DEVELOPMENT OF A DETACHED VITAL SIGN HOME MONITORING MANAGEMENT SYSTEM

by

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ABSTRACT

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Patients coping with chronic illnesses are often inconvenienced with routine doctor visits for the sole purpose of conducting basic vital sign monitoring. Such visits tend to be disruptive, and are more so when the patient requires a lengthy commute or has a mobility disability. As technology progresses, advances in low powered integrated circuits and network connectivity has opened the doors to a new world of remote patient monitoring. This thesis explores the possibility of using low powered technology to develop a patient monitoring system that's completely detached, thus allowing patients to move around their homes while the monitoring continues. We discuss the development of such a system with various monitoring subsystems incorporated into the device. This system, being modular and flexible, will enable many configuration of monitoring subsystems to be present.

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CHAPTER 1

INTRODUCTION

Telemonitoring is a medical practice that allows patients to be monitored remotely. Health care providers are able to observe test results at a separate location from where the tests were carried out. Telemonitoring is an attractive alternative to conventional patient monitoring as it avoids frequent and tedious doctor visits. It is also beneficial from an economic point of view as the patients themselves execute various tests and avoid commuting. The monitoring normally involves multiple medical measurement and sensing devices and some sort of connectivity for relaying results to the patients' health care provider. Some common monitoring devices include, but are not limited to, blood pressure monitors, blood oxygen sensors, blood glucose monitors, ECG monitors, spirometers (monitoring lung function), and weight measures.

1.1 Motivation

Even within the comfort of one's home, vital sign monitoring can be disruptive and confines the patient to a fixed location while the monitoring takes place. Patients confined to wheelchairs may find it difficult to access these systems depending on the location where they are situated. A monitoring system that's small enough to fit on a wheelchair would provide more convenient access. In addition, power and other signal wires may pose a risk to the patients. The development of the Detached Vital Sign Management System attempts to make telemonitoring less disruptive to the patients.

The Detached Vital Sign Management System is a low powered modular device that allows monitoring to be done wirelessly around the home. The device comprises of a core microcontroller unit, several satellite microcontroller units, and a computer system for data storage and relaying information to the health care provider.

Each satellite microcontroller receives data from one or more satellite monitoring instruments and relays the monitored data to the core unit for Bluetooth transfer to the remote computer. At any given time, the system allows for many configurations of the satellites to be present. This modular design makes the system flexible enough to adapt to the specific needs of the patients. For example, ECG monitoring may not be required for a given patient. In this case, the ECG module could be removed from that system by simply unplugging it from the core unit. In addition, when only one measuring device is needed, the core unit can be omitted completely allowing the satellite unit to communicate directly to the server unit.

1.2 Overview

The rest of this thesis is organized as follows. Chapter 2 offers some background on the individual sensors incorporated into the system and insight on the vital sign parameters that they measure. In particular, an in-depth review of literature related to electrocardiograms is included, since part of this thesis work involves an attempt at the development of an ECG device. In this project, the core unit refers to the sole interface between all measuring subunits and the server. Chapter 3 provides an overview of the system and gives an introduction to the main components. Chapter 4 describes the core unit in detail. Chapter 5 describes the development of a portable, completely detached ECG device and its associated satellite module. Chapter 6 details the satellite module interfacing with a blood oxygen sensor. Chapter 7 discusses the spirometer satellite unit. The architectural design of the spirometer satellite unit is different from the other units because the microcontroller unit communicates with the measuring device via Bluetooth. Chapter 8 details the development of the remote server's three component processes. It also discusses the database system, and the protocol established for data transfers over Bluetooth. Chapter 9 provides the conclusion to this work and discusses future work.

CHAPTER 2

BACKGROUND

Vital sign monitoring is the measurement of the body's basic physical functions. Vital sign monitoring is normally used as a status indicator, granting physicians useful information regarding the current health of their patients. It is also essential for early detection of disease and other illnesses. The main physical parameters routinely monitored by medical professionals include electrocardiograms, body temperature, blood pressure, blood oxygen saturation, pulse rate, and respiration rate. These measurements are, in many cases, critical in early detection and prevention of medical complications.

2.1 Spirometer

In order to sustain life, living organisms depend on cellular respiration to gain useful energy for fueling everyday life processes. The most common type of respiration in organisms is known as aerobic respiration. This process requires oxygen and creates carbon dioxide as a byproduct. The lung, being an essential respiratory organ in the human body, is tasked with relaying oxygen from the outside atmosphere to the bloodstream. From there, the oxygen then makes its way to the cells within tissues in the body. A similar and important function of the lung is to release carbon dioxide from the body. Spirometry is an evaluation of the general lung function. By definition, it is the measurement of air volumes during forced expiration subsequent to a full and complete inspiration. The aim is to quantify how a patient inhales and exhales volumes of air as a function of time. Fig. 2.1 shows an image of a portable spirometer device (eResearchTechnology GmbH).

Figure 2.1 Image showing a portable spirometer

In May 2011, the National Institute of Allergy and Infectious Disease (NIAID) reported that about 1 in 12 people in the US suffer from Asthma costing the US about $56 billion in medical costs (National institute of Allergy). Fig. 2.2 is a graph showing the percentage of Americans suffering from Asthma categorized by age and sex. An even more morbid statistic is that the World Health Organization (WHO) reports that in 2008, 394 thousand people died in the North American continent as a result of respiratory diseases (242,500 of which were at the hands of Chronic Obstructive Pulmonary Disease) (World Health Organization). Spirometric evaluation can be vital in diagnosing respiratory illnesses such as Asthma, Chronic Obstructive Pulmonary disease, and other restrictive lung disorders (Pierce, Rob). Spirometry is also very useful in aiding health care providers to distinguish respiratory disease from cardiac disease in patients complaining of breathlessness.

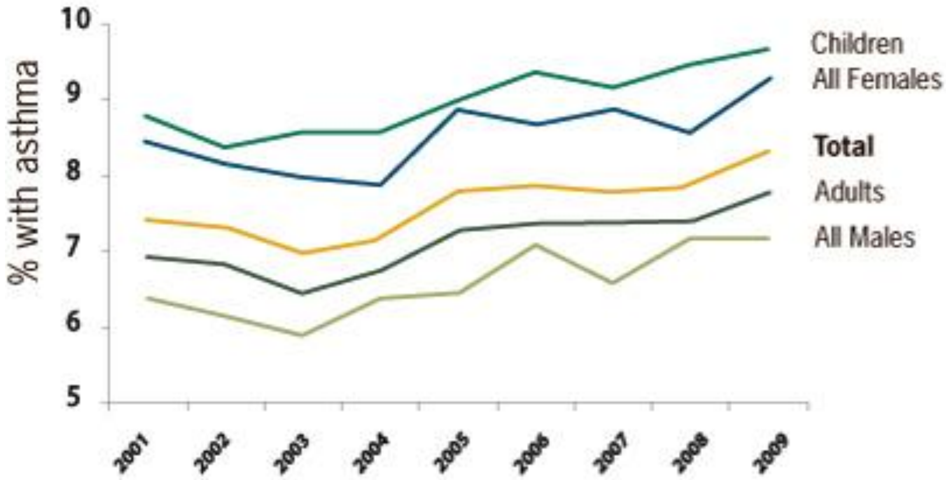


Figure 2.2 Asthma by age and sex in the US, 2001-2009

Some important measures obtained through spirometry are Forced Vital Capacity (FVC) and Forced Expiration Volume (FEV1). FVC is defined as the maximal volume of air (in liters) that can be exhaled forcefully after a full inspiration. FEV1, on the other hand, is the volume of air exhaled within the first second of an FVC test. The ratio of FEV1/FVC has been demonstrated to be a very effective indicator to identify airflow obstruction and thus has obvious diagnostic value. A third common pulmonary function parameter measured by spirometers is called peak expiration flow (PEF). As the name suggests, PEF is a patient's maximum rate of expiration. PEF measurements over time, for example, can indicate degradation or improvement of a patient's condition. It should be noted though that PEF measurements are not highly reproducible and hence is not the best parameter for predicting occurrences of Asthma attacks (Mortimer, Kathleen).

The typical procedure for obtaining accurate results includes inspiration of a lung full of air. Immediately after inhaling, the patient must place his or her lips around the spirometer mouthpiece and, in a forceful blast, exhale as fast as possible until their lungs are completely empty. Some spirometers also calculate inspiration-based measures such as Forced Inspiratory Vital Capacity (FIVC). Such spirometers would require a different test procedure.

2.2 Pulse Oximetry

Pulse oximetry is a noninvasive method of measuring blood oxygen saturation and pulse rate in patients. The measurement of arterial oxygen saturation is of fundamental importance to critical care medicine. Prolonged periods of low oxygen levels in the blood leads to a dangerous condition called Hypoxia. If this condition is not detected and corrected in time, irreversible tissue damage and even death can occur (Mendelson, Yitzhak). Thus, in very ill and high-risk patients, constant monitoring of blood oxygen saturation is often necessary. An older method for measuring arterial oxygen saturation includes the use of clinical blood gas analyzers to sample the patient’s blood at intervals (Mendelson, Yitzhak). The use of blood gas analyzers is obviously more invasive and only provides snap shots of blood saturation data rather than a continuous stream. The ability of pulse oximeters to provide continuous monitoring noninvasively has made them a very important diagnostic tool.

Figure 2.3 Fingertip Pulse Oximeter

As outlined in the article by Mendelson, pulse oximeters rely on the differences in optical absorbance of deoxyhemoglobin and oxyhemoglobin when exposed to light with wavelength of about 660nm (Mendelson 1601). In the spectrum, this wavelength is that of visible red light. Oxyhemoglobin, as the name suggests, is the form of hemoglobin when combined with oxygen. At 660nm light, the optical absorbance of oxyhemoglobin is less than that of deoxyhemoglobin. Also important, is that the opposite is true when exposed to light of wavelength between 815nm and 940nm (infrared light). When exposed to light of this wavelength, the optical absorbance of oxyhemoglobin is slightly greater than that of deoxyhemoglobin. The absorbance of infrared light in this case is used as a reference.

Takuo Aoyagi, a bioengineer in Tokyo, invented the current methodology of pulse oximetry in 1972 (Severinghaus, John). This method works by noting that cyclic (AC) variations in the detected absorbance signal are caused by rhythmic changes in the blood volume. This assumption is based on the fact that blood in the veins does not pulsate. Therefore, any variation of absorbance is due to changes in the volume of arterial blood. Fig. 2.4 shows changes of absorption with time due to different factors in the body (Mendelson, Yitzhak). This distinction is important as arterial blood carries oxyhemoglobin from the lungs and venous blood contains deoxyhemoglobin from the tissue. From this observation, it was determined that blood oxygen saturation can be derived by analysis of the rhythmic variances in absorbance caused by the pulsating arterial blood.

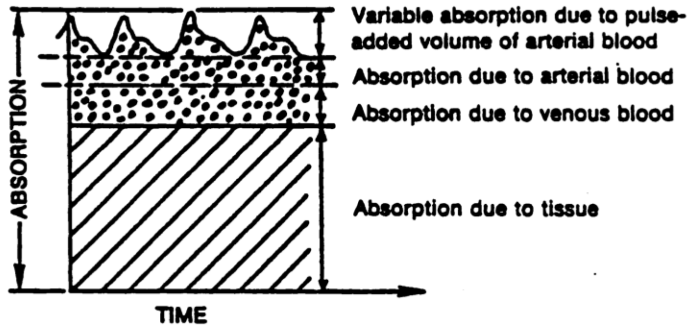


Figure 2.4 Illustration of light absorption in the body

In present day pulse oximeters, the light source is commonly from light-emitting diodes (LEDs). These are very efficient, low powered light sources. The fact that individual LED's emit slightly different intensities of light introduces a calibration issue. The optical sensors used for measuring the absorption may also individually differ slightly and present a similar issue. These issues are dealt with by normalization. Normalization involves dividing the AC component (pulsatile) by the corresponding DC (nonpulsatile) component. Normalization combined with pre-calibration greatly eliminates reproducibility issues between any two devices manufactured.

2.3 Electrocardiograph

Heart disease is the leading cause of death in the US. According to the American Heart Association, in 2008, cardiovascular disease caused 811,940 deaths in the US (Roger, Veronique). This accounted for a third of all deaths that year. Looking at this statistic from a different perspective, there was 1 death every 39 seconds that was attributed to cardiovascular disease. Fig. 2.5 provides a graphical illustration of the number of deaths in the US attributable to heart disease over the last century (Roger, Veronique). It is important to note that not all cardiovascular diseases can be categorized as a heart disease.

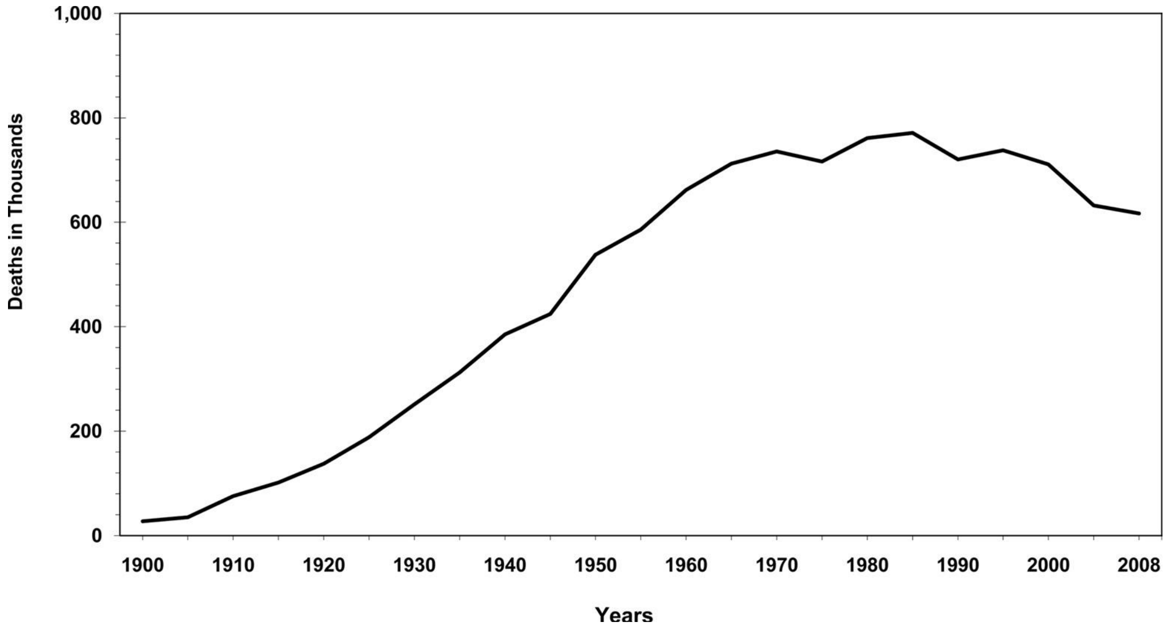


Figure 2.5 Deaths attributable to diseases of the heart in the US from 1900-2009

An important note is that not all states participated in the survey in the early 1900's.

There are many different types of heart diseases. They can be placed into the following categories: blood vessel related diseases (such as coronary artery disease), heart defects (such as congenital heart defects), and heart rhythm irregularities known as arrhythmias. Early detection is key for patients suffering from cardiac disorders. Detection of certain cardiac arrhythmia patterns can lead to identification and treatment of cardiac disorders while still in the early stages of the disease.

Nerves and muscles in the body generate bio-signals by their activity. The heart, which is made up of muscle tissue, generates rhythmic patterns of bio-potentials with every heartbeat. Its primary function being to circulate blood throughout the body, the chambers in the heart (atria and ventricles) contract in a well-coordinated sequence to produce this pumping effect. Potentials originating from repolarization and depolarization of the heart tissue that are measured at the outer surface of the body are referred to as electrocardiograms (ECGs) (Webster, John G. 147). They provide medical professionals with a view of the electrical signals associated to the heart with respect to time. The electrocardiogram has proven to be a valuable diagnostic tool for detection and identification of different types of cardiac disorders. ECG data may also be collected routinely as a means of uncovering hidden conditions through analysis of changes in the traces over time.

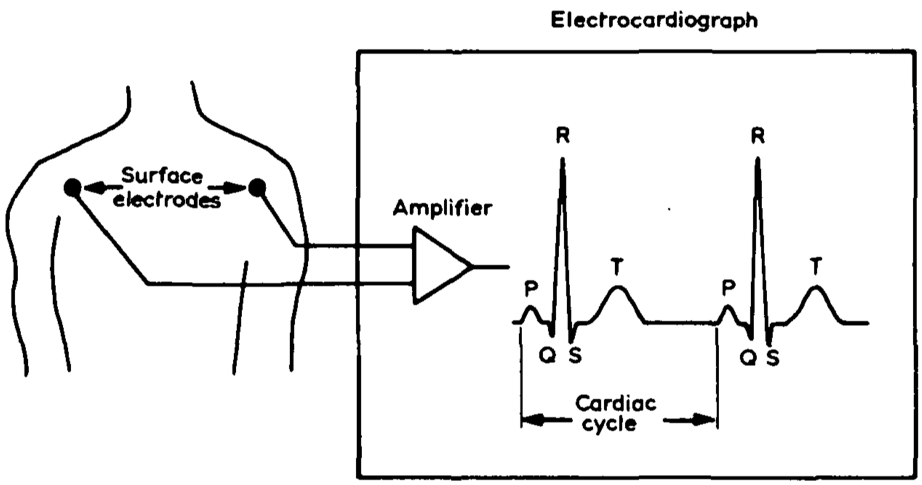


Figure 2.6 Image of a typical electrocardiograph

Fig. 2.6 illustrates a typical ECG waveform. As shown, the repeated cardiac cycles are made up of what are referred to as P, Q, R, S, and T waves. Each wave is attributed to an underlying electrical event emanating from the heart tissue. The P wave in each cycle is produced as atrial depolarization occurs, whereas, the Q, R, and S waves are mainly as a result of ventricular depolarization. Finally, the T wave is a byproduct of ventricular repolarization. The duration between these individual waves contain diagnostic information that physicians utilize.

2.3.1. ECG Electrodes

Cardiac monitoring by an ECG begins at the contact between the electrodes and the surface of the skin. Electric conductivity in the body involves the transmission of charge by ions (Neuman 189). Hence, in order to detect these minute ionic currents within the body, some form of transducer is required to convert these ionic currents into electric currents. Because of its non-polarizable nature, silver/silver chloride (Ag/AgCl) is a popular choice for biomedical electrodes. Once the ionic current has been converted into an electrical current in the electrode wires, the amplification phase follows.

