Cost-effective Design of Real-time Home Healthcare Telemonitoring

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Keywords: Cost-effectiveness, Healthcare, Telemonitoring, Vital Sign Monitoring, Fall Detection, Movement Pattern Monitoring, Smart Home, Internet of Things, Mobile Cloud Computing.

Abstract: The importance of telehealthcare for elderly and out-patients has been widely recognized. However, the adoption rate of home healthcare telemonitoring remains low due to limited evidence for cost-effectiveness. Our core objective of this work is the cost-effective design of a real-time home healthcare telemonitoring system based on mobile cloud computing. A second objective is to develop a simulation environment for evaluating the cost-effectiveness of a telemonitoring system and exploring technology choices. We are at an early stage, yet the results so far have been encouraging. Whilst we may not be able to deliver a complete solution, the methodological contribution of test environment plus simulation models will enable us to put the evaluation of telehealth solutions prior to moving to full-scale trials on a more scientific basis.

1 INTRODUCTION

The rise in both ageing and chronic disease populations has become a global issue which calls for a top policy priority to provide proper access to quality healthcare. Though information and communications technologies (ICTs) have been used in almost all aspects of our life, there remains a considerable question of low adoption rate of remote healthcare technologies. One of the main reasons, as indicated by a number of studies (McLean, Prott and Sheikh, 2011; Limburg et al., 2011), is a lack of robust evidence for cost-effectiveness.

To address this issue, we set up as our core objective the cost-effective design of a real-time home healthcare telemonitoring system based on mobile cloud computing. Our hypothesis is that the increasing availability of commodity sensor technology and computation resource can dramatically reduce the infrastructure costs of telemonitoring. In addition, the usability of the technology is making significant advances - especially in terms of minimising intrusion on the patients' lifestyle (Liang and Krause, 2013).

Our second objective is to develop a simulation environment in order for us to produce robust evidence for the cost-effectiveness of a telemonitoring system so as to explore technology choices prior to moving to full-scale trials. Accordingly, a framework based on data from simulated trials and literature review for conducting comparative cost-effectiveness analysis is also proposed. Here, home healthcare telemonitoring is defined as "the use of ICTs to monitor the vital signs and activities of in-home patients or elderly remotely."

The remainder of this paper is organised as follows. In Section 2, we briefly introduce the development trends in several related areas, such as telehealthcare, Smart Home and mobile cloud computing based on literature review. In Section 3, we present our design and experimental work for the proposed system. Finally, Section 4 provides our concluding remarks and future work.

2 LITERATURE REVIEW AND RELATED WORK

To better understand the development of remote healthcare, as well as the implications of recent ICT advances, such as sensor technologies, smart home, and mobile cloud computing, we have conducted a broad review of literature in related fields.

2.1 Telehealthcare

The concept of telehealthcare (i.e. the use of ICTs to provide healthcare remotely) has been explored for more than thirty years, as evidenced by the

Liang P. and Krause P..
Cost-effective Design of Real-time Home Healthcare Telemonitoring.
DOI: 10.5220/0004723800050015
In *Proceedings of the International Conference on Health Informatics* (HEALTHINF-2014), pages 5-15
ISBN: 978-989-758-010-9

emergence of nurse call centres in the 1970s in the UK. As mentioned in Section 1, in recent years, the problem of ageing and increasing number of people with chronic diseases have further underpinned the importance of telehealthcare. Therefore, a great number of studies on remote home care have emerged. However, the problem of lacking robust evidence for cost-effectiveness of related solutions remains.

A review (Koch, 2006) of the existing scientific literature on home telehealth during 1990-2003 classified 578 articles from the Medline database as being relevant to the targeted research field of home telehealth. Two of the conclusions drawn by this review were that the impact on those designs for special user groups, such as elderly, needs to be further explored, and that in general, evaluation studies are rare and further research is critical to determine the impacts, benefits and limitations of potential solutions.

Another systematic review (Barlow et al., 2007) identified summaries of 8,666 studies available as of January 2006 in 17 electronic databases, for example, the Medline and WTO library. Of those studies, 98 randomised trials and observational studies were included in the review. The key findings included that most studies focused on people with diabetes (31%) and heart failure (29%), and that cost-effectiveness of these interventions was less certain. In addition, there was insufficient evidence of the effects of home safety and security alert systems.

Then a systematic review of economic evaluations (Bergmo, 2010) found only 33 articles that measured both costs and non-resource consequences of using telemedicine in direct patient care. However, the review regarded this as a considerable increase. It concluded that the effectiveness measures were more consistent and well reported than the costings, and that most studies lacked information about perspective and costing method.

