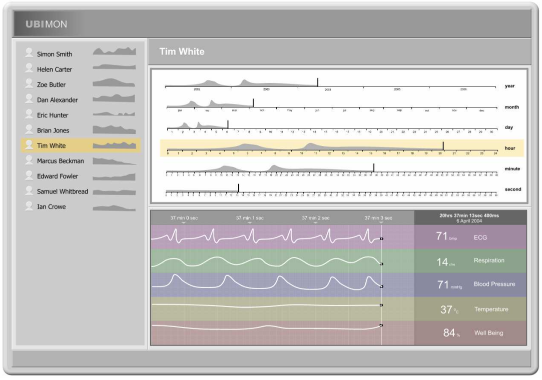


Fig. 5 Workstation and database GUI for UbiMon.

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