2.3.2. Amplification

The minute voltages present at the electrode sites, often between 1uv and 5mv (Nagel 52-1), require amplification in order for the comparator within the microcontroller's analog to digital converter (ADC) to digitize this voltage with minimal error. A differential amplifier is used to amplify the difference between the two electrodes by a set gain. Differential amplifiers multiply any difference in voltage between the two inputs by the gain of the amplifier. Use of the differential amplifier assists in excluding external electromagnetic noise from the signal. This is because any electromagnet noise that may cause a change in potential in one electrode wire would do the same to the other. By measuring the difference between these two wires, the drifting, due to external noise, is significantly eliminated. As noted by (Webster, John G. 91), for the purpose of measuring bio-potentials, the three-op-amp differential amplifier topology is normally preferred. This type of differential amplifier is also referred to as an instrumentation amplifier. Fig. 2.7 is a diagram illustrating a typical instrumentation amplifier (Webster, John).

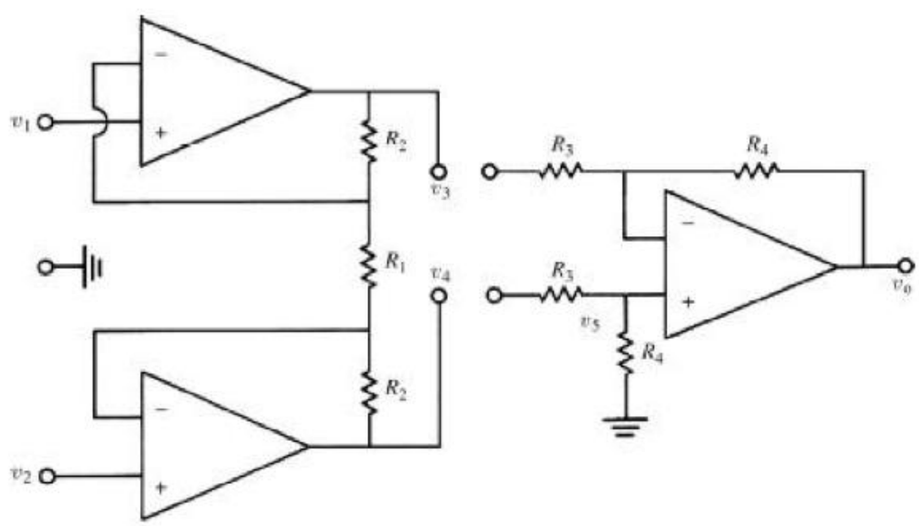


Figure 2.7 3-Opamp Instrumentation Amplifier

Instrumentation amplifiers are normally required for amplifying the very low outputs from transducers in noisy environments. Desired properties of an effective instrumentation amplifier include high common mode rejection, high input impedance, a low offset voltage, and a low input bias current.

2.3.2.1 Common-Mode Rejection

One source of noise encountered while measuring bio-signals is common-mode noise. A common mode signal is one which appears on both inputs of the amplifier having equal amplitude and in-phase with each other (Maxim Integrated). The human body can act as an antenna picking up electromagnetic noise from nearby power lines. This common-mode noise can make it difficult to measure the signal of interest. One characteristic of differential amplifiers is their common-mode rejection ratio (CMRR). This is the ratio between the differential signal gain (the gain of the signal of interest) and the common-mode signal gain (the gain of the common-mode interference). In most cases, when measuring bio-potentials, an instrumentation amplifier with a high CMRR is desired. The ideal differential amplifier perfectly rejects the common-mode voltage. In reality, no differential amplifier performs with such perfection. The CMRR serves as a measure to quantify this imperfection when comparing differential amplifiers.

2.3.2.2 High Input Impedance

The impedance at the inputs of an instrumentation amplifier needs to be very high. In an ideal case, no current should flow through the op-amps and, therefore, an input impedance of infinity is necessary. This ideal case, of course, is not realistic. The high impedance is favorable to prevent loading down of the source. This simply means that a current at the inputs could affect the very phenomenon that's being measured (in this case, the transducer). It is also necessary to have the impedance at both inputs very close in value to one another.

2.3.2.3 Low Offset Voltage

An ideal instrumentation amplifier should produce an output of 0V when the two inputs are the same. In reality, off-the-shelf op-amps are not able to perform with an offset voltage of 0. Whenever an offset voltage is present at the individual op-amps making up the instrumentation amplifier, this small difference is also amplified by the gain. This contributes to an error at the output. Therefore, a very small offset voltage is favorable.

2.3.2.4 Low Input Bias Current

In non-ideal instrumentation amplifiers, small bias currents exist at the op-amp inputs. These currents are converted to a small voltage by the input resistors and are amplified by the gain along with the signal. These bias currents add an error to the output, and hence, are undesirable.

2.3.3. Signal Filtering

The next phase in signal conditioning is the filtering out of unwanted noise that might have made its way through the instrumentation amplifier. The frequency range of the signal generated by the heart is normally between 0.05Hz and 100Hz (Onaral, Banu). Therefore, excluding any frequencies not included in this range is normally desired. By cutting off frequencies less than 0.05Hz, the dc component is filtered out. The dc component causes undesirable baseline shifts in the electrograph. This sort of filtering can be accomplished by building a band-pass filter. Band-pass filters, as the name suggests, only allows a certain range of frequencies to pass. Band-pass filters can be thought of as a low-pass filter (for blocking off frequencies higher than the frequency range of interest) added to a high-pass filter (for blocking off frequencies lower than the band of interest). Concerning filtering, what has been discussed so far is still insufficient. A major source of electromagnetic noise encountered by devices emanate from the 50/60Hz hum in power lines. This 60Hz (in the US) noise (and its harmonic at 120Hz) from nearby power lines needs to be addressed. Band-stop filters can be used to eliminate these frequencies while preserving the other frequencies that we are interested in. As opposed to band-pass filter, band-stop filter blocks a range of frequencies from a signal allowing all other frequencies through. In this project, the 60Hz and 120Hz noise are cancelled with the help of a digital filter within the microcontroller.

2.3.4. Measuring the Signal

The next stage is to digitize the analog signal. An ADC is used to convert the analog signal to digital data that can be transmitted, stored, and displayed later. ADC's are devices used for converting analog continuous-time signals into discrete-time binary representations (Walden, Robert H.). They operate by measuring samples of the input signal at regular intervals of time. The number of samples taken per unit time is referred to as the sample rate. There are several different ADC architectures. The more common architectures include direct-conversion, successive-approximation, delta-sigma, integrating, and sub-ranging ADC's.

The direct-conversion, also known as flash ADC, measures the voltages buffered by comparing the captured voltage with a number of known voltages (fractions of some reference voltage). The highest fraction of the reference voltage that is less than the signal is encoded into a binary representation. The number of reference fractions (quantization levels) compared determines the resolution of the ADC. For example, an 8-bit ADC can only compare a signal to 255 voltage levels. An 8-bit ADC with a voltage reference of 5V compares the signal to references having voltage levels at increasing multiples of 0.0196V (i.e. $5V/(2^8-1)$). Since ECG signals span such a large range of values (1uV - 5mV), an ADC with 16 bit resolution or more is best. An illustration of a flash ADC can be seen below in Fig. 2.8 (Maxim Integrated). Although flash ADC's can achieve very high sample rates in comparison to the other architectures, they are normally not capable of very high resolutions. This is mainly because two to the power of the desired resolution of comparators minus one are necessary for flash ADC's to operate. As an example, an 8-bit ADC requires 255 comparators. This shortcoming makes direct-conversion ADC's less desirable for projects that demand higher precision measurements. The direct-conversion architecture is simplistic and represents a more traditional approach to converting analog signals to digital values.

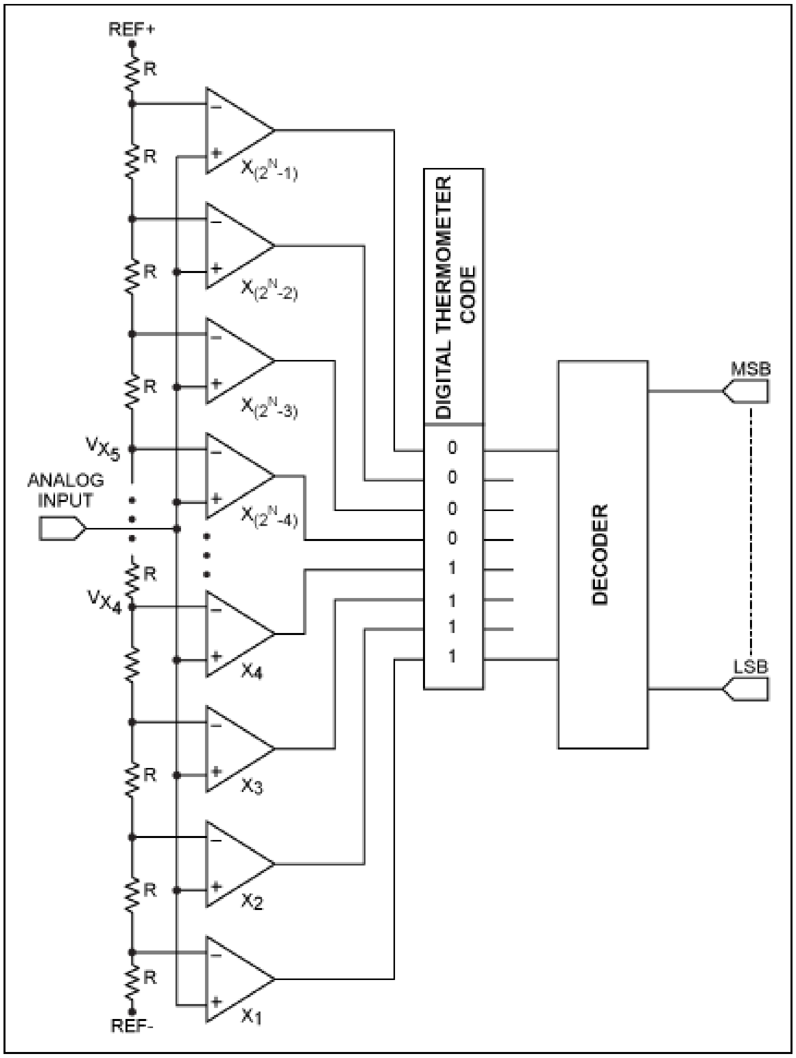


Figure 2.8 Flash ADC Architecture

Another ADC architecture worth discussing, which is more complex than the direct-conversion variety and applicable to this paper, is the Delta-Sigma ADC. Many applications may not demand the high sampling capabilities of a direct-conversion ADC but instead require a high resolution for more precise measurements. The Delta-Sigma ADC is made up of very basic analog electronics. These include a single comparator, a voltage reference, a switch, integrators, and summing circuits. On the other hand, the digital aspect of this architecture is very complex. The digital section consists of a digital signal processor (DSP) that serves as a filter. Fig. 2.9 provides a basic illustration of the Sigma-Delta ADC architecture (Kester, Walt).

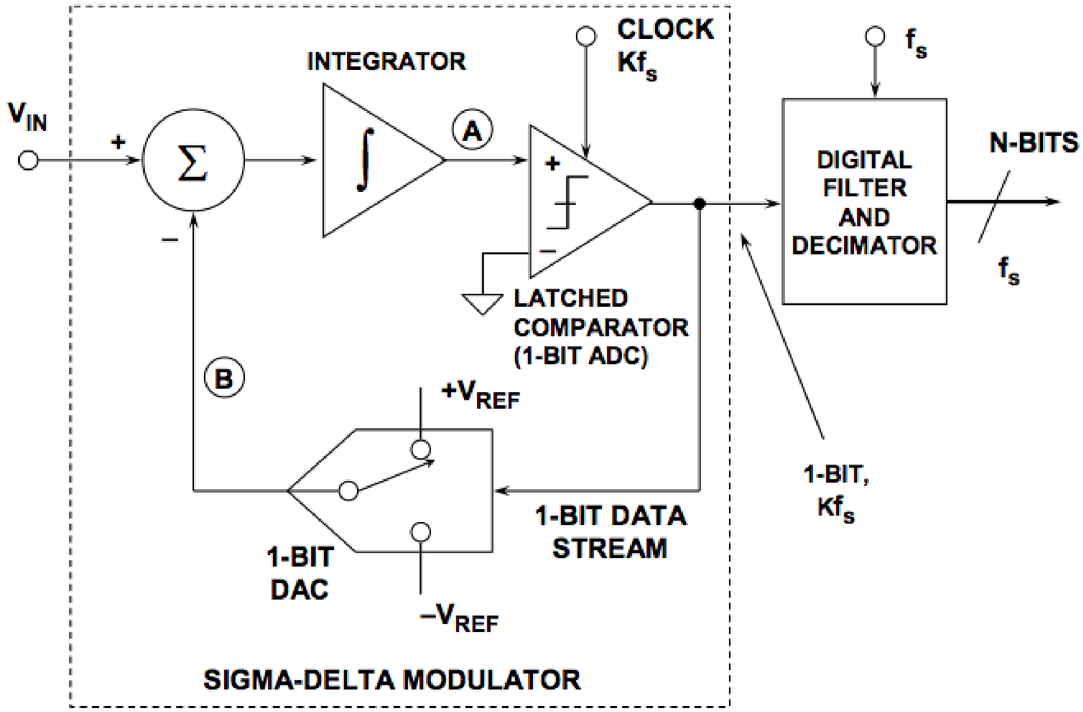


Figure 2.9 Sigma-Delta ADC Architecture

2.4 Cypress PSoC 5

The PSoC 5 is a programmable embedded system-on-chip produced by Cypress Semiconductor Corporation. This particular chip is unique amongst other microcontrollers in that it allows the user to program necessary peripherals on the chip instead of having the chip manufacturer decide on what, and how many, peripherals should be included. Microcontroller peripherals are additional devices integrated on the same chip as the CPU. Such peripherals include ADC's, digital-to-analog converters (DAC's), SPI buses, UART buses, USB, among many others.

Internally, the PSoC 5 is powered by a 32-bit ARM Cortex-M3 central processing unit (CPU). The architecture of the CPU includes a three-stage pipeline with branch prediction. The ARM Cortex-M3 CPU's are known for their low powered capabilities making them the perfect tool for portable embedded projects. Although the CPU is low powered, it is able to run at clock rates of 67MHz max. This performance is necessary for data acquisition applications where events occurring less than a microsecond apart needs to be measured or timed. The CPU supports interrupts and exceptions with its nested vectored interrupt controller (NVIC).

The programmable digital peripherals of the PSoC 5 make them truly customizable chips. Within the PSoC 5 chips, are an array of universal digital blocks (UDB). Each UDB holds a programmable logic array. Various peripheral devices can be programmed into these UDB's. For example, most microcontrollers may provide at most 2 universal asynchronous receiver/transmitter (UART) buses. With the PSoC 5, numerous UART's may be programmed into these universal digital blocks. With the UART, the benefit of such flexibility is clearly apparent as communications with only one external device is allowed per UART. Fig. 2.10 shows a block diagram of the digital system (Cypress Semiconductor 147).

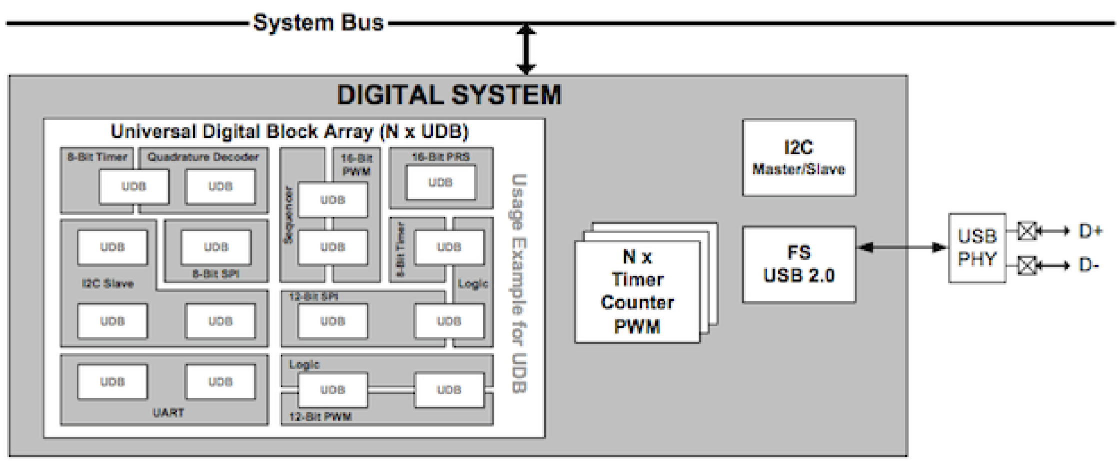


Figure 2.10 PSoC 5 digital system block diagram

The Digital System Interconnect (DSI) in the PSoC 5 enables general interconnectivity of peripherals within the universal digital blocks. The DSI also connects the UDB peripherals to the physical I/O pins and other peripheral devices on the chip. Fig. 2.11 (Cypress Semiconductor 191) provides an architectural view of the DSI. As listed in the PSoC 5 Architecture TRM, the DSI provides transmission of interrupt requests, dynamic memory access (DMA) requests, digital peripheral data signals, connections to I/O pins, and connections to the analog system digital signals.

