Patient Health Monitoring with a Wellness Score Using Body Area Networks

by

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Patient Health Monitoring with a Wellness Score Using Body Area Networks

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In this dissertation project, an entirely wireless and electronic patient health monitoring system is proposed. The project is further motivated as a way to inform medical professionals contextualised sensor data from patients as close to real time as possible and improve patient outcome quality.

The patient health monitoring system proposed in this dissertation takes advantage of the state of art wireless sensing and wireless communication technologies. The system adds a supplementary tier to the typical architecture of a wearable wireless health monitoring system by incorporating a device fixed onto the end-user for the relay of information to a medical professional. In the prototype, four on-body sensors, measuring blood pressure, blood oxygenation, heart rate and movement, form a body area network and communicate via Bluetooth Low Energy with a near contact unit. Sensed values are stored in a server. Values are retrieved from the server, processed and analysed to produce an appropriate warning which is displayed on an end-device. Warnings are issued by a designed and validated wellness health score algorithm which combines gathered sensor readings.

Overall, it is found that the prototype system successfully enables end-users to be correctly notified of patient health conditions remotely and wirelessly in an acceptable timeframe. Further, the designed approach can be scaled to different medical contexts and environments.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Patient health monitoring systems permit the constant monitoring of the physiological activities in the human body. The majority of current systems use wired sensors attached from the patient to beside monitors. As a result, patient movement is restricted and patients are confined to their hospital bed. Despite the continuous monitoring by the systems, nurses and other medical professionals are still required to physically check patients and keep track of vital signs in manual records. Such medical practices consume valuable time and places additional stress on medical professionals. These practices also provide opportunities for human error and inefficiencies, and therefore, may potentially lead to poor patient outcome. With an ageing population and growing life span, the number of patients who require health monitoring increases. Thus, clinicians and healthcare professionals are seeing a rise in the number of patients they attend to every day. The current development demands a more proactive, automated and ubiquitous practice. Technology is the underlying tool for the improvement of patient health observation and the reduction of reaction times.

The advent of mHealth, eHealth and other wireless technologies aims to alleviate the need of unnecessary in-person health assessments and to also guide health monitoring to be more pervasive and unobtrusive. With medical devices growing increasingly smaller and wireless communication technologies being adapted to positively support the devices, patient health monitoring is becoming increasingly comfortable for patients together with medical personnel. Patients are able to be mobile and be monitored simultaneously with the advent of wireless communication technologies designed specifically for the medical environment.

This dissertation will show the use of ubiquitous computing and wearable wireless sensors to develop a wellness health score and warning for medical personnel which may be used by and help medical professionals.

1.1 Motivation

Unobtrusive health monitoring to monitor the well-being of people is becoming progressively desirable in the medical domain. There is a growing need for patient health monitoring to be performed remotely and to become 'smart' and mobile. Nurses and doctors are not always available to continuously monitor patients in person. Thus, there is a desire for warning systems which evaluate the well-being of a person based on a calculated wellness health score and report meaningful data to clinicians. The ability to monitor at any given location will better allow individuals to self-monitor and alleviate any immediate stress placed on medical professionals.

Further, the use of wireless sensors for health monitoring and reporting is becoming increasingly prevalent due to the affordability of sensors. Thus, this report proposes a system which monitors patient health using wireless sensors.

1.2 Aims

This thesis project is aimed at developing a system architecture based on smart devices and wireless body area networks to monitor health of patients. The goal of this dissertation is to propose a system and develop a prototype which produces a wellness health score. This score will indicate health statuses and warnings for patients and medical professionals. The specific aims of this project are as follows:

a) To collect data using wearable wireless on-body sensors and as close to real time as possible.
b) To perform data processing and data aggregation, followed by the analysis of the gathered data.
c) To propose a validated wellness health score algorithm suitable for a medical environment.
d) To issue appropriate warnings to end-users based on the collected and analysed data.
e) To create a system which will affect patient outcome in a positive manner.
f) To develop a system which makes use of commercial products which are readily available to the public while also maintaining a relatively low cost.

Thus, the two overall research questions are:

1) Can a wellness health score yielding health statuses and warnings be calculated from health data gathered from various wearable sensors?
2) Can an entirely wireless and electronic health monitoring system capable of relaying data directly from patient to medical professional be implemented?

1.3 Approach

The proposed system monitors patients using portable and mobile devices. Data is accumulated from an array of wearable sensors. Bluetooth sensors worn on the human body are used to extract data. They will measure the following bodily parameters:

a) Blood pressure

b) Blood oxygen saturation (SpO_2)

c) Heart rate.

Additionally, physical body movement will be determined and measured using accelerometer sensors. The raw data is processed and cleaned. The data is then aggregated with data from the other sensors. Finally, the processed data is passed through an algorithm which calculates a 'wellness health score'. Based on the score, a respective warning is issued to a device worn on a medical professional.

1.4 Contributions

This thesis project attempts to contribute to the design and implementation of a system which uses wireless on-body sensors to ultimately provide assistance for and alleviate stress on healthcare professionals. Furthermore, this project attempts to act as a stepping stone for warning systems to be applied to a broader array of use cases (eg. ambient assisted living). The overall contribution is to improve patient outcomes with the use of the wellness health scoring system proposed.

1.5 Dissertation Structure

This section will provide a high-level outline of the structure of this thesis organised. The thesis document is structured by six chapters as follows:

Chapter 1 is the **Introduction**. It is a general overview of the project focusing on the research area, motivation, aim and overall research question.

Chapter 2 is the **State of the Art**. This chapter provides a description and survey of existing systems similar to the one proposed. It explores the various areas of research which have an impact on and are related to this project. Further, this chapter discusses the technologies used in this project. It provides a summary of how the research areas are interconnected to highlight their relevance to this project.

Chapter 3 is the **Design**. It will give details of requirements, the proposed system architecture and reasoning behind any design choices.

Chapter 4 is the **Implementation**. This chapter describes the actual implementation of the design proposed in Chapter 3. There is a focus on technology in this section of the report.

Chapter 5 is the **Evaluation**. This section presents experiments carried out to test the system and an analysis of results. It gives a brief assessment of the system and details an evaluation of the framework and data.

Chapter 6 is the Conclusion. It will provide a summary of the achievements of this project and further explore possible related future work.

Chapter 2

State of the Art

The previous chapter introduced the dissertation project, outlining the motivations and aims. This chapter will provide an overview of background technologies and summarise the current research and state of the art in which this project falls. The first section, Section 2.1, describes patient health monitoring and its typical infrastructure. Section 2.2 explores body area networks and their use in patient monitoring. Section 2.3 details the existing forms of wireless communication for short ranges and relevant technologies applied to wearable health monitoring. Finally, Section 2.4 provides information on the physiological parameters measured in this thesis project.

2.1 Patient Health Monitoring

Patient health monitoring can be performed either with direct contact or remotely. In recent years, there has been a focus on remote health monitoring in order to alleviate the responsibilities of medical professionals [1]. Remote patient health monitoring is supported with eHealth and mHealth. eHealth refers to the ubiquitous provision of health care services supported by modern communication infrastructures and electronics [2]. On the other hand, mHealth focuses on patient health monitoring by use of mobile devices. Both eHealth and mHealth necessitate a total reform of the health care and patient monitoring through digitalisation [3]. Real-time monitoring of patients through use of eHealth and mHealth means has afforded greater efficiency of tasks and processes and has provided healthcare professionals with improved accessibility [4]. Ultimately, telecommunications technologies have made a positive influence on the overall quality of healthcare services.

Current state of the art systems in the patient health monitoring area focus on systems being wireless and wearable. The primary reasoning behind this is to allow for non-invasive monitoring of the body's vital signs. In their paper, Soh et al. [5] state that the use of body-worn sensors leads to a health monitoring mechanism which is more effective. Wireless and wearable sensors remove any possible interference whilst acquiring data. Systems which employ these sensors still maintain the ability to relay gathered sensor data directly to a medical professional in cases where action is required. They mention that the combined information may also be stored and analysed for preventative health measures.

2.1.1 Wearable Health Monitoring Systems

Over the past few years, wearable health systems for monitoring physiological parameters has experienced major advancements. The previous state of the art in this area involved large and awkward devices connected via wires. In their paper, Rasmus et al. [6] outline the recent developments in radio communications and microelectronics for health monitoring. They mention that the developments have facilitated an increase in computational power, a decrease in form factor and a reduction of power consumption. This became the foundation of health monitoring systems and devices with built-in sensors, microcontrollers, digital signal processing and radio communications. Rasmus et al. further stated that the development of an 'all-in-one' device allowed the health monitoring systems to be wearable as systems can be worn conveniently and unobtrusively.

