

# **SQVID:**

## **Simplified Quad-Vitals Integration Device**

UCF Senior Design Group 1

Sponsored by Philips

Fall 2013 – Spring 2014

**Connor Hogan, EE**

**Jonathan Lamones, EE**

**Lauren Martinez, CpE**

**William Michelin, EE**



# Table of Contents

<b>1.0</b>	<b>Executive Summary .....</b>	<b>1</b>
<b>2.0</b>	<b>Project Description .....</b>	<b>2</b>
2.1	Motivation and Goals .....	2
2.2	Project Objectives and Constraints .....	3
2.2.1	Cable Fabrication: MRI Safety and Compliance .....	3
2.2.2	Connector Choice.....	4
2.2.3	Connection Box .....	5
2.2.4	Embedded System for Central Connection Box .....	7
2.2.5	Software .....	7
2.3	Project Requirements and Specifications .....	8
2.3.1	Hardware Requirements and Specifications .....	8
2.3.1.1	Software Requirements and Specifications.....	10
<b>3.0</b>	<b>Research Related to Project Definition.....</b>	<b>11</b>
3.1	MRI Background Information.....	11
3.1.1	Sensors Utilized .....	11
3.1.2	Signal Paths and Systems.....	15
3.1.2.1	Multiple Sensor Environment .....	15
3.1.2.2	Cable Requirements and Usage.....	17
3.1.3	Potential Hazards .....	17
3.1.4	Risk Management .....	21
3.2	Existing and Similar Projects .....	23
3.2.1	Shared Resources .....	23
3.2.2	Content Similarities .....	23
3.2.3	Consolidated Cable Systems.....	24
3.2.4	Wireless Systems .....	24
3.3	Design-Critical Components and Hardware .....	28
3.3.1	MRI-Safe Qualification of Hardware .....	28
3.3.2	Availability of Components .....	31
3.3.3	Limitations .....	31

<b>4.0</b>	<b>Project Hardware and Software Design Details .....</b>	<b>33</b>
4.1	Overall Design Architecture and Diagrams .....	33
4.1.1	System Interconnect Diagram.....	34
4.1.2	Design Tree and System Flow Down .....	35
4.1.3	Functional Block Diagrams .....	36
4.1.3.1	Hardware .....	36
4.1.3.2	Software .....	37
4.1.4	Schematic Drawings .....	38
4.2	Block 0 System Design .....	40
4.2.1	Cabling System Materials and Design.....	40
4.2.1.1	Reduced-Risk Cable Systems.....	41
4.2.1.2	MRI Compatibility of Cable Systems .....	43
4.2.1.3	Cable-Sensor Interface Design.....	43
4.2.1.4	Cable-Platform Interface Design.....	43
4.2.2	Cable Consolidation Solutions.....	44
4.2.3	Component Selection .....	44
4.2.3.1	Voltage Regulator .....	44
4.2.3.2	Microcontroller.....	46
4.2.4	Microcontroller Analog to Digital .....	48
4.2.5	NiBP System Design.....	62
4.2.5.1	Pressure Cuff.....	62
4.2.5.2	Pressure Transducer .....	62
4.2.5.3	DC Amplifier.....	65
4.2.5.4	Bandpass Filter .....	67
4.2.6	Signal Multiplexing .....	70
4.2.6.1	Cable Management.....	71
4.2.7	Limitations .....	71
4.3	Block 1 System Design .....	71
4.3.1	Wireless System Materials and Design.....	71
4.3.1.1	Integration with Existing Hardware .....	74
4.3.1.2	Operational Frequency/Spectrum.....	74
4.3.2	Software Platform .....	76

4.3.3	Existing System .....	76
4.3.3.1	User Interface .....	77
4.3.3.2	Coding Language .....	79
4.3.3.3	Signal Acquisition and Processing.....	80
4.3.3.4	Scalability.....	81
<b>5.0</b>	<b>Design Summary of Hardware and Software .....</b>	<b>84</b>
5.1	Hardware Design Summary .....	84
5.2	Software Design Summary.....	84
<b>6.0</b>	<b>Project Prototype Construction and Coding.....</b>	<b>85</b>
6.1	Final Coding Plan.....	85
6.1.1	Objective Summary .....	85
6.1.2	Functionality and Features .....	87
6.1.3	Program Flow.....	90
<b>7.0</b>	<b>Project Prototype Testing .....</b>	<b>92</b>
7.1	Hardware Testing Environment .....	92
7.1.1	Faraday Cage .....	92
7.1.2	MRI.....	92
7.1.3	RF-Noisy Environment.....	107
7.2	Hardware Specific Testing.....	107
7.2.1	Microcontroller A/D .....	107
7.3	Software Testing Environment.....	109
7.3.1	Proximity to SQUID Connection Box .....	109
7.3.2	Operating System.....	110
7.4	Software Specific Testing .....	110
7.4.1	Initial Setup: Configuration Screen .....	110
7.4.2	Testing Procedures.....	112
<b>8.0</b>	<b>Administrative Content.....</b>	<b>118</b>
8.1	Milestone Discussion .....	118
8.1.1	Research.....	118
8.1.2	Design .....	118
8.1.2.1	Hardware .....	118
8.1.2.2	Software .....	119

8.1.3	Prototype and Testing .....	119
8.2	Budget and Finance Discussion .....	122
8.2.1	Budget Allocation .....	122
8.2.2	Parts List .....	123
<b>List of Tables .....</b>		<b>125</b>
<b>List of Figures.....</b>		<b>127</b>
<b>Appendices.....</b>		<b>128</b>
	Appendix A – References .....	128
	Appendix A – Datasheets .....	129
	Appendix C – Flow Charts and Diagrams .....	133
	Appendix D – Schematics .....	145

## 1.0 Executive Summary

The Simplified Quad-Vitals Integration Device, or SQVID, project is a proposed solution to a problem the Philips Company is facing with regards to existing magnetic resonance imaging (MRI) patient connections. Currently, patients facing an MRI scan are monitored for various vital signs both during a scan and during their hospital stay. They are subjected to an array of wires and cabling which are unnecessarily large and only complicate an already uncomfortable situation. In an effort to improve the wellbeing and comfort of patients, Philips seeks a clean remedy to replace the existing spider's-web of cabling that presently exists for their healthcare customers and patients' alike.

There are four vital signs typically monitored during a patient's stay in the hospital, before, during, and after an MRI scan. The signals that are of concern include: electrocardiography (ECG), spot oxygen saturation (SpO2), carbon dioxide (CO2), and non-invasive blood pressure (NiBP). Two of these have already been converted into a wireless reading device by Philips, however each one goes to a separate battery-powered hand-held, which still adds to unnecessary clutter, as the individual hand-helds simply lay at the patient's side and need to be adjusted with every movement of the patient. The SQVID cable solution will incorporate these two signals, with the main objective of converting the others into a similar wireless signal, and all four will converge into a central location at the bottom of the patient's bed. This convergence point will be a single box, containing all the microcontrollers necessary to take the signals and wirelessly transmit them to the main software system nearby for the needed manipulation and display.

This central connection box is no larger than a 1'x1'x1' cube. It is imperative that it be extremely mobile, for it will be traveling with the patient wherever he or she goes. The box will have individual connection slots for each vital sign, as the main cable splits into the four signals approximately one foot from its terminating end. The main cable is no longer than eight feet long and does not bend or coil, due to the risk of disrupting the signal being monitored. All materials used in the construction and prototyping of the connection box and the main cable will be subject to Philips' approval and proprietary manufacturing techniques. In other words, the Philips Company already has an existing "secret recipe" for their cable fabrication which they will be incorporating into the team's design during the building phase of this project.

The necessary software system is designed with a "plug-and-play" architecture in mind, and is known as the Intelligent Navigation Controller, or "INC". Because not all four vital signs are always necessary, the system will detect which are connected and thus which need to be monitored. The system will then perform the necessary calculations, scaling, and other forms of manipulation to properly display the signal for the health care professionals in charge of the patient. The goal of this architecture is to reduce errors or

the accidental misreading of information that is currently caused by human negligence or lack of knowledge regarding the system. While this is an automatic feature, advanced and manual manipulation of the vital sign information is also possible if necessary. The software system will run from a tablet, laptop, or desktop computer based on the needs of the physician monitoring the patient. Within the scope of this project the software system, while many features are included, only serves to demonstrate the newly designed hardware's functionality. It is imperative that all vital sign data received from the individual monitoring microcontrollers within the connection box is accurate and reliable. The software system ensures that these two requirements are fulfilled, in addition to adding consumer appeal and functionality.

While the main objective of the SQUID project is a consolidated cabling system, emphasis will be on ensuring the main cable is compatible and safe for use within an MRI environment, as well as converting the two remaining vital signals such that they can be transmitted wirelessly to a central software system as already demonstrated by the Philips Company.

## **2.0 Project Description**

### **2.1 Motivation and Goals**

The Philips Company is a leader in the health industry and continually seeks to utilize the latest technology and improve the lives of their customers and patients. In an effort to innovate and ease the stress placed upon patients facing an MRI scan, the already wireless ECG and SpO2 signals served as a model to follow and starting point for a more robust wireless solution as part of the SQUID Project. While these two signals were an improvement over their predecessors, the remaining vital signs, non-invasive blood pressure (NiBP), and CO2, still involved a spiders-web of cabling which hindered patient transport and comfort. The SQUID Project incorporated the existing wireless signals into a more complete system with the NiBP and CO2 signals added, as well as enhanced the software system to provide a more interactive, hands-off interface for healthcare professionals.

The pre-existing vital signs (ECG and SpO2) were monitored via a battery powered handheld. While this approach provided a portable, effective, and comfortable way to observe a patient's condition, converting the other two necessary vital signs in the same way would have only contributed to unnecessary clutter. It was imperative that the SQUID Project take into consideration extreme mobility as well as the effects the magnetic field would have on the various signals. These two factors were the driving

force for the final design: a small box which resides at the bottom of a patient's bed where each vital sign connects and is transmitted wirelessly to the necessary software system.

The software system has the ability to recognize which vital signs are being monitored and performs the necessary calculations and modifications as per Philips standards to eliminate as much human intervention as possible. It displays the vital signs in a familiar waveform manner, with accompanying digital data. It has a user-friendly design and touch screen interface, allowing health care professionals to get to the information they need effortlessly. It has the ability to run from a tablet interface, a laptop, or a desktop computer, making it easy to customize for a specific need or environment.

Due to the dangers associated with the strength of the MRI magnet, extreme precaution and excessive testing was necessary to ensure the safety of all patients being monitored by the SQVID cable. The materials used in construction were approved and fabricated by Philips to ensure the quality of their products and to maintain their high standards. Exhaustive testing procedures were followed under professional supervision to guarantee the resulting prototype was not only safe, but accurate, easy to use, and efficient.

Much care was taken in designing a product that would be familiar to current Philips' customers. While the software system took a much more innovative approach, this was only due to the sheer complexity of Philips' current software system compared to the scope of this project. Only proof of concept was required, so extra features were added to enhance the demonstration of the new SQVID cable solution. As regards the cable fabrication, connectors, and other hardware aspects, current Philips' vendors were used to maintain consistency and coherence with other Philips' reputable products.

## **2.2 Project Objectives and Constraints**

### **2.2.1 Cable Fabrication: MRI Safety and Compliance**

The following objectives in **Table 2-1** are associated with the safety of all patients and healthcare professionals involved in an MRI procedure as well as the accuracy of data obtained from the vital signs being monitored by the SQVID cable.



**Table 2-1: Cable Fabrication Objectives**

<b>Objective</b>	<b>Requirement Description</b>
CF-001	All cables used to monitor the four required vital signs cannot interfere with the MRI image. The cable(s) must aim for minimum noise, conductivity, magnetism, etc.
CF-002	All cables must meet Philips' approval and their personal requirements for manufacturing and production.
CF-003	Cable(s) cannot bunch, loop, or perform any other unanticipated movement that would disrupt the clarity of the signal being monitored.
CF-004	Cable length will be no longer than 8 feet.

### **2.2.2 Connector Choice**

The following goals illustrated in **Table 2-2** regard the choice of the connectors used for each vital sign necessary for the SQUID Project.

**Table 2-2: Connector Choice Objectives**

<b>Objective</b>	<b>Requirement Description</b>
CC-001	All connectors must take into consideration the magnetic field associated with an MRI scan and thus cannot interfere with the MRI image. The connectors must strive for minimum noise, conductivity, magnetism, etc.
CC-002	All cables must meet Philips' approval and their personal requirements for manufacturing and production.
CC-003	All connectors must be as small as possible to prevent additional bulk to the central connection box.

### **2.2.3 Connection Box**

The following objectives found in **Table 2-3** address the central connection box designed to be located at the bottom of a patient's bed and provide connection points for all vital signs requiring monitoring.

**Table 2-3: Connection Box Objectives**

<b>Objective</b>	<b>Requirement Description</b>
CB-001	The central connection box must take into consideration the magnetic field produced by the MRI scan and cannot allow this interference to disrupt the MRI image. The box must be designed for minimum noise, conductivity, magnetism, etc.
CB-002	The central connection box must take into consideration the magnetic field produced by the MRI scan and cannot allow this interference to disrupt the MRI image.
CB-003	The design and functionality of the box must have Philips' approval and meet their personal requirements for manufacturing and production.
CB-004	The connection box must be designed for maximum portability. Handles or other additions to ease the transport of the box are of high importance.
CB-005	The connection box must not be larger than a 1x1x1 foot cube.
CB-006	The connection box must be structurally stable and sit at the bottom of a patient's bed without interfering with that patient's comfort or mobility.
CB-007	The connection box must be easily moved, thus weighing as little as possible, capable of traveling with the patient throughout the hospital and never hindering bed transfers or other non-stationary processes.

## 2.2.4 Embedded System for Central Connection Box

The following requirements in **Table 2-4** address the electrical functionality and programming of the central connection box.

**Table 2-4: Embedded System Objectives**

<b>Objective</b>	<b>Requirement Description</b>
ESCB-001	The connection box embedded system must take each signal and perform analog-to-digital and/or digital-to-analog conversion as required for each individual signal.
ESCB-002	The connection box embedded system will handle the to-wireless conversion of each signal and the transmitting of this signal as necessary.

## 2.2.5 Software

The following objectives in **Table 2-5** address the software system, Intelligent Navigation Controller, or INC, associated with the SQUID Project.

**Table 2-5: Software Objectives**

<b>Objective</b>	<b>Requirement Description</b>
S-001	The software system must be capable of recognizing which signals are connected to the central connection box.
S-002	The software system must do the necessary calculations and/or modifications as determined by Philips to accurately depict the signal as required for all healthcare professionals using the system.
S-003	The software system must perform the above two requirements automatically without any user intervention.
S-004	The software system must provide a user-friendly, easy to understand and manipulate interface for healthcare professionals involved in its operation.
S-005	The software system must be extremely reliable and accurate.

## **2.3 Project Requirements and Specifications**

### **2.3.1 Hardware Requirements and Specifications**

The following, **Table 2-6**, depicts the SQVID Project hardware requirements and specifications, all of which must also meet the needs and approval of Philips as the sponsor and consumer.

**Table 2-6: Hardware Requirements and Specifications**

<b>Hardware Requirements Specification</b>	<b>Description</b>
HRS-001	All cabling materials used will be MRI safe.
HRS-002	All materials used in manufacturing the central connection box will be MRI safe (no ferro-magnetic materials).
HRS-003	The central connection box and/or any other devices requiring power will utilize an approved (by sponsor) DC supply.
HRS-004	The central connection box will be a maximum of 1ft. in length by 1ft. in height by 1ft. in width.
HRS-005	The central connection box will not exceed 10lbs in weight.
HRS-006	Each connector used will have a small (that is, no bigger than a 2in. by 3in. rectangle) footprint.
HRS-007	Any and all connectors used will be MRI safe.
HRS-008	The consolidated cable length will be no longer than 8ft.
HRS-009	The central connection box will allow for up to four connections, and will operate with as little as one.
HRS-010	All cabling will resist bending or looping.
HRS-011	All cabling will be robust, that is, able to withstand the typical use of such a cable.
HRS-012	All materials used will be subject to sponsor approval due to the safety of others involved in the final product.

### 2.3.1.1 Software Requirements and Specifications

The following (**Table 2-7a** and **Table 2-7b**) shows the SQVID INC software requirements and specifications.

**Table 2-7a: Software Requirements and Specifications**

<b>Software Requirements Specification</b>	<b>Description</b>
SRS-001	The software system will be a standalone program.
SRS-002	The software system will be able to recognize which vital signs are connected to the central connection box.
SRS-003	The software system will provide a user-friendly interface for healthcare professionals and all others using the program.
SRS-004	The software system will perform all necessary calculations and/or modifications to the signal received with little-to-no user intervention.
SRS-005	The software system will perform in real-time.
SRS-006	The software system will display reliable, accurate data, in a familiar and understandable way for users.
SRS-007	The software system will attain the wireless data sent from the central control box.
SRS-008	The software system will be reliable, that is, functioning without errors.

**Table 2-7b: Software Requirements and Specifications**

<b>Software Requirements Specification</b>	<b>Description</b>
SRS-009	The embedded systems software will convert from analog-to-digital or digital-to-analog as necessary.
SRS-010	The embedded systems software will handle the converting and transmitting of the wireless signal(s) to the software system.

## **3.0 Research Related to Project Definition**

### **3.1 MRI Background Information**

#### **3.1.1 Sensors Utilized**

NiBP – Blood pressure monitoring is the process of recording data about a patient’s arterial pressure and, in turn, data about the patient’s heart. There are two categories of monitoring a patient’s blood pressure; invasively and non-invasively. Within those, there are multiple methods of acquiring the data. See **Figure 3-1**.

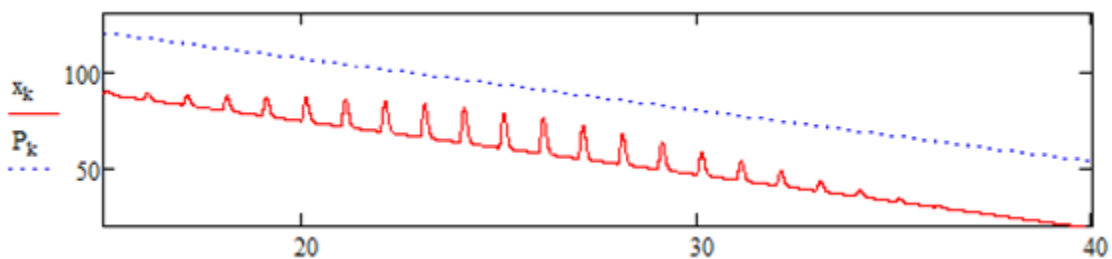
Invasive blood pressure (IBP) monitoring means the patient’s skin must be breached and a device is directly interacting with a patient’s blood. This is, of course, a more critical procedure when dealing with patient safety in the chaotic environment of a hospital. This method would not be advised if other safer options are available or blood pressure is not of concern during the patient’s care. Fortunately, a safer non-invasive method is available and usually more appropriate to use for most patients.

Non-invasive blood pressure (NiBP) monitoring is the most commonly practiced category of blood pressure monitoring. “Non-invasive” means that the data is recorded from outside the patient’s body. Nothing is required to break skin or enter the patient’s body to get a reading. To monitor a patient’s blood pressure non-invasively, a cuff is placed around the patient’s bicep and is filled with air, cutting off circulation of blood through the brachial artery. The pressure of the cuff is slowly released and at a certain pressure, blood will push past the tourniquet. The point at which blood first pulses past



the tourniquet is called the systolic pressure and it is important that this value be recorded accurately. The blood is slowly released into the artery and, as the heart pumps, distinct pulses of blood pressure can be measured. As the cuff deflates, it loses force against the artery and pressure waves become less prominent. The point of the last measurable wave of pressure is called the diastolic pressure and it is also an important figure that should be recorded accurately. With both systolic and diastolic pressures measured, a doctor or trained physician can make an assessment of the patient's heart and its health.

Figure 3-1: Sample NiBP Signal



Within the non-invasive category of blood pressure monitoring, two methods of gathering data are most commonly practiced. The first, a very manual and judgment based method, requires the physician to listen for the first pulse of blood to pass the tourniquet with the use of a stethoscope. The turbulent initial spurt of blood makes a sound, referred to as the first Korotkoff sound, and this marks the systolic pressure. The physician then continues listening and marks the last audible pulse (fifth Korotkoff sound) as the diastolic pressure. This technique's accuracy is reliant on the physician's judgment and this is not the technique our project will encompass, but testing the accuracy of our design may require the use and comparison of this method.

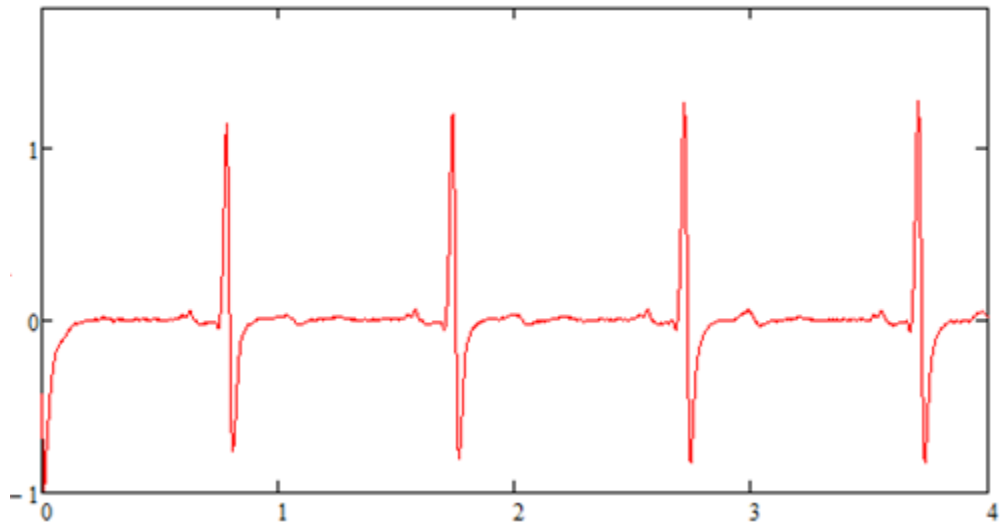
The second method uses the same pressure cuff but reads changes in the cuff pressure by way of a pressure transducer. With proper signal analysis and computation, the patient's blood pressure can be monitored precisely, accurately, and, most importantly, remotely. A physician does not need to physically interact with the patient (aside from applying the cuff) to obtain the data. This is the preferred method of monitoring most patients' blood pressure. With the data being read into a computer, the pulses can be visualized and past data can be stored to show changes in behavior over time. This data can be very useful in patient care. Our project will be implementing this technique of blood pressure monitoring.