2.1.1 Cost-effectiveness Analysis

The increasing demand for better healthcare is manifested in the need to provide better evidence for informed decision making through economic evaluation. In this context, Evidence-based Medicine (EBM), Health Technology Assessment (HTA) and Comparative Effectiveness Research (CER) have been used respectively in many organisations to evaluate the benefits and harms of alternative treatments, technologies or healthcare deliveries. Among all techniques of economic evaluations in healthcare, Cost-effectiveness Analysis (CEA) is widely adopted.

The National Institute for Health and Clinical Excellence (NICE) in the UK (2013) defines cost effectiveness analysis as: “an economic study design in which consequences of different interventions are measured using a single outcome, usually in ‘natural’ unit (for example, life-years gained, deaths avoided, heart attacks avoided or cases detected). Alternative interventions are then compared in terms of cost per unit of effectiveness.”

To conduct cost effectiveness analysis, Phillips (2009) and Muenning (2008) suggested that three types of costs need to be considered:

- Direct costs: such as drugs, staff time, equipment, transport of patients;
- Indirect (or Productivity) costs: production losses, other uses of time; and
- Intangibles: pain, suffering, adverse effects.

The effects of an intervention generally refer to the changes in patients’ health status. Since there is no direct way to measure health status, a cost-effectiveness analysis instead examines patients’ quantity and quality of life with a given health status (Muenning, 2008). Figure 1 represents the concept that there are changes in the health status, associated costs and resulting quality of life and life expectancy of an observed group of patients having received an intervention for a period of time

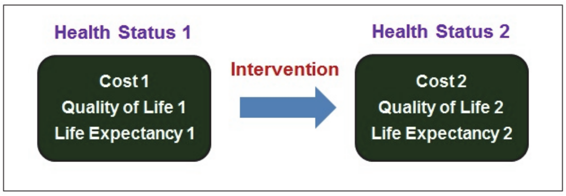

Figure 1: Components of a Cost-effectiveness Analysis, after (Muenning, 2008).

For independent interventions, the cost-effectiveness ratio (CER) is calculated to estimate the effects of different interventions by dividing the costs (C) of each intervention by its health effects (E) produced, e.g. life-years gained (LYG) or quality adjusted life years (QALYs):

$$\text{CER} = \text{C} / \text{E} \tag{1}$$

For mutually exclusive interventions, the incremental cost-effectiveness ratio (ICER) is calculated by dividing the difference in costs (ΔC) by the difference in health effects (ΔE) between two interventions:

$$\text{ICER} = \Delta\text{C} / \Delta\text{E} \tag{2}$$

2.1.2 The Whole System Demonstrator (WSD) Cluster Randomised Trial

In order to better evaluate telecare and telehealth technologies and their implications for elderly and people in independent living, the Department of Health in England (2011) launched the Whole System Demonstrator (WSD) programme in May 2008. Three sites, Kent, Cornwall and Newham, were selected to be part of a cluster randomised controlled trial. With 238 General Practitioners (GPs) and 6,191 patients with diabetes, chronic obstructive pulmonary disease (COPD), and coronary heart disease (CHD), it was believed that this trial is the world's largest randomised controlled trial of telecare and telehealth.

Under this trial, each intervention participant was given a home unit together with a pendant alarm and up to 27 peripheral devices for functional monitoring (such as the home unit and bed and chair occupancy sensors), security monitoring (such as infrared movement sensors and property exit sensors) and standalone devices (not connected to a monitoring centre, such as big button phones) (Steventon et al., 2013).

With regard to the key findings of this trial, the Department of Health in England (2011) announced that if used correctly telehealth can deliver a 15% reduction in Accident and Emergency (A&E) visits, a 20% reduction in emergency admissions, a 14% reduction in elective admissions, a 14% reduction in bed days, and a 45% reduction in mortality rates. However, several in-depth studies on the effect and cost-effectiveness of this trial reached some unfavourable conclusions, as in the following:

- Steventon et al., (2012) concluded that, though both hospital admissions and mortality for intervention patients were lower, there were no significant differences between the intervention group and the control group both in the number of elective admissions, outpatient attendance, and emergency visits and in notional hospital costs to commissioners of care.
- Henderson et al., (2013) found that the QALY gained by patients using telehealth in addition to usual care was similar to that by patients receiving usual care only, and that total costs in relation to telehealth were also higher. As such, this study concluded that telehealth does not seem to be a cost effective addition to standard support and treatment.
- Steventon et al., (2013) concluded that telecare did not significantly reduce the use of health and social care services.

Another study (Sanders et al., 2012) identified that concerns about both competency to operate equipment and threats to identity, independence and self-care (which might be undermined, among others, by not getting outside, but doing monitoring indoors even on holidays) are two of the main barriers to adoption of telehealth and telecare interventions within this trial.

