Integrated Wireless Vital Signs Monitoring System for Specific Anaesthesia Parameters

Submitted in partial fulfilment of the requirements of the Degree of

Master of Engineering (Electrical)

by

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Symbols and Acronyms

In this paper, we will use the following acronyms:

$$\begin{aligned}
\text{WPMT} &= \text{Wireless Patient Monitoring System} \\
\text{ECG} &= \text{Electrocardiography} \\
\text{EEG} &= \text{Electroencephalography} \\
\text{PPG} &= \text{Photoplethysmography} \\
\text{LED} &= \text{Light Emitting Diode} \\
\text{OS} &= \text{Operating System} \\
\text{VNC} &= \text{Virtual Network Computing} \\
\text{NEXT} &= \text{THIS IS A SAMPLE}
\end{aligned}$$

Abstract

This thesis considers the problem of the rejection of exogenous disturbance signals applied to a linear time invariant plant. An analysis of the disturbance rejection performance of periodically time varying feedback controllers is conducted. The performance used is the induced system norm of the closed loop disturbance response system.

The analysis considers both discrete systems, in which both plant and controller operate in discrete-time, and also sampled-data systems, in which the plant operates in continuous-time, while the controller operates in discrete-time. The disturbance input signals under consideration are assumed to belong to the l_p signal spaces (for discrete systems) and the L_p signal spaces (for sampled-data systems).

In the analysis, time invariant controllers are distinguished from strictly periodically time varying controllers. This allows a comparison to be made of the relative disturbance rejection performance of these two classes of controllers. For a given nonlinear time invariant periodic controller, a nonlinear time invariant controller is constructed which stabilizes the closed loop system when applied to the linear time invariant plant. Necessary and sufficient conditions are presented under which the nonlinear time invariant controller gives strictly better disturbance rejection performance than the nonlinear time invariant periodic controller.

Earlier results on l_2 (and L_2) performance of linear periodic controllers are extended to present a unified treatment of l_p performance for all $p \in [1, \infty]$ (respectively, L_p performance for all $p \in [1, \infty]$). Results are obtained for both linear and nonlinear controllers. Thus results in the literature on the inferior disturbance rejection performance of linear periodic controllers are shown to remain valid when the class of controllers is extended to include nonlinear controllers. Thus the principal claims to originality of this thesis are that it obtains results for a wider class of disturbance signals, and that it provides a performance comparison of nonlinear time

varying controllers with nonlinear time invariant controllers.

Contents

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Chapter 1

Introduction and Background

1.1 The Spaghetti Syndrome and its Implications - the need for a Wireless Vital Signs Monitoring System

Modern surgeries are challenging working environments involving a combination of complex devices, computers and humans working under stressful and time critical conditions. However, to date there are far too many wired devices communication between machines, monitoring patient physiological conditions and still requiring considerable attention by experts for monitoring and decision making.

In an era where surgery is ubiquitous, an ever increasing number of devices are attached to critically ill patients, multiplying the number of wires and tubes connected to the patient which results in a net resembling a plate of spaghetti; hence, the coinage of the term the Spaghetti Syndrome [6]. This conundrum has been present in the context of critical care, anaesthesia, and operating theatres for almost three decades with the advent of new technological advances in medicine [7]. This issue clearly illustrates the need for a system which is not physically connected to avoid possible harm and injury to both the surgeons and patients in the operating theatre.

The presence of wires in the surgery room introduces the possibility of increased surgery duration due to tripping hazards. More severe trips could lead to further surgical complications, due to wire disconnections which results in inaccurate readings of vital signs. Consequently, a possible overdose or underdose of anaesthetic agents could follow, leading to patient injury, and in the worst case scenario, the demise of the patient. Indirectly, wires in the operating theatre increase the rate of mortality during surgeries.

One possible course of action to rectify this problem is to remove cables connected to patients by replacing the medium of transmission from a wire to electromagnetic waves. In recent years, multiple research projects have been carried out with the aim to embed vital sign sensors with wireless technology to separate patients from cables [8].

Nevertheless, most advances in this area of wireless device development is limited to the context of medical centres and not operating theatres.

1.2 Benefits of a Wireless Implementation

Having a wireless version of current vital signs monitoring systems will bring additional benefits to

Ease of use - convenience Less risk of injury Faster surgery - smaller delay due to obstruction from wires Safer Better working environment for doctors

1.3 Overview of the Project

This paper will consider the process and challenges of developing a fully integrated wireless vital signs monitoring system for vital signs specifically for anaesthetic parameters such as electrocardiography (ECG), photoplethysmography (PPG), electroencephalography (EEG), blood pressure, and blood temperature. The front end of the project encompasses the collection and processing of raw data from different sensors including the visualisation and presentation of vital signs information, according to some specified performance criterion. The back end of the project involves the wireless transmission and reception of the processed information to a fixed output display and possibly, a secure database.

The aim of this project is to make as many patient monitoring, measuring devices as fully wireless so enabling more freedom of movement for both patients, nurses, and medical staff. What makes this first task challenging is that the wireless network (WA) system must be safe, secure and as reliable as current wired systems. Once completed, we envisage a new program in the development of pervasive wireless network resources for anesthetists and surgical practice in general. In these cases being hands-free, being able to access information, direct activities by simple movement, gestures adds to more efficient and clean surgical practice.

The project involves two parts:

1. programming hardware nodes to collect wireless sensor data using Android, and
2. software application development to visualize the data in real-time. The project also involves estimating missing data and inferring suitable information to medical professionals. The project requires developing a mobile app and also a data analysis platform.

1.4 Anaesthetic Parameters for Patient Monitoring

Countless operations are conducted on a daily basis which requires patients to be under general anaesthesia. To ensure the patient's optimal safety when under anaesthesia, it is necessary to consistently monitor certain parameters to ensure that they remain within a specified range which is considered to be safe or normal. Based on Atlee's Complications in Anesthesia [9], monitoring of anaesthetic admisnistration reduces the probability of anaesthetic overdose or underdose.