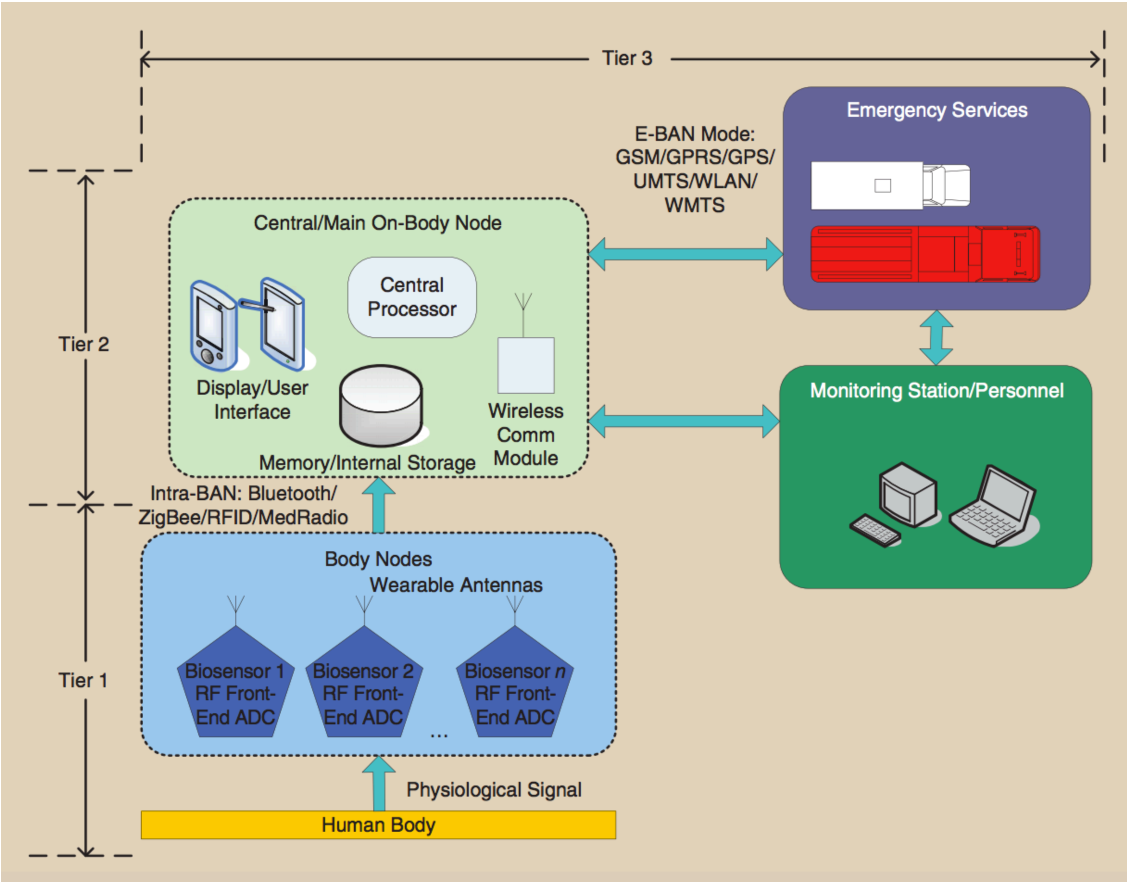

Fig. 2.1: Standard infrastructure of wireless wearable health monitoring system.

A typical infrastructure of a wireless wearable health monitoring system is depicted in Figure 2.1. The infrastructure includes three tiers. Milenkovic et al. [7] provides a breakdown of the architecture. The first tier comprises the use of various sensor nodes. Each node senses, measures and processes different physiological signals from the human body. The second tier and third tier involve the retrieval of the measured by the central node and then, the transmission of the data to a medical domain. Specifically, the second tier encompasses a personal server which is responsible for providing an interface to the user and medical server. Tier 3 contains the servers which collects the information from the user and stores it in the user's medical record.

2.1.2 Survey of Health Monitoring Systems

Lorincz et al. [8] developed the CodeBlue project at Harvard University for the purpose of health monitoring in dynamic, critical care environments. The project entailed a sensor network platform using ZigBee with the MicaZ and Telos motes. Parameters were measured using pulse oximetry, ECG and motion activity. Motion analysis was performed with the use of a three-axis accelerometer, gyroscope and EMG. A publish-subscribe routing framework was implemented to coordinate the different sensor platforms and to relay data to the receivers [9]. The ability for the personal server to discover the sensors and download the sensed data onto a mobile device was made possible with a discovery protocol.

Albeit developed for space and terrestrial applications, the LifeGuard project was designed as a multi-parameter wearable monitoring system [10]. The physiological parameters that LifeGuard was capable of measuring were acceleration, temperature, ECG, respiration, blood oxygenation and blood pressure. The system used a CPOD data logger device which was worn on the body along with the other sensors. Most of the sensors in the system measuring the biosignals were bough off-the-shelf [11]. The sensor system was connected via wires to the CPOD. The CPOD logged the data and was capable of sending data wirelessly via Bluetooth to a base station computer. Thus, although wearable, this system was not entirely wireless.

The Integrated Health Monitoring System presented in a paper by Hammed et al. [12] is a real-time patient monitoring system capable of monitoring, gathering, processing and storing biological data. The system encompasses an array of sensing modalities for measuring ECG, SpO_2, blood pressure, temperature and respiration. To permit remote monitoring, it makes use of integrated networking, electronic patient records and web technologies [12]. The system consists of a wireless health monitoring module, a central managing system module and a personal server. This follows the typical infrastructure depicted in the previous sub-section and in Figure 2.1 whereby the wireless health monitoring module is the Tier 1, the personal server is Tier 2, and finally, the central managing system is Tier 3.

2.1.3 Performance of Health Monitoring Systems

According to Vo et al. [13], performance evaluation of health care monitoring wireless sensor networks is limited. To be an effective health monitoring system, latency in the transmission of data from the patient to the medical staff needs to be minimal. This ensures that the medical personnel receive data updates as close to real time as possible. Egbogah et al. [14] summarise and provide an analysis of existing wireless health monitoring systems. Specifically, they place an emphasis on the latency of each system as a whole. End-to-end latency is chief in importance in the medial environment. In the paper, they present the end-to-end latency of three wireless health monitoring systems. Table 2.1 illustrates each of their delay times.

Wireless Health Monitoring System	**End-to-End Latency (seconds)**
CodeBlue [15]	~ 0.2
MEDiSN [16]	~ 2
MASN [17]	~ 1

Table 1.1: Comparison of the end-to-end latency.

2.1.4 Devices for 'Self' Health Monitoring Systems

Currently, there are a few wearable health devices which are capable of measuring a number of physiological parameters. Specifically, these devices take the form of a wrist watch. The Omron Project Zero wrist watch measures heart rate and blood pressure using a mildly inflatable cuff. Measurements are taken discreetly without large cuffs, wires or hoses. The watch can also measure activity in terms of step count and sleep. Data recorded on the watch is sent wirelessly and stored on a mobile application. By choice of end-user, the information can be relayed to a physician for remote monitoring of a condition.

2.2 Body Area Networks

Body area networks (BANs), also known as body sensor networks (BSNs), act as the backbone for patient health monitoring. Sensors are strategically placed on the human body and networks are used to continuously monitor body activity and surrounding environments. Wireless body area networks monitor physiological activities of a human using a collection of sensor nodes which are miniature in size and have low power consumption. The nodes process and sample gathered data. Data is then sent to a server or base station using a wireless communication technology such as Bluetooth or ZigBee (detailed in the Section 2.3) for further analysis [18]. Body area networks benefit from the development of smart and affordable health monitoring systems [19]. They can further be used to help with diagnostics, maintenance for specific health conditions and remote health supervision.

Body area networks employ features which are better aligned with patient health monitoring in comparison to traditional wireless sensor networks (WSNs) [20]. To support this, Chen et al. [20] briefly compared the two types of networks. WSNs are used for event-based monitoring whereas BANs are used to record human physiological activities at regular intervals, thus using stable data rates. They mention that in terms of mobility, nodes in body area networks share a mobility pattern to support user movement while WSN nodes are generally stationary. Lastly, battery lifetimes in BAN nodes are longer lasting than in that of WSN nodes. For the traditional wireless sensor network nodes to maximise battery life, there is a trade-off with latency. Body area networks are designed for long-term patient health monitoring without interruption of regular movement and physiological state [19].

Wireless body area networks are broken down into two further categories: on-body and in-body. Both allow for the constant monitoring of the vital signs of a patient to help with diagnosis and prescription [21]. Both will be discussed in the following sub-sections: 2.2.1 and 2.2.2.

2.2.1 Wearable 'On-Body' Sensors

Wearable 'on-body' sensors, also referred to as intra-BAN sensors, are sensors which can communicate approximately two meters around the human body [20]. Communication can either be between the body sensors themselves or between sensors and a portable personal server. The on-body sensors must be battery-operated and have a low bit rate. As a result, the media access control (MAC) protocol is designed to be as energy-efficient as possible with quality of service provisioning [18]. Applications of wearable sensors may include sport training, sleep staging and wearable health monitoring [22].

2.2.2 Implantable 'In-Body' Sensors

Implantable 'in-body' sensors are also known as inter-BAN sensors. For communication, the sensors require a medical implant communication services (MIC) [21]. In-body sensors in wireless body area networks are subject to interference of electrical properties of the body. Ultimately, this can interrupt the signal propagations. Further, inter-BAN requires a MAC protocol that uses less power while ensuring that traffic communication has safety and reliability. The IEEE 802.15.4 protocol (detailed in Section 2.3.1) is adequate for intra-BANs, however is not sufficient enough for inter-BANs because of the inter-BAN high power usage. Implantable sensors can be used to monitor cardiovascular diseases as well as for cancerous detection [22].

2.3.4 Requirements for Body Area Networks

Wireless sensors are resource constrained devices operating on restricted power and limited internal processing capabilities. When used in a medical environment, they are required to provide responses in a timely manner to external commands and their internal commands while maximising battery power. A paper by Anthony Lo et al. [23] explores the specific requirements needed for a body area network. They start by first specifying how the networking technologies are required to have high availability. Meeting this requirement would mean that data reported from sensor devices in the network is transmitted without delay and without missing data. For body area networks, this is essential because the BANs are used for real-time monitoring and for warning patients or clinicians. As an additional requirement, the sensor devices must have low power consumption. They state that the in-body sensor devices are a challenge to charge. Thus, in order to meet the low power requirement, the sensors can only have a small range of communication. The last requirement mentioned is for the sensor devices to be implemented at a low cost. Affordability helps to enforce wide usage of such sensors and allows the sensors to be disposable when needed.

Therefore, not all wireless communication technologies are practical for use in body area networks. In the following section, different communication technologies are presented. Each are appropriate for body area networks.

2.3 Wireless Communication Technologies

There are a variety of wireless communications which can transmit data. Communication standards part of the IEEE 802.15 Working Group enable wireless personal area networks (WPAN). These standards include Bluetooth, ZigBee and IEEE 802.15.6. The IEEE 802.15 Working Group supports wireless technologies essential for the transmission of data collected from sensors to monitoring applications and vice versa.

2.3.1 ZigBee (IEEE 802.15.4)

The ZigBee standard is based off the IEEE 802.15.4 standard. The IEEE 802.15.4 standard defines the lower levels of the protocol stack: Physical (PHY) layer and MAC layer. IEEE 802.15.4 is specifically designed for low cost and low rate wireless personal area networks. It supports reliable data communication and maintains a simple and flexible protocol stack [24]. This standard creates the building blocks for further protocol stacks.

ZigBee builds upon the IEEE 802.15.4 protocol stack and further specifies the higher layers: Network layer and Application layer. The ZigBee standard supports the network topologies of mesh, star and tree. Additional network features include multi-hop routing, route discovery and maintenance, joining and leaving the network as well as security [24]. For route discovery, the network uses Ad hoc On-Demand Distance Vector (AODV) routing. Using AODV, the network can react to changes of nodes within the network topology and thus, maintain reliability [25]. In terms of security, ZigBee offers data freshness, message integrity, authentication and encryption.