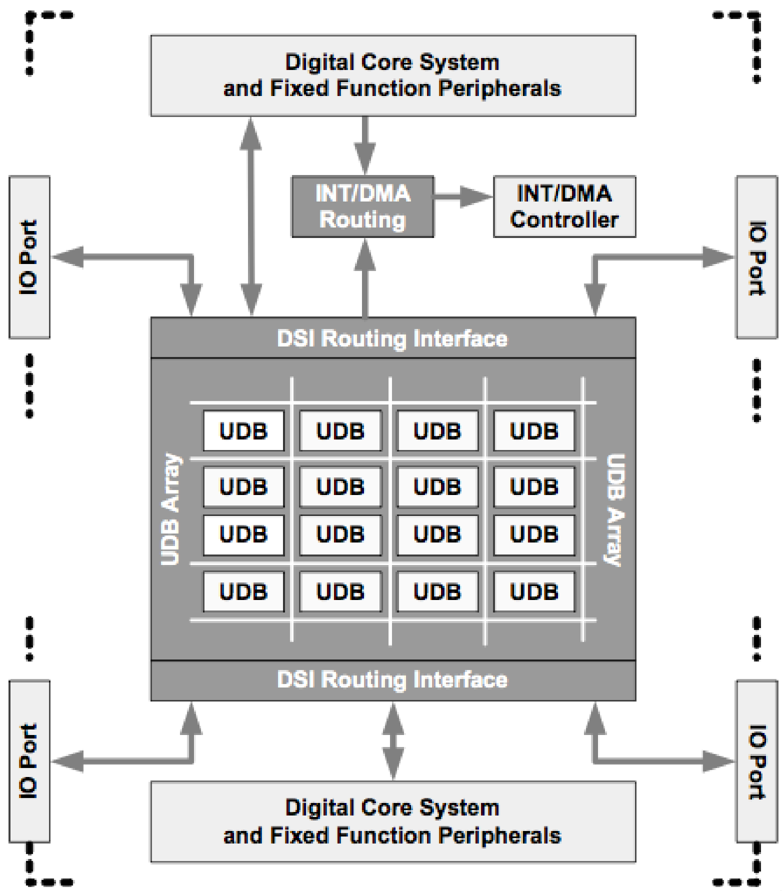


Figure 2.11 PSoC 5 digital system interconnect (DSI) diagram

The PSoC 5 chip also includes many analog subsystems. These include analog multiplexers, comparators, voltage references, operational amplifiers, mixers, analog-to-digital converters, and digital-to-analog converters. The internal analog bus allows any general-purpose I/O pin on the PSoC chip to route signals in and out of the chip. A maximum of 62 discrete analog signals can be interfaced with the chip simultaneously.

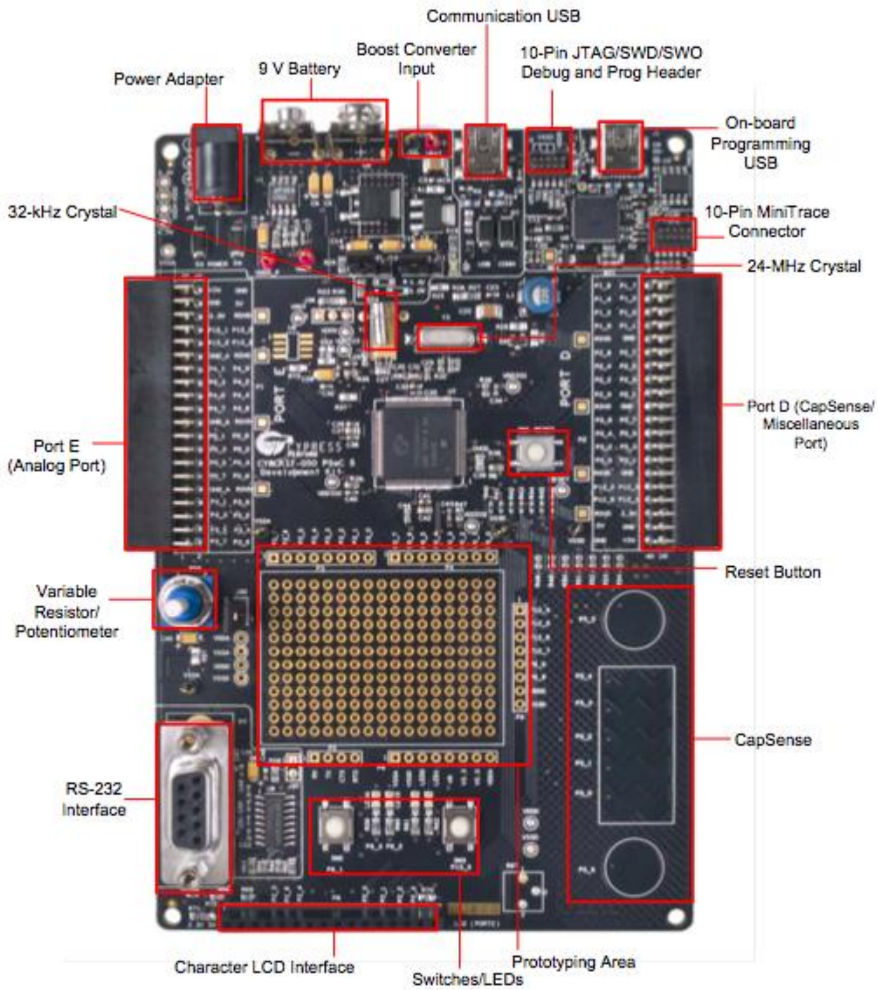


Figure 2.12 Image of the PSoC 5 development kit

A necessary tool for quick prototyping with the Cypress chip is the PSoC 5 development kit (PSoC 5LP 18). Among other things, this board provides the basic necessities that the PSoC 5 chip requires for operation. The development board provides a regulated power supply to the chip. The board is capable of sourcing power from the programming circuit, the USB, a 9V battery, or from a 12V power supply. The CY8CKIT-050 board provides a 24MHz crystal oscillator for the chip's clock source along with a 32KHz oscillator for the real time clock. The programming circuitry provides debugging and programming through USB or JTAG. Finally, the development kit offers easy access connectors to the I/O pins on the PSoC chip.

Additional peripherals added to the development board include LED's and a character display. These prove very valuable for debugging various designs. The LED's can serve as indicators of events or even provide a binary representation of some status in the chip.

CHAPTER 3

SYSTEM OVERVIEW

The main components within the system can be categorized into three device classifications. These include satellite units, a core unit, and a server unit. Fig. 3.1 shows a block diagram of the overall system.

3.1 Satellite Units

Each satellite unit receives data from a vital sign measurement device. The satellite units act as an interface and translator between each vital sign measurement device and the rest of the system. Excluding the ECG unit, all other vital sign units used are OEM devices. Therefore, they all have their own vendor specific communication protocols and data formats. The satellite units must translate between these vendor specific data formats and one that conforms to the system wide communications protocol. The satellite units are low powered battery operated units that don't require external power.

3.2 Core Unit

The core unit serves as an interface between the satellite devices and the remote server unit. It routes messages between the server unit and multiple satellite devices via Bluetooth and SPI. The core unit also performs other tasks on behalf of the server unit. One such task is determining which satellite units are present at a given time. Similar to the satellite units, the core unit is battery operated and does not require external power to operate.

3.3 Server Unit

The server unit serves as a central data store for incoming vital sign measurement results. The unit stores incoming data in a database system. Another major role of the server unit is to serve as an interface for human interaction with the system. One of the sub processes in the server unit is a graphical user interface for presenting the collected data to the user.

The server unit is the only part of the system with power and network connections to the wall. Unlike the other subunits within the system (which are embedded microcontrollers), the server unit is a single board computer running an operating system. Having Internet connectivity, the server unit is able to autonomously transmit email messages to the healthcare provider.

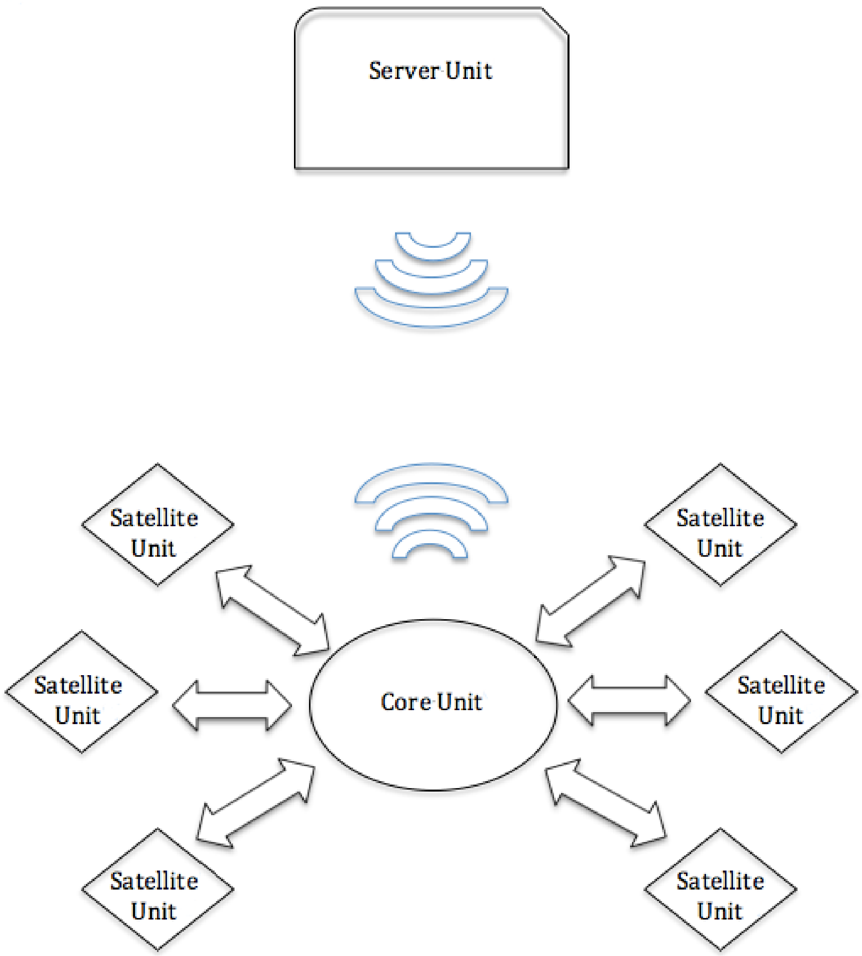


Figure 3.1 System Overview

CHAPTER 4

CORE UNIT

The core unit makes up the heart of the system. It allows communication between multiple satellite devices and the server unit. This module consists of a PSoC 5 CY8CKIT-050 development board and an RN-41-SM Bluetooth module by Roving Networks. This unit functions as the sole interface between all remote satellite devices and the single board computer where the data is viewed, analyzed, and stored.

4.1 Architecture

The unit has the capability of routing data coming from a maximum of 8 independent satellite devices. As soon as a complete message is received, it is routed to the remote single board computer. Each satellite device communicates with the core unit over a dedicated SPI bus. One of the benefits of this configuration is that each satellite device controls its own SPI clock for asynchronous data transfers to the core unit. Therefore, the bus is not shared and a slave select is not necessary. Another benefit from this configuration is that each SPI peripheral on the core unit keeps a private read buffer. This keeps the incoming messages from independent devices isolated while the data transfer is in progress. Fig. 4.1 shows an architecture diagram of the core unit. Data routed outbound to the single board computer is transmitted over UART to the RN-41-SM Bluetooth device. Once the RN-41-SM receives the data, it automatically relays the stream of bytes to the single board computer over a secure person area network (PAN). Some detail on the RN-41-SM is provided later in this chapter.

The SPI buses used for communicating with the external satellite devices are used in three-wire mode. Although the flow of data is mostly from the external devices to the core unit, some devices may receive data from the core unit. The chip select on the SPI bus is eliminated as each satellite communicates on a dedicated bus. Thus, only the master out slave in (MOSI), master in slave out (MISO), and clock lines are necessary. This configuration keeps the design simple as up to 8 SPI devices could be in use.

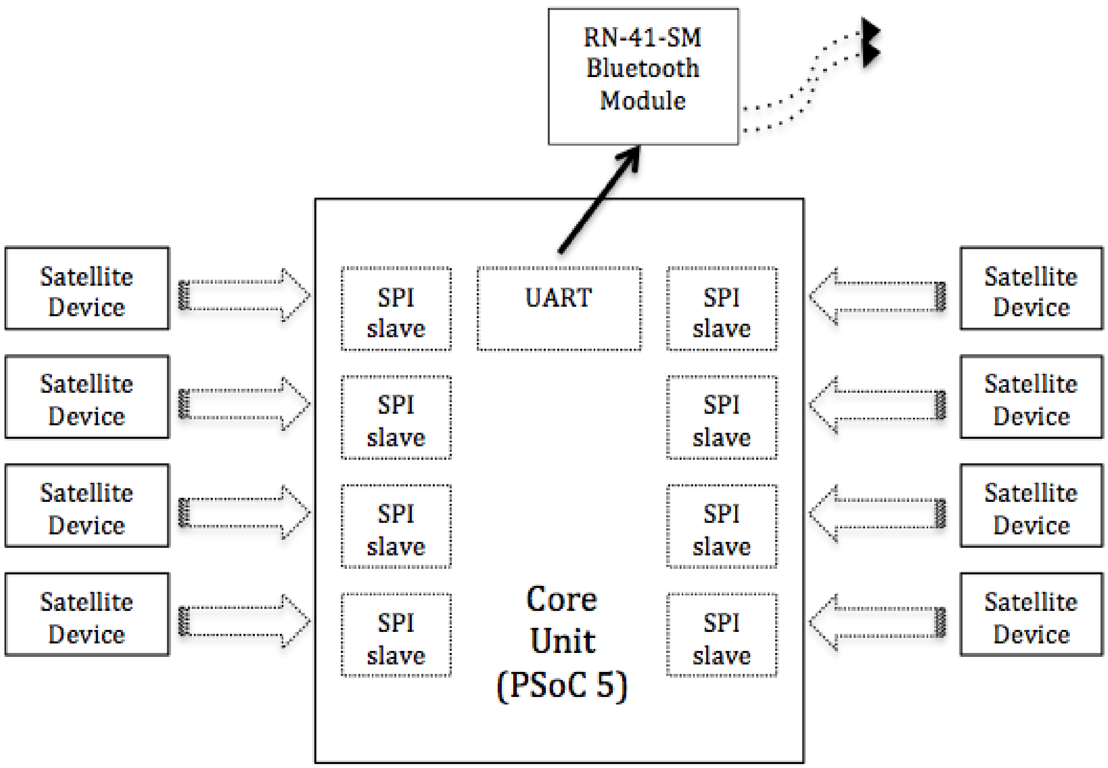


Figure 4.1 Architectural Diagram of the Core Unit

4.1.1. Communication Between The Core Unit And Satellite Units

Each satellite unit communicates with the core unit over SPI using a single predefined protocol. This allows the flexibility of having any satellite unit connected to the core using any one of the 8 communication ports. Each satellite communication port on the core unit is configured to be an SPI slave. This means that the serial clock on the bus will be controlled externally. The satellite devices are responsible for initiating all communication over the bus. Any incoming bytes to the core will set off an interrupt associated with the bus involved. This interrupt will alert the core that there's unread bytes in its SPI read buffer.

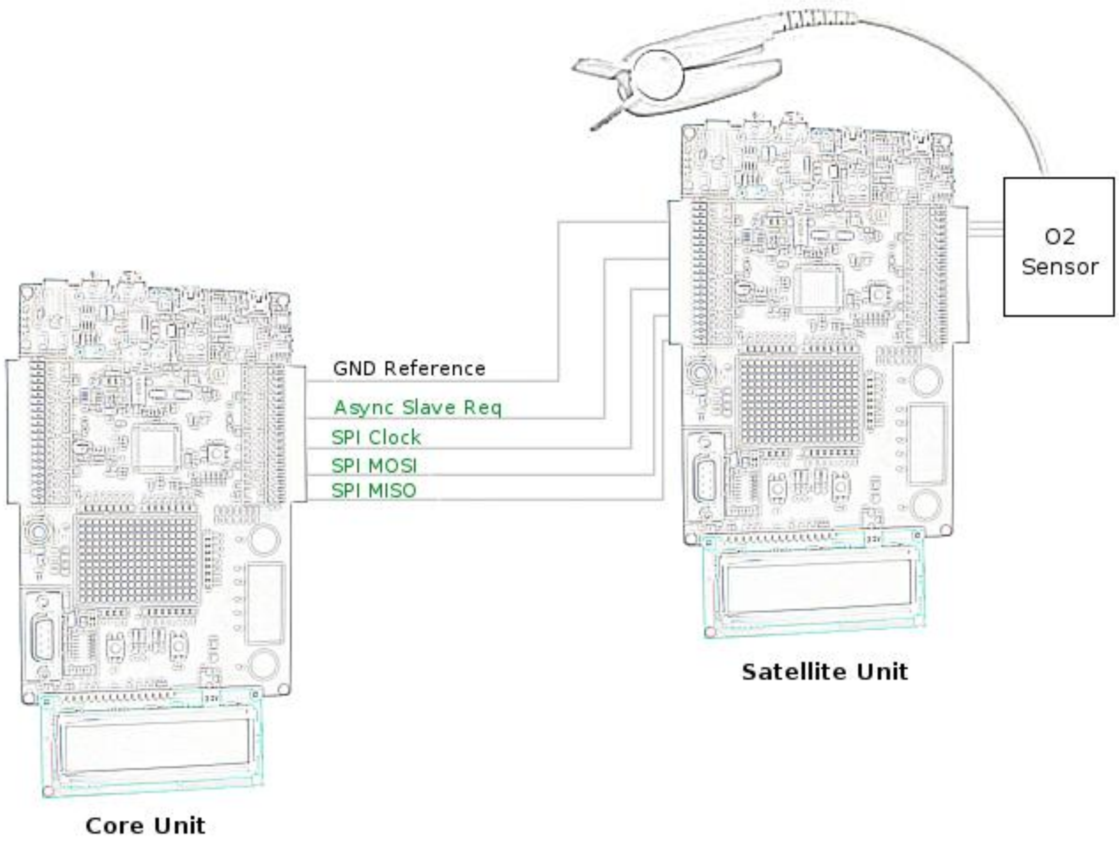


Figure 4.2 Core to Satellite Interconnect

In order to connect each satellite device to the core unit, a total of five wires are required. One wire provides a ground reference between the two boards. Three of the wires are SPI related signal lines. These are the clock, MOSI, and MISO signal lines. Because the core unit will serve as SPI slave to the satellite devices, an additional wire is used as an asynchronous request signal from the core to the device. This additional wire is kept at the source voltage (VDD). Normally, this would be achieved by physically connecting the line to VDD using a 10K pull-up resistor. Due to the PSoC 5 pin configuration system, the slave is able to configure the pin that this wire connects to as resistive pull-up. Whenever the core unit wants to signal to the satellite device (the SPI master in that case) that it needs to clock in data coming from the core unit, it pulls this line to ground. This action causes an interrupt in the microcontroller on the satellite device. The satellite device then produces the clocks needed for the data to be transmitted over the MISO line.