ECG--An electrocardiogram (ECG) is a non-invasive recording of a heart's electrical activity. The monitoring of a patient's heart and its behavior is crucial and can provide physicians with a lot of information about its health. See **Figure 3-2**.

With every muscle contraction, there's a system of nerves instructing it to do so. These nerves, as do all nerves, use cellular and extra-cellular ion concentrations to create potential differences on the scale of millivolts. These potential changes are propagated down the nerves, to and from the muscle. The human heart uses a lot of muscles to pump blood throughout our bodies and these muscles are being controlled by a lot of nerves. The ECG leads read the signals from these nerves and, with this data, a visual representation of the heart's activity can be produced and analyzed. Physicians often need to know how a patient's heart is behaving to diagnose any complications or be sure a procedure is going smoothly. A heart's muscle contraction is a time sensitive cycle so differently timed contractions can mean a heart is operating correctly or not.

A cardiac cycle can be broken into three distinct waves. The P-wave marks beginning of the cycle and occurs over approximately 80 milliseconds. Next, the QRS-complex is the most prominent feature of the cardiac cycle and the heart rate is usually calculated based off its peaks. The QRS-complex lasts about 100 milliseconds, but can vary from patient to patient. The last distinct wave is the T-wave and it can reveal a lot of information about the heart's condition. The T-wave is the period where the heart's ventricles are recovering, or repolarizing, back to restart the cycle. The shape of the T-wave is particularly important to preserve.

Figure 3-2: Sample ECG Signal



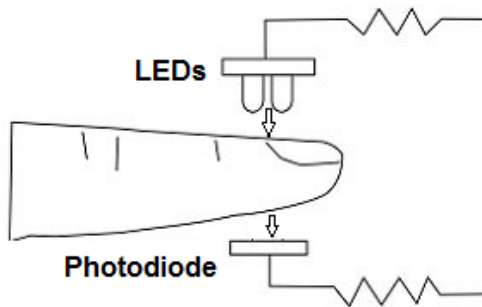
Since the signal corresponds to the motion of the heart, the shape of the graph is an important aspect to preserve and provide to the physician as accurately as possible. This means extra efforts may be required to prevent noise from entering the system and to filter out the noise that does become present. An ECG requires a number of electrodes (two may suffice, but five is common) to be placed on the surface of the patient's skin in certain locations around the torso. These electrodes are sensitive enough to pick up the electrical activity of local nerves, so, in turn, they are sensitive enough to pick up a lot of noise. Noise can be an even larger problem when monitoring within an MRI.

SpO<sub>2</sub>--Pulse oximetry measures a patient's saturation of peripheral oxygen (SpO<sub>2</sub>). This is a non-invasive method of measuring the concentration of oxygen in a patient's bloodstream. Lack of oxygen in the bloodstream leads to organ failure and possibly death, so it is important for physicians to be notified when saturation levels drop. Healthy levels of oxygen saturation are around 95-100 percent. See **Figure 3-3**.

The device used to monitor SpO<sub>2</sub> is called a pulse oximeter. The oximeter clips, non-invasively, onto the patient's fingertip or earlobe and records oxygen saturation via photosensors (typically infrared or near-infrared). Inside the clip are two LEDs and the photodiode. The LEDs use different wavelengths that interact with blood-saturated oxygen differently (one is absorbed more so than the other). The light is shined into the clipped appendage, may it be a finger or ear, and the photodiode receives the levels of the two wavelengths and sends the data to a small processor. Little processing is required to give an accurate SpO<sub>2</sub> reading; the signal just needs analog-to-digital conversion and

those values can correspond to a lookup table. The processor is located within the clip in some models, but it is best to keep the processor out of the magnetic field when being used in an MRI environment so the data is run to a small device away from the patient.

**Figure 3-3: SpO2 Sensor**



Since the magnitudes of light sources are the values being measured, optical fiber can be used to carry the signal to a photodiode away from the magnetic field. Using an optical fiber is ideal because it is not conductive and will not interfere with the MR imaging.

CO<sub>2</sub>--A capnogram measures the CO<sub>2</sub> concentration in a patient's respiration. Its measurements are based off the partial pressure of carbon dioxide versus other gases in a patient's exhale. The electronics used consists of an infrared LED and a photodiode along with the processing tools. A mask is placed over the patient's mouth and nose to contain the respiratory gases and the gases make their way to the sensor as the patient breathes.

Similar to an SpO<sub>2</sub> monitor, the LEDs pass their light through a material (in this case, respiratory gas) and the photodiode picks up the intensity of light that has not been absorbed by the material. Carbon dioxide is known to absorb infrared radiation and the partial pressure can be calculated from the amount of infrared radiation absorbed by the gas.

## **3.1.2 Signal Paths and Systems**

### **3.1.2.1 Multiple Sensor Environment**

When a patient is in such a condition that requires four vitals (ECG, SpO<sub>2</sub>, NiBP, and CO<sub>2</sub>) to be monitored simultaneously, the mess of cables running from patient to monitor

can become bothersome and even hazardous. This is especially so if the patient needs to be moved through the hospital or into an MRI. These vitals used to each require a hard connection to the monitor, which could easily get tangled or caught on something. Currently, though, two of these vitals can be monitored remotely. Philips has wireless solutions in place for ECG and SpO2 monitoring and both are MRI safe. The remaining two vitals, NiBP and CO2, are still using hard connections running to the monitor. Even though half of the troublesome cables are eliminated from the equation at this point, the monitor still has to be physically attached to the patient and it's still a hassle for nurses or physicians to work around in an emergency situation. Our goal, as stated before, is to completely eliminate the hard connections to the monitor so vitals can be supervised from anywhere.

With such critical information at stake, it is important that each monitor's data transmits cleanly to the display and is calculated correctly. This becomes increasingly trickier to ensure with the more signals being received at the monitor. If each signal were to be transmitted independently and received at a sole monitor, their frequencies would have to not interfere with one another.

In the case of this project, consolidating the sensors to a common hub, many other factors could become an issue with multiple signals needing independent transmission. For example, the added hardware for each RF transmitter inside the hub requires space to be mounted, which takes away from the concept of consolidation. One possible perk to having each signal transmit through separate hardware would be that, in the event of some hardware component failing, the other signals could remain intact while the malfunctioning hardware could be swapped for a backup. The idea of keeping each vital's signal separate was a consideration for the convenience of troubleshooting. However, our goal is consolidation so that's what our design will be: one consolidated and portable device.

As a matter of scope, our primary consolidation efforts will be focused on the transmission of the two soon-to-be wireless signals, NiBP and CO2. The merging of the signals will take place in the microcontroller after the post-sensor analog waveforms are passed through the analog-to-digital conversion program coded into the microcontroller. Once both signals are converted to digital information, they can be transmitted through one channel by way of time-division multiplexing. Time-division multiplexing is essentially transmitting one signal at a time over one channel but taking turns doing so. Each signal is transmitted for a certain duration and gets cycled through at a rate dependent upon the number of signals to be transmitted. At the receiving end, a synchronized receiver separates the signals and passes them to their desired destination in chunks. Each additional signal slows the overall data transfer rate of a single signal by a proportion of  $1/N$  with  $N$  being the number of signals. Since we're multiplexing two signals, the overall data transfer rate for one of the signals would be one half of that if it

had a channel to itself. The data should be sending and receiving fast enough to where even half its potential speed would be close enough to real-time for physicians to react in a timely manner.

As the scope of the project grows, more facets of the system will become consolidated. Ideally, we would like all four signals to be integrated into one device and transmitted together but the wireless solutions currently in place operate just fine so there's no need to rework them. The next step up consolidation-wise would be to combine the physical cables into either an organized grouping or to actually fabricate a new all-in-one cable that bundles everything into a single bus.

### 3.1.2.2 Cable Requirements and Usage

In order to be useful in an MRI environment, all cables must be:

- invisible to the MRI if used inside the imaging area
- adequately shielded from magnetic field if housing a conductor
- sufficient length for patients of various height
- managed in a way that avoids forming loops
- unable to accumulate uncomfortable/hazardous levels of heat from RF radiation

The materials that cannot be used or that are highly advised against using are: Iron, nickel, cobalt, chromium, gadolinium, dysprosium, steel, and some medical grades of stainless steel. Some non-magnetic forms of stainless steel can be made magnetic if altered slightly, including aluminum, tin, titanium, gold, and lead. This is because most metals are not purely made and have impurities that can only be found through the use of a permanent magnet to test how it affects the material before using it in a MRI.

### 3.1.3 Potential Hazards

Other than the strong magnetic field that the MRI causes, it also sends out strong Radio Frequency (RF) pulses that can be built up in conductive materials and cause burns [2]. The MRI's strong magnetic field can pull any metallic item towards the center of the magnetic bore of the MRI [1]. "Metal devices also absorb RF energy and make become hotter than the surrounding tissue" some lead problems to keep in mind are some that were filed with the FDA [3]. The tables below (**Table 3-1a** and **Table 3-1b**) list some factors that need to be considered with every aspect of this project:

**Table 3-1a: Potential Hazards**

<b>Factor to Consider [4]</b>	<b>Hazardous Consequence</b>
<p>Static Magnetic Field Spatial Gradient</p>	<p>A strong magnetic field constantly permeates throughout the room reaching levels of three Teslas or 30,000 Gauss. As the distance from the bore of the MRI machine increases the magnetic field strength greatly reduces and that yields a sizeable spatial gradient. In addition, things may want to align with the poles produced by the magnetic field, just like playing with two bar magnets, and thus induce a torque on various ferromagnetic materials introduced into the room of the MRI machine. The motion can be hazardous not only to people, but small materials in devices because if they are not secured properly, they could spin in and/or be ripped from the device they inhabit. Also, materials that are usually inert in a magnetic field may have their properties changed when bent or geometrically changed; therefore, care should be taken to all materials that have been changed from raw state because they could start out inert and become magnetic after that change.</p> <p>The Static Magnetic Field and Spatial Gradient created from the static field can also induce dizziness and/or nausea reminiscent of vertigo when a person’s head moves quickly near a powerful three Tesla or higher field near the magnetic bore of the MRI machine because electrical currents may be induced in the brain because of the high speed movement [6].</p>

**Table 3-1b: Potential Hazards**

<b>Factor to Consider [4]</b>	<b>Hazardous Consequence</b>
Pulsed Gradient Magnetic Fields	<p>This is used for signal localization, and when it is applied the magnetic field intensity changes quickly which results in a magnetic field varying by time. This change resulting in a time-varying magnetic field induces a voltage in electrical conductors which could be hazardous to several types of equipment used in the MRI room on in the bore of the machine. Such as the analog to digital converter, if not properly shielded, then converted results may come out faulty due to incorrect voltage measurements that may have been skewed by the added voltage noise induced from this pulsed gradient.</p> <p>Pulsed Gradient Magnetic field also generates high acoustic noise levels that are extremely strong in the center of the bore of the MRI machine. This strong noise could cause many ailments ranging from a ringing noise in the ear, tinnitus, or causing permanent hearing loss [6]. Ways to prevent these ailments are listed in the Risk Management section.</p>
Pulsed Radio Frequency Fields	<p>Used to induce Magnetic Resonance signals from tissue in patients; however, in medical equipment, it can induce electrical currents in conductive materials. This induced current could heat up materials and cause surrounding material, if it has a low melting point, to melt or warp. This induced current could ultimately destroy equipment, like melting a printed circuit board or warping the board permanently, which could cut off connections and ruin results or stop result collecting all together.</p> <p>Just by operating a device in the MRI machine room could result in a lot of noise being produced, not only distorting the MRIs signals but the device itself. The noise could prove hazardous for patients and the device by giving incorrect results to both leading to incorrect assumptions.</p>



The FDA showed some incidents with horrific results when factors were not considered in the MRI. They are all shown below in **Table 3-2a** and **Table 3-2b**:

**Table 3-2a: MRI Incidents**

<b>Incident Number</b>	<b>Incident Description</b>
<b>MDR-701219:</b>	A patient received blistered burns on the finger where a pulse oximeter was attached during MR scanning. A skin graft was required to treat the affected area. (2/27/95)
<b>MDR-591457:</b>	A child was burned on their right hand because of an ECG cable on the bare skin of the patient while the patient was under anesthesia. Since the patient was under the effects of the anesthesia they could not move, and thus a skin graft was done in order to repair the affected area. (1/26/95)
<b>MDR-175218 [4]:</b>	Another patient with an implanted cardiac pacemaker died; however, the reason of death was discovered to be due to an interruption by the MR system. (9/18/89)
<b>MDR-100222 [4]:</b>	An iron filing in a patient's eye was moved during an MR scan that concluded with the patient losing appropriate vision in the eye which held the filing. (1/8/85)
<b>MDR-405200 [4]:</b>	A nurse brought a pair of scissors into the magnet room that was pulled from her grasp and pulled into a patient's head causing a cut on the patient's head. (8/2/93)

**Table 3-2b: MRI Incidents**

<b>Incident Number</b>	<b>Incident Description</b>
<b>PRP-19168 [4]:</b>	Two Forklift tines, 80 lbs each, were accelerated, by the magnet, towards a technician and the impact of the interaction between the tines and the technician propelled the technician over 15 feet resulting in grave wounds to the technician. (6/5/86)
<b>MDR-183981 [4]:</b>	RF noise was present in the MRI room which yielded incorrect data acquisition for a patient, and it resulted in a surgery being performed on the patient based off of faulty data. (1/30/90)

### 3.1.4 Risk Management

There are certain measurements that can be taken to prevent things from going wrong during an experiment. As this environment involves a gigantic magnet that is continually running the room that could cause multiple incidents ranging from propelled ferromagnetic materials to heat conductive materials that can get as hot or hotter than/as curling irons. Listed below are steps to take in order to prevent incidents from occurring:

Concerning the pulsed gradient magnetic field which causes high acoustic noise in the MR environment, Work Safe in Victoria, Australia has suggested that the following exposure levels in **Table 3-3** be followed to prevent hearing loss and other hearing related injuries [6]:

**Table 3-3: MRI Exposure Levels**

<b>Exposure Level dB (A)</b>	<b>Exposure Time</b>
85	8 hours
88	4 hours
91	2 hours
94	1 hour
97	30 minutes
100	15 minutes
103	7.5 minutes
106	3.8 minutes
112	57 seconds
115	28.5 seconds
124	3.6 seconds
130	0.9 seconds

Some solutions to increase the time to tolerate being in a high noise MR environment would include wearing noise cancelling headphones (non-magnetic) and to carefully follow the chart above to prevent hearing loss or potentially worse injuries.

To ensure that dizziness does not ensue on a patient, technician, or others involved in the MRI procedure, all who are near the machine should be cautious. Especially if close to the bore of the machine, all should beware of moving their head or body too quickly in the MRI machine area. Sensitivities may differ from person to person so it is possible that even a two and a half Tesla environment could cause a person making rapid movement with range of the machine to experience vertigo.

To ensure that metal “missile” projectiles do not occur in the MR environment, personnel should be screened for ferromagnetic materials, both verbally as well as visually before entering the area. If any metallic or ferromagnetic materials are detected, any and all material must go through a test to resist at least 1000 Gauss to be declared MRI SAFE or MRI CONDITIONAL [6] if the individual wishes to continue into the environment. Otherwise, no magnetic material should be allowed into the MR environment.

Also, any ferromagnetic implants such as cardiac pacemaker, dental implant(s), or bone replacement alternative should not be allowed into the MR environment due to the Static Magnetic Field and the Spatial Gradient. Implants can be dislodged from personnel and cause internal ruptures, bleeding, bruising, other serious injuries, and in some cases death. The Radio Frequency Field can cause heat to build up in the implant if it is conductive which could result in internal burns ranging from first, second, and third degree.

## **3.2 Existing and Similar Projects**

### **3.2.1 Shared Resources**

There are many resources available for projects of a similar nature. Make magazine has published an article on a do it yourself blood pressure monitor which gives good insight into the signal filtering and amplification before passing into the microcontroller. The project described in this article differs in that the processor used was a PIC microcontroller, and the processor to be used for the SQVID is a MSP430 microcontroller.

Additionally, there are a few carbon dioxide sensor projects though none seem to be based on the same hardware as used in the SQVID. The challenge will be to integrate both sensed values into a single multiplexed data stream.

To start as a base platform for the signal analysis, the blood pressure circuit used in the project named above is examined. The initial filter and amplification stage will follow a very similar technique.

### **3.2.2 Content Similarities**

The similarities of the blood pressure project published in Make magazine to the SQVID system are within the signal acquisition and amplification process. Because the

microcontrollers are different, the signal handling beyond acquisition will follow a different process. The amplification and filtering process will be studied and modified to suit this project.

Because the CO<sub>2</sub> sensor does not have as many readily available resources, a more unique approach must be used to successfully integrate the signal. The sensor will sit at the end of the consolidated cable system in order to make the cable system non-disposable. The tubing must then extend from the patient to the sensor. The unique approach for the handling of this signal then will produce new knowledge and prove a viable method for signal communication.

### 3.2.3 Consolidated Cable Systems

Consolidation of the various cables in this project is a major focus, and a custom cable will be developed to meet the needs of this project. The availability of resources for cable consolidation is wide, and no difficulty is expected in obtaining a set of specifications for the cable system.

### 3.2.4 Wireless Systems

There are some systems that already have wireless solutions to some of the sensors. Philips has already found solutions to the ECG to be wireless in the MR environment along with the SpO<sub>2</sub> sensor. Philips says the leads are nearly invisible to the MRI machine when on patients and thus they are perfectly suitable for utilization in the SQUID project.

BIOPAC Systems, Incorporated have also found a wireless solution for the non invasive blood pressure (NiBP) sensor in which it is also useable in an MR environment. They call it the NiBP-MRI and it is a monitoring system that tracks the blood pressure of a patient utilizing pulse-decomposition analysis (PDA) technology and it monitors heart rate. During the MRI scan, this device will give beat-to-beat results in real-time. The basic features of the NiBP-MRI are listed in **Table 3-4** below [11]:

**Table 3-4: NiBP Wireless Features**

<b>NiBP-MRI Main Features [11]</b>	<b>Description</b>
Feature 1	Utilizing WiFi technology, the device sends blood pressure data from Care Taker blood pressure processing unit to the computer.
Feature 2	The real-time data is used to create systolic and diastolic values which are available from two D/A channels.
Feature 3	The device can also be used in conjunction with MRI machine recordings.

The NiBP-MRI comes with many more features which range from hardware advantages to software advantages listed in **Table 3-5**:

**Table 3-5: NiBP Other Features**

<b>NiBP-MRI Basic Features [11]</b>	<b>Description</b>
Feature 1	USB D/A converter and Bluetooth dongle
Feature 2	Automatic blood pressure calibration unit
Feature 3	There is also a HLT100C High-level transducer module that interfaces with an INISO optically isolated input adapter to the MP 150
Feature 4	Utilizes a PC computer with Windows 7 operating system and sends analog signals back to a BIOPAC MP device or third-party A/D converter.
Feature 5	The device weighs approximately 114 grams
Feature 6	The device can operate for approximately 12 hours on a single battery charge
Feature 7	Experiments have been performed which lead to the result that this device may be used for detecting hemorrhages or the technology may be harvested and utilized in conjunction with something else for the detection of hemorrhages. Results that were concluded because of the properties of the PDA in which it is good for tracking pulse pressure, which is a marker for central hypovolemia (a state of decreased blood plasma).

Even though BIOPAC’s NiBP-MRI may be a semi-perfect fit for this project, in addition to the property rights, this device has not been certified by the FDA for clinical use and can thus not be used for medical distribution [11]. However, the significance of this device shows that it is possible to find a solution to the wireless MRI NiBP sensor problem.

Philips has also found a wireless solution to the NiBP; the IntelliVue CL NBP Pod or NBP Pod for short. There are also other wireless solutions in this cable package that Philips covers. The NBP's features are labeled in **Table 3-6** below [12]:

**Table 3-6: Philips NBP Intellivue Features**

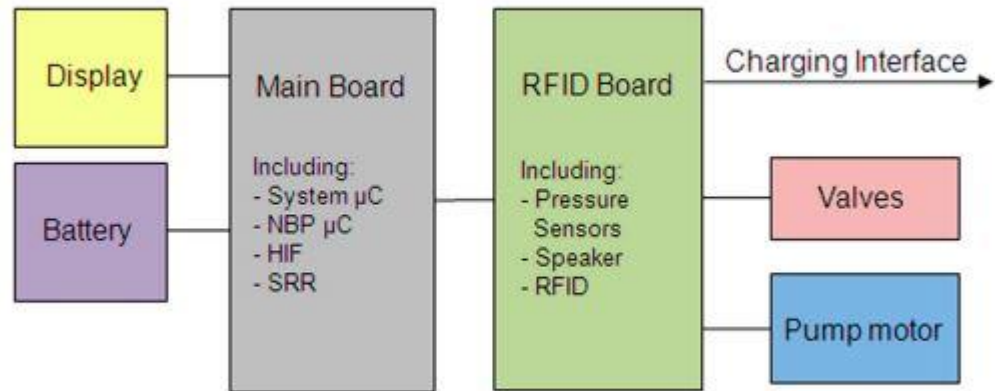
<b>IntelliVue CL NBP Pod Features</b>	<b>Description</b>
Feature 1	Communicates utilizing short range radio (SRR) to an IntelliVue patient monitor or a telemetry transceiver, TRx4841A (x4851A also).
Feature 2	There also a charging station used to charge the pod
Feature 3	The support tool is a PC USB interface that allows access for the support tool Mark2 at the charging station.
Feature 4	The IntelliVue CL Transmitter Base Station is used to connect the device for the purposes of upgrading, cloning, or configuring the device and can be connecting via USB cable to a PC that utilizes the IntelliVue Support Tool Mark2. Therefore, the Transmitter Base Station can be powered via a USB or with an external supply station.
Feature 5	Noninvasive solution to wirelessly detect blood pressure on a patient.

A block diagram of the NBP Pod is presented in **Figure 3-4**.