Complications associated with an improper dosage of anaesthesia could arise such as coma, brain damage, nerve damage, or possibly death, if real-time observations of vital signs are not conducted. The risk of such issues occuring during surgery could be reduced significantly if a feedback system were implemented for the amount of anaesthetics administered to the patient. Such parameters have been stipulated by ANZCA.

1.4.1 Theory of Electrocardiography

The electrocardiogram (ECG) refers to the recording of the "differences in electrical potential generated by the heart" using electrodes which are placed on the surface of the skin [10]. Both the action potentials generated by individual cells and sequence of activation affect the signal registered during electrocardiography [10]. Other factors which alter the final signal include "the position of the heart within the body, the nature of the intervening tissue, and the distance to the recording electrode" [10]. Despite the many factors which can possibly contribute a change to the electrocardiogram, it is still possible to deduce with high accuracy the state of the heart from the surface ECG due to "the careful correlation of electrocardiographic patterns with observed anatomic, pathologic, and physiologic data" [10].

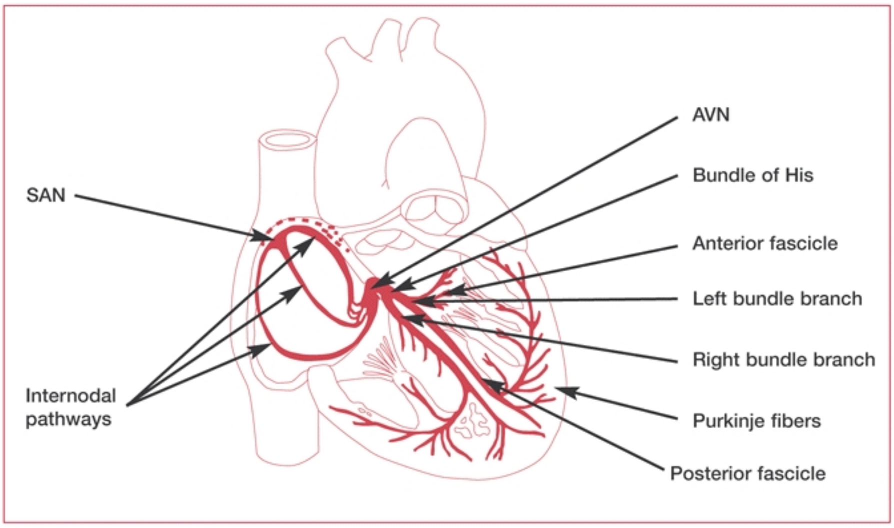

Figure 1.1: The Cardiac Depolarization Route. AVN: Atrioventricular Node; SAN: Sinoatrial Node. [1]

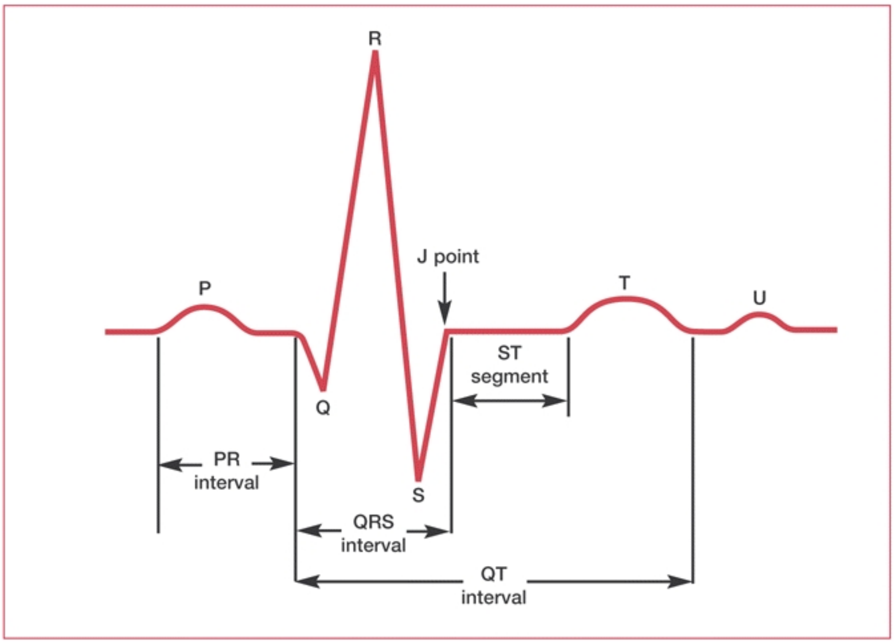

Figure 1.2: The Basic Pattern of Electrical Activity across the Heart [2]

Figure 1.2 shows a graphical representation of a typical electrocardiograph trace of the electrical signals from the heart.

The basic ECG pattern is correlated as follows:

- "Electrical activity towards a lead causes an upward deflection" [2]
- "Electrical activity away from a lead causes a downward deflection" [2]
- "Depolarization and repolarization deflections occur in opposite directions" [2]

Ashley and Niebauer (2004) (p.g. 19) [2] succinctly explains the types of waves and intervals of the ECG trace, (which mainly comprises of three different waves, namely P, QRS complex, and T):

> "The **P wave** is a small deflection wave that represents atrial depolarization.
>
> The **PR interval** is the time between the first deflection of the P wave and the first deflection of the QRS complex.
>
> The three waves of the **QRS complex** represent ventricular depolarization. For the inexperienced, one of the most confusing aspects of ECG reading is the labeling

of these waves. The rule is: if the wave immediately after the P wave is an upward deflection, it is an R wave; if it is a downward deflection, it is a Q wave:

- small **Q waves** correspond to depolarization of the interventricular septum. Q waves can also relate to breathing and are generally small and thin. They can also signal an old myocardial infarction (in which case they are big and wide)
- the **R wave** reflects depolarization of the main mass of the ventricles hence it is the largest wave
- the **S wave** signifies the final depolarization of the ventricles, at the base of the heart

The **ST segment**, which is also known as the ST interval, is the time between the end of the QRS complex and the start of the T wave. It reflects the period of zero potential between ventricular depolarization and repolarization.