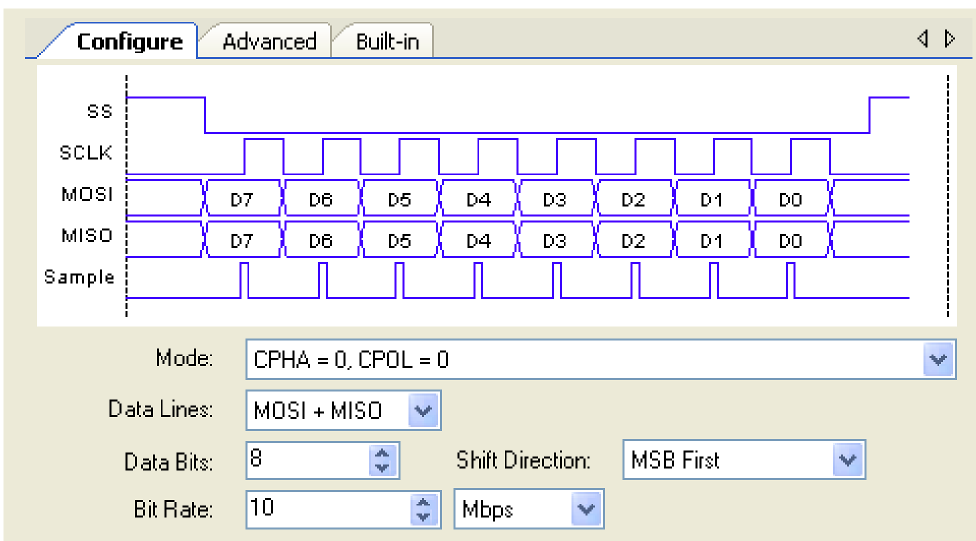


Figure 4.3 SPI slave configurations

This is an actual screenshot taken from the SPI hardware configuration window of Cypress' PSoC Creator 2.1.

Fig. 4.3 shows the selected SPI slave hardware configurations using Cypress PSoC Creator Software. Data is transmitted in the typical 8 bit bursts. The buses are all set to communicate at 10 million bits per second (10Mbps). Also, the data is transmitted in most significant bit first (MSB first) order. Finally, the data lines are sampled on the rising edge of the clock. The logic graph displayed in Fig. 4.3 illustrates the sampling timing resulting from this configuration.

4.1.2. Satellite to core communication specification

A single protocol will define all communication throughout the entire system. Table 4.1 describes the protocol that all devices will use to communicate. Each satellite device is responsible for translating data from their sensors into this unified format.

Table 4.1 System-Wide Message Format

MSG Header	Length	Device Type	MSG Type	Originating Device	Destination Device	Payload
0x53, 0x4D, 0x53, 0x47	2 bytes	1 byte	1 byte	4 bytes	4 bytes	…

4.1.2.1 Message Header

The first 4 bytes in a message is the message header. All messages will begin with the byte sequence: 0x53, 0x4D, 0x53, and 0x47. This sequence of bytes represents ASCII string ‘SMSG’, which means start message. Receiving devices will use this sequence to identify the start of a message.

4.1.2.2 Message Length

The message length provides the number of expected bytes contained in the message. This includes everything following the length. Hence, the first 6 bytes are excluded from the length calculation. The message length field is 2 bytes wide. This sets an upper bound on the message size to 65,535 bytes, which is acceptable for the type of messages that will be communicated throughout the system. On the other hand, the length field should have a value of at least 10, as the next 10 bytes before the payload field are mandatory.

4.1.2.3 Device Type

The next byte in the message indicates the originator's device type. This byte, for example, could identify a message to be coming from a spirometer. This information will be used for routing incoming data at the system server.

4.1.2.4 Message Type

Some devices may send and receive multiple types of messages. This one byte field specifies the type of message for the given device type. Message types are only unique for a given device type. For example, there may be a message with message ID equal to 2 under different device types.

4.1.2.5 Originating Device Identifier

This four-byte identifier provides a unique tag declaring the originator of the message. This is primarily for routing messages coming from the server and for debugging and logging purposes.

4.1.2.6 Destination Device Identifier

This field, also four bytes wide, provides the tag of the destination device. The core unit needs this field in order to accurately route an incoming message from the server over the correct SPI bus.

4.1.2.7 Message Payload

The payload field is an optional and variable in length. The length of this field must be no more than 65,525 bytes. This constraint results from the fact that the length field is only 2 bytes wide and there are 10 mandatory bytes before the payload field.

4.1.3. Communication between the core unit and the server unit

The core unit's main function is to relay data collected from the satellite devices to the remote server. This data is routed over a wireless Bluetooth connection. In order to make this possible, the data is forwarded using the Roving Networks RN-41-SM module. This device is a class 1 Bluetooth device supporting up to the Bluetooth v2.1 communication protocol (Roving

Networks). The RN-41-SM is a low power device consuming only up to 30mA when active. This power consumption is essential for this application.

Figure 4.4 Roving Networks RN-41-SM

According to the datasheet, the RN-41-SM has a range of about 100 meters. This makes it suitable for most home applications. The module provides a UART bus, allowing for easy interfacing with microcontrollers. Apart from a few other protocols, the module is capable of transmitting data following the Serial Port Profile (SPP). SPP is a Bluetooth profile that emulates a serial cable connection between two devices (MettŠla, Dellien and Sšrensen 20).

The RN-41-SM is a very flexible module allowing many configurable features. Configuring the device is done either wirelessly through the Bluetooth link or via the UART interface. The RN-41-SM is programmed using an ASCII command language outlined in the Roving Networks Bluetooth product manual. ‘Set’ commands configure the module whereas ‘Get’ commands returns the current configurations. The following is a list a configurations that’s directly related to the current project.

4.1.3.1 Master/Slave Mode

The RN-41-SM can operate in numerous modes. The modes relating to this project is slave mode and master mode. In slave mode, other Bluetooth devices can discover and initiate connection with the device. In slave mode, the module is also allowed to initiate outbound connections itself. In master mode, only outbound connections are allowed.

4.1.3.2 Command/Data Mode

The device powers up by default in Data mode. In data mode, the module simply forwards streams of bytes from the UART interface to the Bluetooth link and visa versa. Within 60 seconds after the device is powered up, an ASCII sequence of “$$$” followed by cursor return sets the device to configuration mode. In this mode, the configuration settings can be displayed or modified.

4.1.3.3 UART Settings

The UART interface can be configured while in configuration mode. Adjustable settings for the UART interface include the baud rate, flow control and parity.

4.1.3.4 Bluetooth Settings

The device allows a large number of Bluetooth related settings that can be modified. Some of which includes encryption settings, the device name (seen by other devices when in slave mode), the Bluetooth address, and the security code that will be required in order to pair with the module.

4.1.4. Core Unit’s Program Flow

On power up, the module initializes its on-chip peripherals and the interrupt vector. Most activity within the core unit is interrupt driven. Each bus has its related interrupt that’s triggered by reception of new data. Whenever an interrupt occurs on one of the buses, program flow switches to the interrupt service routine related to that peripheral. In order to make the interrupt as brief as possible, the interrupt service routine only sets a flag before clearing the interrupt and returning to normal execution. This flag will be picked up later within the main loop. A macro view of the core unit’s program flow is illustrated in Fig. 4.5.

4.1.4.1 Satellite to Core/Server Data Flow

The main loop services the eight SPI buses in order. Fig. 4.6 shows the program flow involved in servicing each bus. The device must first determine whether the data-in flag for the given bus was set. If nothing has changed on the bus, the system moves on to service the next bus. If the flag indicates that new data is ready on the bus, all the bytes are read onto a circular buffer. Then the buffer is processed to ensure it starts with a valid message header. All unknown bytes are purged until the message header is detected or the buffer is emptied. Once a valid message header is detected, the length field in the message is used to determine whether the entire message has already been read in to the buffer. If the message is determined to be incomplete, the system moves on to the next bus with the expectation that the remainder of the message will arrive later. If, in fact, the entire message is present, the system forwards the message over the UART to the RN-41-SM.

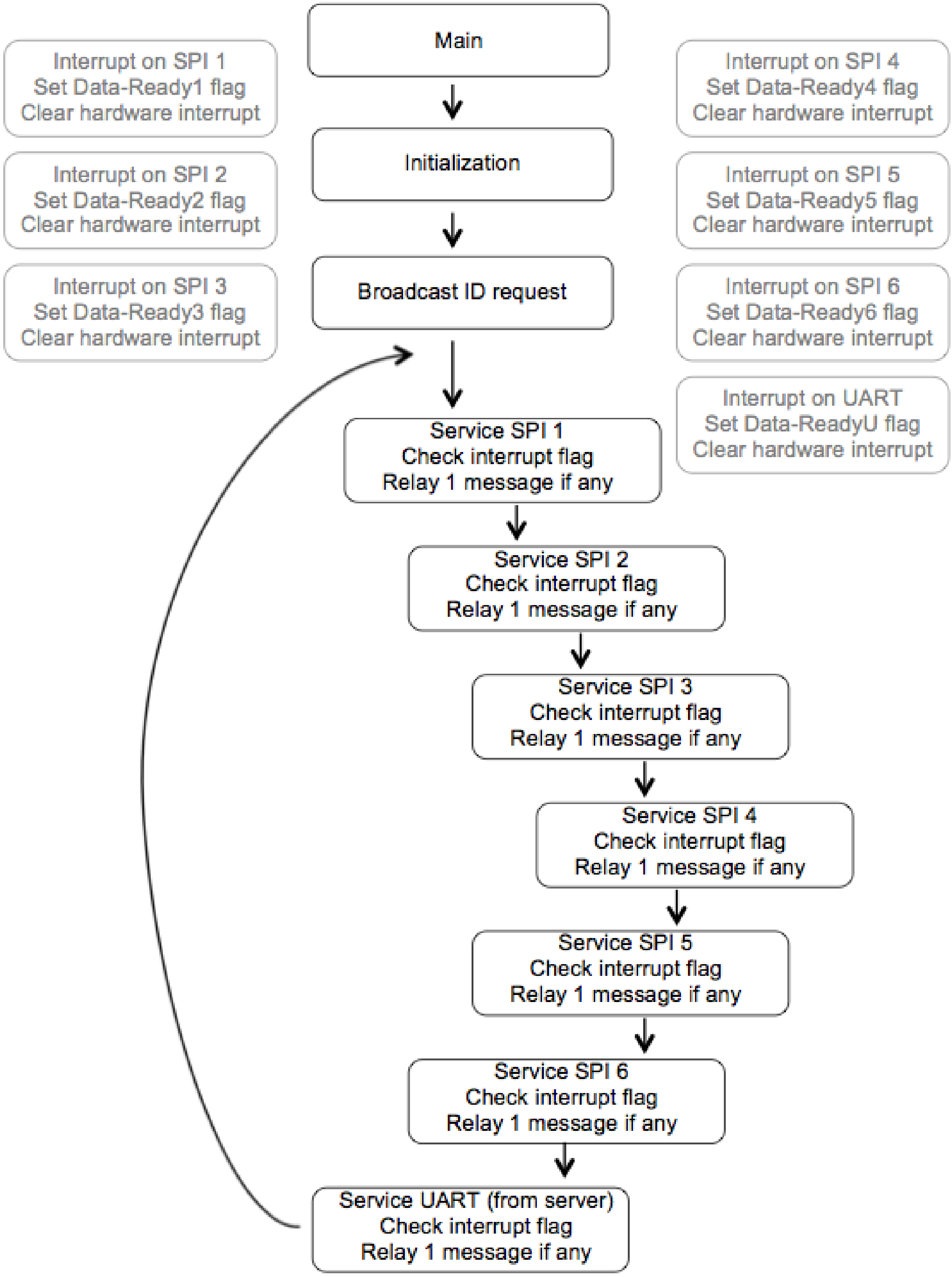


Figure 4.5 Core Unit's Program Flow

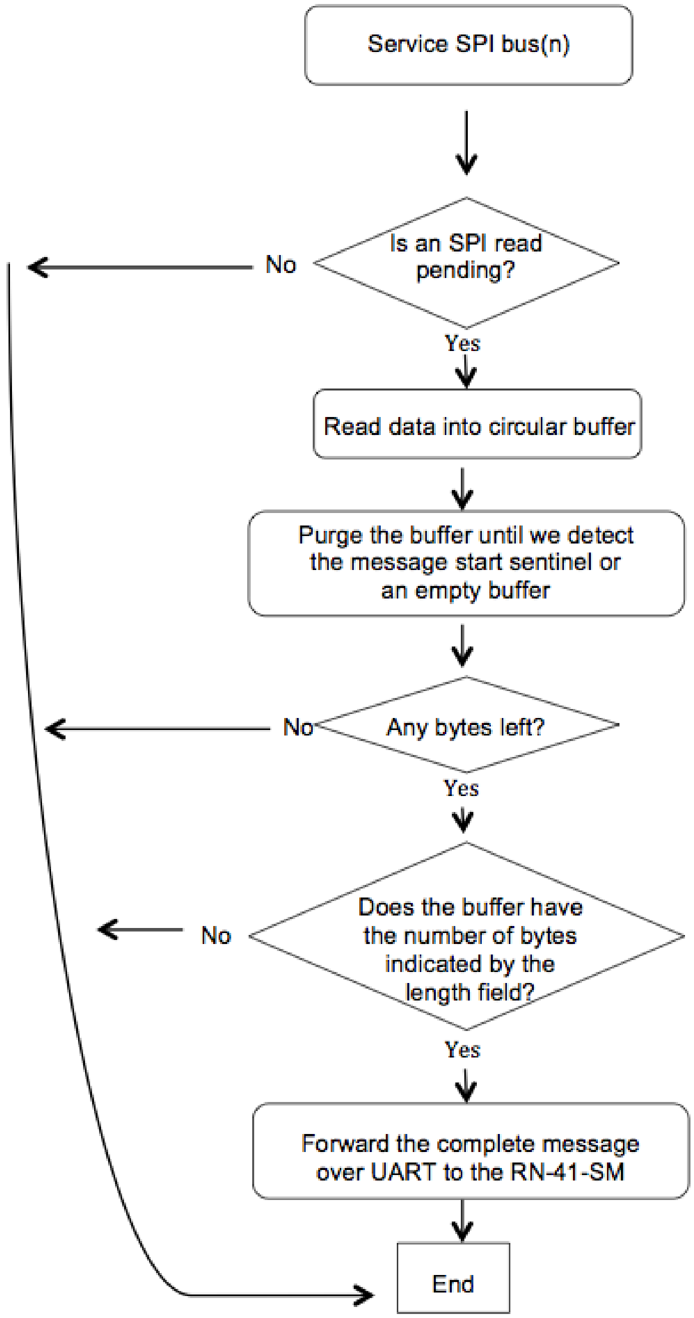


Figure 4.6 Service SPI bus program flow

4.1.4.2 Server to Core/Satellite Data Flow

The SPI peripherals are not the only sources of interrupts on the core unit. Messages originating from the server may cause data-in interrupts on the UART peripheral. The RN-41-SM relays these messages to the UART bus on the core unit. Interrupt servicing of the UART bus is handled in a similar fashion to that of the SPI. The difference relates to how the message gets forwarded to its destination. Additional steps are required before the message can be relayed to its destination. The destination tag in the message needs to be retrieved so that the correct forwarding bus could be determined. This is achieved by searching a small eight row routing table for the destination tag. The table converts the destination identifier extracted from the message to a pointer to the intended SPI port. Once the correct SPI bus is determined, the core unit inserts the message on the transmit buffer of the bus and pulls low the asynchronous slave request line mentioned earlier in Fig. 4.2. This prompts the satellite device, which serve as the master, to drive the clock line so that the data could be transmitted.

The core, by default, keeps all asynchronous slave request pins for the various satellite buses low. On every satellite device, this pin is configured internally as a resistive pull-up pin. This means that the chip emulates a pull-up resistor keeping the pin high. Whenever new satellite devices are plugged to the core or an existing one is placed on another bus, the pin on the core, which is low, pulls the line low. This signals the satellite device to try to clock in a message from the core. Since the core did not place any valid messages in the send buffer, the satellite device reacts by sending a device identifier message to the core. This mechanism assures that the core always have the updated position of devices on the bus.

Most messages within the system don’t originate from the core. They are simply routed by the core to their final destinations. One message that originates from the core is a device identifier request message. This message is broadcasted over every SPI bus two seconds after the core powers up. The primary function of this message type is for populating the bus routing table.

CHAPTER 5

ELECTROCARDIOGRAPH SATELLITE UNIT

This chapter details the complete design of the ECG satellite unit. The chapter first provides an overview of the unit before covering, in detail, the analog circuitry and the digital design using the PSoC 5 development board.

5.1 Unit Overview

Fig. 5.1 provides an overview of the ECG unit. Ionic currents originating from the heart muscle are converted to electric signals by silver/silver chloride electrodes. Minute signals from the two electrodes are then transmitted to an instrumentation amplifier. This differential op-amp amplifies the voltage difference between the two signals. The output from the amplifier is fed into a series of filters in order to significantly reduce the noise in the signal. This is achieved by eliminating the unwanted frequencies. At the output of the filters, only frequencies within the range of the signal of interest will remain. The signal, up to this point, fluctuates between positive and negative voltage values with time. This occurs as, at a given moment, the potential at one electrode placement may be more positive than at the other, and at another moment, its potential may be more negative than the other. This creates an issue, as the ADC is only able to measure positive voltages with reference to its ground. In order to sample the signal at the ADC, it is necessary that the signal be modified so that, even at its lowest value, it will have a positive voltage. In order to achieve this result, the output from the filters is passed on to a summing circuit. The summing circuit simply offsets the signal by a certain voltage.

