ABSTRACT

Long-term monitoring of mobility is beneficial in quantifying a person’s functional health status. An SMS-based (Short Message Service) telemonitoring system has been redeveloped to remotely monitor the long-term mobility trends of elderly people in their living environment. Mobility is measured by an accelerometer-based portable unit, which is worn by each monitored subject. Mobility level summaries are transmitted hourly, as SMS messages, directly from the redeveloped portable unit to a remote server for long-term analysis. Each subject’s mobility levels are monitored at the remote server using custom-designed mobility alert software and the appropriate medical personnel are alerted, by SMS, if deterioration in the subject’s mobility levels is detected. This paper describes the process used to calibrate accelerometers for the wearable element of this telemonitoring system.

KEY WORDS

Patient Monitoring, Telemedicine, Accelerometers, Elderly

1. Introduction

Rising healthcare costs and a decreasing care ratio (the ratio of the number of persons aged between 16 and 65 to those aged 65 and over) [1] are placing a strain on current healthcare services. Elderly patients, particularly those with chronic conditions, require continuous long-term monitoring in order to detect changes in their condition as early as possible. Changes in health can be detected by healthcare workers in a hospital; during daily home visits by a district nurse; or using telemonitoring. The first and second methods are costly (estimated at US$74 per day for home visits and US$820 per day to monitor a hospitalised subject [2]), labour intensive and may be subject to the “white-coat effect”. Long-term home telemonitoring allows elderly subjects to remain in their own home, which is their preferred setting and reassures the elderly person and their carer that their health status is being monitored. Telemonitoring is an accurate and relatively inexpensive (estimated at US$30 per day [2]) method, which produces clinically useful data for clinicians to base their medical decisions on.

The relationship between health status and mobility is well recognised [3]. A person’s mobility refers to the amount of time he/she is involved in dynamic activities, such as walking or running, as well as static activities, such as sitting, standing or lying. An ability to accurately monitor the real mobility levels of a person in their living environment would provide vital clinical data to the person’s healthcare providers, particularly if the person is elderly or suffering from a pathological condition, which are both associated with declines in physical activity levels [4].

Mobility can be remotely monitored by a smart home system, a wearable system, or a combined system. Smart homes systems monitor mobility indirectly using ambient sensors placed throughout the subject’s home. Ambient sensors are unobtrusive and have fewer design constraints than wearable sensors. However, they have little access to physiological measurements and they cannot monitor the subject outside of the home. Wearable systems measure mobility directly using sensors (typically accelerometers, or gyroscopes) carried on the person. These systems can be classified as data logging, data forwarding or data processing [5]. Data logging systems store data from the sensors in a data-logging device for offline analysis. Data logging systems can monitor mobility regardless of the subject’s location, but these systems will not detect the development of an alarming situation until the data is uploaded and analysed. Data forwarding systems transfer sensor data directly to a local data analysis station using wireless communication. However, the subject’s mobility data is lost if they are outside of the range of receiver. Data processing systems contain a processing element to analyse the sensor data in real-time. These systems consume more power than data logging or data forwarding systems but they can monitor the subject regardless of their location. However, many data processing systems require a local pc to upload their data to the remote server.
The ready-built, extensive GSM (Global System for Mobile communications) network has been increasingly used for the long-distance transfer of bio-signals and data in recent years [6, 7]. SMS messaging over the GSM network is a low-cost and reliable method of transferring data under 160 characters to any SMS or DECT (Digital Enhanced Cordless Telecommunications) enabled phone on any network in the world. Initially SMS messaging in telemedical applications was limited to notification messages from healthcare workers to patients [8]. Ren-Guey [9] then used SMS to send predefined alert messages to a carer, if a wearable alert button is pressed by the subject. However, this system is dependent on RF to transmit a signal to a local PC, which controls the SMS-sending modem. Al-Ali [10] uses SMS messaging to send bio-data (body temperature and blood pressure) to predefined carer numbers, if preset temperature or blood pressure thresholds are exceeded.

Figure 1 System Overview
The system described in this paper is a data processing system, which overcomes the location dependence of previous mobility monitoring systems by measuring the subject’s mobility using wearable sensors, and transmitting the mobility data directly from the wearable system to a server using SMS messaging and mobile telephony.