T waves represent ventricular repolarization (atrial repolarization is obscured by the large QRS complex)."

1.4.2 Theory of Electroencephalography

1.4.3 Theory of Photoplethysmography

1.4.4 Theory of Blood Pressure

1.4.5 Theory of Blood Temperature

Chapter 2

Survey of Related Previous Work - Overview of Wireless Sensor Network Technology

2.1 Wireless Sensor Networks

In line with the expansion of Internet of Things, this project is able to incorporate the idea of smart and ubiquitous connections between devices [11].

2.2 Body Area Networks

2.3 Methods of Wireless Transmission

2.3.1 Comparison between VNC and Raw Transmission

VNC encryption isolation - big point security - authentication full remote control over patient's devices

Raw Less processing power required Less delay

2.4 WiFi

2.5 Bluetooth

2.6 Zigbee

2.7 Comparison of Different Protocols

Test1	Test2

Chapter 3

Project Implementation

3.1 System Overview

The hardware of this vital signs monitoring system has been divided into three major sections, namely:

- Sensors - Collects raw measurements of separate vital sign parameters
- Terminals - Processes data and handle transmission/reception of information
- Display - Visualises output of critical vital sign information

A block diagram of the Wireless Vital Signs Monitoring System is shown in Figure 3.1 down below. The system consists of three major portions: the Sensors which collect the raw measurements of separate vital sign parameters, the Terminals which process the data and handle transmission/reception of information, and the Display which visualises the output. The details of the development and options considered for each portion are further described in Sections 5, 4, and 6.

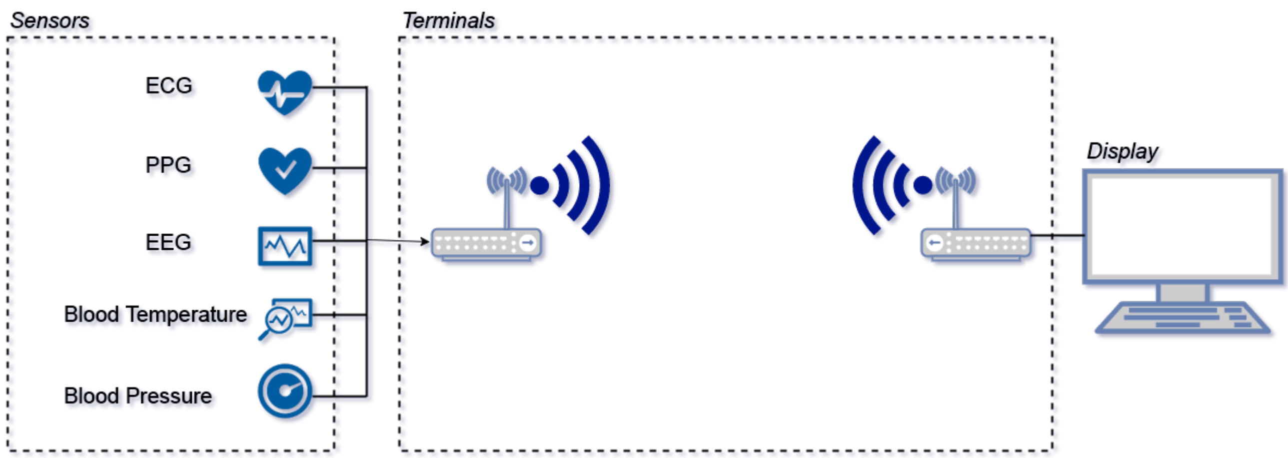

Figure 3.1: Wireless Vital Signs Monitoring System Block Diagram

3.2 Hardware Design and Development

3.2.1 Design Specifications

3.3 Software Design and Development

3.4 Analysis of Competitors - Similar Papers - Literature Review

Chapter 4

Terminals for Data Processing

The **Terminal** or **Platform** in this report refers to the machine or computer (hardware) which handles the processing of the raw measurements acquired from the sensors, the visualisation of the data received, in addition to the transmission and reception of the information from one geographical location to another through electromagnetic waves. Multiple types of terminals were considered and the factors which were accounted for were:

1. Processing Power
2. Operating System
3. Price
4. Power Consumption
5. Wireless Capabilities
6. Number of Input/Output Ports

4.1 Operating System

Of all the factors mentioned above, the OS for the Terminal is the most important and deserves a section of its own for further discussion. The OS must be fully capable of running the software required for data processing, data visualisation, virtual network computing (VNC) server hosting, and wireless transmission. Consequently, the OS determines which Terminal should be chosen as some platforms are designed based on a specific OS.

Based on the above criteria, Linux was chosen for this project due to the open source nature of the OS. Many software programs and applications required for the functionality specified, such as the ones mentioned in Section 3.3, are readily available without cost from the Linux software database. Despite being an open source technology, security is not a concern but on the contrary, a significant advantage [12]. By releasing the source code of the OS to the general public, security experts from various backgrounds and fields are able to identify major security flaws in the system [12]. This allows for the swift resolution of such breaches by developers around the world, making security issues nullified as soon as they are found. Unlike proprietary OS such as Windows, the international community of developers are the ones who maintain the system for Linux, rather than a fixed number of employees working in specific locations around the world.

Nevertheless, one substantial problem with Linux OS is drivers for new hardware components [12]. However, due to the lower level nature of this project, drivers can be developed and so does not pose a major threat. Other drivers required for microcontrollers such as the Arduino Uno/Arduino Pro Mini for analogue to digital conversion are readily available and hence, does not pose a major threat.