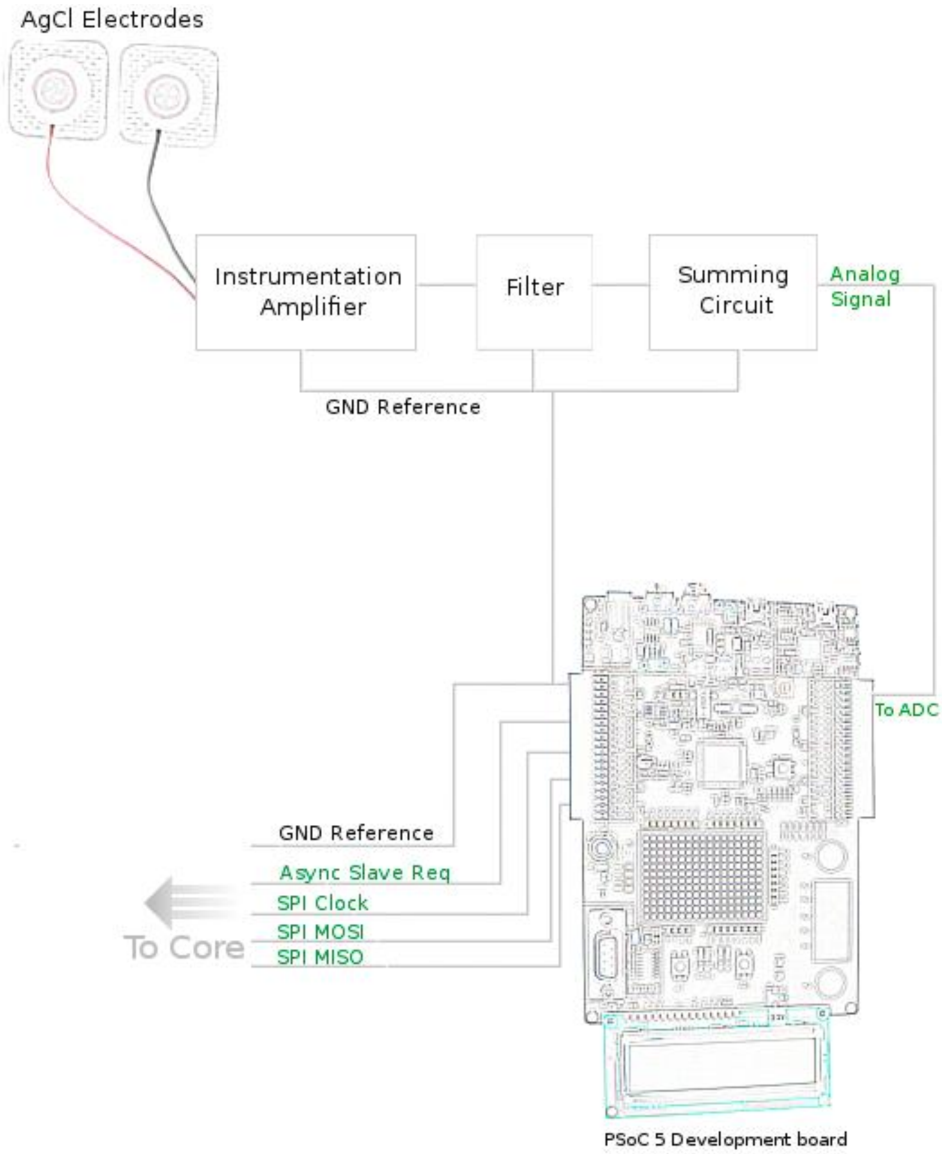


Figure 5.1 ECG Unit Overview

The signal leaving the summing circuit is then ready for quantizing by the ADC. The ADC samples the signal at a sample rate of 200Hz and converts the measured voltage to a 16 bit binary representation. A sample rate of 200Hz is selected, as the highest frequency component in the signal is 100Hz. By the Nyquist theorem, a sample rate of at least twice the signal's highest frequency component is required. The ADC marks the start of the digital subunit of this device. The unit's CPU then takes the stream of samples and loads them onto a buffer. There, they can be wrapped with the message protocol bits and relayed to the core unit.

5.2 Analog Circuitry

The analog circuitry includes all the units involved before the signal is fed into the ADC for conversion. The main units include the electrodes, the amplifier stage, the filter stage, the summing circuit, and a circuit for providing the power rails.

5.2.1 Silver/Silver Chloride Electrodes

For efficient sensing of the minute bio-signals caused by the heart, a transducer is needed to convert the ionic currents in the body to electronic currents in the wires. For the purpose of this project, electrodes manufactured by Bio Protech Inc. are selected. These electrodes use silver/silver chloride (Ag/AgCl) as the sensing element for converting the ionic currents to electronic currents (Bio Protech).

At an electrode site, motion artifacts can be an issue. During measurement, if an electrode moves, the charge distribution is affected causing the measured signal to be temporarily disturbed. In order to reduce motion artifacts, Bio Protech electrodes contain a solid adhesive hydro-gel. The hydro-gel increases the bond between the sensing element and the skin.

5.2.2 Amplifier Stage

The amplifier stage involves magnifying the voltage difference at the electrode sites by a gain in order to later filter and accurately measure the signal. The amplification, in this project, is performed by an INA128 integrated circuit (IC) from Texas Instruments. The INA128 is a low power instrumentation amplifier with a common mode rejection of 120dB max (INA128). The INA128 has a low offset voltage of 50 microvolts and an input bias current at 5nA max. These properties make the INA128 suitable for this type of application, as very little error will be introduce to the output signal. The INA128's circuit diagram is shown in Fig. 5.2 below. The

INA128's general design resembles that of the standard differential amplifier discussed earlier in the second chapter. The additional features include over-voltage protection circuitry on the inputs. This feature gives the IC the ability to withstand up to positive and negative 40V.

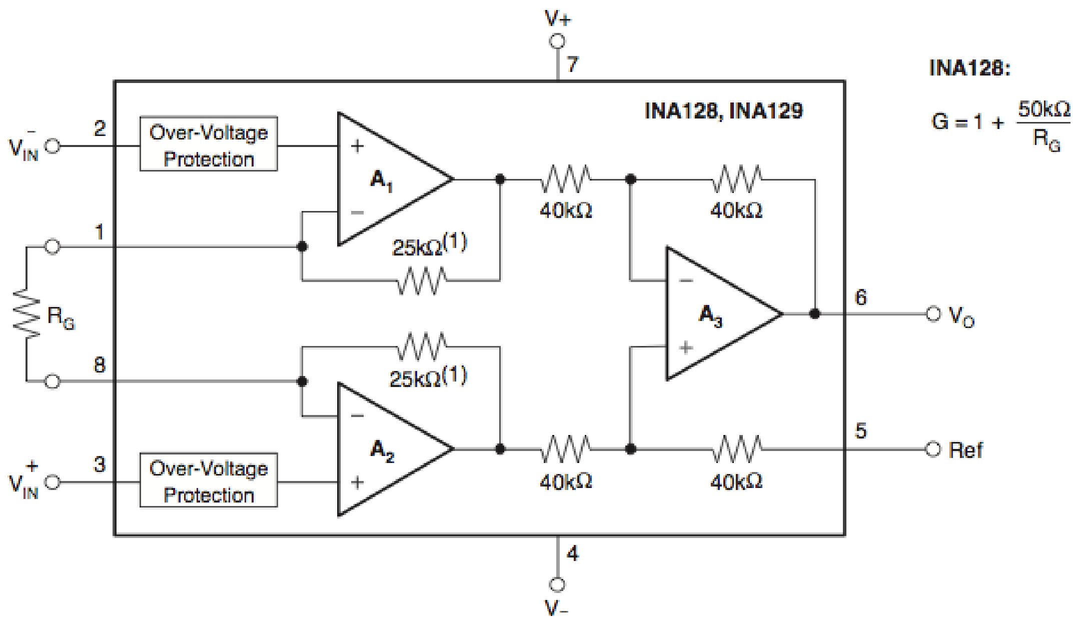


Figure 5.2 INA128 circuit diagram

The gain of the INA128 is adjustable. The value of the gain resistor R_g determines the gain. The relationship between the gain resistor and the output gain is represented by the formula in Fig. 5.2 (INA128). For this project, a gain of 600 is desired. This gain allows maximum amplification of the signal without getting to the rails of the circuit. The internal op-amps can't produce an output that is higher than the positive rail or lower than the negative rail. Therefore, if at any given point, the input signal multiplied by the gain surpasses the rail, signal information will be lost. To achieve the desired gain of 600, an 83ohm gain resistor is selected.

5.2.3 Filter Stage

In order to isolate the noise from the signal, a filter stage follows the instrumentation amplifier's output. This filter stage comprise of a passive band-pass filter. It allows only the desired frequency range to go through. This band-pass filter is made of a low-pass filter in series with a high-pass filter. The high-pass filter, with a cut-off frequency of 0.05Hz, only allows the components of the signal above this frequency to pass through. The low-pass filter, on the other hand, allows components of the signal below 100Hz to make it through the filter. For both the high-pass and low-pass components of the filter, the cut-off frequency is determined by the values of the capacitors and resistors. The formula in Fig. 5.3 shows the calculation for the cut-off frequency.

$$f_c = \frac{1}{2\Pi RC}$$

Figure 5.3 Cut-off Frequency Equation

5.2.4 Summing Circuit

The function of the summing circuit is to shift the output signal range above the ground reference (0V). This keeps the signal voltage positive in order to enable the ADC to sample the entire range of values produced by the analog circuit. This is achieved by offsetting the signal by a voltage greater than the most negative signal voltage. Fig. 5.4 shows the circuit diagram of the summing circuit.

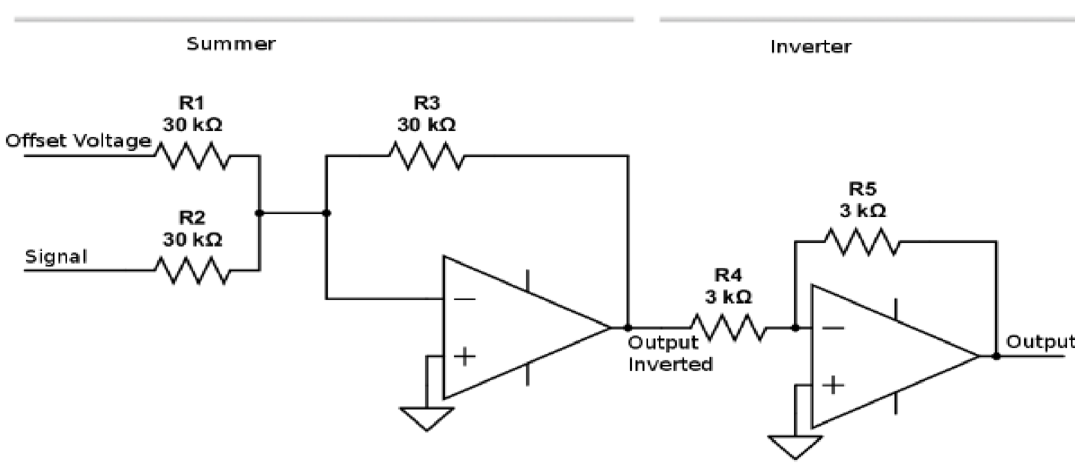


Figure 5.4 Summing Circuit

The output voltage from a summing amplifier is determined by the equation in Fig. 5.5 (Carter, Bruce). From the formula, if all the resistors share the same value, then the output voltage is equal to the sum of the input voltages inverted. Since the output voltage is inverted, an inverting circuit is added after the summing circuit. Since the two resistors in the inverting circuit are equal, the output is inverted but not amplified.

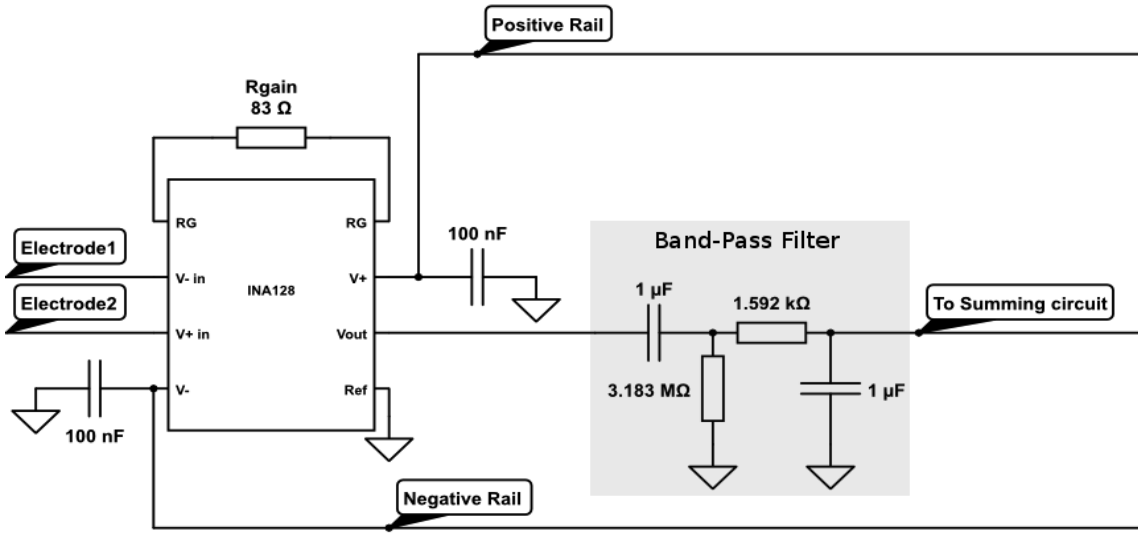
$$V_{out} = -R_f \quad \frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}$$

Figure 5.5 Summing Amplifier Equation

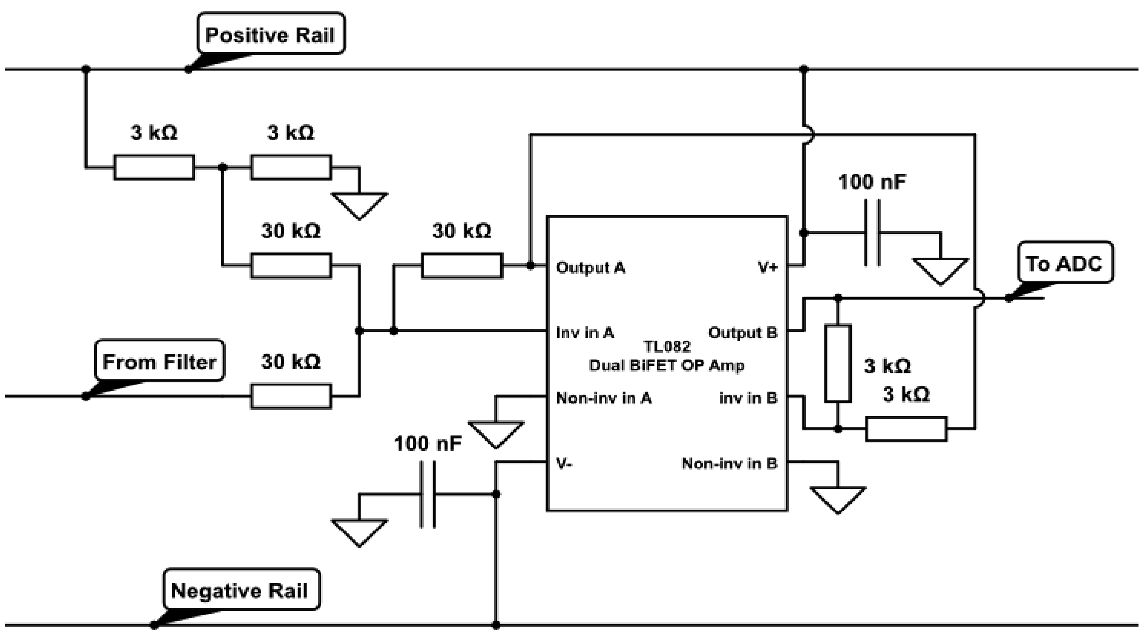
5.2.5 Power Circuit

A single 9V battery powers both the analog and digital circuitry. The digital circuitry (the PSoC 5 development board) is set to operate at 5V, whereas the analog circuitry requires a 6V supply. In order to provide the 6V needed by the analog section, the 9V power from the battery needs to be dropped to 6V. This is accomplished by using a 6V voltage regulator. For this project, the Micro Commercial Components' MC7806CT is utilized. The MC7806CT is a three-terminal positive voltage regulator. Having a dropout voltage of 2V, the MC7806CT requires at least 8V for proper operation (MC7806CT).

The analog circuitry includes components with op-amps, which require a positive as well as a negative rail for operation. The 6V regulator provides power to the positive rail. To provide the negative rail, the MAX1044 switched-capacitor voltage converter is used to invert the regulated 6V. The MAX1044 is capable of inverting, doubling, dividing, or multiplying an input voltage (MAX1044/ICL7660).



(a)



(b)

Figure 5.6 ECG Circuit Diagram

Circuit diagram showing (a) the amplifier stage, filter stage, and (b) the summing stage.

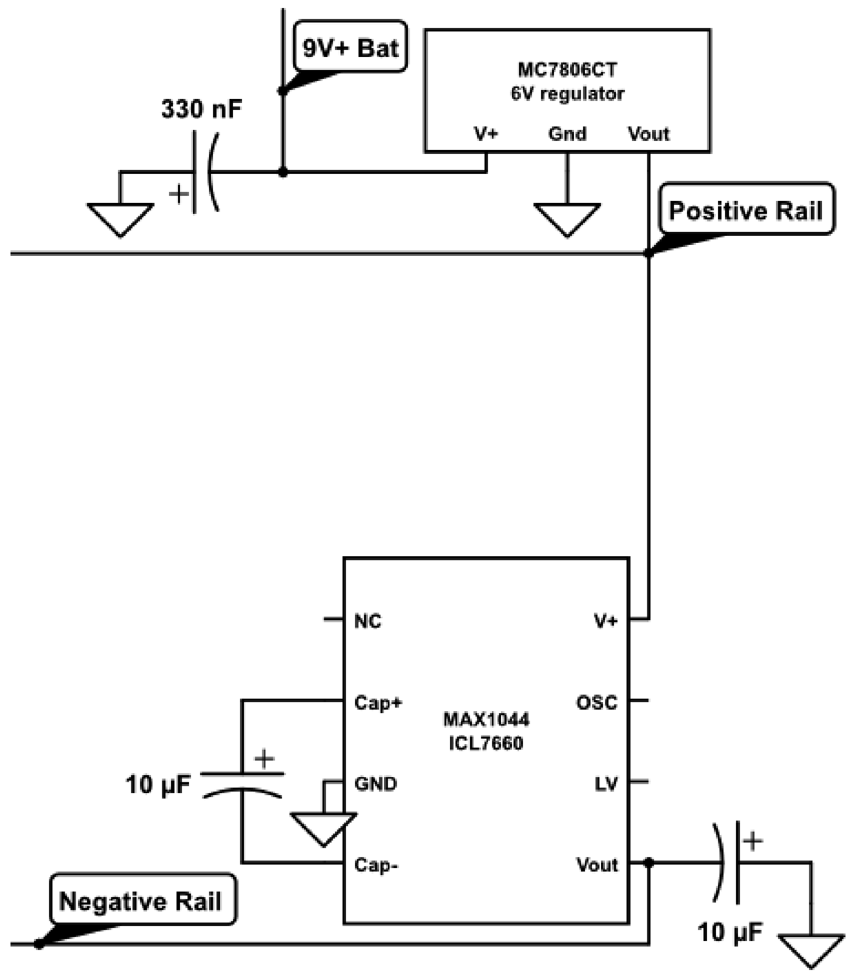


Figure 5.7 ECG Power Circuit Diagram

This circuit diagram shows the 6V voltage regulator and switched-capacitor voltage converter. These components provide power to the negative and positive rails of the analog circuitry.