Figure 3-4: Philips NBP Pod

## NBP Pod








Although this is a wireless solution provided by Philips, it cannot be exposed to strong magnetic fields and thus cannot be used in the Magnetic Resonance Imaging machine environment [12].

## 3.3 Design-Critical Components and Hardware



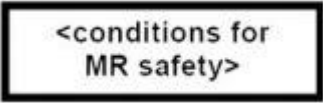


### 3.3.1 MRI-Safe Qualification of Hardware

Not all materials can enter an MR environment. There are tests that must be done in order for materials/devices to be marked safe or acceptable in a MR environment. Tests should address all factors that are present in the environment of the MRI machine (e.g., magnetically induced torque on objects, magnetically induced displacement on objects, heating in conductive materials, etc). Visibly marking the materials or devices should never compromise the purpose of the material/device no matter its size. Some come in varying sizes and shapes, and for those that are not big enough or properly shaped to withstand a sticker or stamp, they should still have some form of safety marking that would indicate whether the material/device is allowable in the MR environment and what precaution to take when operating it. When materials pass these tests they are marked a certain way depending on which tests they pass. This marking system is shown in **Table 3-7a** and **Table 3-7b** below [7]:

**Table 3-7a: MRI Safe Qualification**

<b>ICON [7]</b>	<b>Description</b>
<p>MR SAFE Filled square w/ color</p> 	<p>Background color should be green while the letters are capitalized Arial font ‘MR’ in white with the size that is large as possible without touching the edges of the square.</p>
<p>MR SAFE Filled square w/o color</p> 	<p>Background color should be black while the letters are capitalized Arial font ‘MR’ in white with the size that is large as possible without touching the edges of the square.</p>
<p>MR Safe Hollow square w/ color</p> 	<p>Background color should be white while the letters are capitalized Arial font ‘MR’ in green with the size that is large as possible without touching the edges of the square; the edges will be a frame with a visible thickness, approximately 10% of the side length of the square, the same color as the letters.</p>
<p>MR Safe Hollow square w/o color</p> 	<p>Background color should be white while the letters are capitalized Arial font ‘MR’ in black with the size that is large as possible without touching the edges of the square; the edges will be a frame with a visible thickness, approximately 10% of the side length of the square, the same color as the letters.</p>
<p>MR Conditional w/ color</p> 	<p>Should be an equilateral triangle with a background color of yellow and letters ‘MR’ capitalized in black Arial font with a black frame and letters that are large as possible within the frame without touching the edges of the frame.</p>

**Table 3-7b: MRI Safe Qualification**

<p>MR Conditional w/o color</p> 	<p>Should be an equilateral triangle with a background color of white and letters 'MR' capitalized in black Arial font with a black frame and letters that are large as possible within the frame without touching the edges of the frame.</p>
<p>MR Cond. Supplemental w/ color</p> 	<p>Rectangular black frame with a yellow background and black arial font text. The background color yellow which indicates the caution needed for this elected material/device should always cover at least 50% of the total area of the icon.</p>
<p>MR Cond. supplemental w/o color</p> 	<p>Rectangular black frame with a white background and black arial font text.</p>
<p>MR Unsafe w/ color</p> 	<p>Circular background of white icon with a, 45 degree inclined from horizontal, red slash through the black arial font capitalized 'MR' letters that are not touching the frame but are large as the frame can possibly hold, the frame is red and encapsulates the entire circular icon.</p>
<p>MR Unsafe w/o color</p> 	<p>Circular background of white icon with a, 45 degree inclined from horizontal, black slash through the black arial font capitalized 'MR' letters that are not touching the frame but are large as the frame can possibly hold, the frame is black and encapsulates the entire circular icon.</p>

It should be quantifiably noted within the markings of what safety tests the material/device passed or did not pass because all MR environments differ in strength, size, magnetic field, etc. Therefore, some materials/devices may behave differently and may or may not work properly in one MR environment even if the device/material originally did work well in a different MR space.

### 3.3.2 Availability of Components

Since Philips is sponsoring this project almost everything is provided by them. They have a secret chemical technique for insulating the leads of the ECG, SpO<sub>2</sub>, CO<sub>2</sub>, and NiBP sensors. Almost everything is available for us to sample and test, including two wireless solutions that have already been created for the ECG and SpO<sub>2</sub>. Access to the CO<sub>2</sub> and NiBP sensors is also available to our group including the transducers in the machine that converts the air from the CO<sub>2</sub> and NiBP into electrical signals. They have a couple MRI machines for us to run tests off of. These tests will range from making sure that our devices and materials will not be magnetized in the MRI room to testing for temperature increases that may be susceptible to RF energy absorption, for example, coiled conductive materials like copper. Overall, a lot of materials, sensors, and devices are provided for our group, leaving only the matter of taking everything that is available and putting it together in a portable solution that is sensitive to the factors of the MR environment.

### 3.3.3 Limitations

In order to be useful in an MR environment, all cables must meet a certain requirements. The requirements are listed below in **Table 3-8**, and if not followed could result in problematic situations:

**Table 3-8: Cable Requirements**

<b>Requirements for Cables</b>	<b>Description</b>
Requirement 1	Invisible to the MRI if used inside the imaging area, so the material must be made near completely magnetically porous in order for it to be nigh undetectable in the MRI bore.
Requirement 2	Adequately shielded from magnetic field if housing a conductor, and must do this while still satisfying requirement 1.
Requirement 3	Sufficient length for patients of various height, while being shielded from absorbing too much RF energy which could result in heating and thus burning patients.
Requirement 4	Managed in a way that avoids forming loops while still satisfying requirement 3, so a solution to requirement 3 could not be synonymous to winding of a water hose.
Requirement 5	unable to accumulate uncomfortable/hazardous levels of heat from RF radiation

Some materials have a high disadvantage in a MR environment. Some can change properties or have completely different properties from what they are usually believed to have. Listed below in **Table 3-9** are some of these materials to be wary of when designing the consolidated SQUID cable.

**Table 3-9: Material Requirements**

<b>Material Limitation [5]</b>	<b>Description</b>
Highly Disadvantageous Materials	Iron, nickel, cobalt, chromium, gadolinium, dysprosium, steel, and some medical grades of stainless steel
Caution Warranting Materials	Some non-magnetic forms of stainless steel can be made magnetic if altered slightly: Aluminum, tin, titanium, gold, and lead are just some examples and this is only because most metals are not made purely and have impurities that could only be found out through the test of using a permanent magnet and seeing how it affects the material before use in a MRI.

This by no means indicates that these materials absolutely cannot be used. However, it does mean that extreme caution should be exercised when using them inside the MR environment.

## **4.0 Project Hardware and Software Design Details**

### **4.1 Overall Design Architecture and Diagrams**

The system is designed using a modular approach, as the details of equipment provided for integration were not made readily available at the beginning of this project. Initially, we consider signal acquisition process using the sensors named below in **Table 4-1**.

**Table 4-1: Sensor Signal Acquisition**

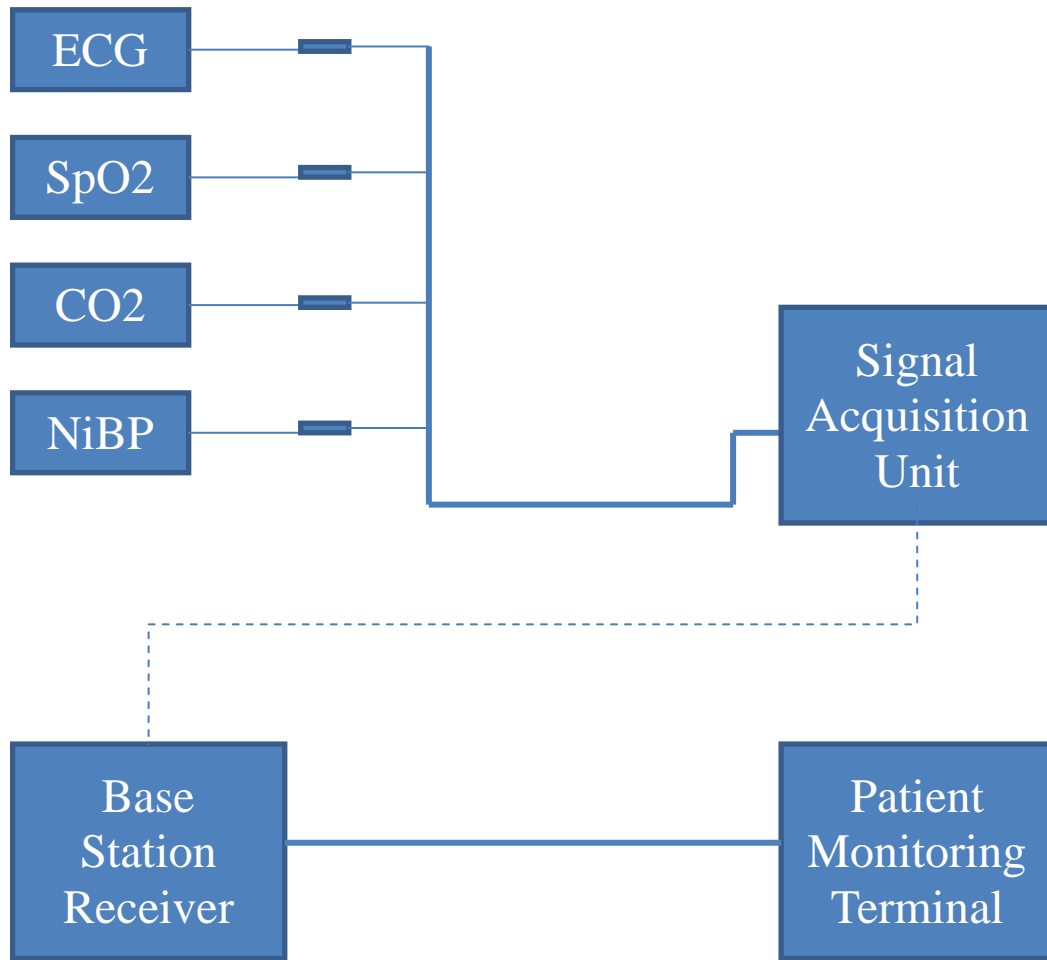
<b>Sensor</b>	<b>Measurand</b>	<b>Existing Process</b>
SpO2	Blood Oxygen Saturation	Sensor connects to wireless handheld, transmit to base station.
ECG	Heart Electrical Activity, Pulse Rate	Sensor connects to wireless handheld, transmit to base station.
NiBP	Blood Pressure	Cable directly to base station
CO2	Carbon Dioxide Respiration	Cable directly to base station

The signals are passed into a central hub under the patient’s bed, through the SQUID consolidated cable assembly. A major component of this project is the design and construction of this SQUID cable. The requirements of the system specify that the hub should provide plug and play capability, in that it should detect which sensors are attached through different cable sets and respond accordingly.

#### **4.1.1 System Interconnect Diagram**

The interconnect diagram for the system is given below in **Figure 4-1**. Of the four sensors, two (ECG and SpO2) will have a pre-existing wireless module that will be integrated into the signal acquisition unit. The other two sensors will use a newly developed platform similar to what is already in place. On the base station/receiver side, the signals will be received and demodulated, before passing the values into the software platform at the patient monitoring terminal.

Figure 4-1: System Interconnect Diagram

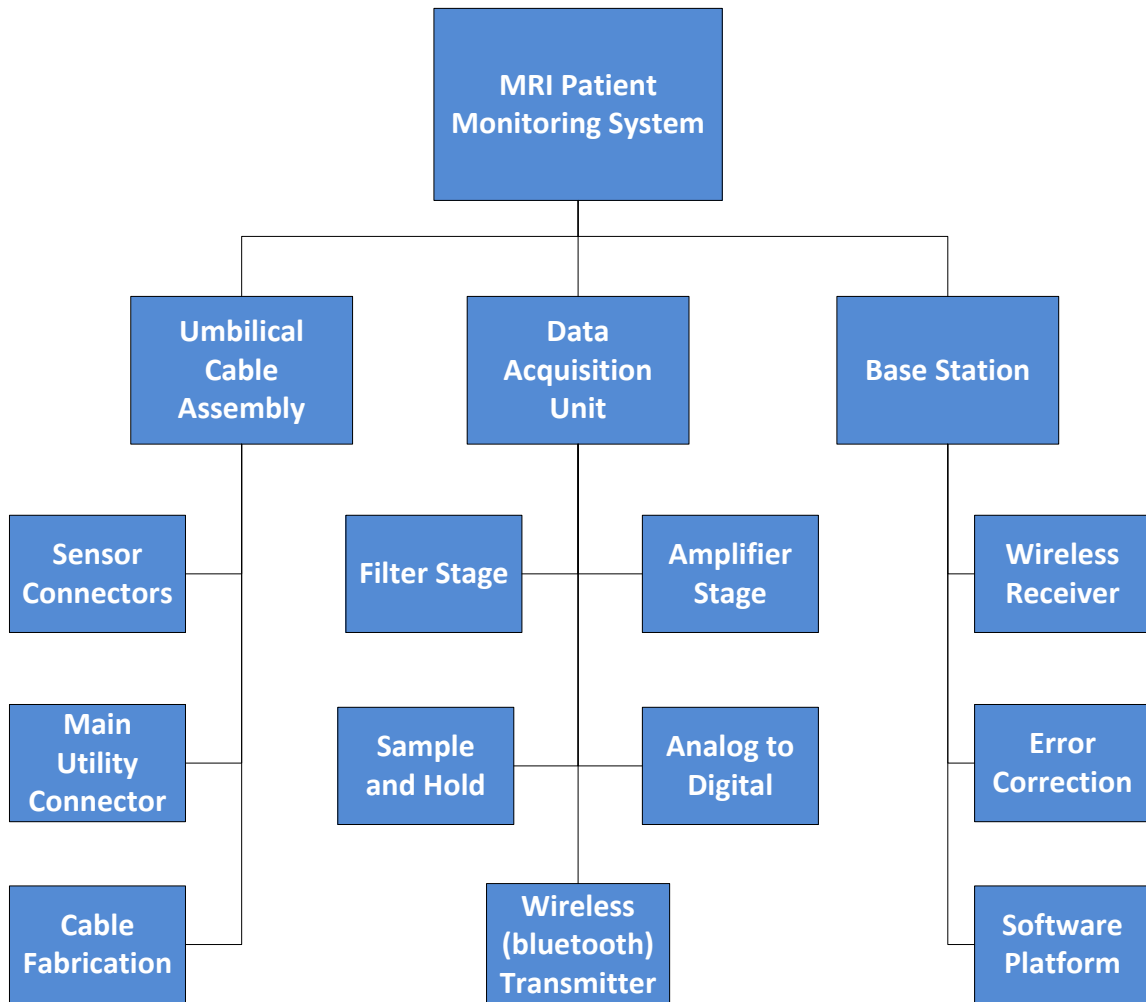


#### 4.1.2 Design Tree and System Flow Down

The design tree for this project can be observed in **Figure 4-2** below. The process of development on the project will follow the top down order of the design tree, with equal effort divided throughout the project amongst the three main subcategories; the SQUID cable assembly, the data acquisition unit, and the base station.



Figure 4-2: System Design Tree

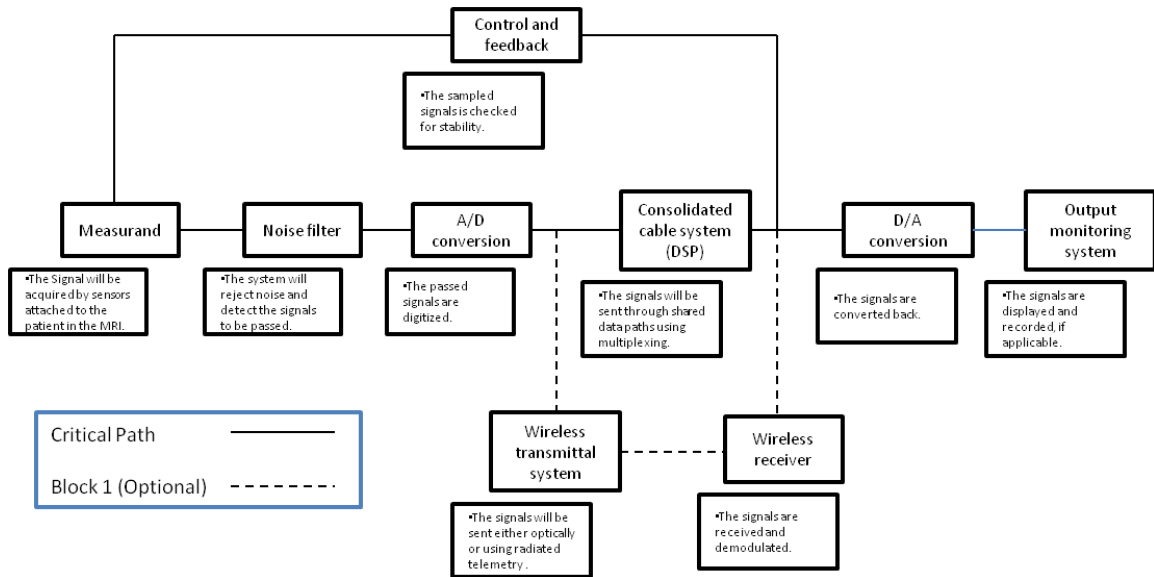


### 4.1.3 Functional Block Diagrams

#### 4.1.3.1 Hardware

The initial development of the system has been considered as a general feedback controlled bioinstrumentation platform. The system will be designed as detailed below in **Figure 4-3**.

Figure 4-3: Hardware Block Diagram



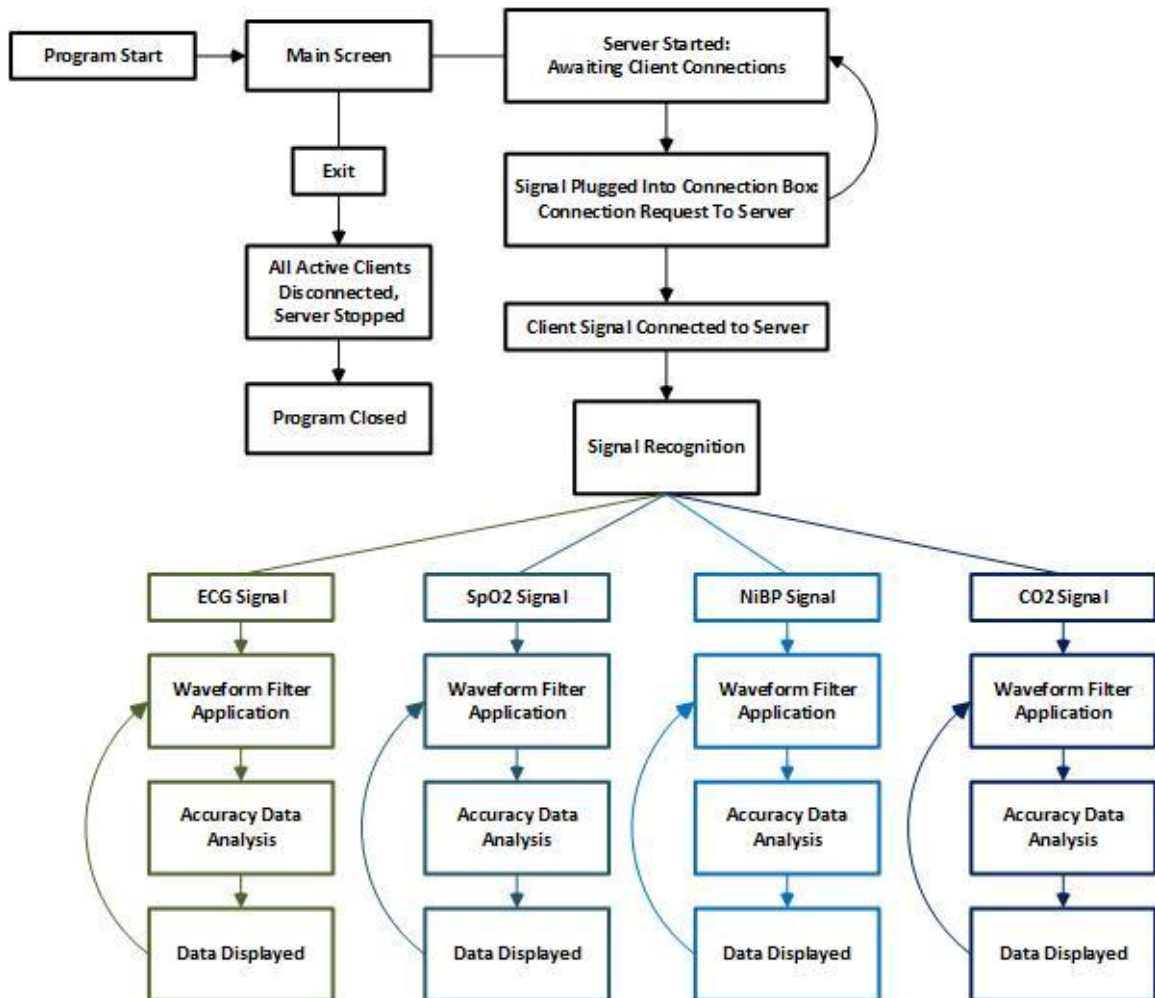
Note that the critical path in the above block diagram does not include a wireless component. This shall be considered as Block 0 in development, and the primary goal of this stage is to successfully pass the signals from the sensors to the monitoring platform.

The Block 1 stage of development will most likely be incorporated into the final design, assuming an integration of the developed wireless platform with what is currently in place is possible. Technical details of the current wireless implementation of two signals are currently unavailable.

#### 4.1.3.2 Software

The following block diagram (**Figure 4-4**) gives a basic overview of the functionality of the software program. This diagram does not include the added features that are explained in Sections 4.3.2 or 6.3.3, or error catching, but instead focuses on the main program flow with regards to data acquisition and analysis.