One such platform which runs on a Linux kernel is the Rasberry Pi 3. The Linux distribution which was suggested by default for this miniaturised computer is the Raspbian Jessie, which is the Raspberry Pi derivative of the long standing Debian distribution. More information about the Raspberry Pi 3 can be found in Section 4.2.

Having a platform that runs on a Linux kernel provides the significant advantage of the ease of migration. As the project is a pilot study in wireless vital signs monitoring systems, there is a foreseeable need to continuously upgrade the platforms in terms of hardware capabilities to accommodate other important features. As long as the Linux kernel is used, it is not difficult to migrate to another Linux-based platform as the applications database and drivers available do not differ greatly for specific Linux distributions.

of all these, the OS is the most important - deserves a section of its own for discussion very important - terminal is chosen based on this

Raspbian Jessie - Linux kernel - open source - more software and support available

- ease of migrating to other platforms - as long as the kernel remains the same

- windows considered -but proprietary - software will be expensive - issues if no support - limited support - need for payment

linux provides [22]

4.2 Raspberry Pi

from raspberry pi website - specifications

4.3 Intel Nuc

Chapter 5

Sensors

The **Sensors** in this report refer to the separate sensors connected to the body of the patient which collects raw measurements of vital sign paramaters, conditions the data so that it is suitable for analogue to digital conversion, and converts the data into a digital signal that can be interpreted by the platform which we refer to as the **Terminals**.

The sensors used in this project are enumerated as follows with the respective vital sign parameter measured:

1. ECG - AD8232 Heart Rate Monitor
2. PPG -
3. EEG -
4. Blood Pressure -
5. Blood Temperature - Thermistor coupled with Phase Shift Oscillator

The following sections below further discusses the reason behind the choices made for the individual sensors, the mechanism of operation, and how it interfaces with the entire system.

5.1 Analysis of Existing Systems

5.1.1 Consideration of Bionomadix

5.1.2 Consideration of Libelium and Waspmote

5.1.3 Consideration of Cooking Hacks

5.2 ECG

The ECG front end design consists of a number of parts.

The typical range of an ECG signal lies between 0.01-300Hz and 0.05-3mV in terms of frequency and amplitude respectively [13]. The voltages sampled from the surface of the skin through electrodes are too miniscule to be directly plotted and displayed. In addition, there are multiple frequencies which are of interest in ECG signals but the raw measurements will contain unwanted signal artifacts from other sources. Hence, it is necessary to amplify and filter the signal before any analysis or visualisation is performed.

In 1997, Strohmenger [14] did an analysis of ventricular fibrillation ECG signal amplitude and frequency parameters for both successful and unsuccesful cardiac arrest countershocks. In this paper, the frequency range and amplitude range of both cases corroborates with the typical values stated above.

5.2.1 SparkFun

In this project, in line with the aim of producing a system that is a working proof of concept, a simplified version of the ECG is used. The AD8232 Heart Rate Monitor from SparkFun Electronics [4].

Front End

The Analog Devices AD8232 was used to implement the ECG part of this project. The AD8232 is "an integrated signal conditioning block for ECG", "designed to extract, amplify, and filter small biopotential signals" [3]. The functional block diagram is included below in Figure 5.1.

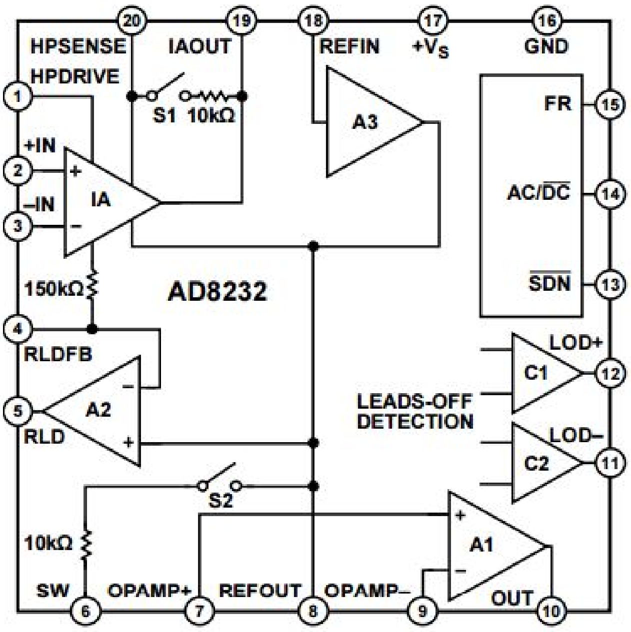

Figure 5.1: AD8232 Functional Block Diagram [3]

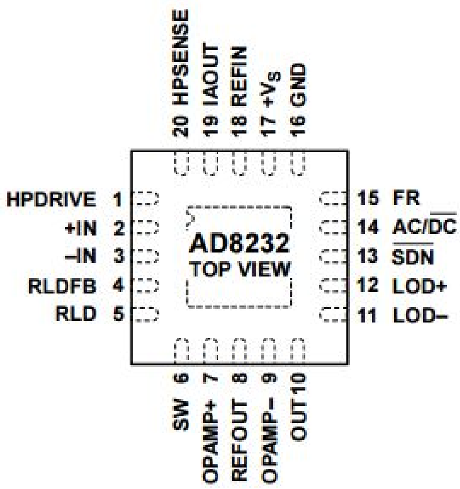

Figure 5.2: AD8232 Pin Configuration [3]