5.3 Digital Subsystem

The digital subsystem of this module comprises solely of a PSoC 5 development board. Its main functions include converting the signal from the analog circuitry into digital data, relaying the stream of samples to the core unit, clocking-in messages from the core device over the MISO line of the SPI bus, and executing these incoming requests from the core unit.

5.3.1 Analog to Digital Conversion

A Delta Sigma ADC on the PSoC chip is employed to quantize the conditioned signal for the analog circuitry. The Delta Sigma is configured with its default sample rate of 10,000 samples per second. This sample rate, of course, is in excess of what's required to observe cardiac events. Although the sample rate is kept high, the ADC buffer is polled at a much slower rate of 200Hz for the converted data. The PSoC's Delta Sigma ADC allows various configurations for the input range. For this particular application, a range of VSSA to VDDA is preferred. VSSA represents the analog ground reference voltage of the board, whereas VDDA represents the analog source voltage. Although the PSoC 5 development board allows 3.3V and 5.0V operation, an operating voltage of 5.0V is preferred so that voltages above 3.3V would be able to be measured by the ADC. The ADC is configured to produce samples with 16bit resolution. This means that the signal can be measured with 2^{16}-1 distinct values. And, since the range is set to VSSA-VDDA (0V-5V), each step in the converted value represents 5/65535 or 76.3 microvolts.

5.3.2 Preparation and Forwarding of Data

An interrupt handler connected to a 1KHz timer on the PSoC chip is responsible for collecting samples from the Delta Sigma's sample buffer. This reduces the effective sample rate to 1KHz. Once the data is retrieved from the ADC's buffer, it is placed on a holding buffer for transmission later. This procedure is preferred for two reasons. Firstly, instructions within the interrupt service routine are kept to a minimum. Instead of doing any processing of the data, it is simply moved to a location when it will be attended to at a later time. Secondly, to minimize the interval traffic is sent over the bus, ECG samples are transmitted in groups of 5 samples. Therefore, the device will transmit the next message out to the core only after a minimum of 5 samples has accumulated in the holding buffer.

5.3.3 Servicing Incoming Requests

Because all satellite devices (including this one) is the master on the SPI bus, requests originating from (or relayed by) the core needs to be clocked in by the satellite device. In order to do so, the core must pull the asynchronous slave request line high then low. This event causes an interrupt within the satellite's CPU. When this occurs, execution is switched to the incoming request interrupt service routine. This routine is kept as brief as possible. The routine simply sets a flag to indicate later to the main loop that an incoming request needs to be dealt with. The routine then clears the interrupt before returning. A section of the main loop poles the incoming request flag. If the flag is set, the system clocks in the first 6 bytes. As discussed in the previous chapter, all messages should begin with the 4-byte message start sequence and the 2-byte length field. This information is useful for first determining if there is a valid incoming message. Secondly, the length field indicates the number of bytes that's remaining to be clocked in. In situations where the first 4 bytes indicate that there is no valid message, the device assumes that it has recently been plugged into to the core and sends an identification message. As discussed in the previous chapter, the core uses the identification message to update its routing table.

5.3.4 Messages Types

As described earlier, the ECG module sends and receives a small variety of messages. The remainder of this chapter describes the message types relating to the EGC unit. Table 5.1 provides a summary of these message types.

5.3.4.1 Device Identification Message

This is considered an outgoing message. This message type is sent from the ECG device to the core unit. The core unit depends on this message for updating its routing table.

The destination device for the ECG device identification message is always the core. Also, this message type never includes a payload. Therefore, the length field is always 10.

5.3.4.2 ECG Data Message

This is the most frequently transmitted message by this device. This message type is used to transmit the stream of sampled measurements to the server unit. The message length is always 30 bytes as the payload for this message type is a fixed 20 bytes of data. In the payload, 5 samples of ECG data are transmitted per message. And each sample is a 2-byte word. For this message type, the destination is always the server unit.

5.3.4.3 Start Message

This message type is transmitted from the server unit to the ECG device. The server unit uses this message to start ECG measurements remotely. This message type does not have a payload so the length is always 10 bytes.

5.3.4.4 Stop Message

Similar to the start message, the stop message is transmitted from the host to the ECG device. Hence, the originating device is always the server unit. This message type, as the name suggests, is used to remotely halt measuring and transmission of samples by the ECG device.

Table 5.1 ECG Module Message Specification

Description	Header	Length	Device Type	MSG Type	Originating Device	Destination Device	Payload
Device Identifier Message	0x53, 0x4D, 0x53, 0x47	10	21 (ECG)	1	Device ID	2 (core)	None
ECG Data Message	0x53, 0x4D, 0x53, 0x47	30	21	2	Device ID	1 (server)	20 bytes of ECG Data
Start Message	0x53, 0x4D, 0x53, 0x47	10	21	3	1 (server)	Device ID	None
Stop Message	0x53, 0x4D, 0x53, 0x47	10	21	4	1 (server)	Device ID	None

CHAPTER 6

BLOOD OXYGEN SATELLITE UNIT

This chapter describes the design of the blood oxygen satellite unit. The chapter first provides an overview of the unit before covering, in detail, the digital design using the PSoC 5 development board.

6.1 Unit Overview

6.1.1 ChipOx Pulse Oximetry Module

For this satellite module, a low-powered pulse oximetry module named ChipOx is incorporated. Its manufacturer, EnviteC-Wismar GmbH, produces the ChipOx unit as an OEM module for use in medical devices or other human applications. The ChipOx module operates with the standard principles for non-invasive pulse oximetry discussed in chapter 2 (EnviteC User Manual). The device measures the absorbance of red and infrared light by hemoglobin in the blood using light emitting diodes (LEDs). Fig. 6.1 shows an image of the ChipOx unit (Digital Pulse Oximeter). The unit operates on a source voltage of 3.3V and consumes less than 25mA of current. The unit provides a serial UART interface for transmitting digital measurements and allowing configuration changes.

According to the ChipOx manual, the unit uses its own packet protocol for transmitting messages. The outer layer is called the transfer layer. In the transfer layer, packets are divided into 4 major sections. A ChipOx packet comprises of a start flag, the packet's data, a checksum, and an end flag. The checksum in the packet is used to determine whether or not the received packet is corrupt.

Figure 6.1 ChipOx Pulse Oximetry Module

6.1.2 ChipOx Development Kit

For easy prototyping, the ChipOx development kit is employed in this project. The kit provides a socket for the ChipOx module. This socket breaks out the pins on the ChipOx module for easy access between itself and the prototyping circuit. The kit provides a finger sensor clip and its accompanying MiniMed connection jack (EnviteC User Manual). Also, the development kit provides a UART to RS232 adapter. Apart from the physical RS232 connector, the adaptor's circuit must convert the TTL signal levels from the ChipOx module's UART to RS232 voltage levels. Finally, the kit provides a regulated voltage source for the ChipOx module, the sensor head, and the RS232 conversion circuit. The power circuitry on the board allows for input voltages varying from 7V to 16V. The ChipOx development kit can be seen in Fig. 6.2 (OEM Module).

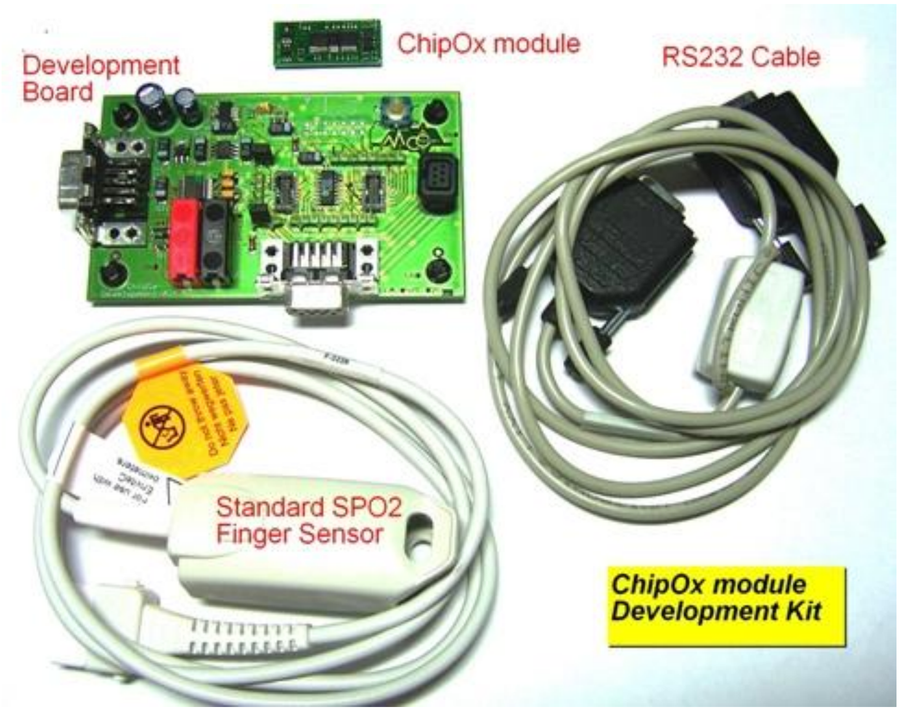


Figure 6.2 ChipOx Development Kit

6.1.3 System Layout

Fig. 6.3 is an illustration of the entire blood oxygen satellite unit. The ChipOx development board is connected to the unit's PSoC 5 board through the RS232. It's worth noting that, in a non-prototyping situation, the ChipOx development board would be eliminated. This would allow the UART from the ChipOx unit to connect directly to the UART on the PSoC chip. In the prototype design, the development board also shares power with the PSoC board.

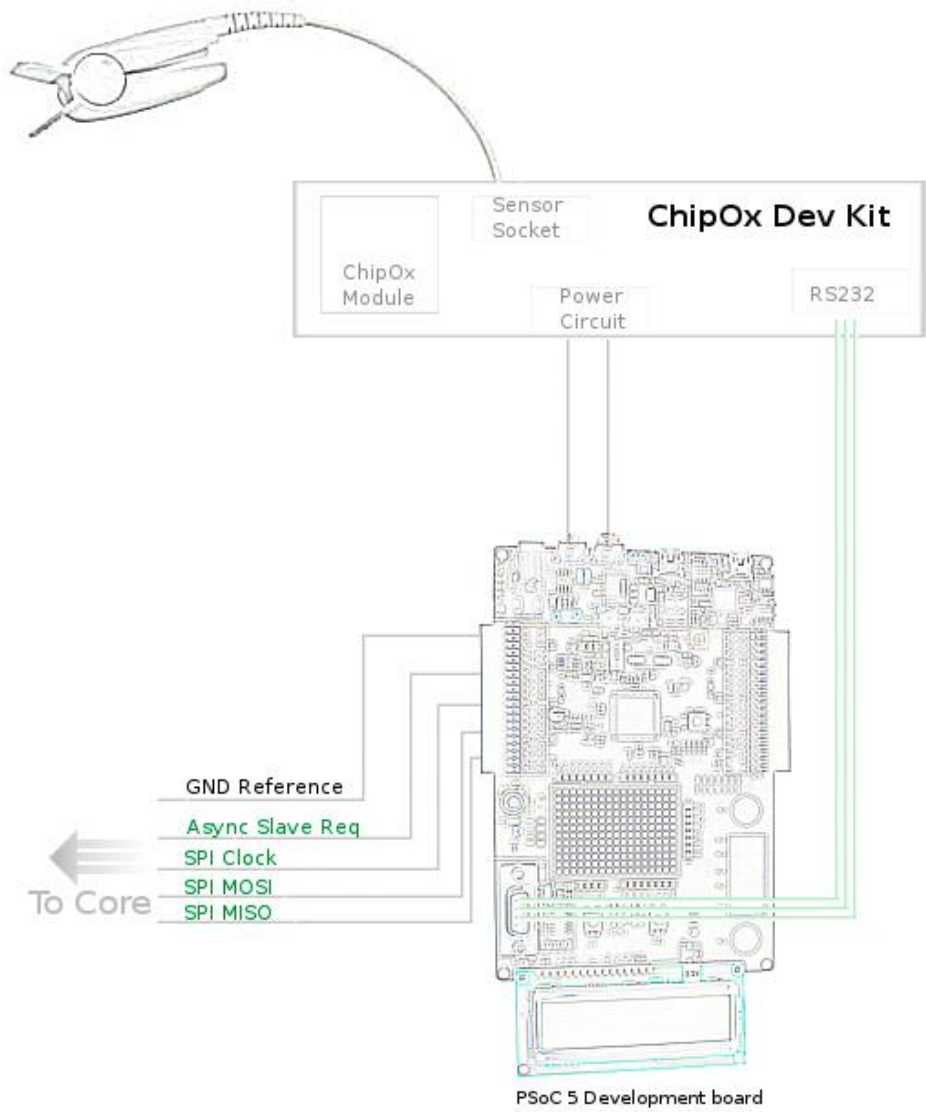


Figure 6.3 Pulse Oximety Satellite Unit Overview

6.2 Program Flow

On power up, processing on the PSoC5 unit begins by initializing the peripherals and enabling global interrupts on the chip. Once initialization is complete, the unit attempts to send a device identifier message to the core unit before processing enters the main loop.

6.2.1 Handling data from the ChipOx module

Bytes coming in from the ChipOx module are initially buffered in the UART on the PSoC chip. The arrival of new data on the bus results in an interrupt. The related interrupt service routine sets a data ready flag and clears the interrupt. Polling of this flag occurs in the main loop. Once it's determined that new data is available, data is read one byte at a time from the UART. After each byte is retrieved, it is added to a circular buffer. When all the bytes in the UART's read buffer have been pushed into the circular buffer, the buffer is processed.

6.2.1.1 Processing of ChipOx Packets

Processing the buffer includes first determining whether a complete ChipOx packet exists. Bytes at the start of the buffer that's not the ChipOx start sentinel are purged from the buffer. All other bytes leading up to the end sentinel are left in the buffer. The presence of the end sentinel indicates a complete packet. Using the message identifier field of the completed ChipOx packet, the content of the packet is translated into a message type defined for this project. The packet is removed from the circular buffer and the translated message is sent to the core unit over the SPI bus.

6.2.1.2 ChipOx Packet Specification

Wrapped within the payload section of the ChipOx data packet is another layer, which is referred to as the communication layer. This layer defines the channel and message types (EnviteC User Manual). The first byte in the payload represents the channel ID. Per the manual, channel 127 is used. The next byte indicates the message type. The ChipOx user manual defines a plethora of ChipOx message types. For the purpose of this project, only a subset of these message types will be focused upon. Table 6.1 provides a summary of these ChipOx message types. The final section of the payload is actual data. The length of this field varies for different message types.

Table 6.1 ChipOx Message Format

Message Identifier	Description	Field Length (bytes)
0x01	SpO2 Value [0-100%]	1
0x02	Pulse [0-300 bpm]	2
0x03	Signal Quality [0-100%]	1
0x05	Pulsation Strength [0-255]	1
0x08	Status Information (Bit coded)	2
0x51	Realtime Data (multi-data packet)	Variable
0x71	Error. Unknown Channed ID	2
0x72	Error. Unknown MSG Identifier	2
0x73	Error. Corrupt Parameter	2
0x74	Error. Transfer Protocol Error	1

ChipOx message types 0x01 and 0x02 provide the oxygen saturation and pulse rate. Message identifier 0x08 provides status information. Having a width of 2 bytes, this field provides 15 individual status indicators. Table 6.2 provides a summary of the data presented in the status message. The most significant bit in the status field is not used and should be ignored.

Table 6.2 Bit Definitions of ChipOx Status Message

Bit	Description
0	Sensor off
1	Finger out
2	Pulse wave detected
3	Searching for pulse
4	Pulse search timeout
5	Low pulse strength
6	Low signal
7	Too much ambient light
8	Too many disturbances
9	High motion artifact
10	Sensor defective
11	Power supply out of tolerance
12	Operating temperature out of tolerance
13	Wrong sensor
14	Vital parameter data outside of measurement range

Table 6.3 Pulse Oximetry Message Specification

Description	Header	Length	Device Type	MSG Type	Originating Device	Destination Device	Payload
Device Identifier Message	0x53, 0x4D, 0x53, 0x47	10	22 (SPO2)	1	Device ID	2 (core)	None
SPO2 Data Message	0x53, 0x4D, 0x53, 0x47	11	22	2	Device ID	1 (server)	1 byte
Pulse Data Message	0x53, 0x4D, 0x53, 0x47	12	22	3	Device ID	1 (server)	2 bytes
Status Message	0x53, 0x4D, 0x53, 0x47	12	22	4	Device ID	1 (server)	2 bytes
Error Message	0x53, 0x4D, 0x53, 0x47	11	22	5	Device ID	1 (server)	1 byte
Start Message	0x53, 0x4D, 0x53, 0x47	10	22	6	1 (server)	Device ID	None
Stop Message	0x53, 0x4D, 0x53, 0x47	10	22	7	1 (server)	Device ID	None

6.2.1.3 Satellite Device Messages

Table 5.3 is a summary of the oximeter satellite's message types. Incoming packets from the ChipOx module are translated into these messages prior to being forwarded to the core.

CHAPTER 7

SPIROMETER SATELLITE UNIT

This chapter describes the design of the spirometer satellite unit. The chapter first provides an overview of the unit before covering, in detail, the digital design on the PSoC 5 development board.

7.1 Unit Overview

This device comprises of three subsections. The spirometry module is the AM1+ BT spirometer by eResearchTechnology GmbH (ERT). The next subsystem involves a module for adding Bluetooth capabilities to the satellite device. The final subsystem is responsible for controlling, translating, and forwarding of messages between the core unit and the spirometer. The spirometry module and the satellite module are not physically attached, but rather are connected via a Bluetooth link. Fig. 7.1 provides an overview of the system.