Another important feature of ZigBee is that it provides long battery life. It achieves this by locking into a transmission timeslot and sleeping in between [26]. ZigBee is directed at devices which use minimal power and have an operational range of approximately 10 to 80 meters [25].

2.3.2 Bluetooth (IEEE 802.15.1)

Bluetooth is specified by the IEEE 802.15.1 standard and is the most commonly used form of short-range wireless communications [27]. Bluetooth radios operate at 2.4 GHz and has a data rate of 1 Mb per second. The Bluetooth protocol can handle the transfer of data in the form of voice, images and files in ad hoc networks. It has a Personal Operating Space (POS) of 10 meters.

An advancement of standard Bluetooth is Bluetooth Low Energy (BLE) or Bluetooth Smart. The purpose of BLE was to consume less power than standard Bluetooth whilst also transmitting small packets of data. This technology is one of the frontrunners to connect the ‘Internet of Things’ [28].

Rashid et al. [29] explore the practicality of the Bluetooth technology in Personal Area Networks (PAN). They tested and analysed the latency of Bluetooth communication at several different ranges by sending various files of different sizes. Files less that one kilobyte did not have a significant impact on transmission time. For these files, the average latency grew proportionally with the file size. Any file greater that five kilobytes experienced transmission delay. Files larger than five kilobytes experienced an exponential delay growth with file size. The general trend they observed was that the greater the range, the higher the delay. Therefore, from these findings, Rashid et al. [29] concluded that Bluetooth is a practical wireless technology for transmitted data below one kilobyte in size. Any size above one kilobyte would mean that Bluetooth is not the fitting technology for that application.

A feature comparison of ZigBee and Bluetooth wireless communications is shown below in Figure 2.2.

	ZigBee	**Bluetooth**
Range	10 – 80 m	10 m
Data Rate	250 Kbps	1 – 3 Mbps
Power	30 mW	100 mW
Security	128-bit AES	128-bit AES

Table 2.2: Comparison summary between wireless technologies: ZigBee and Bluetooth.

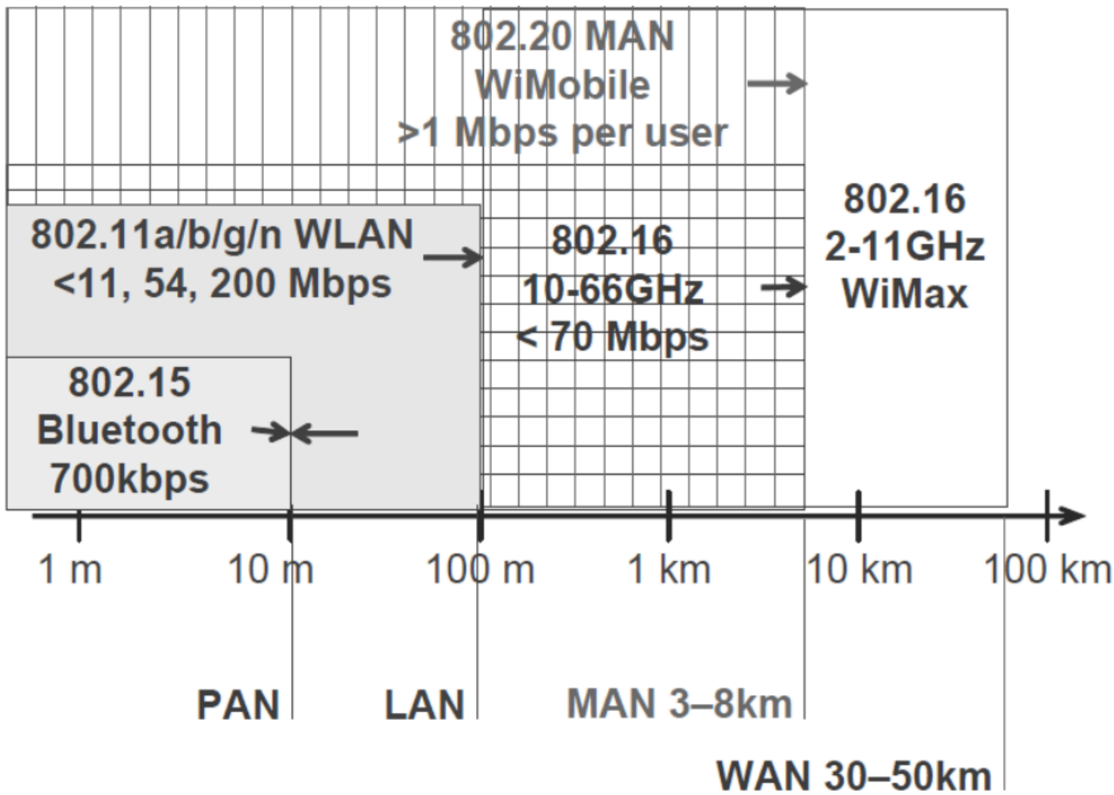

Fig. 2.2: Comparison of different wireless communications. [30]

Figure 2.2 depicts a further comparison of wireless communication technologies. Specifically, it highlights values for data ranges and data rates of the different wireless communications.

2.3.3 IEEE 802.15 Task Group 6

Published in 2012, the relatively new IEEE 802.15 Task Group 6 or IEEE 802.15.6 standard was specifically designed for wireless body area networks (WBAN). The standard is optimised for low power nodes which are in, on or of close proximity to the human body. The focus was for ultra-low power consumption and low data rate networks [31]. The IEEE 802.15.6 standard defines a MAC layer which supports a variety of PHY layers [32]. The IEEE 802.15.6 standard provides efficient communication solutions directed for ubiquitous healthcare systems [33]. A limited number of off-the-shelf consumer products operate with the IEEE 802.15.6 standard.

2.4 Physiological Measurements

2.4.1 Blood Pressure

According to the World Health Organisation (WHO), the normal blood pressure (BP) for adults is defined as 120 mm Hg and 80 mm Hg for the systolic and diastolic measurements respectively. A high or raised blood pressure is defined as when the systolic blood pressure is equal to or greater than 140 mm Hg and/or the diastolic measurement is equal to or greater than 90 mm Hg. This raised blood pressure is known as hypertension. Hypertension is an indicator for heart attacks, strokes and cognitive impairment. On the other hand, a fallen blood pressure, known as hypotension, can lead to dizziness, fatigue and blurred vision. A systolic value consistently below 100 mmHg is assumed to be hypotension. Thus, blood pressure is an important measurement for determining health statuses. Table 2.3 summarises the blood pressure levels and respective classifications.

	Systolic (mm Hg)	**Diastolic (mm Hg)**
Optimal BP	<120	<80
Normal BP	<130	<85
Mild hypertension	140-159	90-99
Moderate hypertension	160-179	100-109
Severe hypertension	≥180	≥110

Table 2.3: Summary of blood pressure levels.

Blood pressure is measured using a blood pressure monitor which may be wired or wireless. The monitor can take the form of an arm cuff, a wrist cuff or a finger cuff. The cuff will automatically inflate to cut off blood flow and then slowly release. Points at which the blood flow starts and stops are recorded as the systolic and diastolic values respectively.

2.4.2 Blood Oxygen Saturation (SpO_2)

Blood oxygen saturation is a measurement of the percentage of haemoglobin molecules which are saturated with oxygen in the arterial blood. Measurements are taken using a pulse oximeter and vary between 0% and 100%. A typical healthy adult would have a reading ranging from 95% to 100%. At this normal level, the human body is capable of performing basic functions. Research has shown that SpO_2 levels can change quickly, and thus, without continuous monitoring, health problems may arise. Mild respiratory problems can be indicated with a SpO_2 level between 92% and 95%. Any readings below 91% represent an abnormality in health and a cause for concern. Lower blood oxygen saturation levels indicate the build up of carbon dioxide in the blood. Ultimately, this may lead to fatigue and sleepiness.

Pulse oximeters are used to measure blood oxygen saturation levels. The devices are optical-based and placed on the fingertip. Two beams of light of different wavelengths screen the blood vessels and capillaries of the finger. These light beams reflect the amount of oxygen in the blood. Figure 2.3 depicts the architecture of a pulse oximeter.

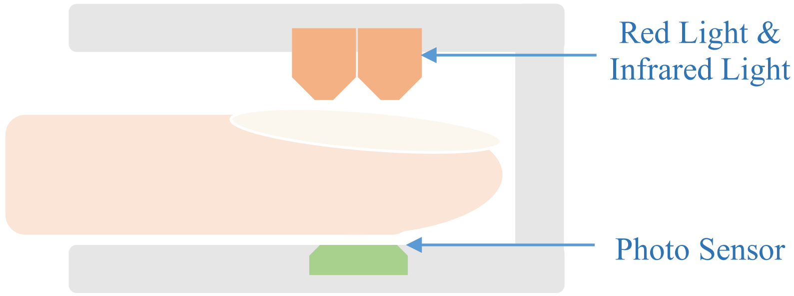

Fig. 2.3: Architecture of pulse oximeter.

2.4.3 Heart Rate

According to the National Institute of Health and American Heart Association, the average resting heart rate for adults is between 60 and 100 beats per minute. Continuous and repeated high heart rate (>100 beats per minute) readings are a sign of tachycardia and can lead to the disruption of heart functions.

2.4.4 Physical Movement

Physical movement is an important part of everyday life which helps the body stay healthy and regulated. It is an evident sign that a patient is alive. Physical movement can be detected with acceleration values. This is helpful for recognition of sudden movements which may indicate a jolt of the body or a fall.

2.4.5 Summary

The physiological parameters of blood pressure, blood oxygenation and heart rate are important measures to help determine the health status of a human. Movement recognition is another application which provides insightful information. In their paper, Mundt et al. [10] state that depending on the application, a varying subset of physiological measures can be used for health monitoring. Specifically, they say that most cases use heart rate, activity (acceleration) and respiration rate. A summary of the used biomedical parameters in this thesis project along with their applications in wireless wearable health monitoring are demonstrated in Table 2.4 [5].