Theory of Operation of the AD8232

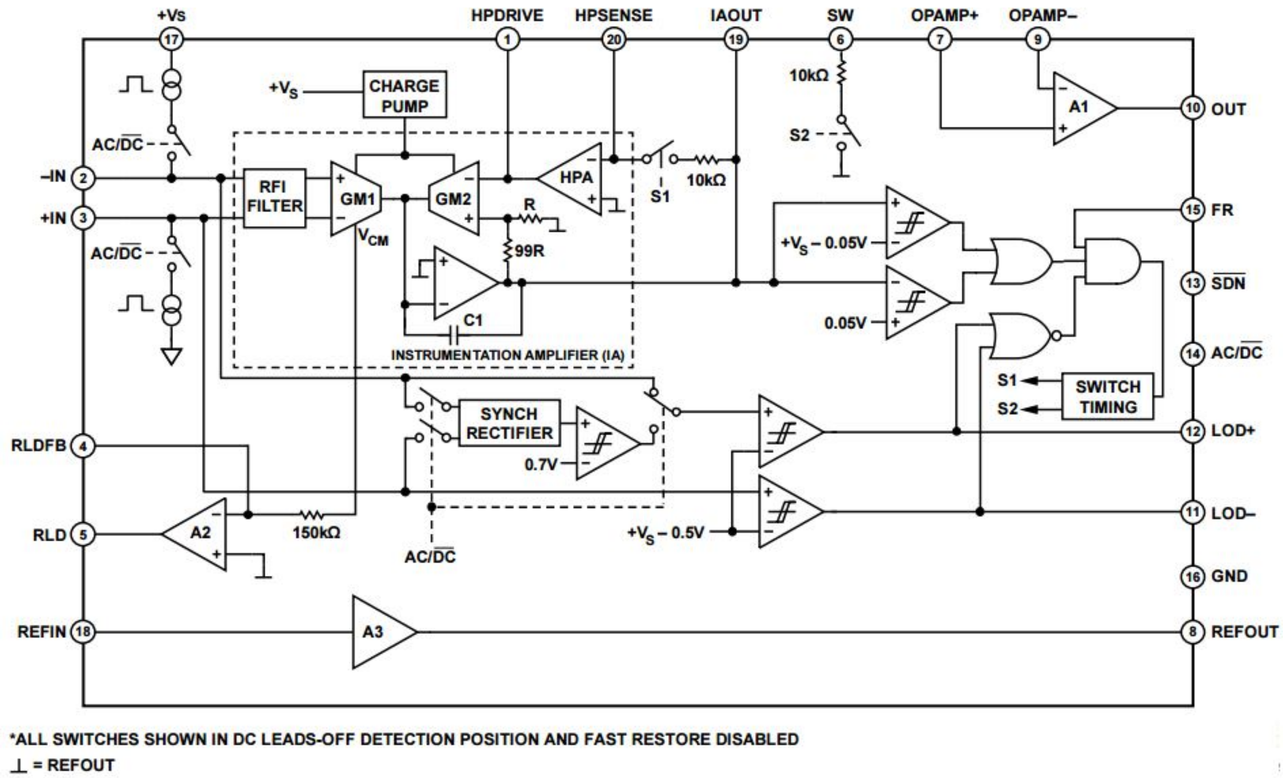

Figure 5.3: AD8232 Simplified Schematic Diagram [3]

Figure 5.3 above shows the architectural overview of the AD8232 chip from Analog Devices used for the "front end signal conditioning of cardiac biopotentials" [3] and is comprised of the following components:

- Specialized instrumentation amplifier (IA) - Amplifies ECG signals
- Operational amplifier (A1) - For low pass filtering and supplying extra gain
- Right leg drive amplifier (A2) - Improves common-mode signal rejection by inverting the signal
- Midsupply reference buffer (A3) - Provides a reference signal for the IA by creating a virtual ground between the supply voltage and system ground
- Leads off detection circuitry - Senses and indicates if the electrodes have been disconnected

- Automatic fast restore circuit - Decrease settling time of the ECG signal for a quicker response

[15]

[16]

[3]

AD8232 Cardiac Monitor Circuit Configuration

The datasheet for the AD8232 provided by Analog Devices supplies a typical circuit setup and configuration for a cardiac monitoring as seen in the schematic diagram in Figure 5.4 below [3]. A printed circuit board with this configuration could have been assembled and constructed using Altium Designer but due to time and cost constraints, an exact implementation of this circuit (with additional headers, an LED indicator, and a 3.5mm jack for biomedical pad connection) from SparkFun Electronics was used instead [4].

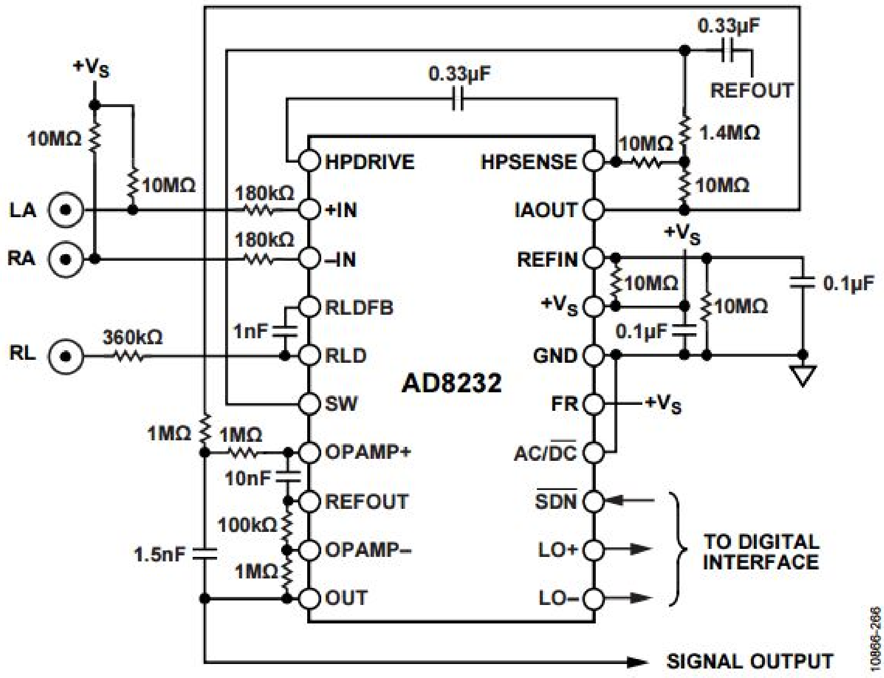

Figure 5.4: Circuit Configuration for ECG Waveform Monitoring using the AD8232 [3]

The schematic of the actual implementation of the AD8232 by SparkFun can be found in Appendix B.1.