7.1.1 ERT AM1+ BT Module

The AM1+ BT is an electronic peak flow meter for measuring lung function. According to the AM1+ BT user manual, the device is suitable for monitoring the respiratory status of asthma and chronic obstructive pulmonary disorder (eResearchTechnology 67). The device is also useful in applications such as occupational medicine and disease management.

The AM1+ BT saves measurements taken in its internal database. A maximum of 400 readings can be stored at any given time in its non-volatile memory. Measurements stored in memory can later be exported from the device memory over its Bluetooth link. For each measurement, the device provided parameters include FVC, PEF, and FEV1. The device also provides the date and time of each measurement.

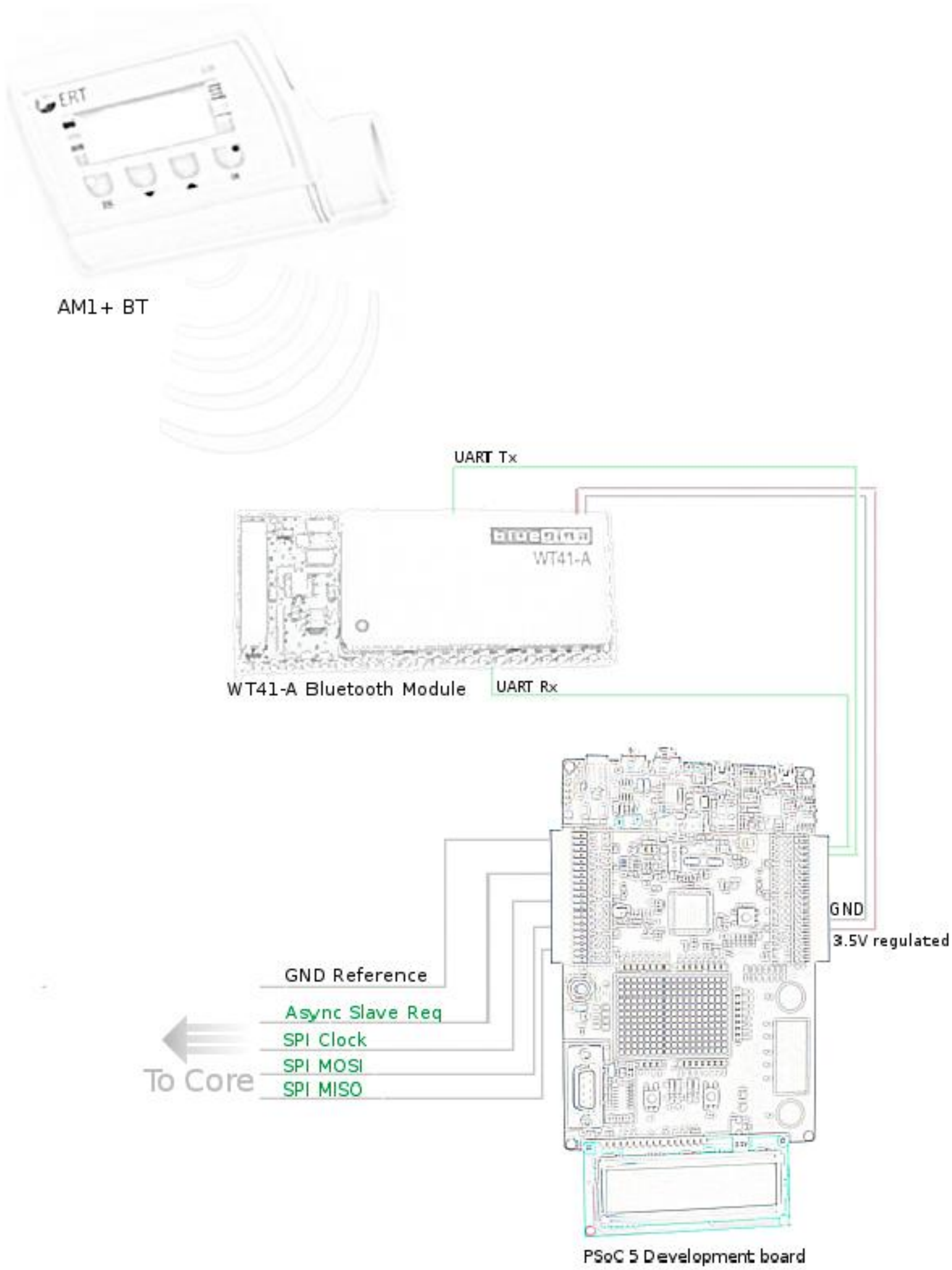


Figure 7.1 Spirometer Satellite Overview

7.1.2 WT41 Bluetooth Module

Bluegiga Technology's WT41 is a Bluetooth module sharing the same basic features as the RN-41-SM discussed earlier in chapter 4 with a lot of additional capabilities. This module was required as the internal buffer of the RN-41-SM proved to be insufficient for the transfer burst of the AM1+ BT. The WT41 is a class 1 device with a range of up to 800 meters (Bluegiga 6). The module is equipped with an SPI, a USB, and a UART communication bus. In the pursuit of simplicity, the UART is the bus of choice for this project.

7.1.2.1 iWRAP4 Firmware

iWRAP4 is the embedded firmware running on the WT41 module (iWRAP4 10). This firmware arms the WT41 with the full Bluetooth protocol stack and many Bluetooth profiles. The iWRAP4 firmware accepts commands and configuration changes in the module via ASCII instructions over the UART interface. Table 7.1 provides a small subset of iWRAP4 commands relevant to this project.

Table 7.1 Subset of iWRAP4 Commands

iWRAP4 Command	Description
AT	Test that the iWRAP is functional
SET	Returns configurations of the Bluetooth device
SET {category} {option} {value}	Change configurations Category: BT, CONTROL, PROFILE, link_Id Eg. SET CONTROL BAUD 115200
SET BT AUTH {device address} {pin}	Sets the pin that would be used for pairing with a device
INQUIRY [timeout]	Scans for nearby discoverable Bluetooth devices
CALL {device address} {channel} {mode}	Initiate a Bluetooth connection. For serial port profile channel = 1101 For this project mode = RFCOMM
LIST	Shows the count of active connections
CLOSE {link ID}	Close a connection at the link ID
<1 second>+++<1 second>	Escape sequence. Toggle between command mode and data mode.
SELECT {link ID}	Switch from command mode to data mode for the specified link

The iWRAP4 firmware allows the device to be connected to multiple devices at the same time. Of course, only one connection can be selected at a given time. Using the commands in Table 7.1, the PSoC chip is able to pair with the AM1+ BT spirometer and request stored data.

7.1.3 The PSoC 5 Control Unit

The control unit for the satellite is implemented on a PSoC 5 development kit. Because the unit communicates with the WT-41 via UART, a UART peripheral is added to the logic array. The usual SPI peripheral for communication with the core is present. Before a communication link with the AM1+ BT can be established, its Bluetooth must be manually enabled. This must be done every time communication is needed as the Bluetooth on the AM1+ BT automatically disables if a link is not made after a certain period. Because of this requirement, the system is designed such that the press of buttons on the PSoC5 development board initiates all interaction between the PSoC5 chip and the AM1+ BT.

A button on the PSoC5 development board is responsible for initiating the data export function on the spirometer. The pin on the PSoC chip is configured as a resistive pull up. The press of the button pulls the pin to ground. This event causes an interrupt and, eventually, the related interrupt service routine to execute. This routine sets a flag, which in turn, causes the main loop to execute code to establish a connection with the spirometer through the WT41-A. Once a connection is established, the satellite's control unit issues commands to AM1+ BT to export any saved data.

7.2 Program Flow

On power up, the PSoC chip initializes the SPI and UART peripherals. It also enables global interrupts on the device. Like the other satellite units, the unit sends a device identifier message over the SPI bus to the core. All activity in the main loop is initiated either by the press of command buttons on the PSoC board or upon receiving a slave request from the core unit.

7.2.1 Data Export Command Sequence

A flag set by the data export command button's interrupt service routine is polled in the main loop. If the flag has been set, a data export sequence is initiated. The device first sends the 'AT' command from Table 7.1 to the WT41-A module. A response of 'OK' allows the transition to the next stage of the state machine. This is a simple check that the Bluetooth module is up and running. Then a connection to the spirometer is made using the 'CALL' command. A response of "CONNECT {link number} RFCOMM 1" indicates that the connection was successful. At this point, any bytes sent over the UART will be forwarded to the AM1+ BT. Before any commands are sent to the device, the AM1+ BT communication protocol suggests that hexadecimal value 0x05 (ENQ) is sent to the device for synchronization (Asthma Monitor 4). Once the device acknowledges with a response of hexadecimal 0x06 (ACK), the data request command can be sent. To request the data, the ASCII command "B01<CR>" is sent to the device. It should be noted here that when the data makes it way to the server unit, a clear memory message is immediately sent back to the satellite device. Upon receipt of this message, the device issues a "L<CR>" delete command to the AM1+ BT. This clears the memory for future measurements. Two seconds after the satellite device forwards the data to the core, the "+++" escape sequence is issued to the WT41-A. This transitions the WT41-A to command mode where the "CLOSE" command is used to disconnect the Bluetooth link. The timeout of two seconds allows time for the clear memory message to get back. If for some reason this message does not make its way back, the link is disconnected without clearing the memory.

7.2.2 Translation and Forwarding of AM1+ BT Data

The format of the data export transmitted from the AM1+ BT is shown in Fig. 7.2 (*Asthma Monitor)*. The device always returns 11 lines of data. The rows of result data are horizontally aligned and the columns vertically. Thus, each line contains the total number of results pertaining to one particular parameter. Each line begins with a 3-byte string, which indicates the length in bytes of the line. The next 4 characters make up a code indicating the parameter that the current line represents. Following the parameter code is the list of stored results for that parameter. A colon delimits each result in the list. The line ends with the cursor return (0x0D) and line feed (0x0A) characters. These two bytes are also included in the length count.

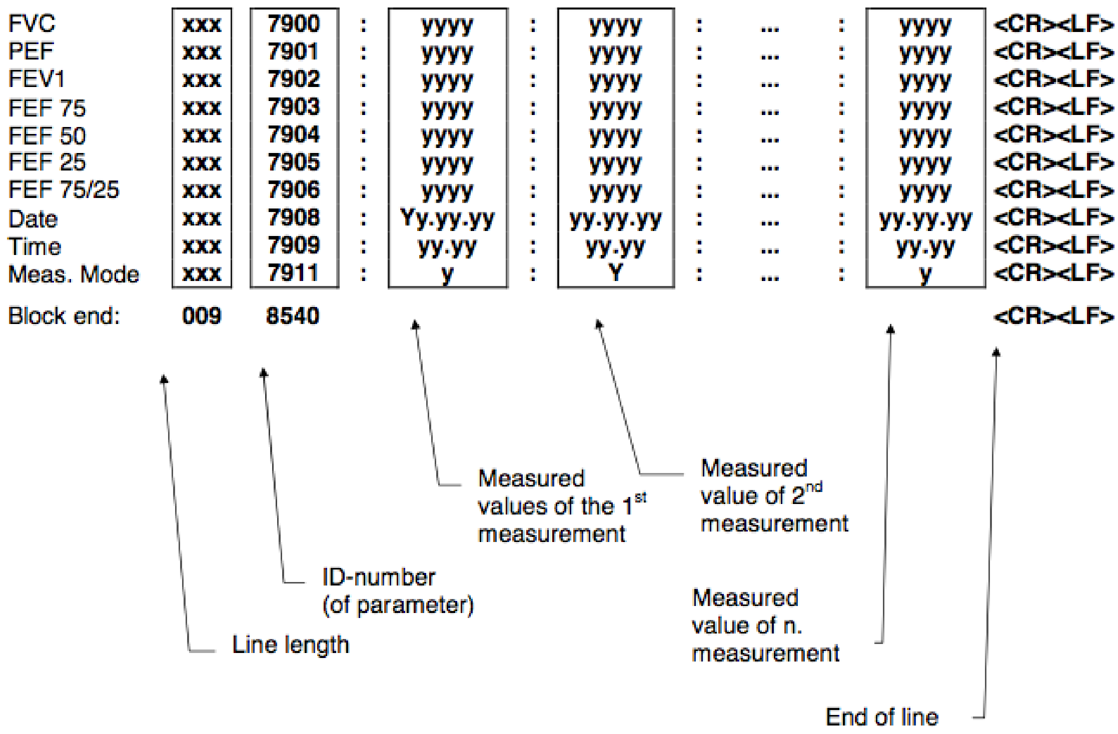


Figure 7.2 AM1+ Data Export Format

For the purpose of forwarding the retrieved data, the satellite device creates one message for each stored test set. Therefore, a single data export from the AM1+ can result in multiple satellite messages. Before the messages containing the test results are transferred to the server, a result header message is sent. The sole purpose of this message is to inform the server of the number of expected results. Because the server needs to respond with a clear memory message only after all the results are received, the expected number of messages is needed.

Table 7.2 provides a summary of the satellite's message types. In the spirometer's data messages, all parameters are transmitted as integer values with the exception of the date and time parameters. In other to do so, the satellite unit converts the ASCII representations transmitted by the AM1. The date and time parameters are kept as ASCII strings within the message.

Table 7.2 Spirometer Message Specification

Description	Header	Length	Device Type	MSG Type	Originating Device	Destination Device	Payload
Device Identifier Message	0x53, 0x4D, 0x53, 0x47	10	23 (Spirometer)	1	Device ID	2 (core)	None
Spirometer Data Message	0x53, 0x4D, 0x53, 0x47	29	23	2	Device ID	1 (server)	19 bytes
Spirometer Data Header Message	0x53, 0x4D, 0x53, 0x47	11	23	3	Device ID	1 (server)	1 byte
Clear AM1 Memory Message	0x53, 0x4D, 0x53, 0x47	10	23	4	1 (server)	Device ID	None

CHAPTER 8

SERVER UNIT

This chapter describes the design of the server unit. The primary function of the server unit is to serve as a central data repository, to function as an interface between the patient and the doctor's office, and to present historical data from the connected devices in a meaningful way.

8.1 Unit Overview

Although the prototype was done using a laptop, the server unit can exist on any computer system having Bluetooth capability and the UBUNTU Linux operating system. Other versions of the Linux operating system may be used provided that the necessary libraries are available for these operating systems. The key components making up the server unit includes the communication core, the data store middleware, and a graphical user interface (GUI). Both the communication core and the data store are daemon processes. Events within the system either emanates from the GUI or as a result of data events in the communication core. Fig. 8.1 provides an illustration of the server unit's overall architecture.

8.1.1 The D-Bus

Because the server unit consists of independent processes working together, a system for inter-process communication (IPC) is necessary. In order to transmit messages and events between processes, the D-Bus messaging system is put into use. D-Bus is a well-known IPC mechanism in the Unix domain. It allows local communication between processes running on the same host. The D-Bus allows both one-to-one messaging and publish/subscribe type communication (Warsaw, Barry 1). Apart from allowing messages to be shared between processes, D-Bus also emulates function calls by supporting message parameters and return types. These are referred to as methods.

The parameters and return values are not treated simply as raw bytes, but as structured data types. This allows the D-Bus to be able to validate the data it carries. Processes wishing to communicate over the D-Bus have the option of two distinct components for doing so. One option is the point-to-point dbus library. The dbus library allows any two processes to exchange messages. The other is the dbus daemon. The daemon runs a bus with which any number of processes may be connected to at any given time. The dbus daemon is also capable of providing authentication mechanisms and access controls for processes running under different users that wish to communicate. Each bus has an address that describes how to connect to it. Typically, this address will be a filename.

Connections to the bus are addressed using the connection's bus names. These names consist of dot-separated identifiers. Processes access the bus using what are called proxy objects. They are referred to proxies, as these objects, which are local to the individual client processes, are simply local representations of bus objects. Bus objects also have names or paths. Each object exists within the context of a particular connection. Therefore, in order to find an object, both the name of the connection and that of the object are necessary.

In the context of the D-Bus, method invocations differ from conventional function calls. Method invocations could be either synchronous or asynchronous. Conventional function calls are synchronous. This means that when a function is called, the calling program must wait until the function returns. Asynchronous method invocation allows the requesting process to accomplish other tasks while waiting for a response. In asynchronous invocation, a process can actually call other methods while waiting on a response from a previous call. Also, the D-Bus provides timeouts for message returns. If a method does not return within this timeout, an exception will be produced. For the purpose of this project, the Glibmm binding to the D-Bus library was utilized.

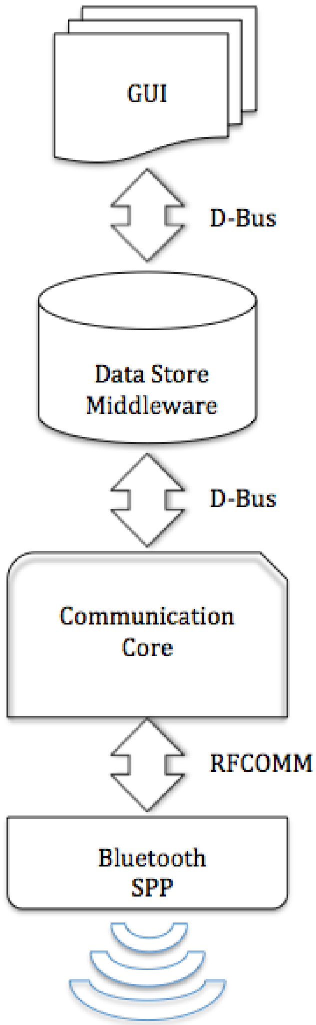


Figure 8.1 Server Unit Block Diagram

8.1.2 Communication Layer

The communication layer is the interface to the machine's Bluetooth hardware. The communication layer is implemented as a daemon process monitoring the emulated serial Bluetooth port. Unlike the GUI, this process must be running for the system to function.

8.1.1.1 Interface to Hardware

The system gains access to the hardware by opening a file descriptor to the Bluetooth device node. The device node is an interface to the hardware driver provided by the operating system. Bluetooth communication is done using the serial port profile (SPP). SPP emulates serial cable communication over a Bluetooth link (Palo Wireless 1). The port is configured using a baud rate of 115200. The port is configured with the common 8 data bits, no parity and 1 stop bit.

Once the file descriptor is opened, the system monitors the file descriptor at regular intervals using the select command. This method is normally applied to network server processes for monitoring whether new data is ready to be read on a socket. The select command waits on either the arrival of new data or expiring of a timeout. This timeout allows the execution to cancel the read if there isn't any data available after the set duration. This is important for such processes as a blocking call could prevent other important tasks from taking place while there's no data coming in from the port.