Figure 4-4: Software Block Diagram



#### 4.1.4 Schematic Drawings

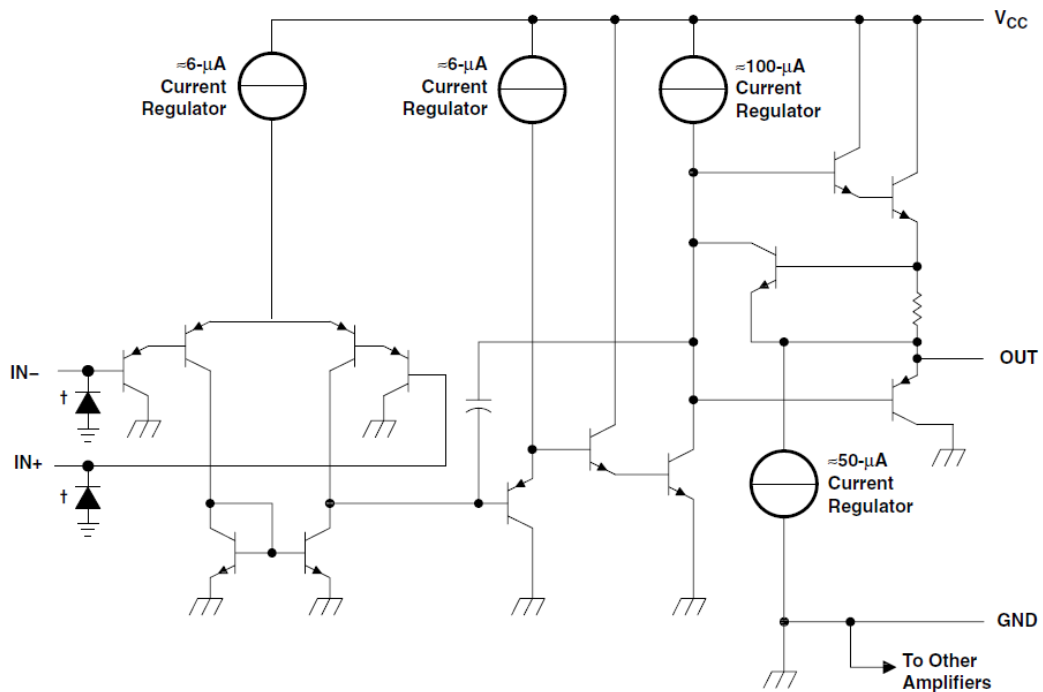
The schematic drawings for the system are in development, and are not yet fully functional. Some of the Philips hardware technical data to be provided for integration has yet to be disclosed and will result in changes to the following design as new developments occur.

The main focus of this project is now on the development of a wireless solution for the non-invasive blood pressure and exhaled carbon dioxide sensors. In order to achieve this

end a pressure transducer and carbon dioxide sensor must be used to collect the signal. The signal is amplified and filtered, then digitized and multiplexed before wirelessly transmitting to the receiver.

Using a pressure transducer will require signal conditioning with a band-pass filter, using operational amplifier (op-amp) circuits. The op-amp selected for this purpose is the LM324 Quadruple Operational Amplifier. The circuit for each amplifier within the IC is given below in **Figure 4-5**.

**Figure 4-5: Op-Amp Circuit**



COMPONENT COUNT (total device)	
Epi-FET	1
Transistors	95
Diodes	4
Resistors	11
Capacitors	4

† ESD protection cells - available on LM324K and LM324KA only

## 4.2 Block 0 System Design

### 4.2.1 Cabling System Materials and Design

The SQVID cable is designed to meet the requirements and specifications of the all-up-round system as listed in **Section 2.3 – Requirements and Specifications**, and follows the particular set of requirements given below in **Table 4-2**.

**Table 4-2: SQVID Cable Requirements**

<b>Requirement</b>	<b>Description</b>
HRS-UC-001	The cable shall have shielding to reduce interference and data loss
HRS-UC-002	The main SQVID connector shall have a small footprint
HRS-UC-003	The cable shall not exceed 8 feet in length, or be allowed to coil or bunch.
HRS-UC-004	The cable must be durable and able to withstand frequent mating/de-mating and transportation.
HRS-UC-005	No ferromagnetic materials may be used for the cable or connectors

In an effort to meet the above criteria and provide a good fit for the project, a few types of connectors are reviewed below in **Table 4-3**.

**Table 4-3: Connector Options**

<b>Option</b>	<b>Name</b>	<b>Description</b>
A	<b>Micro-D Connector</b>	Very small footprint Difficult to mate Limited plug cycles
B	<b>ODU Medi-Snap Connector</b>	Very small footprint Easy to mate Proprietary connector type, procurement issues
C	<b>Hypertronics Clearimage Connector</b>	Extremely nonmagnetic Low contact resistance Easy to mate Proprietary connector type, procurement issues
D	<b>Non-magnetic D-Sub mini Connector</b>	Readily available from various suppliers Familiar interface Easy to mate Low cost

#### 4.2.1.1 Reduced-Risk Cable Systems

The SQVID cable fabrication is a proprietary process to Philips, and is not disclosed. The specifications for the cable have been noted and will be used to develop a cable that meets this standard. In order to reduce risk related to cable systems, the following items

in **Table 4-4** are observed. To mitigate these risks, the cable is designed to meet the sets of given requirements in **Section 2.3 – Requirements and Specifications** and **Section 4.2.1 – Cabling System Materials and Design**, paying close attention to the following details:

**Table 4-4: Cable Risk Factors**

<b>Risk Factor</b>	<b>Description</b>	<b>Mitigation</b>
Looped Cable	<p>Even a single coil in the cable can induce a large current in an MRI environment.</p> <p>The powerful magnetic flux can create a current that can burn a patient or destroy equipment.</p>	<p>All materials used in cable construction including connectors must be non-magnetic.</p> <p>The Shielding shall be semi-rigid and resist coiling or bunching.</p>
Excess Length of Cable	<p>Excess length of cable causes clutter and could potentially cause a safety hazard, such as an individual getting tangled or tripping over a cable.</p>	<p>The cable shall be no longer than required, or 8 feet, whichever is shorter.</p> <p>The cable shall be routed such that it is safely out of the way.</p>

#### 4.2.1.2 MRI Compatibility of Cable Systems

The cable and connectors must be made of non-magnetic materials. A few non-magnetic metals that could be used in the construction of this system are:

- Aluminum
- Platinum
- Copper
- Lead

The majority of materials to be selected from in this design fall into the “safe” category, as most cables and connectors are made using the above listed materials. The cables used, however, will be fabricated by Philips using a proprietary process and will not be subject to disclosure. The technicians responsible for the cable fabrication are to be aware of the restrictions for cabling materials and requirements for cable resilience. The connectors will be selected so as to provide the most seamless integration with the current system, while maintaining a modular and efficient design.

#### 4.2.1.3 Cable-Sensor Interface Design

The modular approach to this project allows for a custom setup of different sensor combinations as needed. In order to receive maximum utility from the SQUID cable assembly, an interface for each of the sensors will be included in the final cable build. The signal acquisition unit will discern which sensors are being used by which are plugged into the other end of the SQUID cable, and respond accordingly.

#### 4.2.1.4 Cable-Platform Interface Design

The SQUID cable interface with the platform will be arranged such that integration with the existing platform will be possible through a shared connector between all of the sensors. The data acquisition unit will house the current wireless solution for the ECG and SpO2 sensors, and a similar wireless platform will be developed for the CO2 and NiBP sensors and housed in the unit as well. The data acquisition unit will take in the signals and transmit them in a multiplexed data stream to a receiver base station outside of the MRI room. The design of the connector is governed by the requirements set forth in this document with the overriding principle of MRI compatibility taking precedent.



## 4.2.2 Cable Consolidation Solutions

The current system relies on four separate cables, which creates clutter and presents safety concerns. To consolidate the cabling systems, a custom cable will be fabricated by Philips following our design specifications and hardware suggestions. The chosen connectors and cable shielding are incorporated into Philips' fabrication process, which is proprietary information and may not be disclosed.

## 4.2.3 Component Selection

The hardware to be used in the initial signal collection and processing stages has not yet been entirely decided. As new components are chosen, they are weighed against other current options and exchanged if necessary. As mentioned previously, the extent of integration will be limited to the non-invasive blood pressure and exhaled carbon dioxide signals. The other two signals (electrocardiogram and pulse oximetry) have existing wireless monitors that will be mounted on the outside of the SQUID system, sitting flush against the surface with the cables routed internally and connected to the SQUID cable port.

The sections below cover the various hardware selections that have been made in development of this system. Options for each component are researched and compared (where applicable), and reasonable justification is given towards the selection of each component in the final design.

### 4.2.3.1 Voltage Regulator

Many different options for a DC voltage regulator exist for this design. The options were narrowed down by power requirements, and specific output voltages limited to a small range. Some options are listed below in **Table 4-5a** and **Table 4-5b**.

**Table 4-5a: Voltage Regulator Options**

<b>Option</b>	<b>Name</b>	<b>Description</b>
<b>A</b>	<b>LD1117 V33 Fixed</b>	Fixed to 3.3V output  Provides a low dropout voltage of about 1V.  Provides up to 800mA output current.  Various packages available.
<b>B</b>	<b>uA7800 Series 7805</b>	Fixed output to 5V.  High power dissipation capability.  Output current up to 1.5A  Internal thermal overload protection

**Table 4-5b: Voltage Regulator Options**

<b>Option</b>	<b>Name</b>	<b>Description</b>
<b>C</b>	<b>LT1121-3.3</b>	<p>Fixed output at 3.3V.</p> <p>Very low dropout voltage of 0.4V.</p> <p>150mA output current and 30uA quiescent current.</p> <p>8-pin DIP package.</p>
<b>D</b>	<b>ADM7150</b>	<p>Fixed output at 3.3V or 5V.</p> <p>Ultra low noise operation.</p> <p>High power supply rejection ratio (PSRR).</p> <p>Dropout voltage or 0.6V.</p> <p>800mA output current and 4.3mA quiescent current.</p>

#### 4.2.3.2 Microcontroller

There are a few microcontroller brands to compare as well. The focus was narrowed by the requirements for low power consumption and ease of integration with the sensors. The first line of comparison is with the different brands of processors available. A short description is provided as **Table 4-6** takes a look at the best options for microcontroller brands.

**Table 4-6: Microcontroller Options**

<b>Option</b>	<b>Name</b>	<b>Description</b>
<b>A</b>	<b>TI MSP430</b>	<p>Well suited to low power and bioinstrumentation solutions.</p> <p>Familiarity with the architecture from embedded systems laboratory.</p> <p>Low cost and easy prototyping.</p>
<b>B</b>	<b>ST ARM</b>	<p>More powerful and ubiquitous platform.</p> <p>Newer microcontrollers from this family have increased performance with decreased power consumption.</p>
<b>C</b>	<b>Atmel AVR</b>	<p>High availability of resources and open source support.</p> <p>Low-power and wireless capabilities in the zigbee wireless standard.</p>
<b>D</b>	<b>Microchip PIC</b>	<p>8-bit microprocessors available for very small low power applications.</p> <p>Robust third-party support and development kits.</p> <p>Larger and more powerful units available as well.</p>

#### 4.2.4 Microcontroller Analog to Digital

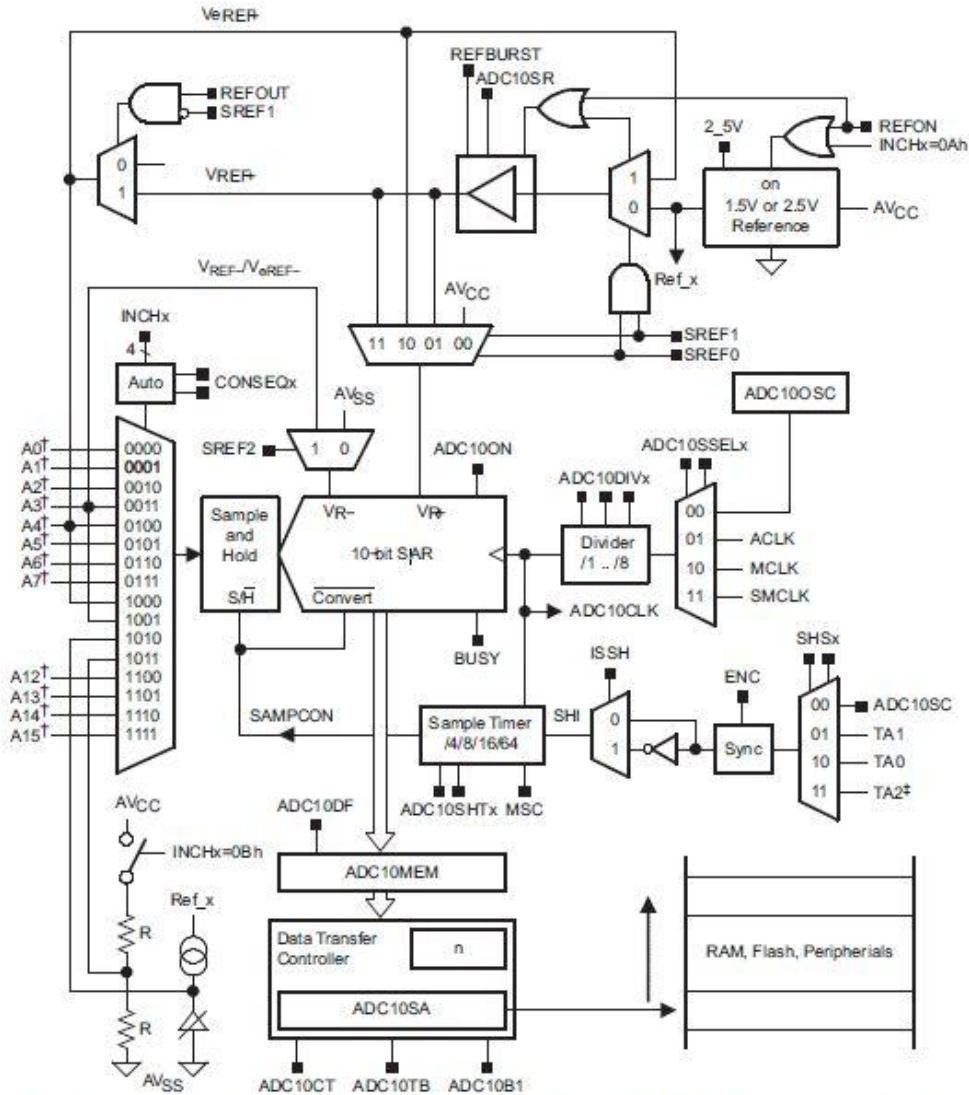
The MSP430 G2 series has some types of analog-to-digital and digital-to-analog modules. The ones that will be focused on are the 10-bit and 12-bit analog-to-digital module and a 12-bit digital-to-analog module. **Table 4-7** below will be the start of the benefits of using the ADC10 module, which is a 10-bit analog-to-digital converter (ADC) [13].

**Table 4-7: Microcontroller ADC10 Benefits**

<b>Perks of the ADC10 Module [13]</b>	<b>Description</b>
Benefit 1	Greater than 200 kilo-samples per second maximum conversion rate.
Benefit 2	Software selectable on-chip reference voltage generation with selections of 1.5 volts or 2.5 volts.
Benefit 3	Sample-and-hold with programmable sample periods
Benefit 4	Up to 8 external input channels.
Benefit 5	Selectable conversion clock source.

The ADC10 module's block diagram provided by Texas Instruments (**Figure 4-6** below) shows the structure of the module:

**Figure 4-6: TI ADC10 Block Diagram**



†Channels A12-A15 are available in MSP430F22xx devices only. Channels A12-A15 tied to channel A11 in other devices. Not all channels are available in all devices.  
 ‡TA1 on MSP430F20x2, MSP430G2x31, and MSP430G2x30 devices

Considering how the ADC10 is dependent upon software to be configured to the user's specifications, there are a lot of functions available to meet this project's particular needs. Those needs are listed in **Table 4-8a**, **Table 4-8b**, and **Table 4-8c** below:

Table 4-8a: ADC10 Features

ADC10 Feature/Function	Description
10-Bit ADC Core	<p>The ADC core converts the analog signal and then changes the signal into its 10-bit digital representation and stores the result in the ADC10MEM register. However, before any conversion can take place, the Enable conversion (ENC) register must be set to 1. The core uses two distinguishable voltage levels, <math>V_{R+}</math> and <math>V_{R-}</math>, which are completely programmable/selectable to define the upper and lower limits of the conversion from analog to digital. The digital output (<math>N_{ADC}</math>) is full scale (03FFh or <math>1023_{10}</math>) when the <math>V_{IN} \geq V_{R+}</math> and zero when <math>V_{IN} \leq V_{R-}</math>. The conversion formula for the ADC when in binary format is:</p> $N_{ADC} = 1023 \times \frac{V_{IN} - V_{R-}}{V_{R+} - V_{R-}}$ <p>The ADC10 core must be enabled with the ADC10ON bit when configuring the two control registers, ADC10CTL0 and ADC10CTL1, and they can only be modified when ENC = 0.</p>
Conversion Clock Selection	<p>The ADC10CLK is used for both conversion clock purposes and to generate the sampling period, the source clock is selected using ADC10SSELx bits and can be divided from 1 to 8 using the ADC10DIVx bits, and possible source clocks for the ADC10CLK are SMCLK, MCLK, ACLK, and internal oscillator ADC10OSC (however, there are a lot of variables that must be considered first when using the ADC10OSC, so caution must be taken while using the ADC10OSC).</p> <p>The user must ensure that the clock chosen for ADC10CLK remains active until the end of a conversion or the operation will not complete and any result will be invalid.</p>
Analog Port Selection	<p>The ADC10 external inputs <math>Ax</math>, <math>V_{eREF+}</math>, and <math>V_{REF-}</math> share terminals with general purpose input and output ports, which are digital CMOS gates. When using the CMOS gates, parasitic current can flow from VCC to ground, so the port pin buffer must be enabled with the ADC10AEx bits in order to eliminate parasitic current flow and reduce current consumption.</p>

Table 4-8b: ADC10 Features

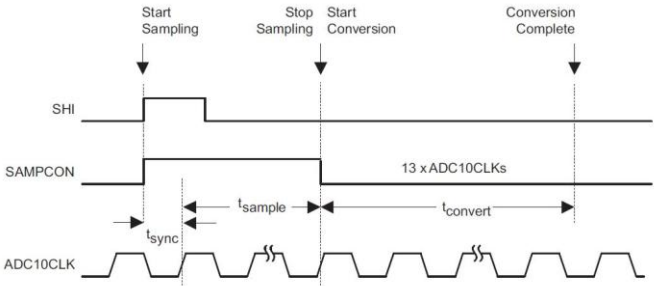
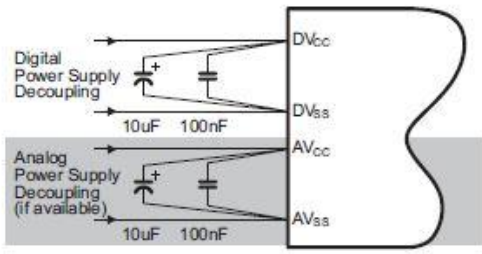
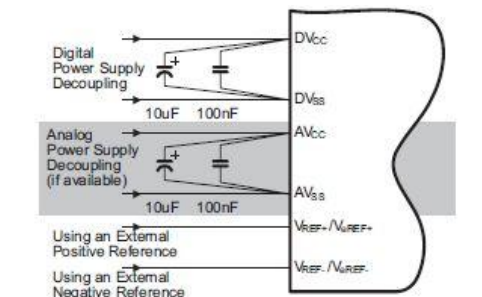
ADC10 Feature/Function	Description
Voltage Reference Generator	The ADC module has an internal voltage reference that must be turned on via the REFON register by setting it to 1. It can be used internally, REFOUT = 0, or externally, pin $V_{REF+}$ = REFOUT = 1. The internal reference voltages are 2.5V when REF2_5V is set to 1 and 1.5V when REF2_5V is set to 0.
Auto Power-Down	Since the ADC10 is meant for low power applications, the core is automatically disabled and re-enabled when needed depending on whether the ADC10 is actively converting or not.
Sample and Conversion Timing	<p>An ADC is initiated with a rising edge of input signal sample SHI, for which the source is selected with the SHSx bits and includes the following registers: the ADC10SC bit, Timer_A Output Unit 1, Timer_A Unit 0, and Timer_A Unit 2. The polarity SHI signal can be inverted with the ISSH bit, the SHTx bit selects the sample period <math>t_{sample}</math> to be 4,8,16, or 64 ADC10CLK cycles, and the sampling timer sets the SAMPCON high for the selected <math>t_{sample}</math> after synchronization with the ADC10CLK. The conversion and cycles are shown in the <b>figure</b> below with the high-to-low SAMPCON transition as the starter for the analog-to-digital conversion:</p>  <p style="text-align: center;">Figure 22-3. Sample Timing</p>



Table 4-8c: ADC10 Features

ADC10 Feature/Function	Description
<p>ADC10 Grounding and Noise Considerations</p>	<p>Certain configurations can be made in order to keep from creating ground loops and other noise complications because ground loops are formed when return current from the A/D travels via paths that analog and digital circuitry share. The current can generate differentiations than expected in the reference voltages or input voltages of the A/D converter. In addition to grounding, the conversion result can be skewed due to ripple and noise spikes being induced over the supply lines from changing power supply lines (digitally or manually).</p> <p>Fix for noise and grounding issues that can affect the internal reference voltage results:</p>  <p>Fix for noise and grounding issues that can affect the external reference voltage results:</p> 
<p>Using the Integrated Temperature Sensor</p>	<p>The analog input channel must be set with the INCHx register to 1010. When using this sensor, the sample period must be greater than 30 micro-seconds. Since the temperature sensor's offset error is large, calibration is necessary for accurate results.</p>

Below in **Table 4-9** are conversion modes that are chosen by the CONSEQ<sub>x</sub> bits within the ADC10.

**Table 4-9: ADC10 Conversion Modes**

<b>CONSEQ<sub>x</sub></b>	<b>Mode</b>	<b>Operation</b>
<b>00</b>	Single channel single-conversion	A single channel is selected by INCH <sub>x</sub> , sampled, converted once, and the result is written in ADC10MEM.
<b>01</b>	Sequence-of-channels	Sequence of channels are sampled and converted once, beginning with INCH <sub>x</sub> selection in conjunction with decrementing channel A0.
<b>10</b>	Repeat single channel	A single channel is selected by INCH <sub>x</sub> , sampled and converted continuously by repeatedly rewriting into the ADC10MEM register with each ADC result.
<b>11</b>	Repeat sequence-of-channels	A combination of all modes in a sequence of channels are taken in and rewritten to the ADC10MEM register and may be the best mode for this experiment as the MRI machine will be outputting several signals in a sequence that will need to be converted all at once (4 to be exact) for optimizing this code as much as possible.