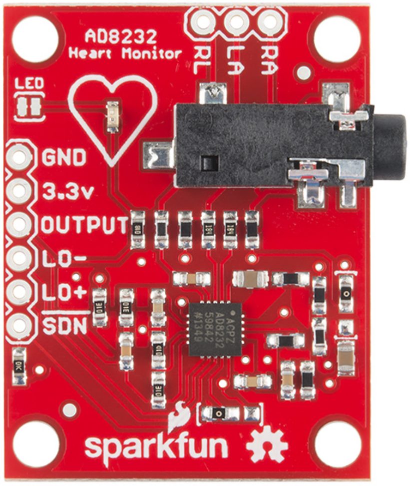

Figure 5.5: AD8232 Heart Rate Monitor from SparkFun Electronics [4]

CONSIDER PUTTING ALTIUM DESIGNER DESIGN

5.3 Blood Temperature

5.4 Interface

5.4.1 USB

5.4.2 Arduino Uno - Analog to Digital Conversion

Sensitivity of Arduino Uno

1023 bits

Chapter 6

Data Processing

6.1 Processing 2.2.1

6.2 Serial Input

6.3 Code

6.4 Visualisation

Chapter 7

Results

7.1 ECG

7.1.1 Operation

For normal ECG systems, 10 cables are sufficient to acquire and display 12 electrical perspectives of the heart [2]. The typical attachment sites are found in Figure 7.1 below.

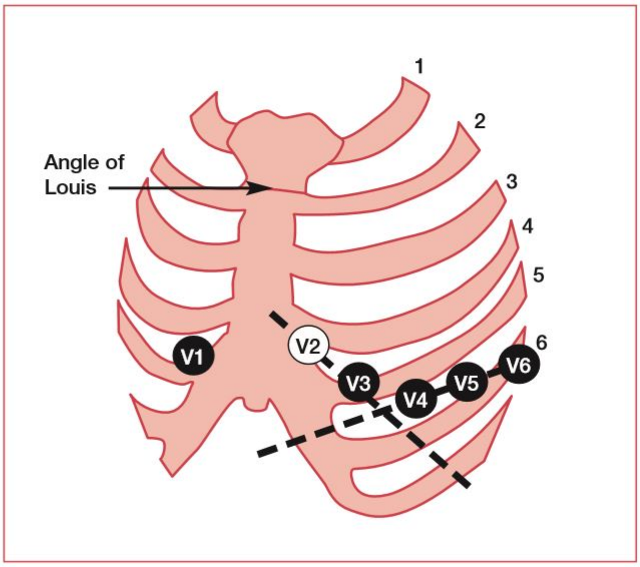

Figure 7.1: Typical Sensor Placements [2]

The AD8232 Heart Rate Monitor from SparkFun Electronics [4] provides three separate sensor pads and should be located in close proximity to the right arm, left arm, and the right leg, as seen in Figure 7.2 below.

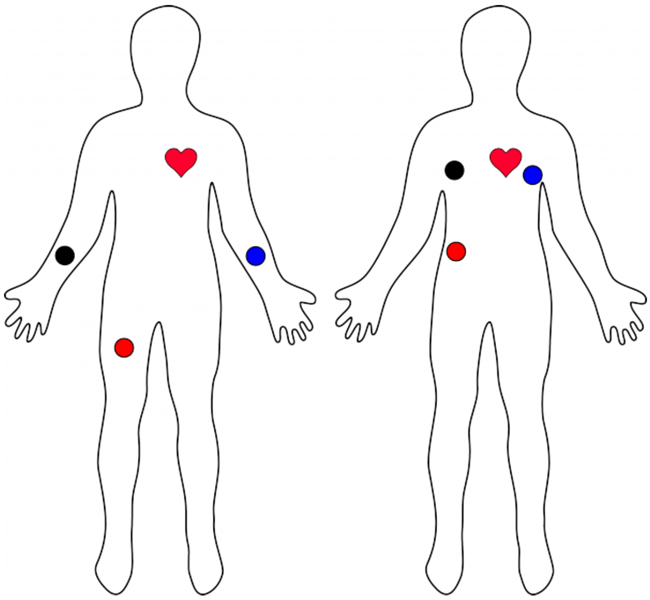

Figure 7.2: Typical Sensor Placements (3 Electrodes) [4]

In compliance with the suggested sites of sensor attachments, the approximate position of the electrodes are:

- 1 inch above the right nipple
- 1 inch above the left nipple
- 2.5 inches right of the navel

When initially operating the AD8232 Heart Rate Monitor, the ECG waveform output was not in the form of a recognisable heartbeat as seen in Figure 7.3. Several adjustments were necessary to reduce noise in the ECG output and to capture the heartbeat waveform.