Whenever new data is available, it is read into a buffer. The system processes the buffer by scanning for the presence of complete messages. Similarly to the core unit, the length field in the message is used to determine whether the entire message is present in the buffer. Once a complete message is detected, the message is forwarded to the data store middleware process via the D-Bus.

8.1.1.2 Interface to Middleware

The interface from the communication core to the middleware process is the D-Bus. Requests coming from the middleware are wrapped in the system message header before being transmitted over the Bluetooth link. Inbound messages processed from the Bluetooth port are unwrapped before being forwarded to the middleware.

8.1.3 Data Store Middleware

The function of the data store middleware is primarily to process then save incoming data to the database. The middleware also functions as a repeater. It emits signals to the GUI alerting it that events have occurred. This process is essential to the server's functionality and must be kept alive while the system is running. Apart from receiving external messages from the communication core, it also receives requests from the GUI. These requests are packed into system messages and forwarded to the intended recipients via the communication core.

When a message passed on from the communication layer is received, the device type and message type fields are used to determine the callback function to process the packet. Processing the packet involves parsing the bytes received and then storing the data in the correct database tables. Once the database inserts has been committed, the process emits a signal to the GUI. This signal alerts the GUI that an event has occurred and that a data refresh is necessary.

8.1.2.1 Event Logging

Another very important function of this process is system logging. Because it exists between the GUI and the communication layer, the middleware is aware of all significant events occurring within the system. GUI initiated commands to the external devices must be routed through the middleware. Also, messages initiated externally make their way from the communication core to the middleware. Another reason why the logs produced by the middleware are very useful is the fact that messages received at the communication core are treated as a black box. The messages are not interpreted passed the message start sentinel and the message length field. The middleware, on the other hand, parses the incoming messages and hence expose information about every message.

8.1.2.2 Email Alerts

The middleware process is capable of performing analysis on received data and sending out alert emails when necessary. The arrival of certain message types can initiate analysis of the data in the database. In cases where it is determined that urgency exists, the system sends out emails using a system call to the MUTT utility (MUTT is a text-based mail utility available on most Unix systems). This functionality depends on a persistent Internet connection.

8.1.2.3 The Database

It is required that events in the system originating from the Bluetooth hardware are eventually saved in some format in a database. Data stored in a database will be easily available later for display and analysis. Not only is a database necessary for storage and retrieval of measurement data, but it's also required for storing system settings and state variables. The database system of choice for this project is PostgreSQL. PostgreSQL is an "open source object-relational database system" (PostgreSQL 1). In order to access the PostgreSQL database from within the GUI, an interface library is required. For this requirement, the pgSQL C++ library, "libpqxx," is included in the source.

8.1.2.4 Status Monitoring

Another function of the middleware is to occasionally poll the core unit for status updates. Every 10 seconds, a message is sent to the core unit to request an update on which devices are currently connected. 10 seconds provide an updated status without producing too much traffic on the bus. Upon receiving this message, the core unit broadcasts a device identification request over each SPI bus. The responses are then forwarded to the middleware.

8.1.4 The Graphical User Interface

Unlike the other processes in the server, the GUI is not essential for the system to function. The GUI is only necessary for presenting information from the database to the user. It also provides other information such as notifications of certain events in the system. The GUI is developed with the gtkmm library. GTK refers to the GIMP Toolkit and is a library collection for creating graphical user interfaces. The gtkmm library provides a C++ interface to GTK+ which is natively C.

8.1.3.1 The Start Page

Fig. 8.2 shows a screenshot of the GUI. The main window comprises solely of a notebook widget and a status area. Within the notebook, each vital sign device has its own tab. The status area below displays the availability of devices within the system. A red indicator shows that the device is currently unavailable, whereas a green indicator shows that the device is currently online. This function is implemented by connecting a status update handler to the middleware. Whenever the middleware detects a change in the availability of devices connected to the system, it emits a signal to the GUI.

Figure 8.2 Graphical User Interface Start Page

8.1.3.2 The Oximeter Page

The oximeter page offers a graphical representation of the data coming in from the oximeter satellite unit. The page displays real-time graphs for pulse and blood oxygen saturation. When the middleware receives data messages from the oximeter satellite, the data is stored and emitted to the GUI as an argument in a signal. The callback for that specific signal in the GUI adds the new data to the buffer and redraws the screen. The buffers for both of these graphs withhold data until the buffer outgrows a determined size. After this limit, new messages added causes the older data to be dropped producing a moving real-time graph.

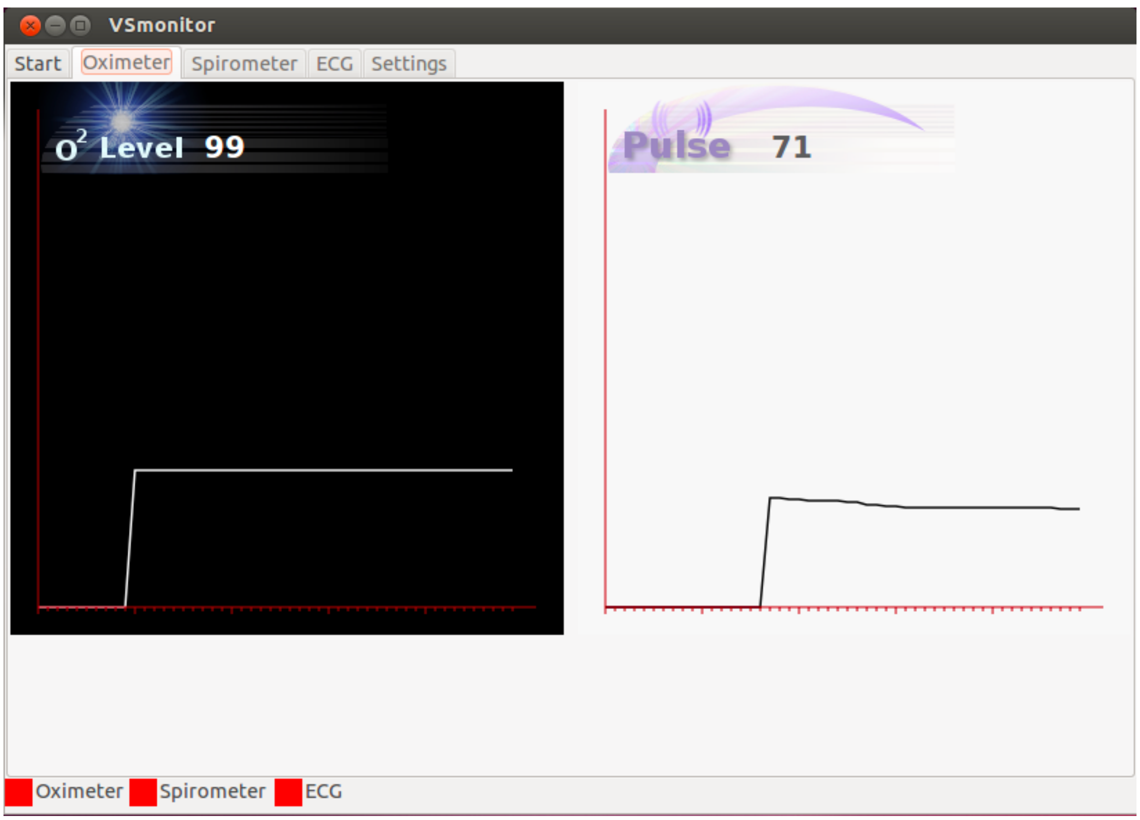


Figure 8.3 Graphical User Interface Oximeter Page

8.1.3.3 The Spirometer Page

The spirometer page provides a history of readings in a tabular and a graphical view of the 10 most recent reading. This version of the plot widget was designed to draw multiple data groups on a single graph. Since the PEF values are generally much smaller than the FVC and FEV1 values, the plot widget was designed to allow independent zoom factors to the y-axis of each plot. This allows the three parameters to be within view. Similarly to the plots in the oximeter page, the plot will begin dropping data once the 10-point limit is reached. The spirometer page also updates automatically when new data arrives from the middleware daemon.

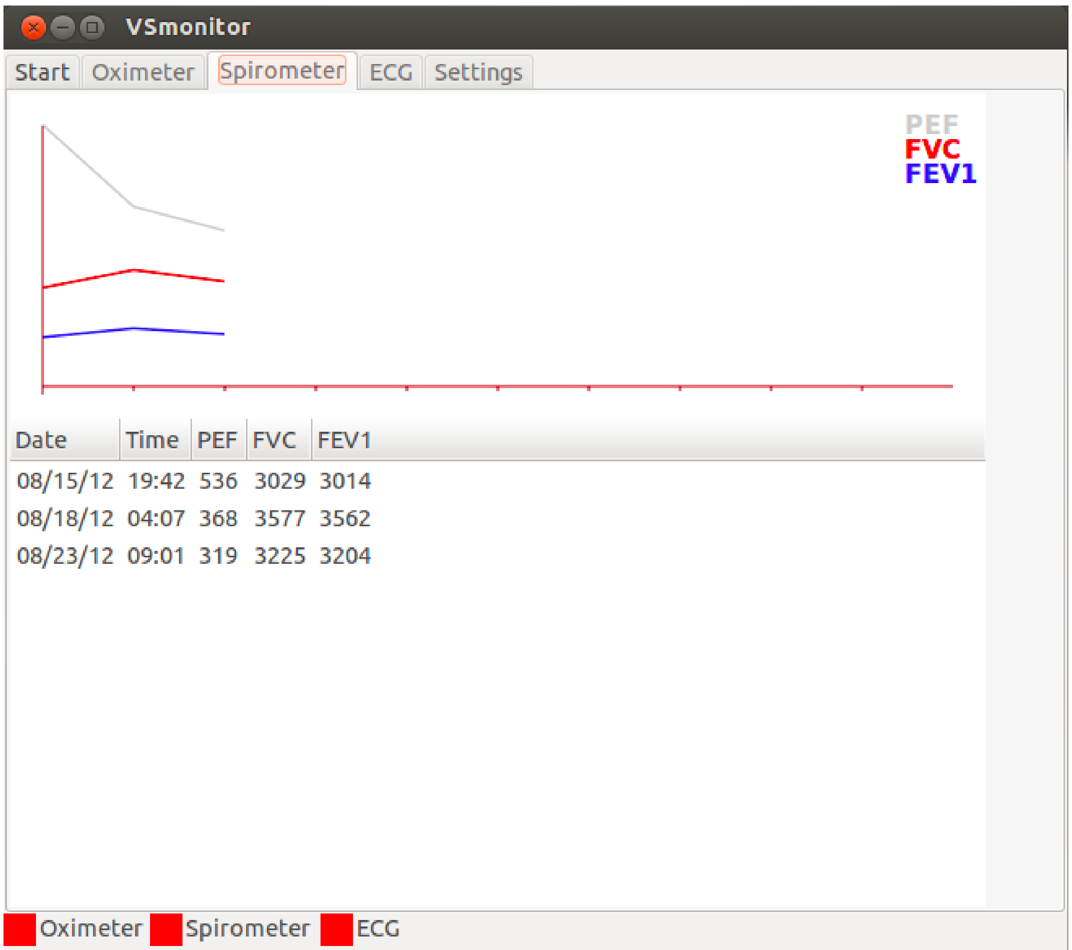


Figure 8.4 Graphical User Interface Spirometer Page

7.1.3.4 The ECG Page

The ECG page provides a more visual representation of the incoming stream of data from the ECG. The ECG page also contains a start and stop button, enabling the server to start and stop the remote satellite device. The start and stop buttons emit D-Bus signals to the middleware process prompting it to generate and send command messages to the satellite unit. The plot is configured to hold a maximum of 500 data points before it starts scrolling. The plot also displays the last received voltage value from the ADC in millivolts.

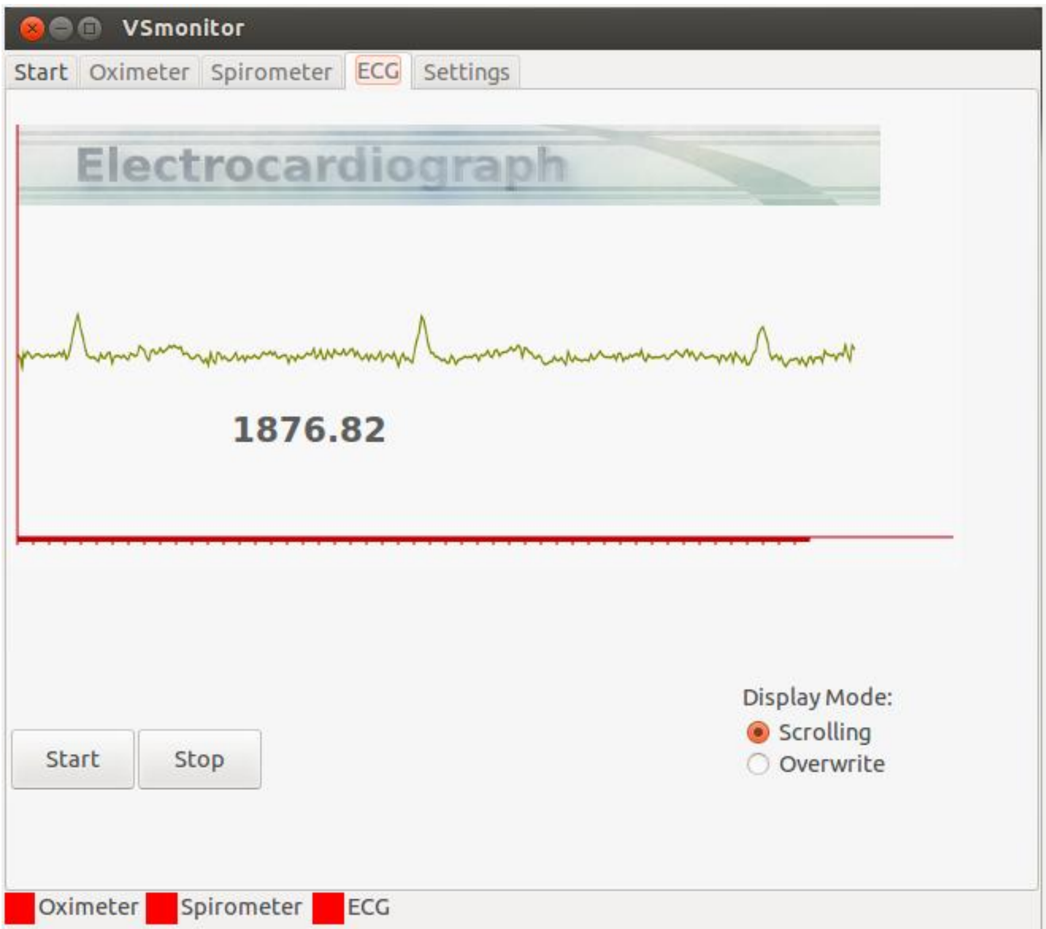


Figure 8.5 Graphical User Interface ECG Page

The plot is able to update the display in two modes. In scrolling mode, the plot shows the normal behavior when the 500 data points limit is met. The oldest data point is removed from the end of the buffer before the new data point is added. In overwrite mode, the plot behaves like the usual ECG display. The buffer is implemented as a fixed array with a moving index. Each time a new data point arrives, it simply replaces the old data at the current index then the index is incremented. Of course, the index is reset to zero when it gets to the end of the array buffer.

CHAPTER 9

CONCLUSION AND FUTURE WORK

This chapter discusses the results achieved from the research performed in this thesis. The scope of this research focused mainly on the design and development of a detached vital sign management system. The system was required to be flexible (having the ability to hold different configurations) and disconnected from any wall sockets.

9.1 Conclusion

The five subsystems discussed in this thesis paper were developed. When connected together, messages were routed throughout the system allowing measurements to be stored remotely by the server.

The core unit was developed with the PSoC 5 development kit and the RN-41-SM module. The core unit acts as a wireless bridge between satellite devices and the remote server. Multiple satellite devices were able to connect to the core unit forming a star network. Activity passing through the core was observed by the alternate blinking of two LEDs indicating that a complete message has been received or routed.

The spirometer satellite unit was developed with the PSoC 5 development board and the WT41-A Bluetooth module. At the touch of a button, the spirometer unit initiates Bluetooth connection between the WT41-A and the AM1+ BT device. The device then requests the stored data on the AM1. The data is received by the satellite unit and parsed. Each individual result is then sent to the server via the core unit. After initiating the data exchange, new spirometer data were seen on the database and the GUI automatically refreshed displaying the new data.

The pulse oximeter satellite unit was developed with the ChipOx OEM module and the PSoC 5 board. Data transmitted by the ChipOx device was formatted to meet the system communication specification before being forwarded toward the server via the core unit. Pulse and blood oxygen reading were observed in the database and on the GUI.

The ECG unit was developed with both the analog circuitry and the PSoC 5 board. ECG data were observed passing through the core unit and making its way to the server. The results were observed as a live plot on the GUI. Although heart activity was clearly observed on the plots, the expected P wave, the QRS complex, and the T wave were not well defined. Additional work is required to refine the ECG traces.

Finally, the server unit was developed with its three sub-processes. The server communications process was developed as a daemon process. This process serves as the link between the server's Bluetooth modem and the other components. The server core process receives messages and signals from the communication process and the graphical user interface. The server core process generated logs and saved inbound data from the communication process to the PostgreSQL database. The graphical user interface was developed using the GTKmm library. The GUI provided a visual view of what's going on with the attached devices in the system. Inter-process communication between the server's processes was implemented with the Glibmm bindings to the D-Bus.

9.2 Future Work

As mentioned in section 9.1, the ECG satellite unit needs additional work in order to improve the waveform. The filter stage needs to be improved upon to reduce interference and avoid filtering out of wanted frequencies. Input guarding circuitry needs to be added to the ECG design as an additional measure to reduce interference. The ECG unit would also show improved performance with the addition of a third electrode for reducing common mode noise. Finally, the ECG unit could be made even less obstructive to the patients by implementing it as a wearable device with communication to the core unit solely by Bluetooth.

To allow for use in multi-level homes, work on a Bluetooth forwarding system using the WT41-A is proposed. This would increase the range of the system to multiple floors within a home.

Additional satellite devices, including a wireless glucose monitor and a blood pressure meter, should be designed and added to the arsenal of devices that are able to integrate and work with the system.

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