2. System Description

The system (Figure 1) described in this paper consists of a portable unit, worn by each monitored subject, and a central recording and monitoring server. Each portable unit acquires and analyses the accelerometer signals each second, and transmits hourly mobility summaries to the server. The mobility data is received, analysed, and stored on the server’s database. This database is automatically queried every day, and the appropriate medical personnel are informed if an alarming trend is observed in a patient’s mobility status. Communication between the portable unit and the server is via the GSM network using SMS messaging.

a) The Redeveloped Portable unit

The portable unit consists of a waist-mounted unit and two accelerometers – one mounted radially on the trunk and the other mounted radially on the thigh, as proposed by Veltink [11]. The analog output from the y-axis of the accelerometer is analysed to determine the subject’s posture. When a subject is standing, gravity exerts a force of –1g on both accelerometers, when the subject is sitting gravity exerts a force of –1g on the trunk accelerometer and no force on the thigh accelerometer, and when the subject is lying both accelerometers experience no acceleration due to gravity. For elderly subjects, dynamic data, which indicates walking and running, can be assumed to correspond to walking. Thresholds of ±60° to the vertical axis of the trunk and ±45° to the horizontal axis of the thigh were set to allow for variation within postures such as leaning (Figure 2). This simple configuration of accelerometers was adopted to measure the mobility status of elderly subjects in a clinical setting and has been confirmed by Culhane et al. [12] to deliver detection accuracy in excess of 95%.

Figure 2 Posture detection using accelerometers
The accelerometer used in this study was the Analog Devices ADXL203\(^1\) biaxial integrated accelerometer. This device is a small (5mm X 5mm X 2mm), low-cost ($10.20), low power (<0.6 mA), dual-axis accelerometer with a range of ±1.7g, and has a typical sensitivity of 1V per g.

The first revision of the portable unit, described by Ni Scanaill [13], was based on the most suitable GSM device available at the time - the Falcon A2D-1 GSM terminal. Evaluation of this portable unit showed the system having an overall average mobility detection accuracy of over

\(^1\) Analog Devices BV, Limerick, Ireland
www.analog.com
90%. The system was shown to accurately detect mobility in both a controlled environment (healthy subjects on a university campus) for 10 hours and in an uncontrolled field environment (elderly subject in their own home) over a period of 2.5 hours. During a long-term 20-hour field evaluation, the system performed its essential function of transmitting mobility data to a remote server using SMS messaging and the server recorded this data on an hourly basis in a subject specific database. During the evaluations, the system was demonstrated to be portable and it did not interfere with, or impede the subject’s normal daily activities. However, this unit is too bulky and consumes too much power to be suitable for long-term monitoring of frail elderly subjects.

A new portable unit was developed by replacing the bulkiest element of the portable unit, the GSM terminal, was replaced with a smaller, lighter and less demanding Telit GM862-GPRS module (Figure 3). The Telit module uses a similar AT command set to the Falcom terminal, and can also be controlled using standard UART communication.

New battery circuitry was designed to power the Telit module, microcontroller, and accelerometers. The new modem and batteries reduced the volume of the portable system by 67% and the mass of the portable system by 65%. The portable unit, which once required two boxes (one to house the circuitry and a second to house the battery pack), now fits into the box, which was previously occupied by the battery pack (Figure 4). This box has been fitted with a belt-clip, so it is no longer necessary to use a bag to carry the system. The reduced mass of the overall system, due mainly to the reduced battery mass makes it more practical for frail elderly subjects to wear it throughout the day.

Figure 3 Falcom A2D-1 (left) and Telit GM862 (right)

b) The Remote Server

The server was implemented using a PC interfaced to a Falcom A2D-1 GSM modem. A C++ server application was developed to control the receipt, analysis, storage and presentation of mobility data. It consists of four elements – a SMS handling element, a database-handling element, a query-handling element and a GUI (Graphical User Interface). The SMS handling element communicates with the serial port using functions from the COMM-DRV/LIB™ Professional Serial Communication Libraries & DLLs and Hayes AT commands, sent via these COMM-DRV functions, control the server modem. The database-handling element controls data entry and retrieval from the database using an ODBC connection and SQL statements. The query-handling element queries each subject’s data to find alarming trends in the subject’s mobility. The application’s MFC (Microsoft Foundation Classes) GUI provides a user-friendly method for the user to enter, change, and view each patient’s data records.