Applications	**Sensors**	**Measurements**	**Target Data Rate**	**Number of Nodes**	**Desired Battery Life**
Blood Pressure Monitoring	BP / cuff based	Oscillometric	< 10 kb/s	< 12	> one week
Blood Oxygenation Monitoring	Pulse oximeter	O_2 concentrations / saturations	< 10 kb/s	< 12	> one week
Heart Rate Monitoring	Heart rate monitor	Cardiac activity	72 kb/s	< 6	> one week
Movement Recognition	Accelerometer	Direction (activity)	1 Mb/s	< 6	> 24 hrs

Table 2.4: Biomedical parameters and their applications.

2.5 Summary

Overall, this chapter provided summaries of research performed by experts and provides reasoning behind the choice of certain technologies for this thesis project. It addressed the current systems which have similarities to the one proposed in this thesis project. Between these state of the art patient health monitoring systems, there are commonalities such as acquired measures and used architectures which this thesis project will draw from. Further, the exploration of wireless technologies influences the wireless communication incorporated into the design of the prototype system. Each wireless communication presented are suitable for patient health monitoring because they fit the requirements for body area networks stated in Section 2.3.4.

Chapter 3

Design

The previous chapter summarised the background and state of the art of this thesis project, including an overview and description of wireless communication technologies and patient health monitoring. It also explored the current systems which cover health monitoring. This chapter will detail the proposed design of the system for generating wellness health scores based off collected data from sensors. The chapter will begin with the general requirements of the system along with their motivations behind them. Subsequently, there is a brief description of the system architecture and the functionality each module has. Following this, the wellness health scoring system and algorithm will be detailed.

3.1 Requirements

Summarising the list of goal statements made in the introductory chapter, Chapter 1 Section 1.3, the objective of this proposed system is to collect data from a body area network made from affordable sensors and to issue appropriate warnings to an end-user. Thus, the design of the system must meet a variety of requirements in order to satisfy these goals. Sensors used must have low power consumption, quick transmission of data and the ability for it to be wearable and unobtrusive. The collation and analysis of the blood pressure, blood oxygen saturation, heart rate and movement data must be executed in a timely manner. Further, as a whole, the system is targeted to run as close to real time as possible. The following sections will detail aspects of the system which influence the requirements.

3.1.1 Hardware

One of the goals of this dissertation is to create an easy-to-use commercial warning system for people working in a medical environment. Thus, the hardware used must be affordable and attainable. Each sensor used is to be a commercially bought 'off-the-shelf' product. An additional requirement is that the sensors be as unobtrusive to the patient as possible. Thus, the hardware sensors used must be small and wireless. By meeting the latter requirement, more reflective and natural values of the measured bodily parameters will be acquired; any chance of hindrance to the data collection is reduced significantly. Further, as the sensor devices are wireless, adequate battery life must be ensured to guarantee continuous and reliable monitoring without interruption. Moreover, a minimum of two hardware devices will be required in the proposed system. Consequently, this maintains independence between sensing and end result display.

A potential hardware design of the sensors is a health monitoring watch which is capable of measuring an array of physiological measures, similar to the Project Zero watch mentioned in Section 2.1.4. When a watch which encompasses all the specific biomedical parameters appears on the market, it should be utilised. An 'all-in-one' device such as this is ideal to eliminate any variability in the readings from the sensors. At this time, there is no such device on the market. Thus, individual sensors will be employed in this project.

An Android mobile phone will be used to extract accelerometer data. Android is selected due to its higher prevalence in the human population in comparison to iOS. Android phones are generally cheaper than Apple phones, thus supporting the requirement of affordability. Also, commercial software is not required for application development and deployment. In addition, the Pebble smart watch is chosen. Pebble is selected over other smart watches such as Android Wear due to its longer battery life, compatibility with iOS and Android and affordable price. However, the smart watch is simply a proof of concept. Any smart watch could be used in the system.

3.1.2 Physiological Parameters

Blood pressure, blood oxygenation and heart rate were the physiological parameters measured in the thesis project. Movement data was also gathered. These parameters are common amongst the existing state of the art prototypes discussed in Chapter 2 under Section 2.4. Additionally, also mentioned in Chapter 2, Mundt et al. [10] specified that the chosen parameters depend on the application. These values act as a proof of concept for the collection of health monitoring data. Further, these parameters were chosen because sensors were readily available in the market which met each of the hardware sensor requirements. Moreover, accelerometer values and movement was included in the design of the system as supplementary data. Motion detection is a useful piece of information. When analysed, it has the ability to be classified as a slow movement or sudden movement. The latter may be interpreted as a potential fall. Further, detecting various motions supports the scalability of the system to different contexts. For example, health monitoring for the elderly in a home environment would benefit from movement data.

3.1.3 Data Characteristics

Blood pressure, blood oxygen saturation and heart rate data are to be gathered from different sensors worn across the body. The raw data must then be processed as to retrieve only necessary information from the sensors. Accelerometer data will be extracted from the built-in hardware sensors of an Android mobile phone. The accelerometer readings must be processed as the data will have noise and gravity present. Thus, the noise is to be filtered using a low-pass filter and gravity must be excluded. Data processing is required to ensure that the values are of the same format. This, in turn, will make them easier to work with and aggregate.

After the raw data has been collected and processed, it needs to hold value for users of the system. The data is to be meaningful and contextualised. Medical professionals are under time constraints and work under high levels of stress, thus, the data that they view should instantly provide meaning. This allows them to provide better service and ultimately, affect the outcome of patients in a positive manner.

3.1.4 Data Transmission and Communication

Data collected from the on-body sensors will be transmitted wirelessly using Bluetooth Smart or Bluetooth Low Energy. As mentioned in Section 2.4, specifically Section 2.4.2, BLE is a short-range, wireless communication for body area networks. Bluetooth is selected over the alternate wireless technologies presented in Section 2.4 due to its prevalence and higher availability to the public. Despite ZigBee having a higher data rate, larger range and lower power consumption, those of BLE are sufficient to meet the requirements of the system. As Bluetooth is a form of short-range communication, a close range device is required to receive the data. Thus, an Android device with applications for the sensors is used.

3.2 System Architecture

The proposed system architecture is comprised of three major modules, modelled in Figure 3.1. It is based on the typical tiered system presented in Chapter 2 Section 2.1.1; however, with an additional tier.

1) **The Patient Module (Tier 1)**

   This module consists of the three separate sensors worn on the body: blood pressure sensor, blood oxygen saturation sensor and heart rate sensor. In addition, the accelerometer sensor contained in an Android phone is part of this module. The function of this module to simply collect and transmit the biomedical values from each sensor.

   The system is designed to allow for an arbitrary amount of wireless sensors to fetch data from the human body.

2) **The Central System Module (Tiers 2 & 3)**

   This module is sub-divided into the following parts and functionalities:

   a) **The Data Receiver**: a personal server which receives data using wireless communications. The role of the receiver is to also store previous readings from the sensors into the medical server.

   b) **The Data Aggregator**: an aggregator which collates data from the various sensors in the patient module. It should be noted that before the aggregation of data occurs, the raw data must be processed to obtain only the necessary values.

c) **The Data Analyser**: an analyser which provides advantageous meaning to the data values. It applies the wellness health score algorithm on the processed and aggregated data.

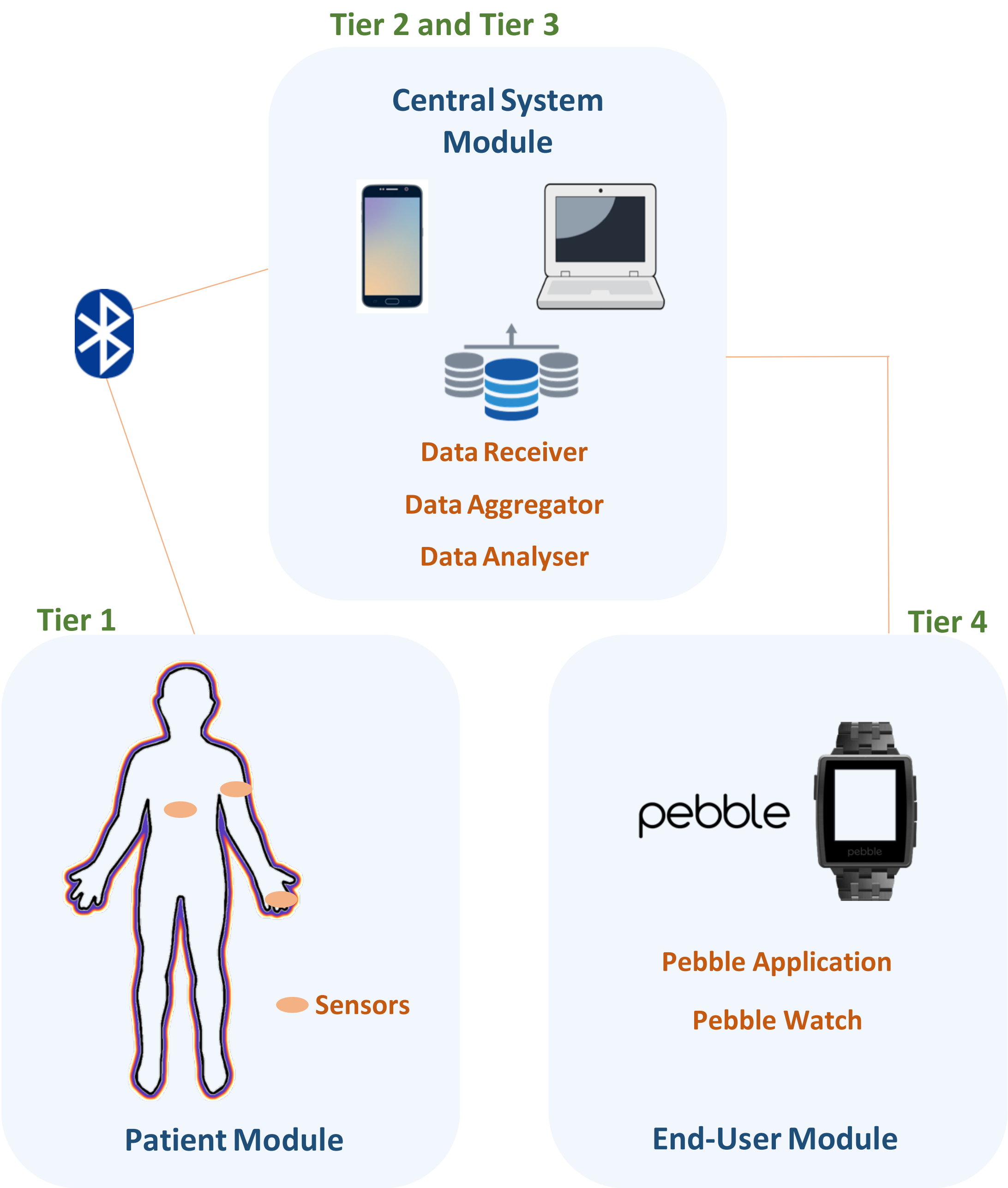

Fig. 3.1: Proposed 4-tiered system architecture.