**Table 4-10** below gives the registers associated with the ADC10:

**Table 4-10: ADC10 Registers**

<b>Register</b>	<b>Meaning (all ADC10)</b>	<b>Register Type</b>	<b>Address</b>	<b>Initial State (POR = Power-on-reset)</b>
ADC10AE0	Input enable register 0	Read/Write	04Ah	Reset with POR
ADC10AE1	Input enable register 1	Read/Write	04Bh	Reset with POR
ADC10CTL0	Control register 0	Read/Write	01B0h	Reset with POR
ADC10CTL1	Control register 1	Read/Write	01B2h	Reset with POR
ADC10MEM	Memory	Read	01B4h	Unchanged
ADC10DTC0	Data transfer register 0	Read/Write	048h	Reset with POR
ADC10DTC1	Data transfer register 1	Read/Write	049h	Reset with POR
ADC10SA	Transfer start address	Read/Write	01BCh	Reset with POR

**Table 4-11** below illustrates some of the benefits if using the ADC12 module, which is a 12-bit analog-to-digital converter (ADC) [13].

**Table 4-11: Microcontroller ADC12 Benefits**

<b>ADC12 Benefit</b>	<b>Description</b>
Benefit 1	Greater than 200 kilo-samples per second maximum conversion rate.
Benefit 2	Software selectable on-chip reference voltage generation with selections of 1.5 volts or 2.5 volts.
Benefit 3	Sample-and-hold with programmable sample periods
Benefit 4	Up to 8 external input channels.
Benefit 5	Selectable conversion clock source.
Benefit 6	16 conversion-result storage registers (word conversion-and-control buffer).

The ADC12 module's block diagram provided by Texas Instruments is shown in **Figure 4-7**, illustrating the structure of the module:

Figure 4-7: TI ADC12 Block Diagram

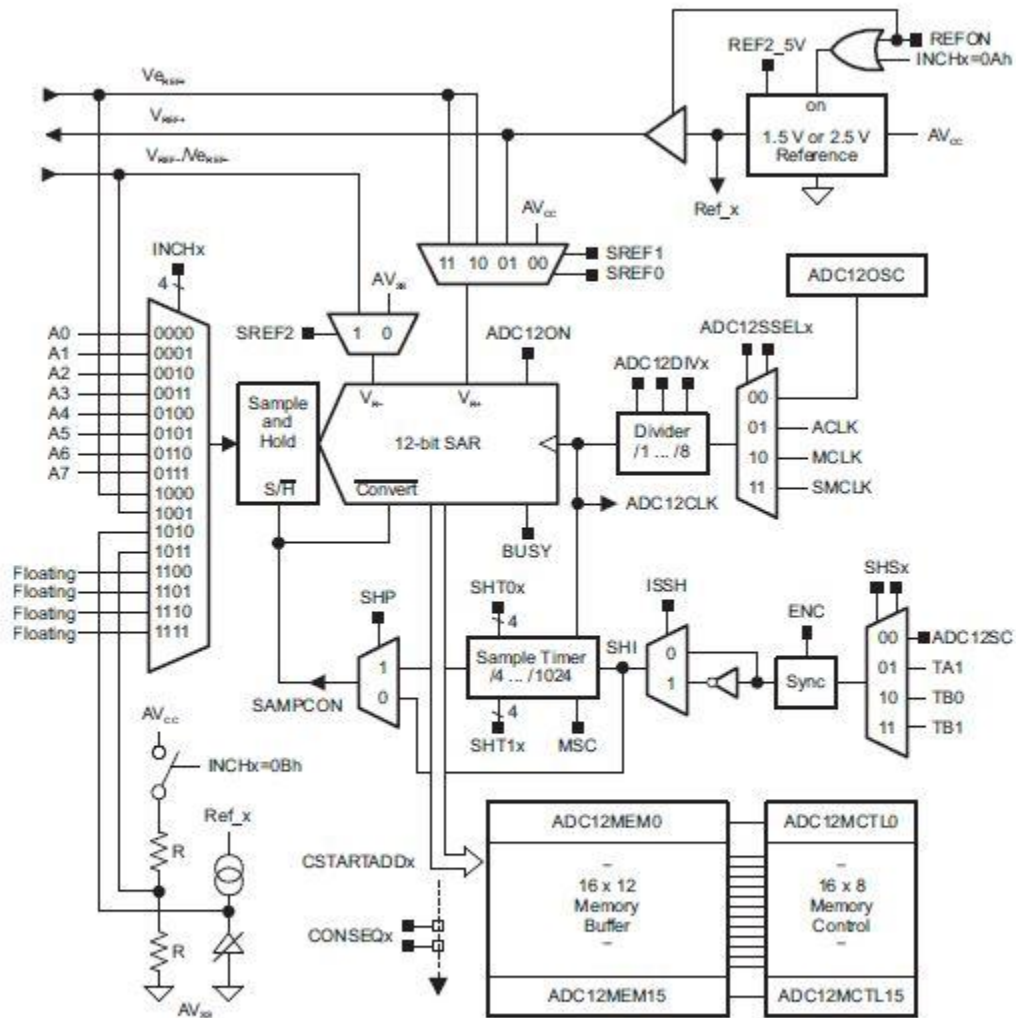


Figure 23-1. ADC12 Block Diagram

The ADC12 is dependent upon software in order to be configured to the user's specifications. There are a lot of functions available to meet the user's particular needs. Examples of those potential needs are listed in **Table 4-12a**, **Table 4-12b**, **Table 4-12c**, and **Table 4-12d** below:

Table 4-12a: ADC12 Features

ADC12 Function/Feature	Description
12-Bit ADC Core	<p>The ADC core converts the analog signal and then changes the signal into its 12-bit digital representation and stores the result in the conversion memory. However, before any conversion can take place, the Enable conversion (ENC) register must be set to 1. The core uses two distinguishable voltage levels, <math>V_{R+}</math> and <math>V_{R-}</math>, which are completely programmable/selectable to define the upper and lower limits of the conversion from analog to digital. The digital output (<math>N_{ADC}</math>) is full scale (0FFFh or 4095<sub>10</sub>) when the <math>V_{IN} \geq V_{R+}</math> and zero when <math>V_{IN} \leq V_{R-}</math>. The conversion formula for the ADC when in binary format is:</p> $N_{ADC} = 4095 \times \frac{V_{IN} - V_{R-}}{V_{R+} - V_{R-}}$ <p>The ADC12 core must be enabled with the ADC12ON bit when configuring the two control registers, ADC12CTL0 and ADC12CTL1, and they can only be modified when ENC = 0.</p>
Conversion Clock Selection	<p>The ADC12CLK is used for both conversion clock purposes and to generate the sampling period, the source clock is selected using ADC12SELx bits and can be divided from 1 to 8 using the ADC12DIVx bits, and possible source clocks for the ADC12CLK are SMCLK, MCLK, ACLK, and internal oscillator ADC12OSC (however, there are a lot of variables that must be considered first when using the ADC12OSC, so caution must be taken while using the ADC12OSC).</p> <p>The user must ensure that the clock chosen for ADC12CLK remains active until the end of a conversion or the operation will not complete and any result will be invalid.</p>
Analog Port Selection	<p>The ADC12 inputs are multiplexed with port P6 pins, which are digital CMOS gates that can cause parasitic current to flow from VCC to GND when taking in analog signals. This extra current consumed can be avoided by disabling the port pin buffer, the P6SELx bits.</p>
Voltage Reference Generator	<p>The ADC12 module has an internal voltage reference that must be turned on via the REFON register by setting it to 1. The internal reference voltages are 2.5V when REF2_5V is set to 1 and 1.5V when REF2_5V is set to 0.</p>

Table 4-12b: ADC12 Features

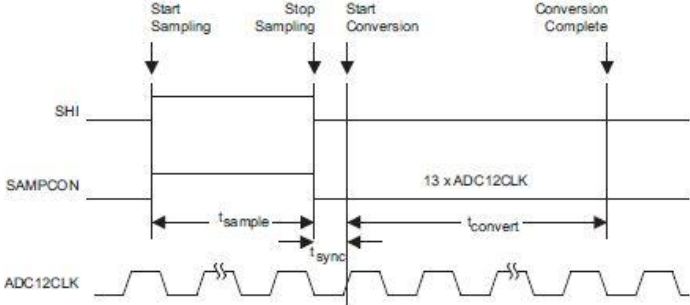
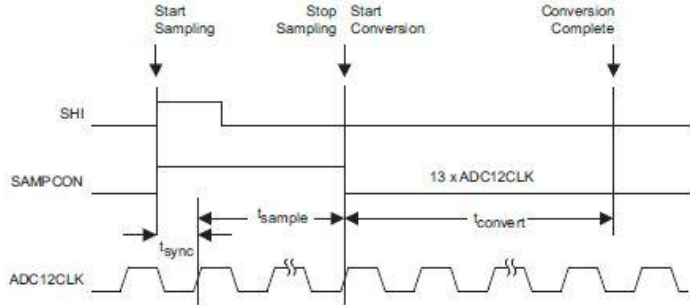
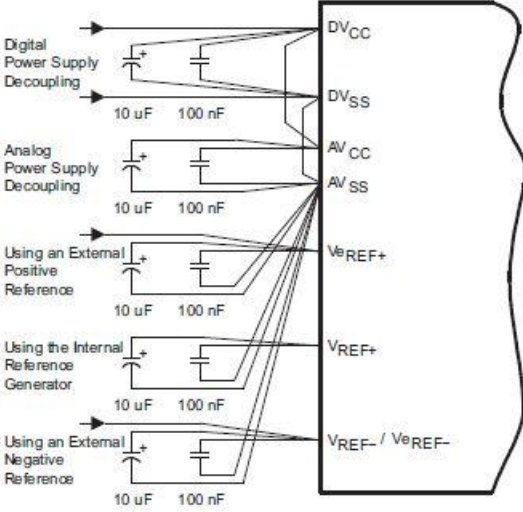
ADC12 Function/Feature	Description
Sample and Conversion Timing	<p>An ADC is initiated with a rising edge of input signal sample SHI, for which the source is selected with the SHSx bits and includes the following registers: the ADC12SC bit, Timer_A Output Unit 1, Timer_B Unit 0, and Timer_B Unit 1. The high-to-low SAMPCON transition is the starter for the analog-to-digital conversion for the ADC12CLK and two different time sampling methods can be chosen with control bit SHP:</p> <p><b>Extended Sample Mode figure:</b></p>  <p>Selected when SHP = 0. The SHI signal directly controls the SAMPCON and defines the length of the <math>t_{\text{sample}}</math> period.</p> <p><b>Pulse Sample Mode figure:</b></p>  <p>Selected when SHP = 1. The SHI signal is used to start the timer of the sampling while the SHT0x and SHT1x bits in ADC12CTL0 control the variables that make up SAMPCON's sample period <math>t_{\text{sample}} = t_{\text{sample}} + t_{\text{sync}}</math>.</p>

Table 4-12c: ADC12 Features

ADC12 Function/Feature	Description
ADC12 Grounding and Noise Considerations	<p>Certain configurations can be made in order to keep from creating ground loops and other noise complications because ground loops are formed when return current from the A/D travels via paths that analog and digital circuitry share. The current can generate differentiations than expected in the reference voltages or input voltages of the A/D converter. In addition to grounding, the conversion result can be skewed due to ripple and noise spikes being induced over the supply lines from changing power supply lines (digitally or manually). Fix for noise and grounding issues that can affect the reference voltage results by using separate analog and digital ground planes with a single-point connection:</p>  <p>The diagram illustrates the power supply and reference voltage connections for an ADC12. It shows a common ground plane on the right with several pins: DV<sub>CC</sub>, DV<sub>SS</sub>, AV<sub>CC</sub>, AV<sub>SS</sub>, V<sub>REF+</sub>, and V<sub>REF-</sub> / V<sub>REF-</sub>. On the left, there are five rows of components, each connected to a specific pin:</p> <ul style="list-style-type: none"> <li><b>Digital Power Supply Decoupling:</b> A 10 <math>\mu</math>F capacitor and a 100 nF capacitor connected to DV<sub>CC</sub> and DV<sub>SS</sub>.</li> <li><b>Analog Power Supply Decoupling:</b> A 10 <math>\mu</math>F capacitor and a 100 nF capacitor connected to AV<sub>CC</sub> and AV<sub>SS</sub>.</li> <li><b>Using an External Positive Reference:</b> A 10 <math>\mu</math>F capacitor and a 100 nF capacitor connected to V<sub>REF+</sub>.</li> <li><b>Using the Internal Reference Generator:</b> A 10 <math>\mu</math>F capacitor and a 100 nF capacitor connected to V<sub>REF+</sub>.</li> <li><b>Using an External Negative Reference:</b> A 10 <math>\mu</math>F capacitor and a 100 nF capacitor connected to V<sub>REF-</sub> / V<sub>REF-</sub>.</li> </ul>

**Table 4-12d: ADC12 Features**

<b>ADC12 Function/Feature</b>	<b>Description</b>
Conversion Memory	<p>Each of the 16 ADC12MEMx conversion memory registers store conversion results and have a ADC12MCTLx control register associated to it for configuration purposes. SREFx bits define voltage reference, INCHx bits select input channel, EOS bit defines end of sequence for sequential modes (discussed later) used, and when the EOS bit is not set, a sequence will roll over from ADC12MEM15 to ADC12MEM0. The CSTARTADDx bits define the first ADC12MCTLx when used for any conversion and points to specific x's when the mode conversions are single or repeat-single.</p> <p>The corresponding flag in the ADC12IFG register is set when conversion results are written to the ADC12MEMx.</p>
Using the Integrated Temperature Sensor	<p>The analog input channel must be set with the INCHx register to 1010. When using this sensor, the sample period must be greater than 30 micro-seconds. Since the temperature sensor's offset error is large, calibration is necessary for accurate results.</p>



**Table 4-13** below gives conversion modes that are chosen by the CONSEQx bits within the ADC12.

**Table 4-13: ADC12 Conversion Modes**

CONSEQx	Mode	Operation
00	Single channel single-conversion	A single channel is selected, sampled, converted once, and the result is written in ADC12MEMx defined by the CSTARTADDx bits. Successive conversions can also be triggered by the ADC12SC bit when the ADC12SC triggers a conversion.
01	Sequence-of-channels	Sequence of channels are sampled and converted once, beginning with writing the ADC results into the ADCMEMx defined by the CSTARTADDx bits and ending when the EOS bit is reached with its set standard.
10	Repeat single channel	A single channel is selected, sampled and converted continuously by repeatedly rewriting into the CSTARTADDx bit defined ADC12MEMx after it has been read (read so it won't just be continually written over without acquiring the previous results).
11	Repeat sequence-of-channels	A combination of all modes in a sequence of channels are taken in and rewritten to the CSTARTADDx bit defined ADC12MEMx and may be the best mode for this experiment as the MRI machine will be outputting several signals in a sequence that will need to be converted all at once (4 to be exact) for optimizing this code as much as possible.

**Table 4-14** below gives the registers associated with the ADC12:

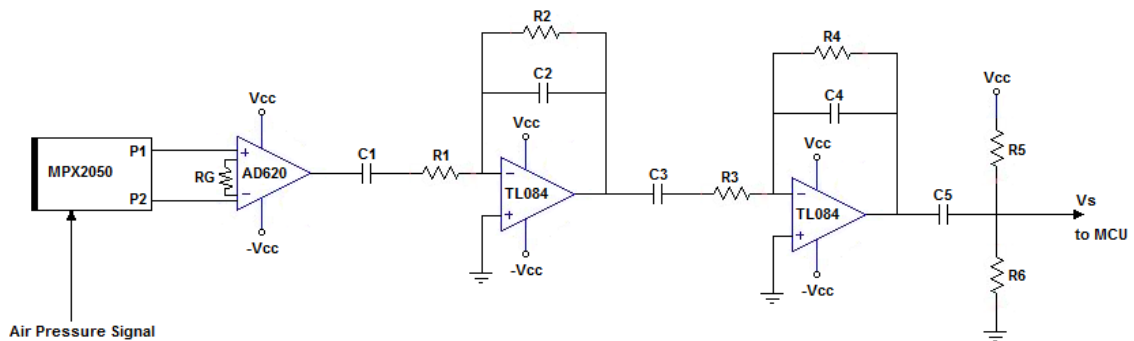
Table 4-14: ADC12 Registers

Register	Meaning (all ADC12)	Register Type	Address	Initial State (POR = Power-on-reset)
ADC12CTL0	Control register 0	Read/write	01A0h	Reset with POR
ADC12CTL1	Control register 1	Read/write	01A2h	Reset with POR
ADC12MEM0	Memory 0	Read/write	0140h	Unchanged
ADC12MEM1	Memory 1	Read/write	0142h	Unchanged
ADC12MEM2	Memory 2	Read/write	0144h	Unchanged
ADC12MEM3	Memory 3	Read/write	0146h	Unchanged
...	...	...	...	...
ADC12MEM13	Memory 13	Read/write	015Ah	Unchanged
ADC12MEM14	Memory 14	Read/write	015Ch	Unchanged
ADC12MEM15	Memory 15	Read/write	015Eh	Unchanged
ADC12MCTL0	Memory control 0	Read/write	080h	Reset with POR
ADC12MCTL1	Memory control 1	Read/write	081h	Reset with POR
ADC12MCTL2	Memory control 2	Read/write	082h	Reset with POR
ADC12MCTL3	Memory control 3	Read/write	083h	Reset with POR
...	...	...	...	...
ADC12MCTL13	Memory control 13	Read/write	08Dh	Reset with POR
ADC12MCTL14	Memory control 14	Read/write	08Eh	Reset with POR
ADC12MCTL15	Memory control 15	Read/write	08Fh	Reset with POR

## 4.2.5 NiBP System Design

This section covers the specifics of the non-invasive blood pressure system we will be implementing and its analog signal from the input at the cuff up until it passes into the microcontroller for analog-to-digital conversion. The complete NiBP sensor circuit is pictured in **Figure 4-8**.

Figure 4-8: NiBP Sensor Circuit



### 4.2.5.1 Pressure Cuff

Starting at the cuff, we will be using a standard adult sized blood pressure cuff (Part #: M1574A) manufactured and provided by Philips. All of Philips' standard cuffs use the same size tubing, so any other model will be compatible with the adapter we build. The reason we chose this cuff over other cuffs is for testing purposes. The M1574A is an appropriate size for all our group members whom will be performing the testing procedures.

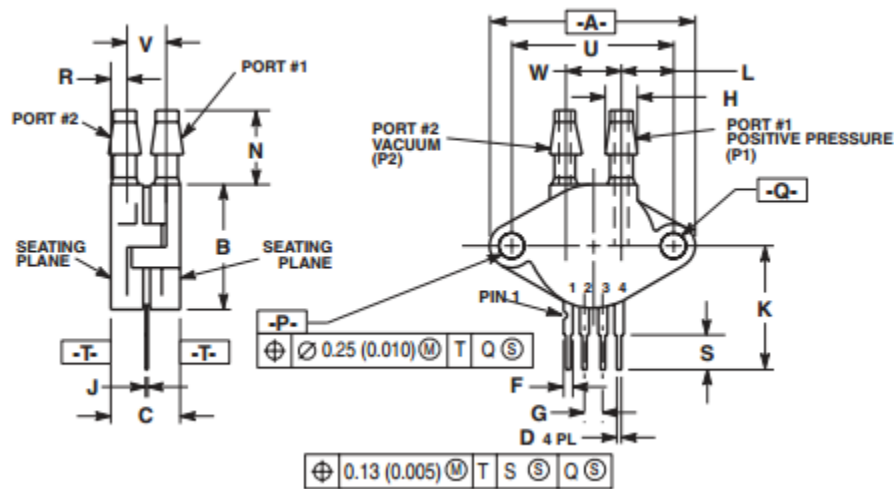
### 4.2.5.2 Pressure Transducer

The pressure transducer we have decided to use is Motorola's MPX2050 with the 344C type casing (See **Figure 4-9**). Motorola is a company we are familiar with and we have been satisfied with the quality level of parts we've used in the past so we had confidence

in using them again. As far as pressure sensors go, the MPX2050 has a good reputation among certain engineering communities and forums.

Aside from trusting the manufacturing quality, the MPX2050 (specifically, the MPX2050DP with the type 344C case) has some practical features that appeal to our intended use. The orientation of the intake nozzles, relative to the designed mounting orientation, is ideal for easy access to the nozzles when the transducer is surface mounted and for structural durability. Effectively, the force from attaching the cuff tubing is applied parallel to the surface it will be mounted to (i.e. along the same axis the nozzles are facing). The majority of the load applied to the mounting joints will be split between shear force acting on the bolt (along the plane where surface and casing meet) and the static friction (between the case and the surface) reinforced by the tightened nut/bolt. The benefit here is that the bolted joint is known to be one of the most structurally stable configurations to handle forces being applied as it is here. This should prolong its structural lifetime and prevent shifting after repeated use.

Figure 4-9: MPX2050DP Package

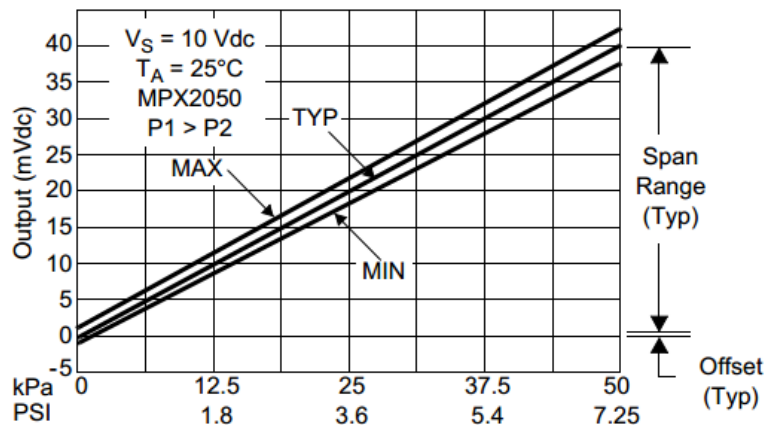


Another potentially useful feature of the MPX2050DP is that there are actually two pressure sensitive transducers in the one package. Each transducer has a nozzle of its own. Though rarely, if ever, is more than one pressure cuff being used at a time to monitor a patient. One potential benefit for having an extra transducer is that one can be used to read pressure from the cuff while the other could remain open to the atmosphere and record a value corresponding to the ambient atmospheric pressure. To take advantage of the control ambient pressure, we could measure the difference in the two transducers instead of referring the input signal to ground. Doing this gives us a more accurate signal

relating cuff pressure to the ambient pressure. Also, since the transducers are very close to each other, physical noise sources (loud sounds, temperature change, etc.) affect both transducers in a similar manner which means an otherwise problematic noise source could be reduced to negligible magnitudes. With MRI rooms having potential to be very loud, this could make a difference. In practice, sudden ambient pressure changes (i.e. sound) would likely be entering the system at different locations; one directly into the open ambience sensor and the other, most prominently, through the actual cuff.