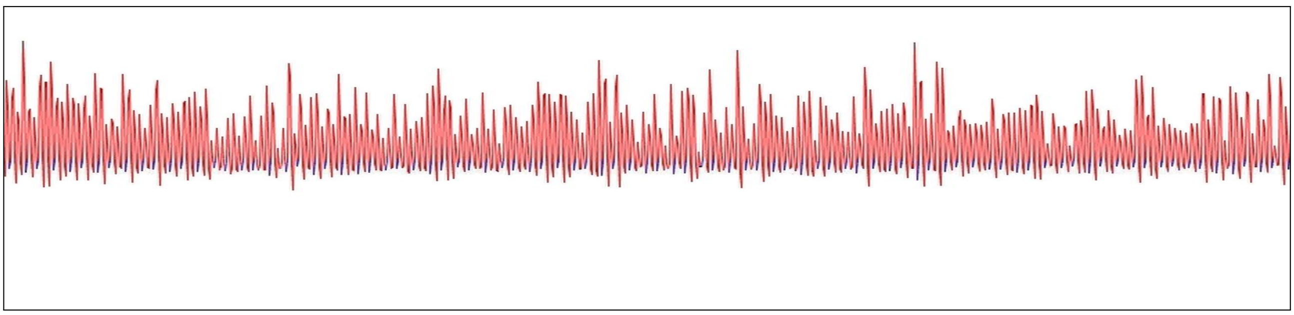

Figure 7.3: ECG Output Test 2

When conducting the experiments, it is noted that the ECG output is significantly affected by posture and position of the body. This is explained more in Section 7.1.2. The best results were obtained from an upright sitting position with hands resting in front on a horizontal platform.

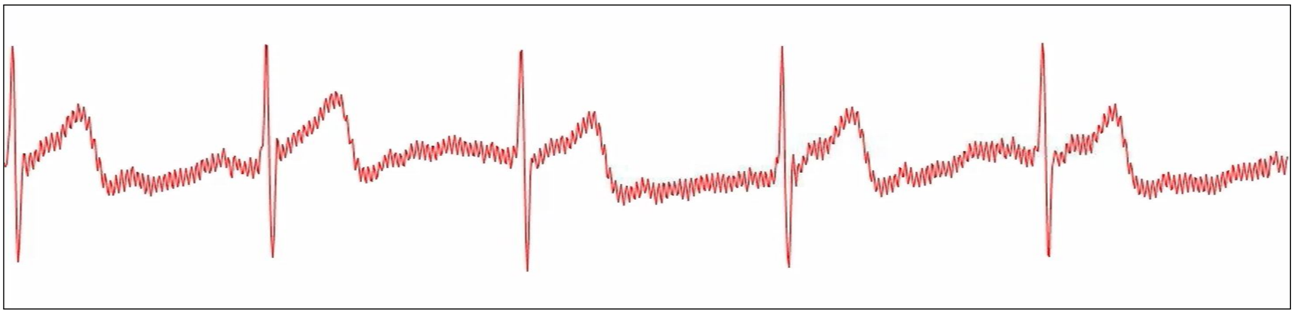

Figure 7.4: ECG Output recorded by the Raspberry Pi over WiFi

7.1.2 Motion Artifacts

At its core, ECG records electrical activity from muscle contractions through electrodes located on the skin [2]. As such, ECG systems are significantly affected by muscle contractions regardless of its origin. In measuring heart electrical activity, it is inevitable that electrical signals from other muscles in the body will be registered by the ECG system. Therefore, the output of ECG systems are highly variable and extremely susceptible to muscle movement, which introduces unwanted noise into the heart ECG output. This includes deep breathing or any movement of limbs while measurements are taken.

The AD8232 cardiac circuit configuration from the datasheet "assumes that the patient remains relatively still during the measurement, and therefore, motion artifacts are less of an issue" [3].

Figure 7.5 illustrates how breathing can affect the vertical axis of the ECG output.

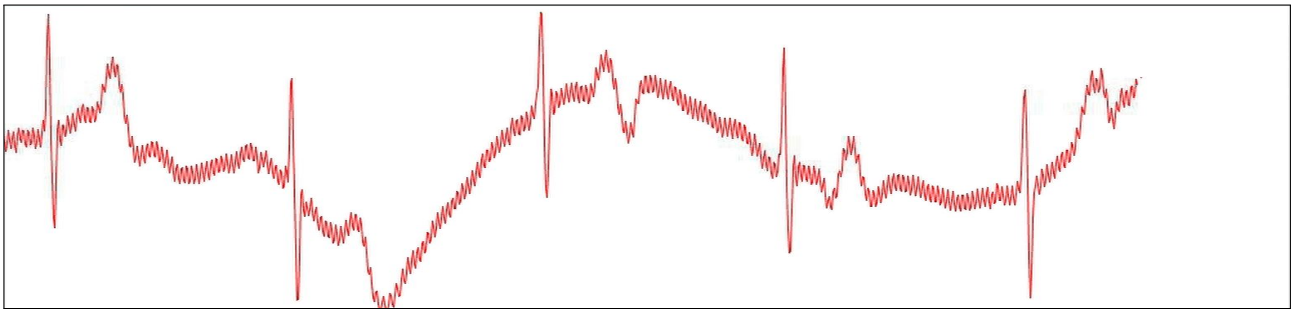

Figure 7.5: ECG Output with Deep Breathing

Figure 7.6 illustrates how moving limbs can affect the output of the ECG system.

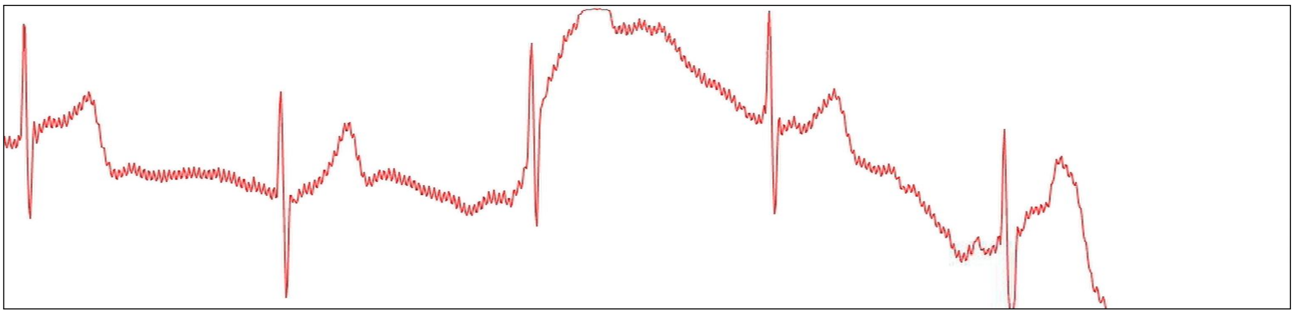

Figure 7.6: ECG Output with Limb Movement

Inconsistent ECG readings are also caused by actual abnormalities or deficiencies in the heart but these cases are not discussed in this report as they are not relevant to the inherent sources of errors found in the ECG system.