Based on the abovementioned findings, we consider that the WSD trial could serve as an important reference for conducting cost comparison, selecting inexpensive technologies, devising proper service models and designing workable system architecture for the proposed home healthcare telemonitoring system.

2.2 Smart Home and Internet of Things

The concept of the so-called "smart home" or "digital home" has been proposed for more than a decade, aiming to transform our home environment into an intelligence-embedded living space. This paper uses these two terms alternately. According to Elderly Accommodation Counsel (2003), the UK's Department of Trade and Industry's "Smart Homes Project" defined smart home as "A dwelling incorporating a communications network that connects the key electrical appliances and services, and allows them to be remotely controlled, monitored or accessed."

There were several industrial initiatives for smart home driven mainly by manufacturers and network providers. For instance, the Open Service Gateway Initiative (OSGi) Alliance founded in 1999 focuses on open specifications for remote management and the delivery of services into the home. At almost the same time, the Konnex Association was formed in 1999 to promote an open standard, called KNX, for home and building control. Other similar effort included the establishment of Universal Plug & Play (UPnP) Forum in 1999 and the Digital Living Network Alliance (DLNA, originally named "Digital Home Working Group") in 2003.

Since their inception, these industrial initiatives have gradually expanded and gained wider support across different industrial sectors and players. For example, today PS2, XBOX 360 and personal computers with MS Windows 7 installed all support DLNA standards, and both OSGi and DLNA specifications support UPnP standards. However, on the service side, the market has only developed to a very limited extent.

With regard to smart home monitoring systems, Gaddam, Mukhopadhyay and Sen Gupta (2011) stated that when more sensors are added to a smart home system, the system becomes complicated to handle and the maintenance becomes a challenge. In our opinion, this is also quite true to home healthcare telemonitoring, as remote home healthcare is generally considered as a subcategory of smart home (Wu et al., 2009).

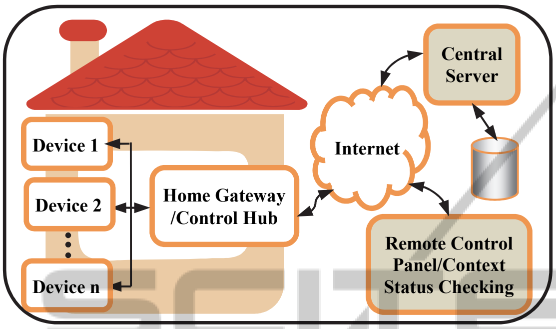

Figure 2: The Concept Diagram of a Typical Smart Home System.

Generally, a home gateway or a control hub (see Figure 2) interconnects one or more home networks and the Internet/access network (sometimes a cable modem or router is also needed), and controls other in-home devices and sensors (den Hartog, et al. 2004; Wei et al., 2010). For a commercialised smart home service package, the central server, i.e. one or a group of computers, is usually located at the service provider's premise. However, in other cases it is common to see that the proposed system architectures require one or multiple servers (or called controllers) to be set up within the smart home environment, one for each platform that is being used by a controlled device (Zimmermann1 and Vanderheiden, 2007). From our viewpoint, this kind of design would increase the complexity of system installation and maintenance.

One important evolution of recent ICTs, which has great implications for the development of smart home, as well as home healthcare telemonitoring, is the emergence of the Internet of Things (or IOTs). The International Telecommunication Union (ITU) (2005) described the IOTs as a new form of communication between people and things, and between things themselves, which "connects the world's objects in both a sensory and an intelligent manner."

The basic architecture of the IOTs consists of three layers: application layer, network layer and sensor layer (Kang et al., 2011), which in our opinion can be naturally fitted into the concept framework of a smart home system as depicted previously in Figure 2.

According to the Cluster of European Research Projects on the Internet of Things (CERP-IoT), a large number of application domains in the field of IoTs have been identified (Sundmaeker et al., 2010). We believe that among others, Intelligent Buildings, Healthcare (monitoring of parameters, positioning, real time location systems), Independent Living (wellness, mobility), and Environment Monitoring, are all applicable to supporting our envisioned smart home, as well as home healthcare telemonitoring.

A 2011 study (McCullagh and Augusto, 2011) investigating the potential of IoTs to monitor health and wellness concluded that the underlying technology is available but needs to be turned into a solution which can become pervasive in society. This is the gap that this research intends to fill by using low-cost, off-the-shelf technologies to build up evidence for a solid solution.