The electrical properties agree with our intended application; the response to change in pressure is very linear and precise over a large range relative to our maximum operating range. Blood pressure cuffs generally don't require more than 160mmHg of applied pressure to act as a proper tourniquet and blood pressure higher than 180mmHg indicates an extreme case of arterial hypertension. Converting kilopascals to millimeters of Mercury (following the conversion factor:  $1 \text{ kPa} \cong 7.5 \text{ mmHg}$ ), the documented maximum input pressure for the MPX2050, 50 kilopascals, is equal to  $\sim 375 \text{ mmHg}$ . This is well above any input foreseeable in practice.

Figure 4-10: MPX2050 Output Voltage vs. Input Pressure



The practical input range of the transducer used to measure blood pressure has extremes of a 180mmHg systolic pressure and a 60mmHg diastolic pressure shown in **Table 4-15**. Anything higher or lower than this range is classified as a hypertensive emergency or hypotension, respectively. The desired systolic and diastolic pressures altogether range from 119mmHg to 60mmHg. From this information, we can get an idea of what to expect from our analog electrical signal.

**Table 4-15: Blood Pressure Classifications**

<b>Patient State</b>	<b>Systolic (mmHg)</b>	<b>Diastolic (mmHg)</b>
<b>Hypotension</b>	< 90	< 60
<b>Desired</b>	90 - 119	60 - 79
<b>Hypertensive Emergency</b>	$\geq 180$	$\geq 110$

The highest pressure we would be concerned about reading accurately from a patient’s cuff would be 180mmHg. Giving a 20mmHg (~11%) margin, let’s say the highest pressure we want to read is 200mmHg (~26.7 kPa). Using the sensitivity 0.8 mV/kPa, given in the MPX2050 datasheet (Appendix B), we can calculate the sensor’s output to be 21.36mV at 26.7kPa and use this as the maximum voltage we care to measure accurately.

Applying the same procedure to the lowest pressure we’re concerned about reading accurately, 60mmHg, let’s use the same margin as before and set our floor to 40mmHg (~5.33kPa). At 5.33kPa, the sensor’s output should equal ~4.26mV. This isn’t the absolute minimum the output can reach, the sensor’s output still produce a 0 V signal if there’s no pressure being read. The target minimum is simply the lowest voltage we want to be distinct; which means we can’t allow any noise to become comparable to 4.26mV.

**Table 4-16: Key Sensor Outputs**

<b>Max. Output (mV)</b>	40
<b>Max. Target Output (mV)</b>	21.36
<b>Min. Target Output (mV)</b>	4.26
<b>Min. Output (mV)</b>	0

#### 4.2.5.3 DC Amplifier

Once we’ve obtained the raw signal coming from the sensor, it needs to be amplified because its amplitude is very low compared to what the microcontroller performing the

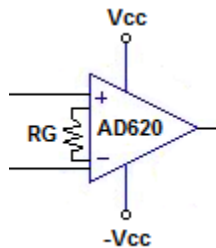
analog-to-digital conversion is capable of handling. The larger the signal passing into the A/D converter is (without exceeding the controller's input restraints), the clearer the digital signal will be because it makes use of more samples. If the step in voltage required to increase one increment in the digital signal's amplitude is 5mV, an analog signal peaking at 20mV will cover 4 increments whereas a signal peaking at 4V will encompass 800 increments. The resolution is proportional to the analog amplitude.

The output signal from the pressure transducer is capable of spanning a peak-to-peak amplitude of 40mV under typical conditions. However, we are not concerned about values over 21.36mV. So our signal can be considered to have a peak-to-peak amplitude of 21.36mV, unless exceeding any following input limitations is a concern and it is not in this case.

In order to use the second pressure transducer as a reference signal and find the cuff's difference in pressure from the ambient atmosphere, we need to subtract the reference signal from the cuff's signal. To find the difference in signals, we decided to use an instrumentation amplifier. Analog Devices' AD620 Instrumental Amplifier was the amplifier we chose to handle the initial stage of amplification (See **Figure 4-11**). Choosing to use the AD620 over other options was simply a matter of being content with a prior experience using the AD620.

Running the cuff's post-sensor signal  $P_1$  to the  $V^+$  pin on the AD620 and the reference signal  $P_2$  to the inverting pin, we establish an output proportional to  $P_1 - P_2$ . The actual output will depend on the gain of the amplifier stage, which is controlled by the resistance of  $R_G$ . Since  $R_G$  lies outside the AD620's packaging, the value of  $R_G$  can be defined by the user. This is the case with many instrumentation amplifiers. The value we choose for  $R_G$  is dependent on the following filters' gain so we will come back to calculate the desired resistance.

**Figure 4-11: AD620 Instrumentation Amplifier**



#### 4.2.5.4 Bandpass Filter

Pressure signals from an NiBP cuff have a large low frequency component due to the relatively slow, steady release of cuff pressure throughout the monitoring cycle. Thermal noise and other noise sources can vary in frequency but it is advisable to eliminate it as best as you can regardless of whether you know at which frequencies it's located or not. Some key frequencies we are aware of are those of human hearts.

A cycle of blood pressure monitoring records a series of blood pressure pulses. These spikes in blood pressure are caused by your heart contracting and releasing periodically, or beating. If we know how fast our heart is beating, we know how fast these pressure spikes are occurring. Or in other words, the frequency of the target pressure signal is the patient's current heart rate.

**Table 4-17** holds a few key values of heart rates. A person's approximate maximum heart rate is commonly estimated by subtracting their age (in years) from 220. If this is the case, then 220bpm must be close to the absolute maximum possible heart rate. An average heart rate lies somewhere between 60 and 100bpm. 50bpm is considered a very low resting heart rate so I set the minimum at 40bpm out of judgment. These heart rate values have been converted to frequencies in Hertz and they correspond to possible spectrum components of the blood pressure signals. For example, a heart rate of 60bpm is equal to 1Hz, which means the fundamental component in that signal's frequency spectrum is located at 1Hz. So, the range from minimum to maximum frequency in **Table 4-17** (0.667-3.667Hz) is the range where one would expect to find the fundamental frequency component of any patient's blood pressure signal. The likelihood is higher near the average values.

**Table 4-17: Estimated Heart Rate Values**

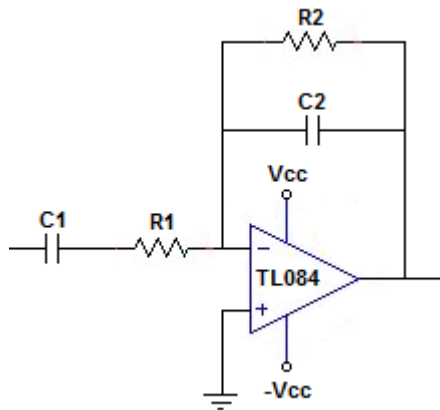
	Heart Rate (bpm)	Frequency (Hz)
Maximum	220	3.667
Average	60 - 100	1 – 1.667
Minimum	40	0.667

With this information, we designed a band pass filter to fit around the frequency range 0.667-3.667Hz. Through prior experience dealing with NiBP frequency spectrums, the

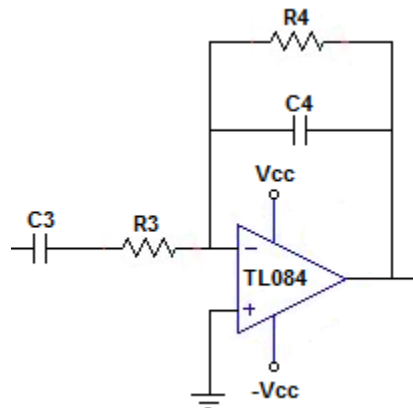


lower edge of the frequency range, 0.667Hz, is noticeably close to the unwanted low frequency component. Doubling the filtering power is advisable to eliminate the low frequency component and flatten the baseline. The second stage also allows for more control in shaping the magnitude envelope on the higher frequencies.

**Figure 4-12: First Stage of Band Pass Filter**



**Figure 4-13: Second Stage of Band Pass Filter**



Designing active filters requires the selection and use of an operational amplifier. The amplifier we have the most experience using is Texas Instrument's TL084 and there are no parameters in this filter design that disagree with the use of the TL084 so it is the amplifier we will be using for both band pass filters.

When designing circuits that will become realized, it's advisable to try to use values of single components that exist. It is possible to create almost any custom resistance out of multiple resistors, but it is not nearly as clean as using a single resistor. The capacitor and resistor values determine the passband corner frequencies. So with limited options of capacitances and resistances, the options for corner frequencies will be limited as well.

To create a steeper drop in magnitude, the lower corner frequencies of both stages are set on top of each other. This is done by setting their corresponding capacitors and resistors to the same values.

$$\begin{aligned} C_1 &= C_3 \\ R_1 &= R_3 \end{aligned}$$

Choosing  $R_1$  to be an easy  $10\text{k}\Omega$ , the corner frequency was set to  $0.4\text{Hz}$  and an ideal  $C_1$  was calculated.  $C_1$  was then shifted to a nearby standard value of  $47\mu\text{F}$  and the new frequency was calculated.

$$f_{low} = \frac{1}{2\pi C_1 R_1} = \frac{1}{2\pi(47\mu\text{F})(10\text{k}\Omega)} = 0.339\text{Hz}$$

A similar process was used for deciding the upper corner frequencies. The difference here is that the resistor values chosen decided the gains of each stage. The capacitors affect the corner frequencies and the intended general shape of the magnitude envelope on the upper side is a slow drop from the average frequency to the maximum and then tapering off along the axis.

$$f_{high1} = \frac{1}{2\pi C_2 R_2} = \frac{1}{2\pi(2.2\mu\text{F})(30\text{k}\Omega)} = 2.41\text{Hz}$$

$$f_{high2} = \frac{1}{2\pi C_4 R_4} = \frac{1}{2\pi(2.2\mu\text{F})(20\text{k}\Omega)} = 3.62\text{Hz}$$

The active band pass circuits use an inverting amplifier configuration. The maximum passband gain of each stage is calculated as follows ( $A_{v1}$  and  $A_{v2}$  correspond to stages 1 and 2, respectively):

$$A_{v1} = \frac{-R_2}{R_1} = \frac{-30\text{k}\Omega}{10\text{k}\Omega} = -3$$

$$A_{v2} = -\frac{R_4}{R_3} = \frac{-20\text{k}\Omega}{10\text{k}\Omega} = -2$$

The combined gain for the two stages is the product of the two individual stages. This passband gain is calculated as follows:

$$A_{v1} * A_{v2} = (-3)(-2) = 6$$

With the active filtering stage contributing a gain of 6, the gain of the instrumentation amplifier can be decided on. Referring back to Table X-6, we note the largest input we're concerned about is 21.36mV. The largest signal we can send to the MCU is 5V in amplitude, so our overall gain from transducer to MCU,  $A_{total}$ , can be a maximum of ~234. To be safe, we use a desired total gain of 200. Calculating the gain we need the instrumentation amplifier to contribute follows as:

$$A_{inst}(ideal) = \frac{A_{total}(ideal)}{A_{v1} * A_{v2}} = \frac{200}{6} = 33.3$$

Using this, we calculate the ideal resistance we want to use for  $R_G$ :

$$A_{inst} = \frac{49.4 k\Omega}{R_G} + 1 \quad (\text{from AD620 datasheet})$$

$$R_G(ideal) = \frac{49.4 k\Omega}{A_{inst}(ideal) - 1} = \frac{49.4 k\Omega}{33.3 - 1} = 1.53k\Omega$$

Approximating the ideal  $R_G$  to a standard resistor value of 1.5k $\Omega$ , the total gain of all three stages comes out to be  $A_{total} = 203.6$ . This amplifies our target inputs of 0 through 21.36mV to an output of 0 to 4.35V.

#### 4.2.6 Signal Multiplexing

The sensed signals are to be collected in the data acquisition unit, digitized, and then down a multiplexed data stream using Bluetooth to the base station/receiver. The current system implementation by Philips has two sensors with independent wireless handhelds. The objective is to integrate the two current handheld wireless systems with the data acquisition unit by dismantling the handhelds and embedding their components into the unit. The two other sensed signals will be digitized within the unit and sent wirelessly in the same fashion. If the integration of the pre-existing system with the two remaining signals is not possible, a parallel process will be used to transmit and collect the individual signals at the base station.

#### **4.2.6.1 Cable Management**

The SQUID cable will consolidate the separate sensor cables into one, but even with the reduced amount of cables some risk is still present. To minimize the chances that the cable will become a hazard, cable management must be considered. Following the system requirements, the cable must not bunch or loop, and must be as short as possible while still allowing seamless patient transfer from the MRI chamber to a recovery area. The data acquisition unit will be located under the patient's bed, and will be easily transferred from one location to another. Along the underside of the bed, and anywhere the cable must be routed, a series of cable clips will be installed in order to ensure the cable slack is well managed and will not present a safety hazard.

#### **4.2.7 Limitations**

The system design is subject to limitations present in the high magnetic field of an MRI environment such as the need for non-ferromagnetic metals in cable and connector design. The sensitivity of the system to noise must be considered and appropriate shielding used where applicable. Any interference must be filtered out before transmitting the signal to the receiver base station. The information available on the current platform is limited and has resulted in a large portion of the proposed system upgrade to be based upon speculation and may be altered to comply with new requirements as they are formed.

### **4.3 Block 1 System Design**

#### **4.3.1 Wireless System Materials and Design**

An existing wireless platform is used by Philips to monitor and transmit two of the four signals from the sensors. Integration with this platform is the goal, in which the two sensors without wireless solutions (CO<sub>2</sub> and NiBP) will be passed through an extension to the current wireless system and transmitted in the same manner to a receiver/base station.

For the proposed system upgrade, the signals must all be collected in the data acquisition unit located under the patient's bed, and transmitted in a multiplexed data stream to the receiver base station.

If the platform is to be designed with an open-ended approach, a wireless module would be included to pass the signals to the receiver. A few options for wireless modules are listed below in **Table 4-18a** and **Table 4-18b**.

**Table 4-18a: Wireless Modules**

<b>Option</b>	<b>Name</b>	<b>Description</b>
<b>A</b>	TiWi-uB2 Bluetooth Module	Bluetooth 2.1+EDR and BLE 4.0  Integrated Band-Pass Filter  Miniature Footprint: 7 mm x 7 mm
<b>B</b>	XBee Pro 60mW Wire Antenna - Series 1 (802.15.4)	250kbps Max data rate  6 10-bit ADC input pins  128-bit encryption  Built-in antenna  1 mile (1500m) range
<b>C</b>	XBee Pro 900 XSC RPSMA	Up to 2000 ft Indoor range with high-gain antenna  10 Kbps data rate  Up to 24 dBm (250 mW) Transmit Power  Receiver Sensitivity of -109 dBm at 9600 baud

**Table 4-18b: Wireless Modules**

<b>Option</b>	<b>Name</b>	<b>Description</b>
<b>D</b>	TI CC2560	<p>Supports Bluetooth 4.0 dual-mode (BR/EDR/LE) protocols</p> <p>Support of up to 6 simultaneous connections</p> <p>Flexibility for Easy Stack Integration and Validation Into Various microcontrollers, Such as MSP430 and ARM Cortex M3 and M4 MCUs</p>
<b>E</b>	TI CC3000	<p>IEEE 802.11 b/g</p> <p>Embedded IPv4 TCP/IP stack</p> <p>Works with low MIPS and low-cost MCUs with compact memory footprint</p> <p>Integrated crystal and power management</p>

Of the above options, the TI CC3000 is likely the most viable. Some of the reasons for justification of this decision are listed below:

- Compatibility and ease of integration with the MSP430 architecture.
- Large amount of available resources on development with CC3000.
- 802.11 b/g WIFI preferred connection method by Philips.

#### 4.3.1.1 Integration with Existing Hardware

The wireless platform used by Philips must be studied in order to mimic the current design. The provided platform will give a base for which to build the wireless platform of the CO<sub>2</sub> and NiBP sensors. If the system is unable to be built upon or seamlessly incorporated into the final design, the two above named sensors will use a new platform similar but separate to the current wireless solution.

The level of integration will be limited to embedding the existing two wireless monitors into the exterior of the SQVID cube. The two monitors will sit flush on the surface and their cables routed alongside the two internal cables. The routing of the cable will be handled internally and an extension will be used from each wireless monitor to the connector of the SQVID cable. The connector at the other side of the SQVID cable will interface with the sensor and pass the signal back to the wireless monitor.

#### 4.3.1.2 Operational Frequency/Spectrum

For the wireless signal to retain as much information as possible while being subject to as little interference as possible, a certain wireless spectrum must be adhered to. **Table 4-19** lists the different ranges of the industrial, scientific, and medical (ISM) frequency bands.

**Table 4-19: ISM Frequency Bands**

Frequency Range		Bandwidth	Center Frequency	Description
6.765 MHz	6.795 MHz	30 kHz	6.780 MHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 kHz	13.560 MHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	27.120 MHz	Worldwide
40.660 MHz	40.700 MHz	40 kHz	40.680 MHz	Worldwide
433.050 MHz	434.790 MHz	1.74 MHz	433.920 MHz	Region 1 only and subject to local acceptance <sup>1</sup>
902.000 MHz	928.000 MHz	26 MHz	915.000 MHz	Region 2 only (with some exceptions) <sup>2</sup>
2.400 GHz	2.500 GHz	100 MHz	2.450 GHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	5.800 GHz	Worldwide
24.000 GHz	24.250 GHz	250 MHz	24.125 GHz	Worldwide
61.000 GHz	61.500 GHz	500 MHz	61.250 GHz	Subject to local acceptance
122.000 GHz	123.000 GHz	1 GHz	122.500 GHz	Subject to local acceptance
244.000 GHz	246.000 GHz	2 GHz	245.000 GHz	Subject to local acceptance

<sup>1</sup> Region 1 includes Europe, Africa, the Middle East west of the Persian Gulf including Iraq, the former

<sup>2</sup> Region 2 includes the Americas, Greenland, and some of the eastern Pacific islands.



Overall, the 2.4 GHz frequency ranges are the most desirable as to provide a standardized wireless system that is used for multiple sensor environments and minimal interference. Development resources are widely available, and the ubiquitous nature of the 2.4 GHz spectrum ensures greater availability and lower cost of parts.











### 4.3.2 Software Platform

The software system, the Simplified Quad-Vitals Integration Device Intelligent Navigation Controller (SQVID INC), works in conjunction with the connection box to recognize which vital signs are connected, perform the necessary waveform modifications, and display the data automatically for the healthcare professionals caring for the patient. The standalone program runs on a standard Windows 8/8.1 operating system and utilizes a user-friendly touch screen interface when necessary. The Windows operating system was chosen due to its universal acceptance and current use in the Philips industry. Due to the tactical functionality enabled on Windows 8/8.1, it was determined there was no need for any application development for iOS or Android.

### 4.3.3 Existing System

In conjunction with their cableless measurements solutions, Philips uses IntelliVue Guardian Software, the accompanying system which receives the wireless signals and processes them. Philips' entire IntelliVue Guardian Solution includes the software, patient monitor, cableless measurement devices, and mobile management support, in addition to more sophisticated and advanced services. The core of the system, IntelliVue Guardian Software, analyzes a patient's vital signs for deviations, is highly configurable, and connects to a hospital's enterprise system. Due to the scope of this project as well as its proprietary nature, it was decided that the new system would be a dramatically simplified version of this software, only providing the necessary functions to ensure proper functionality and demonstration of the newly designed hardware. **Table 4-20** displays the main features of the current Philips system in comparison to the new program for this project.

Table 4-20: IntelliVue Guardian vs. SQUID INC

IntelliVue Guardian Software	SQUID INC
Acquires Vital Signs	
Automatically Verifies the Accuracy of Data	
Smoothes Workflows, Reduces Human Errors	
Aids in Early Detection of Deterioration by Analyzing Data	
Highly Configurable	
Configurable Action List with Recommended Care	
Aligns with Clinical Practices	
Automates Early Warning Scoring	
Connects to a Hospital's Enterprise System	
Several Additional Services Available	

#### 4.3.3.1 User Interface

Various user interface designs were considered for this project. The first option considered was a similar layout to Philips current IntelliVue Guardian system, as seen below on the IntelliVue bedside monitor in **Figure 4-14**. This approach, while it would have been familiar to current users of Philips' software, did not emphasize the four signals the team would be focusing on, and did not highlight the central focus of this project: the cabling system. The team felt that choosing such a layout would have overcomplicated the software. A cleaner design was thus drafted to help draw attention to the four signals being displayed and to demonstrate the accuracy in the data attained from the hardware and software pairing.