3) **The End-User Module (Tier 4)**

This module acts to issue an applicable warning based on the analysed data. It is directed at the end-user. The module consists of a smart watch whose watch face can be programmed and customised.

3.3 Wellness Scoring System

As part of the analysis stage carried out by the data analyser mentioned in the previous section, a 'wellness health score' will be formed via an algorithm. The data collected and processed is passed through an algorithm to determine the score. The score is based off a simple traffic light warning system and yields either 'red', 'amber' or 'green'. After consulting a medical professional, the interpretations of red, amber or green from a health perspective are as follows:

- Red result: indicates that the patient is in a progressively worsening condition and immediate action to flag an attending physician is required.
- Amber result: demonstrates that there is a cause to be concerned albeit not necessitating any immediate action. It indicates that the patient has slightly abnormal readings and requires more frequent observations.
- Green result: implies that the patient has good health and is in stable condition. Thus, no extra check-ups are required from a medical professional; only the standard nurse check-up every four hours.

A summary of the interpretations is depicted in Table 4.2 in the following Chapter under Section 4.4. Ultimately, the wellness health scoring system is an indicator and measure of the health status of a person. Based on the outcome of the algorithm, a respective warning is to be issued. The role of the algorithm is to give meaning to the gathered sensor values, thus, making it useful for medical professionals.

3.3.1 Designing the Wellness Algorithm

The design of the algorithm was based on the World Health Organisation thresholds. As an extra validation a qualified medical professional was consulted for an initial indicator of how the alerting should be carried out. Table 3.1 acts as the basis for the algorithm. For each specific range of the physiological measures, a respective score was associated with it. In terms of the scoring, a zero represented a normal parameter score whereas a two represented an increasingly poor outcome.

Blood Pressure (mm Hg)		**Score**
Systolic	**Diastolic**	
< 130	< 85	0
140 – 179	90 – 109	1
≥180 or < 100	≥110 or < 75	2

SpO_2 (%)	**Score**
≥ 96	0
92 – 95	1
< 91	2

Heart Rate (bpm)	**Score**
50 – 90	0
90 – 130 or 40 – 50	1
> 130 or < 40	2

Table 3.1: Individual scoring for each physiological measure.

These individual scores are then summed together to create an overall score. A total score of zero or one will yield a green warning. An overall score of two or three will issue an amber warning. Scores of four, five or six will yield red warnings. A summary can be seen in Table 3.2. As an additional condition, if either blood pressure, blood oxygenation or heart rate returned a warning value of two independently, an overall red warning was issued. For example, if the blood pressure value yielded a score of two, a red warning is issued automatically without regard of the other readings. Figure 3.2 demonstrates the flow of the wellness health algorithm. In terms of the overall scoring, a zero and one represented a normal parameter score whereas a four, five or six represented an increasingly poor outcome for the patient. Overall, the higher the score, the less stable the patient.

Total Score
0
1
2
3
4
5
6

Table 3.2: Total scoring for combined physiological measures.

The wellness health score algorithm designed in this thesis project is not aimed to be absolute and indefinite. It primarily acts as a proof of concept. The algorithm can be adapted depending on its application. Varying forms of the algorithm can be provided for different patients or different medical environments.

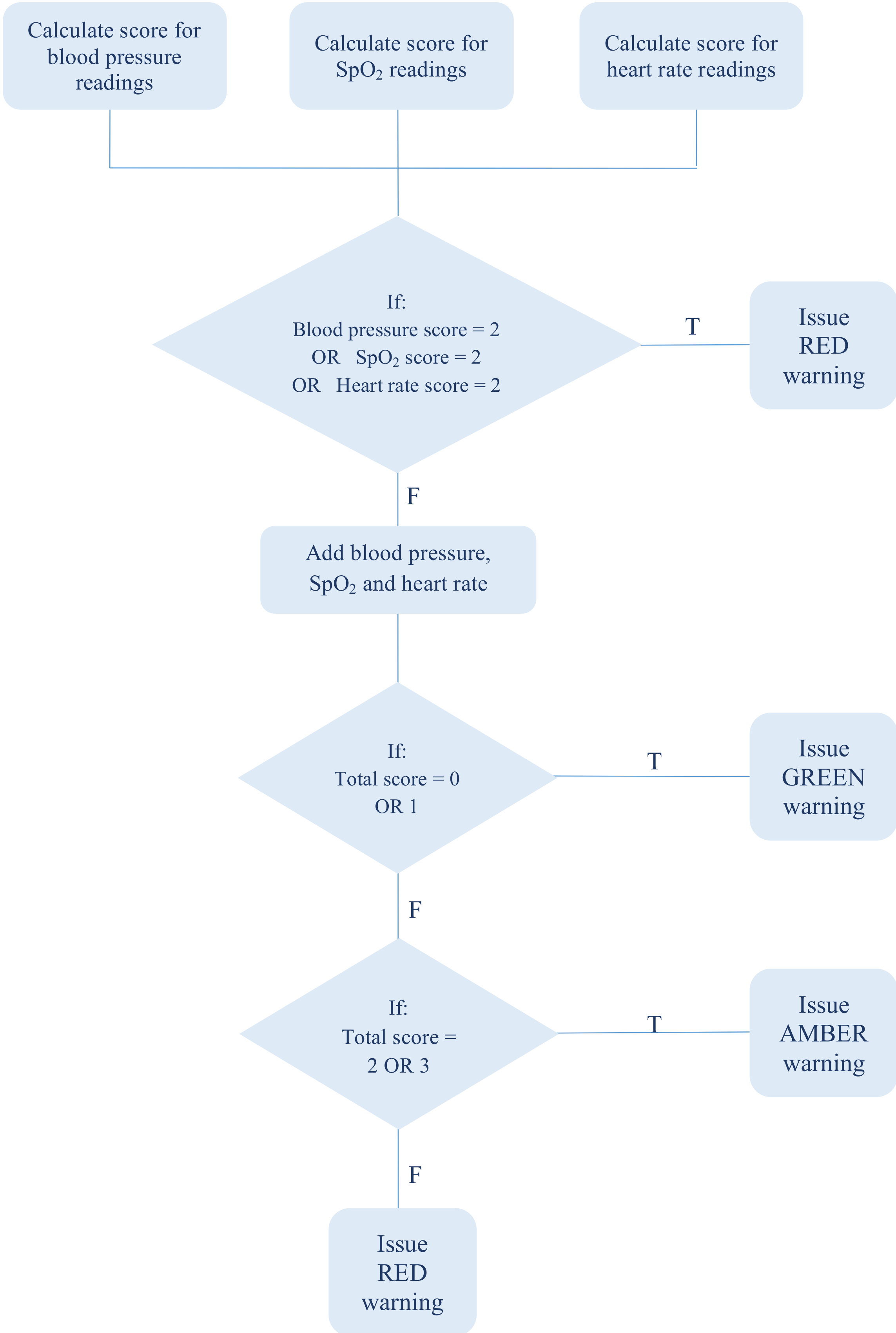

Fig. 3.2: Flow diagram of the wellness health algorithm.

3.4 Summary

The design of this project was geared towards carrying out three main broad functionalities: fetch data from multiple sources, transmit the data and display the data. In total, there are five devices encompassed in this project – four sensors to retrieve data and one device to display the data. Devices sensing data and devices displaying data are to be independent of one another. The sensors are to be on-body sensors transmitting data via Bluetooth. A smart wrist watch is used to display the data that has been collected, processed and analysed. The system is designed for it to work under different contexts. For example, in the hospital environment, ambulatory environment or home environment. Modification of the wellness health score algorithm is required to fit the system for a specified context.

Chapter 4

Implementation

The previous chapter described the overall design specifications of the system for patient health monitoring. In this chapter, the implementation of the prototype is detailed with respect to those outlined design specifications.

4.1 Sensor Data Collection and Processing

The prototype made use of four separate sensors which are detailed in the following sub-sections. They were utilised to capture readings as to simulate a body area network. Each sensor was wireless and worn or placed on the body strategically. The wireless communication technology used for each sensor was Bluetooth Low Energy or Bluetooth 4.0. Each sensor device was powered by coin cells or regular batteries. Figure 4.1 depicts the generalised process of data collection using the wireless sensors. The collecting of data via the sensors occurred simultaneously. All four sensors were fixed on the patient's body and measurements were taken concurrently.

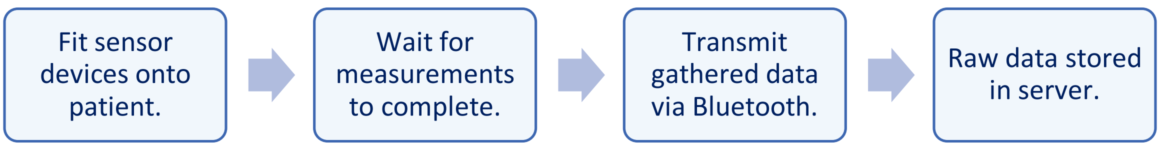

Fig. 4.1: Process of collecting data from sensors.

Data processing took place directly after the data collection. Processing of the raw data was completed in a developed Python program. This program pulled data from each of the servers and performed the necessary manipulation of data. A basic outline of the process is shown below in Figure 4.2.

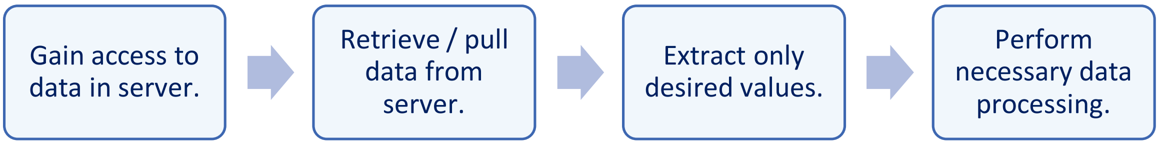

Fig. 4.2: Process for processing gathered data.