2.3 Sensor Technologies

As mentioned in Section 2.1, sensors form an indispensable component of a smart home system, as well as a healthcare telemonitoring system. In general, a sensor is capable of detecting three but intrinsically related categories of events (Faludi, 2010):

- Direct or proximal phenomena: events that directly trigger the sensor device;
- Indirect or distal phenomena: remote causes of the local events actually triggering the sensor; and
- Context and subtext: the situation surrounding an event.

However, contextual information inferred from both direct and indirect phenomena might still involve some degree of uncertainty. This demonstrates the importance of a well-designed event reasoning algorithm that can increase the accuracy of context inference based on a limited set of monitored data.

Today there are a great variety of electronic sensors available in the marketplace. In the field of telehealthcare, there are also increasing focuses on the development of the so-called Body Sensor Networks (BSNs) for on-body applications. For the purpose of our cost-effective design of home healthcare telemonitoring, this research pays special attention to existing inexpensive, portable and easy-to-use sensor technologies/platforms.

2.3.1 ZigBee

ZigBee is a standards-based low-power wireless technology mainly operating in the 2.4GHz radio frequency band. It is based on the IEEE 802.15.4 standard with add-on network and security layers and an application framework. The ZigBee Alliance was established in 2002 to develop relevant specifications and to promote ZigBee standards adoption. Today, the ZigBee Alliance has over six-hundred certified products, ranging from home appliances, energy efficiency apparatuses, networking devices, to health and fitness sensors. ZigBee Health Care was introduced to provide an industry-wide standard for exchanging data between a variety of medical and non-medical devices (ZigBee Alliance, 2009).

Based on different topologies, such as pair, star and mesh, a ZigBee sensor network consists of one coordinator node and at least one router or one end-device node (Faludi, 2010). In a ZigBee network, each node can communicate with all the others by way of its nearest neighbour so that only small amount of power is needed for radio transmission. In addition, with the embedded capability to perform self-healing, a ZigBee mesh network can reconfigure itself and route around a problem area when some nodes are failed or removed. Other important features of Zigbee 2012 specifications (ZigBee Alliance, 2012) include data security based on Advanced Encryption Standard (AES), low-power consumption for better battery life, and low cost in comparison with other wireless technologies.

At the time of this writing, there are only a few kinds of sensors available in the health and fitness sub-category. Besides, ZigBee's limited programming capacity to perform software logic/data processing suggests that all raw data needs to be dealt with by other layers in a smart home or IoT system. This would result in a greater amount of data traffic and lower data reliability.

2.3.2 Arduino

Arduino is an open-source microcontroller platform for physical computing. It was originally designed in 2005 to provide students with an inexpensive microcontroller to drive their robotic projects. To date, it has evolved into a popular tool kit for prototyping and do-it-yourself work.

By attaching different combinations of various sensors and actuators to a programmable microcontroller board, many different tasks, such as environmental (e.g. temperature and humidity) monitoring and home automation (e.g. door/window opening), can be performed in a way that is based on the user-uploaded software programme. There are also a number of different communications modules, such as serial port (e.g. USB), Wi-Fi, Bluetooth, and web server, available for use to transmit the programmed outputs, such as the status of the board and/or the monitored data, to other devices or a web client.

According to Arduino website (2013), the main advantages offered by Arduino include: low-cost as compared with other microcontroller platforms, cross-platform (among MS Windows, OS X, and Linux), simple programming environment, and open source with extensible software and hardware. From our point of view, the capabilities both to conduct on-board data processing by the microcontroller to provide more reliable and meaningful monitored data, and to interconnect and interoperate with a variety of devices, such as smartphone and ZigBee, are two other important features that enable Arduino to provide more flexible sensory solutions.

2.4 Mobile Cloud Computing and Home Healthcare

Along with the recent prevalence of smart mobile devices in our daily life, hundreds of thousands of available mobile applications, or the so-called "Apps" are targeting a great diversity of consumer segments. According to Sarasohn-Kahn (2010), "as of February 2010, there were 5,805 health, medical, and fitness applications in the Apple AppStore. Of these, 73% were intended for use by consumer or patient end-users, while 27% were targeted to health care professionals." There were also Apps using available sensors, including accelerometers, infrared photo-detectors and glucometers, for home measuring. These figures and developments represent both challenges and opportunities to this research.

Meanwhile, both mobile computing and mobile cloud computing have recently gained increasing attention from ICT researchers and developers. According to Huang (2011), mobile computing research refers to the study on how mobile devices learn their own status and surrounding contexts to better support mobile applications.