Figure 4-14: IntelliVue Bedside Monitor



*Image Reprint Courtesy of Philips*

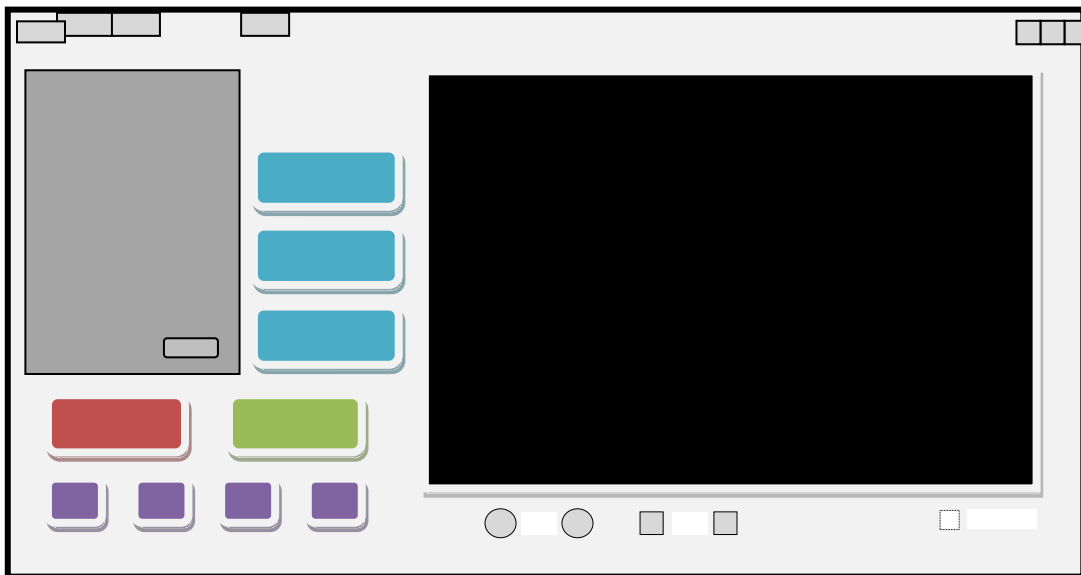
With the main concerns being simplicity and functionality, a basic elementary design was chosen. It was decided that a touch screen interface would be a great feature to add for demonstration purposes as well as portability. This particular feature is becoming more and more commonplace in the professional industry, and will soon be expected rather than desired. The recent versions of the Visual Studio IDE make writing a program compatible with tactile input too manageable to be ignored. Combined with the popularity of the Windows 8/8.1 operating system and its versatility among tablets and desktop computers alike, implementing a touch screen interface became a trivial decision.

The user interface displays all four vital signs available for monitoring. However, only the currently connected signals will be enabled for further modification or viewing. Each enabled signal selected for monitoring will display graphically as a waveform for the user, accompanied by real-time numerical data values for quick and easy readability on the vital signs' button itself. The patient's information is displayed next to the vital signs. This includes, but is not limited to: name, age, gender, date of admittance, diagnosis and any other imperative information needed at a glance. Other information, such as blood type, medication or food allergies, special care instructions, and any notes made by caring healthcare professionals can be accessed by selecting the "More..." option, which opens a second window. Additional patient notes can also be made from this screen, and if deemed necessary, displayed on the main screen.

If needed, the user has the option of recording the current vital signs being monitored in the form of an .XML file, which can then be saved and analyzed at a different time. Other features and patient information specifics are discussed in greater detail in Section 6.3.3.

**Figure 4-15** gives a basic idea of the main screen's layout.

**Figure 4-15: User Interface Design for SQUID INC**



#### 4.3.3.2 Coding Language

Two coding languages were considered for this project: object oriented Pascal using Embarcadero RAD Studio/Delphi 2010 and C# using Visual Studio 2013. Pascal was only considered because of the main programmer's extensive experience with the language and pre-existing code that could be of use. The pre-existing code already had the ability to take in digital and analog signals and graph them, using TCP/IP and UDP messaging protocols. However, while a versatile language with many capabilities, Delphi Pascal is not necessarily a common coding choice and is not widely used in a professional environment. It is one of the oldest languages still in existence with very few open-source resources in comparison to newer languages like C++, Java, and C#. In addition, only recent versions of the IDE, such as Delphi XE2, have gesturing and touch screen interface support comparable to what Visual Studio has to offer. Delphi XE2 is an

expensive and license-only product, inaccessible to the typical hobby coder. Visual Studio 2013, however, is offered for free to students studying a related programming field. The C# language was thus explored further, and even with very little experience with the language, the opportunity to learn it was appealing to the programmer.

The language provided the real-time data acquisition capabilities necessary for the system, while yielding simplicity and power, as well as seemingly nonexistent limitations. Microsoft Visual Studio was chosen as the coding IDE due to its comfortable and familiar environment. The software system takes advantage of the .NET framework and the language enables easy UI design and touch interface features to be effortlessly integrated. The diverse open source libraries available to the language allow for various features to be added with a few lines of code both during initial coding of the program as well as at a later time to enhance the performance of the program if necessary. While the system is intended for use on a touch screen device running Windows 8/8.1, it is also capable of running on a standard Windows desktop of the same operating system version if portability is not of great concern.

#### **4.3.3.3 Signal Acquisition and Processing**

The two main methods discussed for transferring data between the connection box and the software program were Bluetooth and wireless TCP/IP communication. Further research into the IntelliVue Guardian software as well as previous programming experience led the team to decide on using TCP/IP protocol communication. This method was chosen not only to mimic Philips' current software system but because of its reliability and ease of use.

A TCP/IP wireless connection is used to communicate between the connection box and the software program. Each signal possesses an individual port number, and each patient's connection box a specific IP address. Due to the prototype nature of this project, there is only one IP address being considered. Once started, the software program begins its server and awaits requests from clients. When the signal is physically plugged into the connection box a connection to the server is made and data begins transferring through various packets to the software system. If at any time a packet is lost or suspected of being corrupted, its contained data is not displayed and a log file records the issue. If the connection between client and server is lost, an error message is shown to the user and data display is stopped until the problem is acknowledged and/or fixed. An automatic reconnect is attempted up to 3 times when a connection is lost, however if a connection cannot be reestablished, the user must intervene.

Before being displayed graphically or numerically, the received data goes through a waveform filter specific to the vital sign being monitored. These filtering techniques are designed and approved by Philips and due to proprietary requirements are not discussed in detail. As per Philips standards, if any data is suspected of being inaccurate it is not displayed. This is determined by random sampling taken at various intervals, once again, as instructed by Philips. The user is able to select an “Advanced” option via the software program to adjust the used filtering techniques, however it is not recommended for the standard user. To protect against accidental obscuring of the data, a “Reset to Default” item is available under the “Filters” menu to reapply the original filters.

#### 4.3.3.4 Scalability

Due to the coding choice as well as the IDE, the final software program will possess countless options for improvement at very little cost. Apps can be created if necessary for the Windows 8/8.1 environment, depending on what is needed. For instance, a version compatible with Windows 8.1 can be created while maintaining a version of the app compatible with Windows 8 all from within Visual Studio 2013. However, a developer license is needed to develop and test Windows Store apps before the Windows store can certify them.

Being designed to run on Microsoft’s latest operating system, compatibility and legacy support should not be of great concern for several years. Many features were considered when drafting the design of this program, and those that weren’t considered vital to the prototype nature of this project could easily be added with the necessary information from Philips and some time to make the changes. A few of these features and what would be required to include them are summarized in **Table 4-21** below, with details of each feature and steps for implementation described afterward.

**Table 4-21: Additional Feature Requirements**

<b>Feature</b>	<b>Required Information</b>
<b>Early Detection of Patient Deterioration</b>	Philips’ proprietary data analysis techniques
<b>Hospital Enterprise System Integration</b>	Philips’ permission and detailed network information
<b>Advanced Configurability</b>	Access to Philips’ current software system to analyze and mimic existing code functionality
<b>Multiple Patient Profiles</b>	No information needed, just time to make the change and test its functionality

**Early Detection of Patient Deterioration:** One of the most powerful tools integrated into Philips’ IntelliVue Guardian Software system is the analysis of a patient’s vitals automatically with the intention of predicting if the patient’s health is or will be deteriorating. Philips refers to this as “EWS”, Early Warning Score, which is the first of its kind to provide assistance and recommendations to caregivers based on their hospital’s policies, all from a spot-check monitor with the patient. The system is completely customizable and can be adjusted for varying vital sign collection periods. To duplicate this feature within this project’s scope the algorithms and calculations Philips uses to detect variances in a patient’s vital readings would have to be shared with the team. Lots of time would be required for implementation as well as thoroughly testing the system to ensure it performed correctly, consistently, and was up to Philips’ high standards.

**Hospital Enterprise System Integration:** Philip’s IntelliVue Guardian Solution enables connectivity to a hospital’s enterprise system using IntelliBridge Enterprise. This provides interoperability between the Philips clinical systems and the facility’s enterprise information systems, with efficient connection points, secure data transferring, and incredible reliability. This feature was not considered appropriate or necessary for the main objectives of this project as it did not relate to the construction or demonstration of the SQUID cable. To add this feature to SQUID INC would require a significant amount of research into the development and functionality of IntelliBridge Enterprise, and how a

typical hospital's enterprise system works, all before any code could be changed within the program.

**Advanced Configurability:** It was determined that only a minimum amount of configuration options would be necessary to properly demonstrate the functionality of the SQUID cable and hardware system. In fact, an objective of the program, as stated in Section 2.2.5, is that the INC software obtains the vital signals and does the necessary manipulations to properly display the waveform data automatically, with preferably no human intervention to prevent accidental human error. To enhance INC with advanced customization features comparable to that provided in IntelliVue Guardian, a deeper understanding to how the software is used by Philips' customers would need to be attained. Taking into consideration only the four signals being monitored, a lot more research would need to be done with regards to filtering techniques for each waveform and how manipulation would affect the data. While adding aesthetic customization features for the user's benefit may be trivial, enhancing INC with the sophisticated techniques used by Philips to provide accurate, reliable, and detailed patient information would prove to be quite the challenge.

**Multiple Patient Profiles:** This feature would be most applicable in an instance where multiple SQUID boxes and their cables were in circulation. The feature would allow for multiple patients to be saved into the INC program's database, each with their own individual IP address linking them to their respective SQUID box. This information could be accessed and edited from the main screen of the program, and a "Connect to Patient" option could be added to control the servers currently active. That is, only selected patients, known to be using their SQUID box, would have a server awaiting client connections. The most difficult part of implementing this feature would be the production of multiple SQUID boxes and their cables for thorough testing, assuming SQUID INC would be running as a stand-alone program separate from a hospital's network or Philips' existing software system as written to do so for this project.

Unfortunately, full integration into the existing Philips system is nearly impossible due to not only to the proprietary nature of this project and Philips' understandable discrepancy to relay specific details of their existing system to members of the team, but because of the sheer scope and amount of work that would be involved in such an undertaking. The INC program written to interface with the new SQUID cable is purely for demonstrational purposes, and while features were added to enhance the functionality and emphasize design aspects of the hardware, it was never intended to be installed and used in a professional, hospital setting as a replacement or even an accompanying system for Philips' IntelliVue Guardian Software.

The scalability of the hardware will be limited by the level of integration allowed with the current system provided by Philips. If the two existing wireless sensors are integrated



using Philips' proprietary wireless solution, the system will have plenty of remaining input/output space for future sensor integration. The wireless nature of the device will allow for greater system expansion without the associated bulk of additional cable connections. Expanding upon the wireless capabilities, the system may be used to connect to a larger mesh network and communicate between multiple base stations and peers on the network.

## **5.0 Design Summary of Hardware and Software**

### **5.1 Hardware Design Summary**

The primary goal in designing the hardware for the SQVID, as is with most designs, is functionality; the device does what it needs to do in the conditions it will be used in. So, we designed the device as simply as possible using parts that will operate in and not interfere with an MRI environment. Once that is achieved, we can move to other aspects like reliability and consolidation.

Knowing the sensor cables running from the patient to the SQVID will be provided to us by Philips, we started our design at the hub where the cables will all connect. The ECG and SpO2 sensors already had wireless transmission solutions, so we were left with NIBP and CO2 to handle. NIBP sensors are relatively straightforward so we designed our own. Capnography is not as simple, so we may need to use Philips' current CO2 sensor design. However, no schematic for the CO2 sensor has been provided. The NIBP and CO2 sensors run to a microcontroller (TI MSP430) for A/D conversion and multiplexing. Then an RF transmitter sends the data wirelessly to a monitoring display.

### **5.2 Software Design Summary**

The accompanying software system, the Simplified Quad-Vitals Integration Device Intelligent Navigation Controller, uses wireless TCP/IP protocol communications to acquire the various vital signs connected to the SQVID connection box. These signals then undergo a filter specific to their content, as designed and approved by Philips for the most accurate display of data. The vital sign is shown graphically and numerically for the user through a touch screen GUI. The program is written to have minimal human intervention during operation, however, possesses a few useful features to demonstrate the functionality of the SQVID cable.

Each vital sign's embedded systems board possesses a unique port number, and each SQUID connection box a unique IP address. The microcontrollers are programmed to each act as a client, and when connected or powered on, request connection with the INC server. The program identifies which signal is connected based on these port numbers, which are set by the user using the configuration screen at program startup.

Based on connectivity and communication status, only the currently active signals are available for display. They are disabled if not connected. By default each signal is graphed when the "Start" button is pressed, but the user has the option of only including certain vital signs in the graph plot if desired. Each active vital sign's button behaves as a latch. To include the signal in the graphing plot it simply needs to be pressed, and to remove it from the graphing plot, depressed.

Information about the patient being monitored is displayed "at-a-glance" in the Patient Information window on the main screen. This information includes the patient's name, age, gender, diagnosis, and admittance date, as well as any special care notes made by attending physicians. These notes and the information displayed can be edited and customized by the user to better suit the needs of the patient and procedures of the facility.

The INC software program runs on a Microsoft Windows 8/8.1 operating system. It includes a touch-screen interface design, which makes it possible to run the program on a tablet device for easy portability.

## **6.0 Project Prototype Construction and Coding**

### **6.1 Final Coding Plan**

#### **6.1.1 Objective Summary**

The main objectives the SQUID INC software must accomplish are found in Section 2.2.5 and the table is reprinted below (**Table 6-1**) for convenience.

**Table 6-1: Coding Plan Objectives**

<b>Objective</b>	<b>Requirement Description</b>
S-001	The software system must be capable of recognizing which signals are connected to the central connection box.
S-002	The software system must do the necessary calculations and/or modifications as determined by Philips to accurately depict the signal as required for all healthcare professionals using the system.
S-003	The software system must perform the above two requirements automatically without any user intervention.
S-004	The software system must provide a user-friendly, easy to understand and manipulate interface for healthcare professionals involved in its operation.
S-005	The software system must be extremely reliable and accurate.

Objectives S-001 and S-003 are met through the use of a TCP/IP protocol connection initiated at the start of the program. Running the program begins a TCP server which waits for client requests for connections. Each vital sign possesses an individual port number and each connection box a unique IP address corresponding to the TCP sever. When a vital signal is connected to the SQUID box it starts its port-specific client which wirelessly requests connection to the server residing in INC. Both the port number of each vital sign and the common IP address are customizable. All of this data is easily modified from within INC by editing the patient's information. However, it is not customizable from the standpoint of the SQUID box: each signal's embedded system is pre-programmed with its respective port number. Thus, INC is able to recognize which signal is connected to the central connection box by matching the client's port to its saved information. This recognition process happens automatically once a vital sign's cable is plugged in.

Objective S-002 is met through the algorithms implemented within the program that filter the received data as per Philips standards and instructions. Once filtering is complete, the data is displayed both graphically as well as numerically for the user.

Objective S-004 is met through the designed GUI as described in Section 4.3.3 and shown in **Figure 4-15: User Interface Design for SQVID INC**. The touch screen interface and intuitive layout provide the user or healthcare professional with important patient information at a glance, accurate displays of vital signs both graphically as well as numerically, and easy to use features that assist in data analysis and enhance patient care.

Objective S-005 is met through exhaustive testing procedures as described in Section 7.3, as well as Philips guidance and supervision throughout this project, holding the team to their high standards of patient safety and customer satisfaction.

### 6.1.2 Functionality and Features

The following tables (**Table 6-2**, **Table 6-3a**, and **Table 6-3b**) list the functions and features available from the main screen of the SQVID INC software system accompanied by detailed descriptions of how each operate.

**Table 6-2: Functions of SQUID INC**

<b>Function</b>	<b>Name</b>	<b>Description</b>
FNT-001	Selectable Vitals	Each vital sign available for monitoring (plugged into the connection box), is displayed on the left side of the main screen as a button. These buttons function as latches: when pressed they latch and are added to the graphing plot for viewing. When pressed again they unlatch, and are removed. Only vital signs connected to the SQUID box with an active client connection to the INC software server are available for display, the rest are disabled and do not have any functionality.
FNT-002	Start	Places the graph in running mode: Begins graphing the vital signs selected by the user. The graph display is active and updating based on the analog values being received by the program's server. Each signal's button (if connected) is being updated with numerical values of the same data being graphed. The graph area is cleared each time Start is selected, and all previous data is lost.
FNT-003	Stop	Takes the graph out of running mode: Stops graphing the vital signs selected by the user. The graph display halts/pauses wherever it is, maintaining all that was graphed before it. Once stopped the existing graph is scrollable to enable viewing the signal's history.

**Table 6-3a: Features of SQUID INC**

Feature	Name	Description
FEA-001	Record	This option allows the user to record the data being displayed in .XML format to use at another time. It functions as a latch and can only be pressed when the graph is not running. If latched when the Start option is chosen, all data being displayed is recorded numerically in the form of an .XML file which can later be exported and saved elsewhere. This option is disabled while in running mode.
FEA-002	Scroll	The scrolling option is the default viewing option for the waveform. It enables the graphing space to scroll to the left automatically once data has reached the end of the graphing area. It provides a smooth, continuous display of the vital signal's data.
FEA-003	Sweep	The sweeping option is an alternate way to view data being displayed on the graph. Instead of the graphing area scrolling to the left with the appearance that the waveform is moving towards the end of the space, this option causes the waveform to appear as though it is coming from the left-hand side of the graphing area. Old data is pushed off the right side of the screen, rather than the left as with scrolling.
FEA-004	Add Trigger	Triggers allow the user to specify a threshold value for which when crossed the data will begin displaying. This threshold value is customizable and a relationship must be determined for proper functionality: less than, equal to, or greater than. Once a trigger is set and "Start" is selected, only when the relationship is satisfied will the graphing plot begin displaying data. Each active vital sign has its own trigger and multiple triggers can be set at the same time. All triggers are removed after one Start/Stop cycle.
FEA-005	Waveform Mod.	This is an advanced feature not recommended for the average user. It enables modification of the waveform filters used for each signal. The user will be warned before any changes will be applied. It is not accessible while the graph is running.

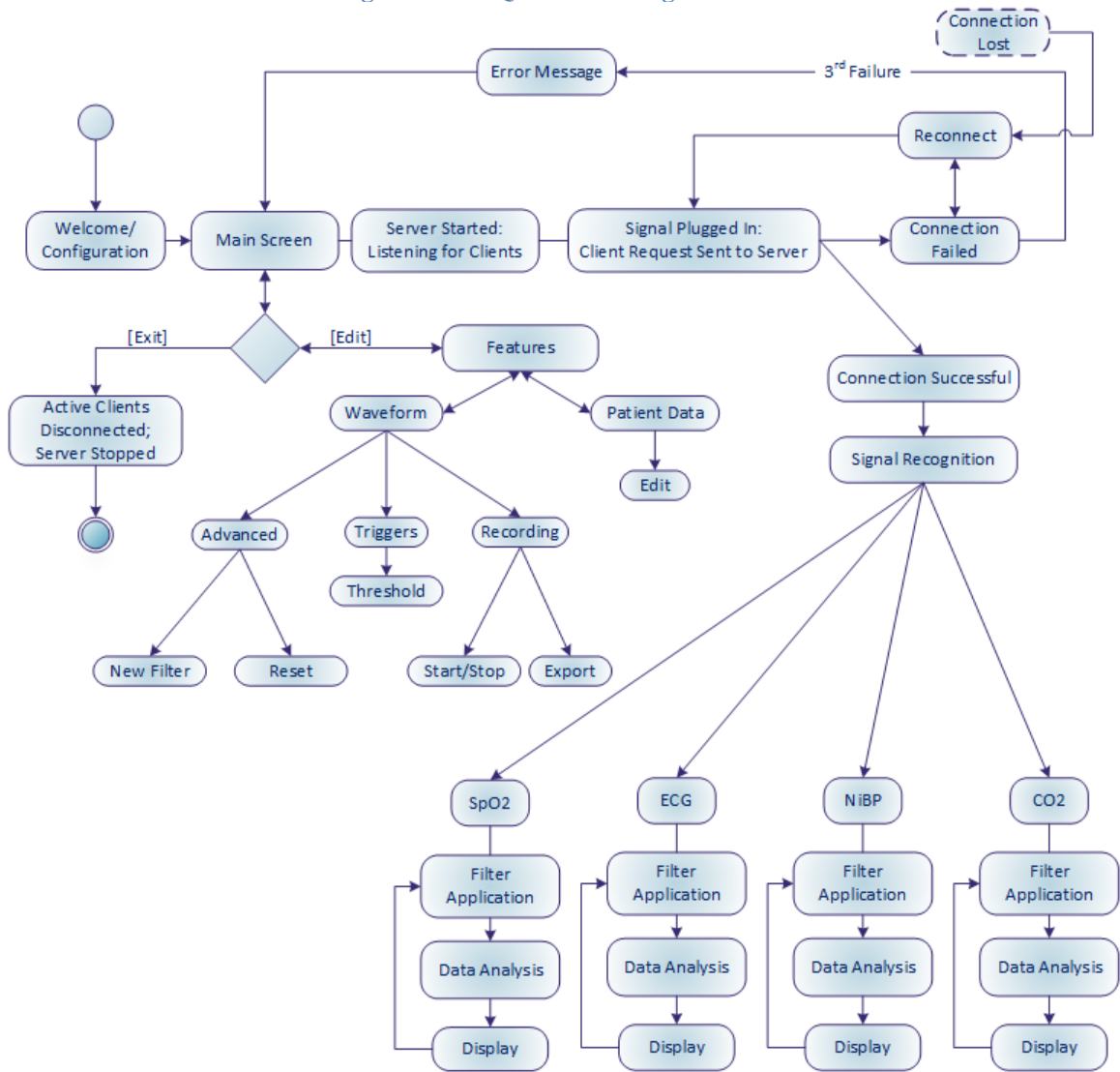
**Table 6-3b: Features of SQUID INC**

<b>Feature</b>	<b>Name</b>	<b>Description</b>
FEA-006	Reset To Default	This feature resets any changes made to the waveform filters back to the default and Philips approved filtering techniques.
FEA-007	Patient Data	The patient data section of the main screen displays important information as added and edited by the caring physicians. Information such as Name, Age, Gender, Diagnosis, and Admittance Date are included in the default view. The user can select the “More...” option located at the bottom of this information window to edit the at-a-glance information and make patient notes if needed.

### 6.1.3 Program Flow

The following figure (**Figure 6-16**) gives a general idea of how the SQUID INC software program will flow from one event to another. Note that not all features are fully detailed in this model as it should be used in conjunction with **Table 6-2**, **Table 6-3a**, and **Table 6-3b** above.