7.2 Statistics

SRW

Chapter 8

Challenges and Limitations

8.1 Power Efficiency

According to Sohraby, Minoli, and Taieb [18], power efficiency can be achieved by having:

1. ”Low-duty-cycle operation.”

2. ”Local/in-network processing to reduce data volume (and hence transmission time).”

3. ”Multihop networking reduces the requirement for long-range transmission since signal path loss is an inverse exponent with range or distance. Each node in the sensor network can act as a repeater, thereby reducing the link range coverage required and, in turn, the transmission power.”

8.2 Interference

One of the major problems identified with wireless systems in general is the high probability of interference.

8.3 Security Risk

8.4 Data Management

8.5 Regulation and Compliance Standards

8.6 Reliability

Raspberry Pi has ”uptime”

8.7 Range

Chapter 9

Conclusion

9.1 Summary of Main Results

9.2 Practical Interpretation of our Results

To provide some practical interpretation of our results, we may consider the following hypothetical scenario. A control engineer has designed a particular periodic discrete or sampled-data controller K for his closed loop feedback system. The engineer finds out about our results and is interested to hear that a time invariant controller can in general give strictly better disturbance rejection performance than his periodic controller. The engineer then asks us to tell him how to modify his periodic controller to obtain a superior time invariant controller. To advise him we

Appendix A

Program Installation

The operating system used for the project is Raspbian Jessie 3.0. This

Courier New - for installing raspbian programs

Appendix B

PCB Design

B.1 AD8232 Heart Rate Monitor SparkFun Implementation

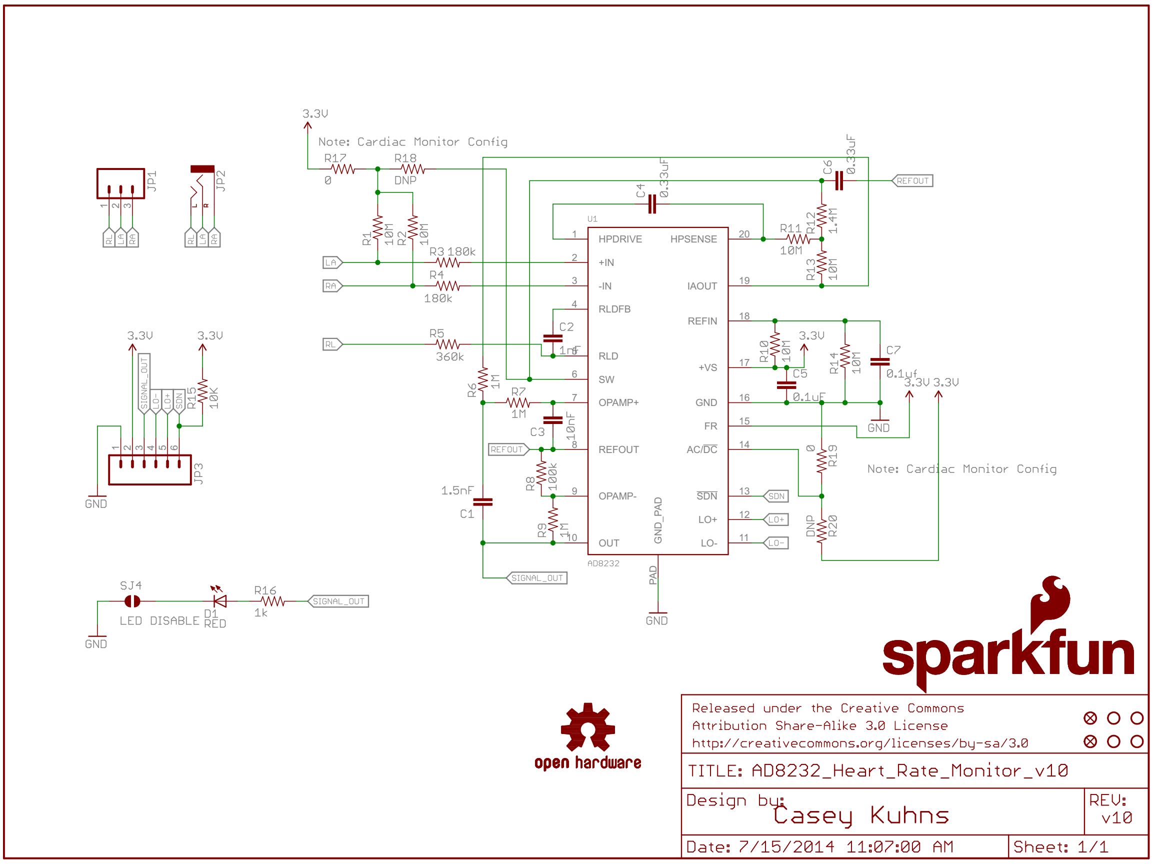

Figure B.1: AD8232 SparkFun Implementation Schematic Diagram [5]

Further details of the design can be found at

https://github.com/sparkfun/AD8232_Heart_Rate_Monitor.

Appendix C

Measurements

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