Regarding mobile cloud computing, there are two different viewpoints (Qureshi et al., 2011). One refers mobile cloud computing as making use of cloud resources, such as computing power and storage, to help perform tasks or store data from mobile devices, which generally have limited computing capacity and data storage. The other recommends that with mobile cloud computing, both data processing and storing be done by the mobile device. For the purpose of this research, we take both views to give a broader definition of mobile cloud computing. With this, it is apparent that by adopting mobile cloud computing, an application can be further empowered by mobility together with the main advantages, such as on-demand self-service, resource pooling, rapid elasticity, and pay-per-use, derived from cloud computing.

Some sophisticated system architectures have been proposed so that several mobile devices can work together to perform a particular task or each device can provide its remaining resources for other devices. For example, Hyrax (Marinelli, 2009), a mobile cloud computing platform, was proposed based on Hadoop to provide data sharing and distributed data processing among a group of networked mobile phones. In its implementation, Hyrax used two conventional computers to perform Hadoop-related NameNode and JobTracker processes and cluster initialisation. Clearly, such complex system architecture would not fit into our requirements.

Cheng and Zhuang (2010) proposed a Bluetooth-enabled, in-home patient monitoring system for early detection of Alzheimer's disease. The proposed system required every room in the house to be equipped with a Bluetooth access point (AP), and all APs needed to be connected to a local database (i.e. a laptop). A Bluetooth-enabled pocket PC was carried by the target person in the house and tried to find an AP with strongest signal to which to connect. If the target entered another room, the pocket PC would try to connect to another AP. By such an approach, the movement pattern of the target could be identified and stored in the local database. The data could then be transmitted to a remote medical practitioner for diagnosis, or be analysed by an assumed decision engine to see if the target had any early signs of Alzheimer's disease. From our perspective, this proposal was not very practical, as both the physical locations of each AP and the layout of the house would seriously affect the detectable Bluetooth signal strength and in some cases would even cause failures in establishing Bluetooth connection. Accordingly, the deployment of Bluetooth APs could be very complex.

MoCAsH (Hoang and Chen, 2010) was a proposed mobile cloud for assistive Healthcare. Its system architecture included (i) sensors and mobile agents, (ii) a context-aware middleware, (iii) a collaborative cloud, and (ix) a cloud portal. The cloud portal allowed authorized users to access offered services, including checking sensor status, updating context-aware rules, and accessing back-end cloud platform management centre. It also proposed a P2P federated cloud model to schedule distributed clouds and their resources, and to enhance data security. In our view, this project could have served as a good reference for our prototyping and design. However, it put its main focus on how to integrate mobile devices into a federated cloud architecture without addressing how to implement non-built-in sensors' deployment and patient monitoring.

Wang et al. (2008), as well as Yang and Zhao (2011), proposed to place a tri-axial accelerometer at the head level with a pre-defined position and angle to detect human falls. In our opinion, this kind of physical setting is not only impractical in home patient/elderly monitoring, but also intrusive to the monitored people. Viet, Lee and Choi (2012) used an Android smart phone which has a built-in accelerometer and an orientation sensor to perform human fall detection. It was concluded that the proposed system reached 85% accuracy in 260 trials. However, since the implementation was based on a standalone mobile phone, the proposed system did not possess any remote monitoring capability.

3 RESEARCH DESIGN AND CURRENT WORK

3.1 Requirements and Considerations

Based on the preceding technology reviews we have identified the following set of requirements for a cost effective telemonitoring system.

3.1.1 Functional Requirements

- Vital sign monitoring: This refers to the on-demand monitoring of patients' vital sign parameters, such as body temperature, heartbeat rate, oxygen in blood, blood pressure, blood glucose, cardiogram, and sweat level.
- Safety monitoring: The main function will be real-time human fall detection with alerts being sent automatically to designated caregivers and/or healthcare professionals via a healthcare dashboard, SMS and video phone.
- Emergency call-for-help tool kits: This refers to the provision of a portable alarm; once pressed by a patient, it would send out an alert to designated caregivers and healthcare professionals via the healthcare dashboard with configurable, automated SMS and video phone call out and call in functions.

- Activity monitoring: This includes movement pattern monitoring, bed and chair occupancy sensing and property exit sensing for social care purposes.
- Service portal/management console and healthcare dashboard: The service portal/management console allows authenticated in-home patients, as well as remote caregivers and healthcare professionals to control and manage the sensors. It also allows them to set their preferences and care plans for healthcare monitoring, as well as to manage and access context/health data via a healthcare dashboard.
- Authenticated database management and access: This refers to a database system that provides authenticated users with remote management and access to the large volume of monitored data.

3.1.2 Basic Considerations

The following considerations with criteria for evaluation need to be addressed throughout the whole system development life cycle to ensure that the research objective can be successfully fulfilled.