4.1.1 Blood Pressure Sensor

In order to measure blood pressure, the Withings Wireless Blood Pressure Monitor was used, depicted in Figure 4.3. The monitor measures blood pressure amongst other additional measures. For data collection, the wearable cuff device was fit on a person's the upper arm. Upon completion of each measurement, approximately thirty to forty-five seconds, the data was transmitted via Bluetooth Smart Ready to the personal server. The latter was a mobile phone application. Next, data was accessed from the cloud server using the application programming interface (API) and an end-user account. User identification, request token keys and secrets, and access token keys and secrets were used to gain permanent access. Lastly, a URL request with the tokens was made.

Fig. 4.3: Withings blood pressure monitor.

The retrieved data was stored in JSON format. A single sensor reading is shown in Figure 4.4. The monitor collects supplementary data, for example, time zone. Most of this additional data was redundant for this thesis project. However, heart rate was a value of use. This was because it was one of the other physiological activities measured as part of this dissertation. The heart rate data was used in the data aggregation stage. The JSON data was parsed to attain only the necessary values. From the raw JSON data, the systolic and diastolic blood pressure readings, and heart rate readings were extracted.

```
{u'status': 0,
 u'body':{u'timezone': u'Europe/Dublin',
         u'updatetime': 1468324429,
         u'measuregrps': [{u'date': 1468317958,
                           u'category': 1,
                           u'attrib': 0,
                           u'grpid': 575229971,
                           u'measures': [{u'type': 9,
                                          u'unit': 0,
                                          u'value': 72},
                                         {u'type': 10,
                                          u'unit': 0,
                                          u'value': 114},
                                         {u'type': 11,
                                          u'unit': 0,
                                          u'value': 80}]
                        }]
            }
  }
```


Fig. 4.4: JSON Format of single blood pressure sensor reading.

4.1.2 Blood Oxygen Saturation Sensor

The device used to collect blood oxygen saturation levels was the Happy Electronics Digital Wrist Pulse Oximeter. Similar to the blood pressure monitor, the pulse oximeter monitored blood oxygenation as well as other additional measures. The device had two wearable parts: an SpO_2 sensor and the body of the pulse oximeter. Both parts were connected for functionality. The SpO_2 sensor was fixed on the patient's finger, shown in Figure 4.5. Each reading of blood oxygenation took approximately two minutes to complete. Once the reading was complete, the collected data was sent to and stored in the server. Measurement data was stored in CSV format where each row had three values: time[sec], rr[sec/beat], SpO_2[%]. The first value is the total time spent measuring. The second value refers to the R-R interval which is the time between heart beats, and finally, the last value represents the blood oxygenation as a percentage. The CSV data was parsed to single out the blood oxygenation readings. Each row of the input data was parsed and converted into a list of strings. Figure 4.6 demonstrates the parsing of data for the first twenty rows. Using the list of strings, the SpO_2 data was extracted.

Fig. 4.5: Blood oxygen saturation hardware sensor.

	A
1	2.6729399999999277,0.7899999999999261,98
2	3.532939999999833,0.8599999999999053,98
3	4.442939999999733,0.9099999999998998,98
4	5.37293999999963,0.9299999999998976,99
5	6.212939999999538,0.8399999999999075,99
6	7.10293999999944,0.889999999999902,99
7	8.042939999999355,0.9399999999999151,99
8	8.862939999999629,0.8200000000002738,99
9	9.692939999999906,0.8300000000002772,99
10	10.492940000000173,0.8000000000002672,99
11	11.332940000000454,0.8400000000002805,99
12	12.112940000000714,0.7800000000002605,99
13	12.882940000000971,0.7700000000002571,99
14	15.81294000000195,0.9700000000003239,99
15	16.67294000000164,0.8599999999996886,99
16	17.472940000001195,0.7999999999995566,99
17	18.232940000000774,0.7599999999995788,99
18	19.01294000000034,0.7799999999995677,99
19	19.732939999999942,0.719999999999601,99
20	20.432939999999554,0.699999999999612,98

```
['2.6729399999999277,0.7899999999999261,98']
['3.532939999999833,0.8599999999999053,98']
['4.442939999999733,0.9099999999998998,98']
['5.37293999999963,0.9299999999998976,99']
['6.212939999999538,0.8399999999999075,99']
['7.10293999999944,0.889999999999902,99']
['8.042939999999355,0.9399999999999151,99']
['8.862939999999629,0.8200000000002738,99']
['9.692939999999906,0.8300000000002772,99']
['10.492940000000173,0.8000000000002672,99']
['11.332940000000454,0.8400000000002805,99']
['12.112940000000714,0.7800000000002605,99']
['12.882940000000971,0.7700000000002571,99']
['15.81294000000195,0.9700000000003239,99']
['16.67294000000164,0.8599999999996886,99']
['17.472940000001195,0.7999999999995566,99']
['18.232940000000774,0.7599999999995788,99']
['19.01294000000034,0.7799999999995677,99']
['19.732939999999942,0.719999999999601,99']
['20.432939999999554,0.699999999999612,98']
```

Fig. 4.6: Translation of CSV data to list of strings for data extraction.

In addition to obtaining the SpO_2 values, heart rate values were also derived. The R-R interval was used to calculate heart rate with a simple conversion. An example is shown in Figure 4.7 below with an R-R interval value of 0.75 seconds per beat. The heart rate data was used in the data aggregation stage.

$$Heart\ rate = \frac{1}{0.75\ {}^{sec}/_{beat}} \times 60\ {}^{sec}/_{min}$$

$$= 80\ {}^{beats}/_{min}$$

Fig. 4.7: Calculation of heart rate from an R-R interval.

In each of the two minute measurements, over one hundred sensor values were obtained for blood oxygenation and heart rate. Thus, to provide more accuracy of the SpO_2 and heart rate values, the all of the values were averaged to return a single more accurate result.

4.1.3 Heart Rate Sensor

The heart rate data was gathered using the Polar Heart Rate Sensor H7. As shown in Figure 4.8, this wearable sensor attached to a moistened electrode area on an elastic strap which is worn around the chest. The sensor detected a heart beat via an electric signal of the heart. According to Polar©, the accuracy and reliability of the H7 are that of an electrocardiogram (ECG). Similar to the Withings blood pressure monitor, the raw data was sent to a cloud server and fetched using an end-user account. Again, tokens and URL requests were used to gain access. Raw data was retrieved in a plain ASCII text file with timestamps, heart rate values and R-R interval values. The text file was parsed using the approach of a delimiter to get the latest reading.

Fig. 4.8: Polar Heart Rate Sensor H7.

4.1.4 Accelerometer Sensor

The accelerometer sensor of the Android device, depicted in Figure 4.9, is hardware-based. To retrieve the accelerometer data from the accelerometer sensor in the Android device, a basic Android application was developed. The application was built using Android Studio 2.2 using Java and XML. It was deployed on a Samsung Galaxy S5 mobile phone and ran on the Android 6.0.1 Marshmallow version.

During each sensor event, the accelerometer returns a multi-dimensional array. This array contains the acceleration force along the X, Y and Z axes. Each force takes the unit of m/s^2.

Fig. 4.9: View of Android application used to gather acceleration data.

The acceleration sensor in the Android mobile phone measures the forces applied to the sensor itself. However, the force of gravity must be taken into account as it influences the measured acceleration, shown in the relationship below in Figure 4.10.

$$A_d = -g - \sum \frac{F_s}{mass}$$

$$A_d = acceleration, \quad F_s = force\ applied\ to\ sensor, \quad g = -9.81 m/s^2$$

Fig. 4.10: Calculation acceleration with the influence of gravity.

This means that the force of gravity was factored into the acceleration when the data was gathered. Thus, in order to measure the real acceleration of the device, gravity was removed from the data. As seen in Figure 4.11, each time the sensor values changed, gravity was isolated and removed. In the onSensorChanged(Sensor event) method:

1) Using a low-pass filter, isolate the force of gravity.

2) Using a high-pass filter, remove the force of gravity from the X, Y and Z coordinates.

```
@Override
public void onSensorChanged(SensorEvent event) {
    final float alpha = 0.8;

    // Isolate the force of gravity with the low-pass filter.
    gravity[0] = alpha * gravity[0] + (1 - alpha) * event.values[0];
    gravity[1] = alpha * gravity[1] + (1 - alpha) * event.values[1];
    gravity[2] = alpha * gravity[2] + (1 - alpha) * event.values[2];

    // Remove the gravity contribution with the high-pass filter.
    float xCoor = event.values[0] - gravity[0];
    float yCoor = event.values[1] - gravity[1];
    float zCoor = event.values[2] - gravity[2];
```

Fig. 4.11: Code isolating and removing gravity from acceleration values.

In the snippet of code, 'event.values[0]', 'event.values[1]' and 'event.values[2]' represent the X, Y and Z coordinates respectively. Figure 4.9 shows the Android application with the force of gravity factored out. The left screen shows values when the device is held still whereas the right screen demonstrates acceleration values for movement.

As a further implementation, for each of the acceleration values retrieved from the sensor, a timestamp was associated with it. This allowed for the ability to determine whether there was movement within a particular timeframe.

Upon retrieval of the acceleration values in the X, Y and Z axes, the next step was to provide meaning to the values. Analysis on the raw values established whether a sudden movement occurred. In order to do this, the change in acceleration values was determined from the previous sensor event to the current sensor event for each axis. If the calculated change was above a particular threshold or within a certain range, the current sensor event was classified as a sudden movement. This was tested by repeatedly physically moving the Android phone either simulating a sudden movement or not. Following this, using the associated timestamps of each reading, if a sudden movement was detected within the last five minutes, a warning of "Movement: < 5mins ago" was issued.

4.1.5 Sensor Data Summary

The table below, Table 4.1, highlights the collected, processed and utilised sensor values for each of the sensors.

Sensor Hardware	Collected and Utilised Data
Blood Pressure Monitor	Blood pressure Heart rate
Blood Oxygen Saturation Monitor	Blood oxygen saturation Heart rate
Heart Rate Sensor	Heart rate
Accelerometer Sensor	Acceleration (excluding gravity) Movement indication

Table 4.1: Summary of data values gained from sensor hardware.