The modem-handling element logs the modem onto the GSM network and continually polls the modem for new messages. The telephone number, date and message strings are extracted from each new message received and the message is then deleted from the modems SIM card. The SMS message and telephone number of the SMS message are then tested for validity by the database-handling element. The telephone number of the message sender is compared to the database list to find the patient; if the number is not found in the database the message is from an invalid source and is discarded. A message string from a valid source is dissected and tested for the presence of the “PATIENTSMS” string at the beginning of the message to ensure message validity. For a valid mobility message, the values following it, in 4-character groups, are the mobility values of interest, namely lying, sitting, standing, and walking. The mobility values for the

2 Willies Computer Software Co, Texas, USA
www.wcscnet.com
patient in question are extracted, converted into percentages and entered into the “PatientMobilityToday” table in the database for that patient for short, medium and long-term mobility trend analysis. A relational database (Microsoft Access 2000) was chosen for this system, as it is flexible and easily extendible. Three related tables were created containing the patient’s personal data, the patient’s average mobility, and the patient’s mobility for that day.

Carers can view mobility trend data by returning to the server and using the GUI element of the server application, or by using the password-protected web interface to the database to remotely view the mobility data on any internet-capable PC or PDA. Carers can also monitor variation in their patient’s mobility trends using the short, medium and long-term graphs and decide if intervention in the form of a personal visit is required.

Worrying trends can also be detected by the automated query-handling element of the server application, which runs on the server each evening. Appropriate mobility thresholds are set for each patient in the database and the automated query compares the mobility levels of each patient to these thresholds. If a patient’s mobility levels are found to be below the pre-assigned thresholds the server software will alert the appropriate carer by querying the database for that subject’s name and address, formatting a string containing this information, and forwarding it, over the GSM network, to the carer as an SMS message, who may, on receipt of an alert, review the patient’s trend data to inform themselves of the extent of the patient’s decline before making a medical decision.

3. Testing
The output from an accelerometer, at a given angle, is dependent on both the input voltage and the individual accelerometer part. This is not problematic in a data logging system, in which the thresholds can be modified after recording the data. However, these inaccuracies are problematic in a data processing system, in which the thresholds must be predefined before using the system. Therefore, each accelerometer must be calibrated in order to determine their output at the threshold angles.

The accelerometer 0g offset and sensitivity of the ADXL203 accelerometer are related to the input voltage applied. The 5V regulator, used to power the accelerometers in the redeveloped portable unit is specified to provide 5V with an accuracy of ± 0.2V. Although this range is small in voltage terms, in hex the difference can be as large enough to necessitate the calibration of each accelerometer to each individual regulator. The output from an accelerometer when rotating through 360º is sinusoidal rather than linear.

Therefore, the rate of change of the accelerometer output is greater when its sensitive axis is perpendicular to gravity than when its sensitive axis is parallel to gravity. The simplest method to calibrate the angle of an accelerometer is to measure the accelerometer outputs at -1g and +1g, and then to use the following formula to calculate the outputs at each angle:

$$\text{output} = \text{amplitude} \times \sin \theta$$

The validity of this method was bench tested by fixing the accelerometers to a rotating platform and rotating the accelerometers in 10° increments from -90° to +90°. The angle of the rotating platform was set using an angle meter. The portable system was programmed to sample the accelerometers at 20Hz (10Hz each), which is the sampling rate used by the portable unit for mobility monitoring. The accelerometer outputs were printed directly to the serial output of the portable system, which in turn was connected to the serial port of a pc. The accelerometers were sampled for a total of 5 minutes at each 10° increment and the resulting accelerometer data were saved to a *.log file using Fog Software Serial-File application. The *.log files were analysed using Microsoft Excel and the standard deviation, average, max, min and mode of each output file were calculated. The average, max, min and mode of each output file were combined in a summary file. These variables, plotted in Figure 5, illustrate the sinusoidal relationship between accelerometer angle and accelerometer output.

![Figure 5 Sinusoidal graphs of accelerometer outputs](image)

The next step in angle calibration was to measure the accelerometer output when worn by a subject sitting at various angles. Each subject donned the redeveloped portable unit and their sitting/lying angle was set using a lounger, with adjustable back and thigh angles (Figure 6). A total of 6 subjects, 3 male and 3 female took part in the trial. The accelerometer outputs from each subject, at each angle setting, will be compared for differences between individual subjects. The subjects were asked to sit at each angle several times to test the reproducibility of angle measurement.