- Low-cost: There should be no significant amount of capital expenditures (Capex) and operational expenditures (Opex) on system setup and operations.
- Easy-to-deploy-and-use: In general, the end-users, especially those living independently, should be able to set up and operate the system.
- Less intrusive: Generally, the monitoring should not hinder patients' normal daily routine and mobility.
- Robust enough: The system should embrace fault-tolerant and resilient design to maximise service availability. When the Internet is not available or the cloud side is unreachable, the application on the mobile device as well as the monitoring task should be able to continuously function properly.
- Security and data privacy: The system should employ proper access control, user authentication, data encryption, and secured data transmission to enhance data privacy and security.
- No vendor lock-in: The system design should avoid or at least minimise the impact of vendor lock-in issue by taking the portability of each monitored patient's data into account.
- Good performance and elasticity: The system performance and elasticity need to be well managed to provide streamlined user experience and service provision.

3.2 System Design

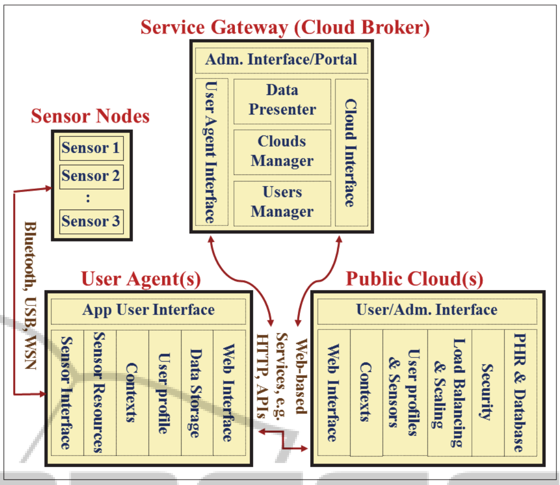

Figure 3: High-level System Architecture.

As shown in Figure 3, the proposed system architecture for the home healthcare telemonitoring system consists of four main modules, i.e. Sensor Nodes, User Agent(s), Service Gateway (Cloud Broker) and Public Cloud(s). The main functionality of each module is illustrated below:

- The User Agent(s) Module: Its main functions include: (i) a user interface for users to control and manage the sensors, to set their preferences and care plans for healthcare monitoring and to manage context and health data; (ii) an intelligent data aggregator that connects with a variety of sensors, collects real-time sensor data through high-level sensor APIs and transmits it to cloud storage, and performs context/health data reasoning based on preset parameters and algorithms to automatically trigger an alert; and (iii) a portable personal healthcare assistant that can work with, and without an Internet connection (Liang and Krause, 2013). Figure 4 illustrates the architecture diagram of this Module.
- The Service Gateway Module: Its essential functions include: (i) a management console both for performing administrative tasks and for providing caregivers and healthcare professionals with a service portal for remote patient data access and alert notification via a healthcare dashboard; and (ii) a cloud manager/broker that performs protocol translations for requests and responses between the User Agent(s) and the Public Cloud(s), and allocates cloud resources based on user preferences or performance criteria.

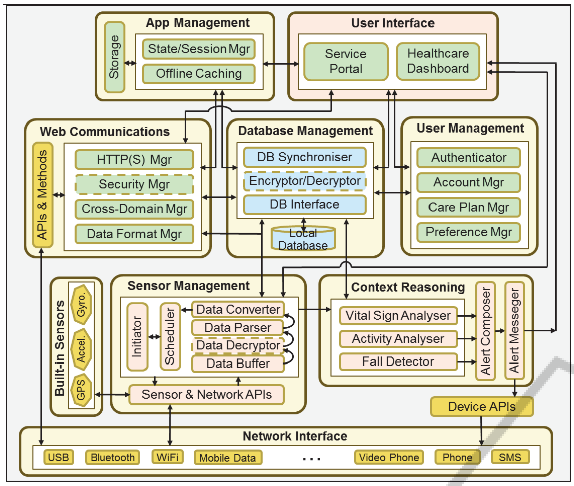

Figure 4: Architecture Diagram of the User Agent Module (Liang and Krause, 2013).

- The Public Cloud(s) Module: With the help of the Service Gateway Module, this Module can consist of a variety of cloud platforms, such as AWS, GAE, cloud-based Social networking websites, and free cloud-based health data storage, e.g. HealthVault.

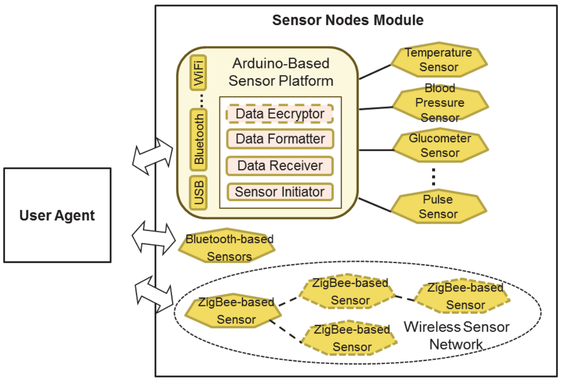

Figure 5: Architecture Diagram of the Sensor Nodes Module.