4.2 Data Aggregation

Following the collection and processing of the raw data, select values were aggregated. As mentioned in the previous section, additional measures were gathered by the blood pressure monitor. Specifically, heart rate was one of those supplementary measurements. The pulse oximeter also provided heart rate as an additional readings. Due to heart rate being one of the physiological measures involved in this thesis project, the heart rate readings from the heart rate sensor, blood pressure monitor and pulse oximeter were averaged. This allowed for a more accurate overall reading.

4.3 Data Analysis with Wellness Score

Data collection, processing and aggregation produced four values per sensor event. These were:

1) A single blood pressure reading including systolic and diastolic (mm Hg).
2) A single blood oxygen saturation reading (%).
3) An averaged heart rate value (bpm) based off three readings from three different sensors.
4) An indicator of a sudden movement in a five-minute timeframe based off accelerometer readings.

The next step was to pass through the data, not including the movement data, into the wellness health score algorithm. First, the algorithm was designed using 'if' and 'else if' statements. Conditions were implemented based on the designed wellness health score algorithm. It involved a combination of the three physiological measures and respective action code was written. Action code returned either one of three options: red warning, amber warning or green warning; as well as a total score. Figure 3.2 in Chapter 3 Section 3.3.1 depicts the control flow of the wellness health algorithm.

4.4 Issuing Warnings

As mentioned in the previous section as well as Section 3.3, specific warnings were to be issued depending on the outcome of the wellness health scoring algorithm. Warnings were relayed to the end-user using the Pebble smart watch. A simple Pebble watch application was built using the Pebble developer SDK in the C programming language. Cloud Pebble and an emulator of the Pebble watch were used to develop the application. The application retrieved the result yielded by the wellness health score algorithm and deployed a respective warning on the watch face. Red and amber scores led to the vibration of the Pebble smart watch whereas a green score yielded no warning. The red and amber scores were distinguished via a specific vibration pattern. The Pebble Development API allowed for vibration patterns to be created and customised, shown in Figure 4.1.2. A summary of the wellness health score algorithm and respective warnings are portrayed in Table 4.2.

```
// Red vibe pattern: LONG ON for 500ms, SHORT OFF for 100ms, repeat:
static const uint32_t const segments[] = { 500, 100, 500, 100, 500 };
VibePattern redPattern = {
  .durations = segments,
  .num_segments = ARRAY_LENGTH(segments),
};
vibes_enqueue_custom_pattern(redPattern);
```

Fig. 4.12: Code for customised vibration pattern associated with a red alert.

	Interpretation	Issued Warning
Red	○ Progressively worsening condition ○ Immediate action to flag attending physician	○ 'RED' appears on screen ○ One long vibration
Amber	○ Health condition a cause for concern ○ Action in near future via more frequent check-ups	○ 'AMBER' appears on screen ○ Two brief vibrations
Green	○ Good health; patient stable ○ No action required except standard check-ups	○ 'GREEN' appears on screen ○ No vibration warning

Table 4.2: Summary of wellness health score and warnings.

4.4 Data Communication

Communication of data was made various times from application to server and vice versa. Firstly, for data collection, data was transmitted from the sensors to the corresponding application and then, to the servers. Next, data was retrieved from the server to a Python program for data processing and data analysis. The issuing of warnings also required data to be communicated from server to application. These will be detailed in the following sub-sections.

4.4.1 Sensor to Application and Server

Values obtained from sensors were sent via Bluetooth Low Energy to the corresponding mobile application of the sensor acting as the personal server. An end-user account was associated with each application and raw data values were then stored in cloud servers under that account.

4.4.2 Server to Python Program

A Python program was implemented to carry out the data processing and data analysis. Retrieving data from the servers required gaining access to them. For each sensor, these are summarised in the sub-sections of Chapter 4, Section 4.1.

4.4.3 Application to Python Program

Data retrieved from the accelerometer sensor in the Android mobile phone were sent to the Python program for data processing and analysis. This involved sending data from an Android application programmed in Java to a program written in Python. The Android application acted as a Java client and the Python program was the server. In the Java client, the Socket and DataOutputStream classes were used to communicate the data. The Python server also made use of sockets. The socket bound to the host and port specified by the client and waited for a connection. Upon an established connection, the message containing the data values was received.

An additional layer was required to permit this data communication. Part of the Android API, the AsyncTask class was implemented. This class allows background operations and allows results to be published without having to manipulate any threads or handlers. The asynchronous task was defined by four steps: onPreExecute(), doInBackground(), onProgressUpdate() and onPostExecute(). The action code to communicate the data was carried out in the doInBackground() function.

4.4.4 Python Program to Application

The last area of data communication was from the Python program to the Pebble watch application. The Pebble watch application was written in C. Thus, data was transferred from Python to C. In order to do so, Popen and sub-processes were utilised. The 'popen' function is available in both Python and C. The function's role is to connect a program of either Python or C with the other using a pipe.

Data from the Python program was to be utilised in the C application. Thus, the C application was a sub-process within the Python program. The C program was started using the 'subprocess' module. Firstly, in the Python program 'Popen' and 'PIPE' were imported from the 'subprocess' library. The key lines to run the C program with the data from the Python program is shown in Figure 4.13 below.

```
warningData = applyWellnessAlgorithm(...);
p = subprocess.Popen("warningSystem.c", stdin=subprocess.PIPE)
p.stdin.write(warningData)
```

Fig. 4.13: Popen and PIPE to communicate data from Python to C.

Note that the '…' as the parameter for 'applyWellnessAlgorithm' were the systolic, diastolic, blood oxygenation, heart rate and movement values.

4.5 Summary

This chapter provided a description of the physical set up, configuration and implementation of the prototype. It provided an overview of the software used in the development process. In terms of hardware, the prototype uses three biomedical sensors, an accelerometer sensor and a smart watch. APIs were used to extract data and to build applications to represent and interpret data.

Chapter 5

Evaluation

In the previous chapter, it detailed how the system was implemented and process of implementation. It highlighted the software and hardware used. This section of the report will address the experiments carried out and their corresponding results. It further discusses the performance and validation of the system. Finally, it provides an evaluation of the select aspects chosen for the system.

5.1 Experimentation

Running tests and experiments was necessary to ensure that the prototype ran according to the specifications mentioned in Chapter 3 and as intended. All experiments were conducted using the prototype system. Each experiment yielded the expected results.

5.1.1 Test/Experiment A

The first experiment conducted was testing the system for a person of normal health. The expected outcome was for 'GREEN' to appear on the Pebble watch face. For the experiment, first, the blood pressure monitor, pulse oximeter and heart rate monitor were placed on the subject, myself. The Android mobile phone with the accelerometer sensor was also on the subject. The Android phone was moved at a slow pace to simulate movement data. Next, the measurements began. After each sensor had completed its measurement, the Pebble watch emulator received an alert. The measurement values were reflective of a 'GREEN' score. The results for one of multiple experiments ran are shown in Table 5.1 and Figure 5.1 below.

Measures	**Recorded Values**	**Score**
Blood pressure	113 / 79 mm Hg	0
Blood oxygen saturation	99 %	0
Heart rate	72 bpm	0
Total Score:		0

Table 5.1: Results of experiment of system for normal health.

Fig. 5.1: Pebble watch displaying warning for stable patient.

The results of this experiment were as expected. Given the sensor values, the warning and wellness score issued on the smart watch reflected the correct output of ‘GREEN’ and ‘0/6’. The display had no mention of movement because the movement that occurred in the experiment was not detected as ‘sudden’ by the data analysis on the accelerometer data. This was correct. Further, this experiment was carried out twenty-six times on myself. For each test, the display on the watch face was reflective of the sensor value interpretations.

5.1.2 Test/Experiment B

The second experiment tested the system for a person in an increasingly worsening condition. Due to circumstances, the system could not be tested on a real human in a serious condition. Thus, data was simulated to reflect poor health. A set of simulated values for each of the categories as shown in Table 5.2. In addition, in this experiment, two minutes before the sensors began their measurements, the mobile phone was moved suddenly as to simulate a fall. The final outcome on the Pebble watch is depicted in Figure 5.2.

Measures	Recorded Values	Score
Blood pressure	97 / 54 mm Hg	2
Blood oxygen saturation	94 %	1
Heart rate	72 bpm	0
Total Score:		3

Table 5.2: Results of experiment of system for very poor health.

Fig. 5.2. Pebble watch displaying warning yielded for a patient with an increasingly poor outcome.

Again, the outcome is as expected. Despite the wellness score reading ‘3/6’, a red warning was issued. It should automatically occur to the end-user that one of the physiological measures has a score of two. Thus, meaning that the patient is in a progressively deteriorating condition. Also, the sudden movement was detected within a five-minute timeframe by the system and, thus, displayed as supplementary data on the watch.

5.1.3 Test/Experiment C

Data was also simulated for a person of mildly poor health due to the same reason as a person with a critical condition stated in Section 5.1.2. In terms of testing movement, a sudden movement of the Android phone was made ten minutes before the measurements began. Table 5.3 below depicts the simulated values and Figure 5.3 shows the outcome of the warning system.

Measures	**Recorded Values**	**Score**
Blood pressure	113 / 79 mm Hg	0
Blood oxygen saturation	92 %	1
Heart rate	42 bpm	1
Total Score:		2

Table 5.3: Results of experiment of system for slightly abnormal health.

Fig. 5.3: Pebble watch displaying warning for a slightly abnormal patient.

The display on the smart watch is, again, correct. According to the simulated sensor values, an 'AMBER' warning and a wellness score of '2/6' is to be displayed. As for the sudden movement executed in the experiment, no data was rightly displayed on the watch face because the sudden movement occurred more than five minutes before the sensor measurements completed.

While the accuracy of the 'AMBER' and 'RED' conditions cannot be tested directly on the patient, each proved to be accurate in the simulations. For Experiment B and Experiment C, over fifty simulated sensor values were generated and tested. Each displayed the correct data on the watch face.

5.2 Performance of System

As mentioned in the Introductory and Design chapters, there was an overall goal for the system to perform as close to real time as possible. Thus, the execution time was measured independently for:

1) data retrieval
2) data processing and aggregation
3) data analysis.