The second phase of the trial tested the repeatability of sensor placement. Each subject donned the portable system himself or herself on three occasions. The accelerometer outputs were recorded as they sat, leaned, and lay at repeatable angles on each occasion. These outputs were compared to determine the percentage error due to sensor placement.

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3 Microsoft Corporation, Redmond, Washington, USA
www.microsoft.com
Figure 6 Accelerometer calibration using an adjustable lounger.

4. Results
The calculated and measured accelerometer outputs proved to be very similar (Table 1). The largest deviation between the calculated and measured values occurs at 20º, where the measured value is equivalent to -20.79º and the calculated value is equivalent to 20º, a difference of only 0.79º.

<table>
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<tr>
<th>Angle (º)</th>
<th>Measured (Voltage in Hex)</th>
<th>Calculated (Voltage in Hex)</th>
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<tr>
<td>90</td>
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<td>1265.16</td>
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<tr>
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</tr>
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</table>

Table 1 Calculated and Measured Accelerometer Outputs
Preliminary results from the second phase of testing show good repeatability and reproducibility of angle data for each subject, although there are variations between the subjects.

5. Proposed Work
The angle variation between subjects will be studied in a further trial. The optimum posture detection thresholds will be calculated based on the data obtained in the first two phases of the trial. These thresholds will be applied in the posture detection software running on the portable unit. The posture detection of this reprogrammed software will be tested in campus trials to determine the system accuracy with healthy subjects. The posture detection capabilities of the system will then be tested with elderly subjects in a clinical environment.

6. Discussions and Conclusion
A wearable remote mobility monitoring system based on SMS messaging, GSM telephony and accelerometry has been developed. Although several accelerometer-based mobility-monitoring systems have been demonstrated in the past [14-17], this system is innovative in several regards:
First, the use of SMS messages to transmit mobility data directly from the wearable system to the server. Data transmission using SMS messaging, over the vast GSM network (208 countries worldwide), ensures the subject’s mobility levels are monitored whenever they are in an area with mobile phone coverage. Data transmission using SMS is a cost-effective, scalable solution, which leverages technology already developed by the mobile phone networks. Previous SMS-based telemonitoring applications [9, 10] depended on a RF link to a PC in order to control the GSM modem. Therefore the GSM modem cannot be used when the subject was out of RF range of the PC. Incorporating the GSM modem into the portable unit ensures that the modem is always available for data transmission.
Second, the automated features of the system promote usage by both elderly people and healthcare providers. Elderly people have been shown to reject any system, which requires a lot of user interaction [18]. For this reason data acquisition, processing and transmission of mobility data are fully automated to eliminate user interaction in manually uploading data to a local PC or to a remote server; this feature should improve patient compliance. The only user interaction required with this system is the daily donning and doffing the system and switching on the battery pack.
The server is also automated, to promote compliance by busy healthcare providers. Once the server software is running, it can automatically retrieve messages from the modem, analyse them and store them in the database without any user interaction. Automated alert queries running on the central monitoring server notify the healthcare worker if alarming trends are detected in a subject’s short, medium or long-term mobility data.
Third, this system demonstrates an accurate, yet simple method for real-time detection of mobility and does not have the large memory requirements of a data-logging system, nor does it have the range limitations of a data-forwarding system. The system does have some limitations; the system must be donned and doffed each day, a task which could be simplified by incorporating the sensors into a piece of clothing. The power consumption of the system is affected by the presence of a GSM modem (17mA when the modem is idle and 190mA when
sending an SMS) with a consequential effect on battery lifetime. However, the two lightweight li-ion batteries (7.2V, 1300mAh) in the portable unit allow monitoring for up to 19 consecutive hours, which should be sufficient duration to judge a subject’s mobility trends, and detect any worrying deterioration in mobility.

A low-cost, functioning, remote monitoring system has been developed which can allow an elderly person retain their independent lifestyle while still being monitored. The system provides long-term data for clinicians to base their clinical decisions on. It has the potential to reduce the financial burden on healthcare services by facilitating more efficient use of healthcare resources.

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References