- Sensor Nodes: This module is composed of a number of off-the-shelf portable sensor devices (see Figure 5) to collect data for vital sign monitoring, safety monitoring and activity monitoring.

3.3 Experimental Design and Cost-effectiveness Analysis

3.3.1 Limitations

Due to limited resources, time and funding in particular, it is impractical for this research to design and implement a randomised controlled trial to measure costs and effects over several years, as normally done in the health sector. Instead, this research will only conduct some simulated trials and adopt a revised comparative effectiveness analysis approach for economic evaluations. The purpose behind this is to evaluate whether there is a case for designing a full scale trial without committing to the expense of such a trial.

Another limitation is the unavailability of low-cost, portable, programmable, and, most importantly, clinically certified, sensor devices in healthcare. As a result, this research will have to use uncertified sensor devices, making a real clinical trial unrealisable.

3.3.2 Experimental Design and Results

To date, a proof-of-concept prototype using Ruby on Rails framework has been developed mainly based on expanding and integrating three standalone projects under the same theme of “Medical Alert Management” in the Department of Computing, University of Surrey, UK. Each of them had different focuses, ranging from data presentation, sensor data collection, to data storage.

Meanwhile, the development of the Sensor Nodes Module and the integration of a real-time remote monitoring function and those three projects, as well as the implementation of the User Agent Module on iPhone 5, are underway. Currently, by using a web browser, an authorised remote user such as a registered GP can use the dashboard to access and review historical patient monitored data stored in a remote server’s MySQL database. In addition, the user can switch some panels inside the dashboard to display dynamic real-time monitored data, such as body temperature, heartbeat rate and ambient temperature, which is first received by the User Agent Module through either a Bluetooth wireless connection or wired.

For the purpose of human fall detection, we currently adopt a wearable device approach, mainly based on accelerometry-related parameters, such as the sum vector (SV) of acceleration in X-Y-Z axes (see Equation 3). Figure 6 shows both SV and acceleration signatures in an intentional forward fall using the on-board accelerometer of the Texas Instruments’ SensorTag.

$$SV = \sqrt{x^2 + y^2 + z^2} \qquad (3)$$

When building our fall detection algorithm, we first assumed that a fall followed by lying motionless is an emergency that needs to trigger an alert. 30

simulated activities of daily living (ADL), each followed by an intentional forward fall on a cushion, were performed by locating either a SensorTag or an iPhone with a built-in accelerometer at different places of a volunteer's body, such as ear side, jacket pocket, shirt chest pocket, pants pocket, or handheld (Liang and Krause, 2013). To make our simulated falls closer to reality, we did not strictly confine the sensors to a certain tilting angle or orientation. Such a research design is apparently different from a number of studies (Kangas et al., 2007; Yang and Zhao, 2011; He, Li and Bao, 2012).

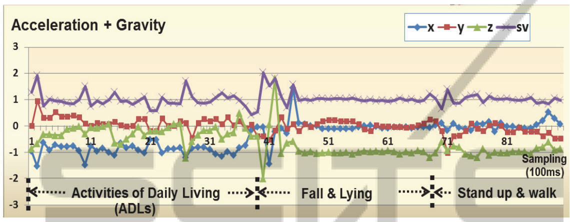

Figure 6: Changes of SV and Acceleration in X-Y-Z Axes in an Intentional Forward Fall.

The results from 22 falls (eight falls were excluded due to noisy data) revealed that when SV first drops below 0.79g (1st threshold) before bouncing over 1.48g (2nd threshold) and then after a few oscillations it remains in the interval between 1.125g and 0.89g (3rd threshold) for more than 2 seconds, a serious fall might have occurred. Nevertheless, dropping or throwing an accelerometer could produce similar SV signature. Consequently, we add another threshold at 0.15g (4th threshold) to detect a free fall situation, which enables us to distinguish all device drops/throws from human falls.

Table 1: Results of fall detection using 3-threshold or 4-threshold algorithms (Liang and Krause, 2013) (accelerometer range: ±2g, sampling rate: 10Hz).