Figure 5.4 depicts the execution times for data retrieval, data processing and aggregation and data analysis. The times were measured on twenty-two separate experiments. It is evident that each functionality varies in execution time. Data processing and aggregation had the longest runtime averaging at 0.1449 seconds. On the other hand, the lowest execution time was for data analysis at 0.000022 seconds on average. Finally, data retrieval had an average of 0.0777 seconds.

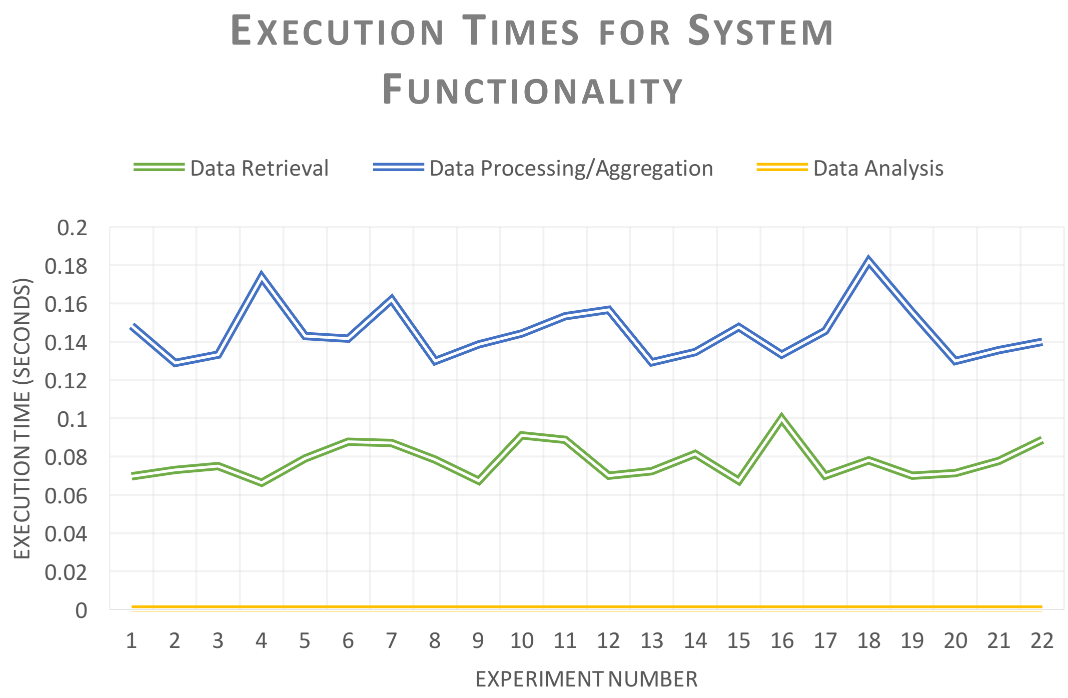

Fig. 5.4: Execution times for various functionality in the health monitoring system.

Additionally, the time it took for the Pebble application to receive the warning data and display it on the watch face was measured. On average, from the twenty-two separate experiments, execution time was 0.2084 seconds. Thus, the total execution time, from data retrieval up to the display of data at the end-user is:

$$\boldsymbol{Total\ execution\ time}$$

$$= data\ retrieval + data\ processing + data\ analysis + issue\ of\ warning$$

$$= \ 0.0777\ + 0.1449 + 0.000022 + 0.2084$$

$$= 0.4310\ seconds$$

Fig. 5.5: Calculation of total execution time of health monitoring system.

The total execution time of the system can be interpreted as the latency between when the physiological measurements are complete on the patient and when the warning appears on the end-user's smart watch. Thus, total execution time is equated to total end-to-end latency. Section 2.1.3 of this report details the end-to-end latency for existing wireless health monitoring systems. These figures were used as a baseline of acceptable latency. The result from the calculation in Figure 5.5 is 0.4310 seconds. Therefore, end-to-end latency of the presented system in this thesis project is greater than that of CodeBlue and less than that of MEDiSN and MASN. Thus, this comparison suggests an acceptable end-to-end latency for the designed and implemented system.

5.3 Validity of System

In terms of the validity of the system, comparisons with the state of the art wireless patient health monitoring systems were drawn. The prototype in this thesis project closely follows the typical system architecture employed by existing health monitoring systems. A tiered system was designed similar to those of the CodeBlue and the LifeGuard projects and the Integrated Health Monitoring System. These systems and the system presented here involve sensing modalities, portable personal servers and use of cloud servers to store data. Additionally, the physiological parameters selected for this thesis show overlap in the various systems discussed in Section 2.1.1.

Further, the creation of the wellness health score algorithm was initially based on the World Health Organisation thresholds for blood pressure, blood oxygen saturation and heart rate levels independently. This ensured that the algorithm be internationally accepted. However, it was necessary that the algorithm incorporate the values from all three sensors as a whole rather than independently. Consequently, the initial proposed algorithm was presented and examined by more than one clinician. For the group of four sensors, the clinicians advised the implementation of a set of rules which captured their understanding of which traffic light warnings should be issued for any combined sensor values. The waning system implemented these set of rules. Red, amber and green alerts were consistent with what the clinicians had recommended. Medical professionals were consulted during the design of the wellness algorithm to ensure that the generated score is accurate and of use in a medical environment.

5.4 Discussion

As mentioned earlier in this thesis, data values collected from the different sensors were stored in separate cloud servers. Each cloud server contained a history of all readings associated with that user. The existing storage of collected data from sensors was exploited in this thesis project to keep records of previous readings. By doing so, the system utilised existing software and implementation was less complex. The use of cloud servers also allowed for remote monitoring and remote data processing and analysis. Further, overlap of sensor readings between the individual sensors provided additional accuracy of gathered data. For example, heart rate readings benefitted from this. Another advantage to repeat readings is if the heart rate monitoring device runs out of battery. With multiple heart rate readings, a heart rate value can still be inputted into the wellness health score algorithm.

The Pebble smart watch was an appropriate choice for the warning system due to its long-lasting battery life. A fully charged Pebble watch typically lasts for six to seven days. Typically, nurses work for four days on and three days off. Running out of power and thus, being uninformed of any issued warnings was not a concern. However, as an extra precaution to avoid any uneasiness, the Pebble watch application was designed to display battery life in the form of percentage. This acted as a preventative measure for running out of battery power. Though, as mentioned in the Design chapter, any arbitrary smart watch with adequate battery life and capability of retrieving information and displaying it on the watch face suffices.

Chapter 6

Conclusion

The previous chapter summarised an evaluation of the proposed system and motivations behind choices. In this chapter, a summary will be provided focusing on the project and findings. Potential future work will also be discussed.

6.1 Project Overview

For this thesis project, the aim of the system was to generate and relay a warning to a potential medical professional from the collected data of a body area network on a patient. With the advent of telemedicine and wireless forms of communication, the system was directed to be as automated, electronic and unobtrusive as possible. In order to fulfil these goals, a design was proposed which integrates three sensor devices connected over Bluetooth Low Energy. The system also had the capability to wirelessly and remotely transmit, receive, process and relay data from the sensors. The design of the system takes on three main functionalities:

1) The reading of the data from various sources.
2) The transmission and analysis of the data.
3) The display of the data on a device.

A prototype was implemented according to the specifications detailed in the design. The prototype demonstrated the accuracy and effectiveness. The system was capable of processing sensed data from multiple sensors, contextualising them with helpful meaning suitable for a medical environment and displaying the analysed data on a smart watch. For every sensor reading, a 'traffic light' warning and wellness health score was displayed on the watch face. Depending on the warning issued and if required action by the end-user was required, a particular vibration of the watch was issued.

6.2 Contribution

This thesis project validates a health warning system. It goes one step further from collecting sensor data and presenting it. The system provides interprets and contextualises the data and provides varying alerts for medical professionals with health statuses for a patient. These alerts are divided into those that are not of concern, may raise concern and are of concern. Alerts, via a smart wrist watch, are 'worn on' the potential clinicians which is more practical than handheld devices. Our evaluation experimented and tested the system on the human body. The results and outcome of the system for each experiment were as expected, thus, demonstrating that the system works. Overall, this system has the potential to be applied in various medical environments including 'at home', ambulatory or hospital contexts.

6.3 Future Work

Despite the presented system providing data of use to clinicians, there is still room for improvement and extensions. To start with, there is always opportunity to improve the system as a whole in terms of providing more accurate health warnings. Three physiological measures alone are not likely to provide enough data for an accurate diagnosis in the hospital environment. Therefore, the integration of additional physiological measures or external environmental measures would be necessary to provide a more accurate diagnosis. For example, respiratory or temperature sensors could be added to the system and incorporated in the wellness health score algorithm. Improvement in terms of performance and accuracy is satisfied with the acquisition and generation of more data. If hardware sensors are not available for measurements, for example the appearance of patient, a handheld device could be used by nurses to input manual data which would then be integrated with the sensor data. Overall, to gain a more flexible, accurate and effective system, an increased number of biometric parameters would need to be measured. Learning and weighted classifiers may also be added to the algorithm.

Further, based off the proposed system, to reduce the variability from using different monitors to measure physiological parameters, a single device could be implemented. As mentioned in the Design chapter, this device would be capable of measuring a set of parameters. There has been recent development of multiple sensor measurements on wrist watches. Thus, the only variability here would be how tight one wears the watch or if there are consistently bad readings. However, the latter case would be detected in the dataset.

Another possible extension could be to provide more detailed alerts to the nurses and physicians. For example, the location of the patient (eg. ward and bed), the possible condition and the potential equipment needed. An alteration to the Pebble or smart watch application would be required to implement this. Adding more information on the end-user watch face would all help to increase efficiency and faster responses.

Appendix A

Abbreviations and Acronyms

ECG	Electrocardiography
EMG	Electromyography
CPOD	Chronic obstructive pulmonary disease
BAN	Body area network
BSN	Body sensor network
WSN	Wireless sensor network
MAC	Media access control
MIC	Medical implant communication
IEEE	Institute of Electrical and Electronics Engineers
WPAN	Wireless personal area networks
PHY	Physical
POS	Personal operating space
AODV	Ad hoc on-demand vector
BLE	Bluetooth low energy
PAN	Personal area network
WHO	World Health Organisation
BP	Blood pressure
mm Hg	Millimeters of mercury
SpO_2	Blood oxygen saturation
bpm	Beats per minute
kb/s	Kilobytes per second
Mb/s	Megabytes per second
API	Application programming interface

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