	3 thresholds	4 thresholds
Sensitivity	95.5%	95.5%
Specificity for device drops/throws	0%	100%
Specificity for ADLs	95.5%	95.5%

In Table 1, sensitivity is defined as the percentage of successfully identified falls and specificity is the percentage of successfully identified non-fall tests. Indeed, we have also developed another algorithm to identify intentional device shaking events, which sometimes can produce almost identical SV signatures to human falls. However, instead of using the new algorithm at the expense of less sensitivity, we add a function to ask for user confirmation before an alert is sent to remote caregivers.

Regarding vital sign monitoring, we use an Arduino-compatible platform (Seeeduino Stalker v2.1 shield manufactured by Seeed Studio) and clinically uncertified sensors (e-Health Sensor Platform v1.0 with optional sensor kits, such as pulse, oxygen in blood, body temperature and body position sensors by Cooking Hacks). Nevertheless, the accuracy and reliability of the used sensors have been disappointing so far. For example, the highest body temperature measured by the e-Health Sensor Platform's thermometer was under 30 degree Celsius and the body position sensor just did not work. According to the manufacturer of the e-Health Sensor Platform, a possible reason might be incompatibility between the e-Health Platform and the Seeeduino Stalker shield, as the former is designed for Arduino. However, after some relatively minor modifications to the sensors and wiring, our User Agent Module can start receiving meaningful data from some of the sensors. We believe the results can be further improved with more work (Liang and Krause, 2013).

As for movement pattern monitoring, we plan to use received signal strength from three triangular deployed reference sensors, such as SensorTags, for in-home patient location and movement estimation. However, due to limited resources, we currently have only one SensorTag. By measuring received signal strength from a man-carried SensorTag, we can roughly estimate the distance between the man and the User Agent with an accuracy of around two to three meters.

3.3.3 Cost-effectiveness Analysis

Due to the above-mentioned limitations, this research calculates neither CER nor ICER directly, but performs simulated trials to predict the effectiveness of the proposed system and then conduct cost-effectiveness analysis based on a revised comparative effectiveness analysis approach. Four types of comparisons, including the comparison between simulated control and intervention groups, for building up evidence of cost-effectiveness are made.

Figure 7 shows the concept diagram for a comparative effectiveness analysis approach which compares our simulated trials with existing randomised controlled trials. Data about the costs and effects (the resulting changes in a group of patients' health status from Health Status X to

Health Status Y) of a known Intervention Y is first obtained from literature review. Then we can claim that our proposed Intervention Z can provide the same QALY effects or better QALY effects (i.e. Health Status Y+ with Quality of Life Y+ and Life Expectancy Y+) than Intervention Y, if Intervention Z has the same or better functionality/performance. Finally, Cost Z and ICER of Intervention Z are calculated for cost-effectiveness analysis (Liang and Krause, 2013).

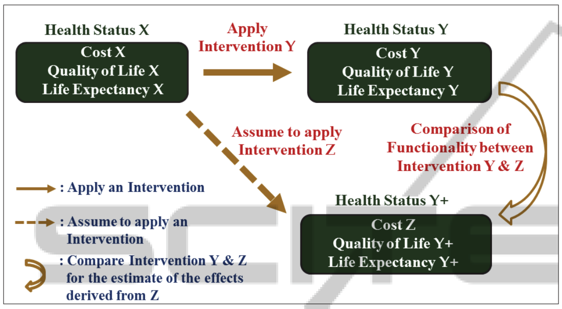

Figure 7: Concept Diagram for a Comparative Effectiveness Analysis Approach (Liang and Krause, 2013).

To enable ourselves to satisfactorily conduct cost-effectiveness analysis and to make claims about the generalisability of this research, we first need to further improve the reliability and accuracy of both our event reasoning algorithms and the sensors. The technical problem of incompatibility among devices also needs to be better resolved. Meanwhile, a more stable and well-defined testing environment has to be carefully designed to make our simulation more meaningful and robust.

4 CONCLUSIONS

In this paper, we have discussed the long-standing problem of lacking robust evidence for cost-effectiveness of healthcare technologies. To tackle this issue, we have broadly assessed the implications of recent advances in sensor technologies, smart home, Internet of Things and mobile cloud computing in support of achieving a cost-effective design of a home healthcare telemonitoring solution. We then have proposed a system architecture based on mobile cloud computing and developed a proof-of-concept prototype together with a novel comparative cost-effectiveness analysis approach based on simulated trials. Through the experimental design, we believe that the proposed system is a good foundation for moving forward.

In addition to the future work mentioned in Section 3.3.3, we will also work on the development of the Service Gateway Module to integrate all the proposed system components as a whole, and complete simulated trials and cost-effectiveness analysis. Whilst we may not be able to deliver a complete solution, we are confident that the methodological contribution of test environment plus simulation models will enable us to put the evaluation of telehealth solutions prior to moving to full-scale trials on a more scientific basis.

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