Figure 6-16: SQUID INC Program Flow





## 7.0 Project Prototype Testing

### 7.1 Hardware Testing Environment

#### 7.1.1 Faraday Cage

The primary testing environment we are concerned with is an MRI room, but we will not have free access to an MRI. Trips to the MRI must be scheduled and not as frequently as we please. So it is important we have our RF signals analyzed as best as we can before we visit the MRI room. We do have access to a Faraday cage in the Invivo labs, so we will make more frequent trips there to do signal testing before testing at the MRI.

#### 7.1.2 MRI

When testing devices inside the MRI chamber, they must be strained in locations where readings are the most extreme and reach the highest peak value. See **Table 7-1** below.

**Table 7-1: MRI Testing Considerations**

<b>Testing Considerations</b>	<b>Description</b>
Static Magnetic Field and Spatial Gradient	The field is strongest at the central bore of the MRI machine and thus all components need to be measured inside the bore for complete safety checks. Also objects need to be tested at varying distances to ascertain that no changes occur while moving through the spatial gradient of the magnetic field. All materials should be tested in finalized forms because their change in geometry may change their reluctance to magnetic pulls.
Pulsed Gradient Magnetic Field	Since this is sent out in pulses it is time varying and it induces a voltage on electrical conductors, during the rise-time of the magnetic field. So this can ultimately be tested anywhere in the MRI chamber. If there is a place where the highest voltage induced is greatest, then all devices need to be tested in that area to make sure that the voltage noise will not affect the machines' electronics.
Pulsed Radiofrequency Fields	This induces currents on electrical devices and induces noise which materializes as static or distortion on screens. So electrical devices should be tested where the temperature in the devices is highest and in that field, the temperatures should be recorded and an insulator made to match that maximum temperature. In the place with the highest distortion, the device should be tested in the area of highest noise and then variably filtered out with that maximum result as a foundation for the filter. Pre-recorded results should be acquired before testing in high noise level areas so proper tests can be performed.

Below are specific tests to that can be performed in order to determine MR environment safety for various factors. One test cannot necessarily determine if a device is MR safe. However, it does determine if the device is safe for that particular factor in the MR environment. **Table 7-2a** and **Table 7-2b** below specifically test how a material or device reacts in the MR environment with relation to the static magnetic field and the propelling force that can be induced on an object in the magnetic field.

**Table 7-2a: MRI Force Test**

<b>Test Sequence</b>	<b>Description</b>
<b>Objective</b>	To measure the magnetic induced displacement force on an object when exposed to the static magnetic field gradients with comparison to the object's weight.
<b>Equipment</b>	A fixture that is nonmagnetic and capable of supporting the weight of the suspended device properly. The fixture should have a protractor attached to it, with one degree increments, with the string being attached at the zero degree mark or any location that is convenient to the tester. The string should have an almost negligible weight, approximately within one percent of the tested device's weight, and should allow the device to hang freely in space. A nonmagnetic scale should also be attached between the string and the device to be tested.
<b>Test Summary</b>	Device is suspended by a string at a specific point in a magnetic field that will induce the greatest pull on the object. If the object deflects less than 45 degrees from its original position, than the objects gravitational pull to the earth is greater than the magnetic pull towards the MRI; however if it is greater than the opposite may be true and the object may not be safe for the MR environment.

**Table 7-2b: MRI Force Test**

<b>Procedure Step 1</b>	After the apparatus has been set up, the device's weight should be recorded.
<b>Step 2</b>	The device should be placed in the MR environment where the magnetic pull is the greatest (Usually near the bore of the MRI machine).
<b>Step 3</b>	Hold the device until it reaches the zero degree mark and the string is completely vertical.
<b>Step 4</b>	Let the string go and record the greatest degree difference from the zero degree mark to the nearest degree.
<b>Step 5</b>	Repeat steps 3 and 4 three to four times.
<b>Calculations</b>	Compute/Calculate the mean angle from zero for the device and document the results, record the mean degree for how far the device was repelled or attracted to the main magnetic structure. Compute the induced displacement force based off of the mean deflection angle.
<b>Report</b>	This should include the device's description, importance and performance, diagram of the test, equipment used to perform the test, mean force, tabulated results, mean deflection angle, displacement force, and conclusion based off of various recorded and observed results of experiment.

This next test observes the effects that the static magnetic field induces on a device in relation to the torque that the field can impose on some objects present in the MR environment. See **Table 7-3a**, **Table 7-3b**, and **Table 7-3c**.

Table 7-3a: MRI Torque Test

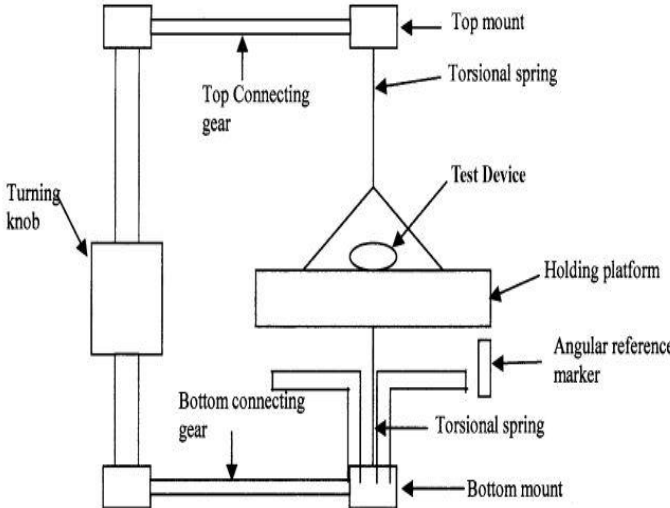
Test Sequence	Description
<p><b>Objective</b></p>	<p>To measure the induced torque on an object when exposed to the static magnetic field produced by an MR environment. If the maximal torque is less than the product of the dimension of the device and its weight then the product may be acceptable for use in a MR environment</p>
<p><b>Equipment</b></p>	<p>The test apparatus is illustrated in the figure below:</p>  <p>In this <b>figure</b>, materials should be non-ferromagnetic and the holding platform should be very sturdy and have torsional springs attached to it connecting the holding platform to the structure. The torsional springs' diameter should also be chosen so that the maximal deflection angle does not exceed nor equals 25 degrees. The device to be tested should be tied, taped, or however it can be, attached to the holding platform usually in some sort of basket holding cell. There should be a protractor, with at least one degree measuring tabs, attached to the structure that is rotated with a turning knob and a marker attached to the holding platform, where the device is housed, so that the angle between the holding platforms held device and the structure can be measured and recorded.</p>

Table 7-3b: MRI Torque Test

<p><b>Test Summary</b></p>	<p>When in the static field of the MR environment, devices susceptible to magnetism try to align along the axis of the magnetic field that is projected from the source. The device shall be tested by a basic torsional pendulum method. The torsional pendulum method works by a device being placed in a holder suspended by a torsional spring and the difference in the deflection angle of the holder from its equilibrium position, the difference being created by the device being placed within the static magnetic field, shall be used to calculate the maximum magnetic torque and the gravity torque. The maximum recorded magnetic torque and maximum gravity torque shall be compared and used to determine the safety of the device with regards to its induced torque in relation to its own weight.</p>
<p><b>Procedure</b> <b>Step 1</b></p>	<p>The device to be tested is set up as the equipment section specifies and is then placed in an area with the greatest uniform magnetic field. Rotate the structure and record the deflection angle between the structure and the rotating platform as the structure rotates from zero to 360 degrees until at equilibrium again. Measure the rotating platform at 10 degree increments of the structure being rotated.</p>
<p><b>Step 2</b></p>	<p>Repeat step 1 two to three times for acquiring data to compute an average.</p>
<p><b>Step 3</b></p>	<p>Lead wires should be arranged in a manner that represents <i>in vivo</i> set-up and should carry the currents that are applicable to an <i>in vivo</i> configuration, if practical.</p>
<p><b>Calculation</b></p>	<p>Torque, <math>\tau = k\Delta\theta</math>, is calculated using the deflection angle, <b>theta</b>, which represents the difference in angle between the marked device and the base structure. The variable <b>k</b>, is the spring constant.</p>

**Table 7-3c: MRI Torque Test**

<b>Report</b>	<p>The report should include all tabulated data.</p> <p>A description of what the device is and what it does and why this test was necessary for it.</p> <p>Materials used and their properties.</p> <p>Weight of the device.</p> <p>Dimensional diagram of the whole apparatus configuration. There should also be a photo of the equipment set-up with labels for each major equipment part detailing its importance.</p> <p>Description of strength and type of magnetic field that the device was subjected to.</p> <p>The calculations used in the experiment using the tabulated results and a mean torque calculated.</p> <p>There should be a conclusion drawn utilizing all results to support initial hypothesis and to determine device's safety concerning induced torque within a magnetic field.</p>
---------------	--

This next test checks for the safety of the patients within the MRI (See **Table 7-4(a-h)**). Some devices are affected by RF energy in the form of an induced current occurring in the wires and then a dissipation of heat into the tissue of the patient's body which is measured in the form of specific absorption rate (SAR). Patients can be badly burned in a MR environment ranging from first to third degree burns. However, because the main focus of this test is for implants within the patient's body, the test will have to be edited in order to focus more on the device itself heating up and how it will be affected in relation to if a patient was in the vicinity of the device itself.

Table 7-4a: MRI RF Heating Test

Test Sequence	Description
<b>Objective</b>	<p>The purpose of this experiment is to measure the effects of radio frequency (RF) on conductive materials that can be subjected to induced heat as a result of being exposed to RF energy during magnetic resonance imaging (MRI), and as a result, leads to patient burning and injury. The amount of RF-induced heat transfer is measured in the form of specific absorption rate (SAR) and will depend on the frequency of RF that is dependent upon the static magnetic field strength. Since the base of this experiment is based on devices that are assumed to be entirely inside the body, this experiment shall be edited for the purpose of devices that may be outside or near the patient's body.</p>
<b>Equipment</b>	<p>The testing apparatus will be composed of a phantom and a MR system or any type of MR system that will replicate the effects of a RF field induced from a MRI machine. The phantom, device, and MR system should completely emulate the same type of scenario in which a patient is exposed to an MRI machine. The scenario should basically establish the heating behavior of a device on top of a phantom in an MR environment. For the purpose of not being affected by the MR environment, the temperature sensor should be a fiber-optic, a fluoroptic thermometry probe, or some technology similar to these and resistant or impervious to the MR environment's effects to measure the temperature versus time in the vicinity of the device on the phantom during the RF exposure. The temperature sensor specifications should vary within, but no more than, 0.1 degrees Celsius, the diameter should be no more than one mm and the results of the test for temperature measurement should be able to be obtained within four seconds of application of the temperature sensor device.</p>



Table 7-4b: MRI RF Heating Test

<p><b>Test Summary</b></p>	<p>In the original experiment, the device was to be placed in a phantom material, materials that simulate tissue of the human body, that simulated the electrical and thermal properties of the human body; but in this experiment, the device will be placed on top of the same type of phantom material instead. The device will be placed in a location with the highest exposure results for severest case scenarios to be recorded. The local SAR will be used to determine how severe the device could be if placed on the patient in that location. The phantom material shall be composed of a gelled saline mimicking the human body’s properties of water make-up. Temperature probes will be placed at the locations where the induced device heating is going to be at its peak. The phantom body should be placed in an RF field that will be outputting a SAR of about 2 W/kg averaged over the volume of the phantom body for a period of at least 15 minutes.</p> <p>The test will be divided into two sections. Section one will test the device in multiple areas on the phantom using fiber-optic thermometry probes, or an equivalent to this type of technology, during approximately 15 minutes of RF application. The temperature should be measured from a reference location in this first section. Section two will be when the device is removed and the same RF application is repeated as in section one. The measurements will be recorded in the same spots that the device recorded was.</p>
<p><b>Procedure Section 1 Step 1</b></p>	<p>The house of the phantom should be composed of nonferromagnetic materials and non-metallic materials. The phantom house should also be built with the same or similar dimensions as shown below:</p> <p>The phantom material as shown in the <b>figure</b> above should have a volume of approximately 24.6 L. The phantom material including the dotted portion (basically optional) lifts the volume to a 28.2 L. For larger devices, look into increasing the depth of the phantom house in order to get consistent results as shown in this experiment.</p>

**Table 7-4c: MRI RF Heating Test**

<p><b>Step 2</b></p>	<p>The phantom material simulating the tissue of a patient should fall in line with the following specs with little deviation:</p> <p>The conductivity of the gelled saline at test temperature should be <math>0.47 \pm 10\%</math> S/m.</p> <p>The dielectric constant, relative electric permittivity (<math>\epsilon_r</math>), should be <math>0.8 \pm 20</math> at the frequency of 64 or 128 MHz for testing.</p> <p>The thermal properties should mimic the human body as closely as possible by being within the specifications of a diffusivity of precisely <math>1.3E-7</math> m<sup>2</sup>/s and a heat capacity of 4150 J/kg°C (which is approximately the heat capacity of water).</p> <p>The viscosity should be of a gelled nature so that it does not allow bulk transport or convection currents.</p>
<p><b>Step 3</b></p>	<p>The properties in step 2 can be attained by having 1.32 g/L NaCl and 10 g/L golyacrylic acid (PAA) in water, in which the air conductivity would be 0.47 S/m, and a viscosity adequate enough to not have convective heat transport. The recipe should satisfy all phantom properties that the experimenter is looking for. However, the solution is very sensitive to the environment, so it should be sealed in an airtight container to avoid evaporation because even evaporation can change the properties of the solution. The solution's properties can also be changed through various other factors, so the solution should be changed/re-made if there are any changes in volume, conductivity, color, or viscosity.</p>
<p><b>Recipe Step 3.1</b></p>	<p>The ingredients of the PAA gelled saline are: deionized or distilled water with a conductivity less than 1 mS/m, 99% pure reagent grade sodium chloride (NaCl), and Aldrich product number 436364, 'polyacrylic acid partial sodium salt.'</p>

**Table 7-4d: MRI RF Heating Test**

<b>Step 3.2</b>	The PAA should be prepped by adding the NaCl to the water and stirring until the NaCl is completely dissolved into the water. The conductivity should be verified to a 10% deviation of 0.26 at 25 degrees Celsius measured at frequencies lower than 15 kHz.
<b>Step 3.3</b>	Add PAA and stir until everything is well mixed and thick. (suspension polymerization)
<b>Step 3.4</b>	After one hour, blend the suspension into slurry in a kitchen grade blender with a blade for 20 min to remove all lumps. Any blender with the same power could be used as long as it removes all lumps of any and most sizes.
<b>Step 3.5</b>	Stir occasionally, and after 24 hours, the slurry should be complete and look semi-transparent, free of bubbles, and free of lumps.
<b>Step 3.6</b>	Check the conductivity to be at 10% of variation from 0.47 at 20 degrees Celsius to 25 degrees Celsius when measured at frequencies lower than 15 kHz.
<b>Step 4</b>	The device needs to be tested in the worst case configuration and orientation so that the greatest heating scenario can be acquired while the device is on top of the phantom. Try various configurations if one has not already been found during previous tests, and show the worst case configuration and provide the evidence that lead to the specific orientation being the worst case placement.
<b>Step 4.1</b>	The location of maximum induced heat can be found by experimentally using multiple temperature probe locations and finding all locations of high heat in different device configurations. The locations of maximum heating can be found computationally by using thermal and electromagnetic simulation tools to calculate the E-field, B-field, SAR and/or temperature distribution on the surface of the device. These methods must also include sound experimental validation data. The best formations may be large loops that can be formed, on the sharp edges of the device, in thin devices with high length to diameter ratios, points, and/or corners.

**Table 7-4e: MRI RF Heating Test**

<b>Step 5</b>	For the device holder, it should be comprised of materials that are resistant to the MR environment (such as non-ferromagnetic and non-metallic devices). The holders should also be oriented such that they do not disturb the original temperature of the area in which it is placed. Since the temperature probes will cause SAR variances, they should be placed within twice the diameter length apart from each other (e.g., if the diameter is 5 mm, then the probe should be placed 10 mm apart from each other).
<b>Step 6</b>	When you know the E-field gradients, choose a location where the E-field and SAR is known to heat the device-less phantom's temperature 10 times the original amount (e.g. if the precision of the temperature probe is 0.1 degrees Celsius, then you want the area where the probe's temperature is increased to 1 degree Celsius). Also choose an area where the E-field is unchanging.
<b>Step 7</b>	Find the device's maximal heating positions, which may be done computationally or experimentally. Locate and label at least three to four temperature probes on those locations where the experiment can be done numerous of times and the precision is within a deviation of 0.5 mm between the sensor and the device. In addition, a reference temperature point should be found in order to not disturb the fields near the device; the point should be adequately far from the device while the E-field should be high.
<b>Step 8</b>	Take pictures and provide dimensions on the device within the photo relative to the temperature sensors while on the phantom. Fill the phantom with the saline solution and visually make sure that there are no position differences before and after the heating experiment begins because even smallest of changes can give high variations in temperature readings. Try to turn off the MRI bore patient fans if possible and limit air flow through the MRI bore because you do not want air flow to vary the temperature readings too much. If the fans cannot be turned off and no obstruction cannot be placed to prevent free airflow through the bore of the MRI then a way to cover the phantom while the device is place on top of it should be implemented in order to mitigate the variable damage that free airflow could cause to the experiment's results.

**Table 7-4f: MRI RF Heating Test**

<b>Step 9</b>	Use a system in which when the RF field is applied the power of the RF will achieve the results as stated in step 6, while having a SAR of precisely 2 W/kg or higher.
<b>Step 10</b>	Prior to the application of the RF energy, up to four temperature probes should be used to record the temperature to make sure everything is uniform and no additional heating is taking place before the application of the RF energy. The temperature in the MR environment should be stable within a standard deviation of no more than 1 degree Celsius.
<b>Step 11</b>	If the values could be, record the MR environment's whole body averaged SAR, local SAR, peak SAR, partial body SAR, flip angle(s), the number of RF pulses applied per unit time, the bandwidth of the RF pulses, the RMS average applied to the B1 field, total time/duration over which the field was applied, and the total average power that was transferred to the phantom material.
<b>Step 12</b>	Begin recording the temperature from each probe once every five seconds at least two minutes before the start of the scan, 15 minutes during the scan, and two minutes after the supply of RF energy is terminated.
<b>Step 13</b>	Repeat steps 6 through 12 until a plethora of results are acquired enough to create a mean.
<b>Section 2 Step 1</b>	Section 1 must be split into two parts. The first part is with the device on top of the phantom device and the second part is without the phantom device on top. Record and properly label all results for preparation of the lab report.
<b>Step 2</b>	When the device is removed, /Using the same RF energy applied in step 9, measure the local heat utransference at the temperature probe locations and make sure that there are minimal bubbles or air pockets formed in the phantom so results are not skewed.

Table 7-4g: MRI RF Heating Test

<b>Step 3</b>	<p>SAR can be calculated by the following equation without the device present: <math>SAR = c (\Delta T/\Delta t)</math></p> <p>Where <b>c</b> is 4150 J/(kg°C), specific heat of phantom, <b>T</b> is temperature in degrees Celsius, and <b>t</b> is the time in seconds. Record the temperature increase over 15 minutes and plot a fitted curve onto the SAR results.</p>
<b>Step 4</b>	<p>For the purpose of being able to label the device with some MR conditions, for safety qualification in the MR environment, this section will give a walkthrough of how to calculate the whole body averaged SAR (WB-SAR) using the calorimetric method on the phantom.</p>
<b>Step 5</b>	<p>Repeat all of Section 1 except this time the phantom body will be covered up when exposed to the MRI scan. The temperature probes will be within the precision of 0.05 degrees Celsius and the device will not be in the vicinity of the phantom.</p>
<b>Calculations Equation 1</b>	<p>Step 2 has of the calculations used for the phantom without the device present.</p>
<b>Equation 2</b>	<p>A similar equation could be used for the first section, except the specific heat of the material would be needed.</p>
<b>Equation 3</b>	<p>All the code for the calculation of the various fields within the MRI machine, if it was needed, in order to find the maximum points where the device’s heating would be peaked.</p>
<b>Report Point 1</b>	<p>A description of the device should be included as to what the device’s function is within the MR environment, its importance, along with a photo of the device.</p>
<b>Point 2</b>	<p>List of materials used throughout the experiment</p>
<b>Point 3</b>	<p>Pictures taken of the overall experiment done with the device on the phantom and the other done without the device on the phantom during the MRI scan and while the phantom is out of the MRI scanner.</p>

**Table 7-4h: MRI RF Heating Test**

<b>Point 4</b>	Pictures should have dimensions of all objects with a role in the experiment from the temperature sensors to the actual holder of the phantom.
<b>Point 5</b>	Provide all information on the type of MRI machine used to conduct this test.
<b>Point 6</b>	Show any code, the programming environment and or any type of analysis tool(s) used to calculate the electrical field gradient in the phantom.
<b>Point 7</b>	The RF output power should be included in the report and also the specifications of the phantom in relation to the output.
<b>Point 8</b>	Graphs should be provided for the temperature probe's recordings in which it is temperature vs. time.
<b>Point 9</b>	The temperature change for each probe should be included in the report also.
<b>Point 10</b>	The SAR calculated in Section 2 should be included also.
<b>Point 11</b>	Tell of why each temperature probe was placed where it was placed in/on the phantom.
<b>Point 12</b>	Give the WB-SAR that was calculated in Section 2 of the experiment which utilized the same SAR equation shown in Section 2.
<b>Point 13</b>	Give the temperature recordings of the minutes before the RF application, during the application, and after the application has been terminated on the phantom body.
<b>Point 14</b>	Tell of any modifications to the test and provide justifications as to why any modifications were needed for this experiment (e.g., this test needed to be modified for our experiment because the "implant" in question will actually be a device that may lay across the patient and it needs to be tested in case it causes any burns while on the patient in the MRI machine).

This test will also expose the worst case scenario in which a nurse or technician may leave the device on the patient while the patient is in the MR environment. And inversely, it will also tell if the device is safe to be left on the patient while in the MR environment or in the bore of the MRI machine. The test can be edited to be applied for testing for devices to be placed into the patient and devices placed on top/outside the patient's body. For the purpose of this project, the experiment shall be conducted within the scope of the device being placed outside of the patient's body.

### 7.1.3 RF-Noisy Environment

Another concern for performance was the SQUID's clarity in an environment polluted with RF noise, such as a hospital hallway. Patients may be transported from room to room throughout a hospital and it is important to keep a strong connection between the SQUID and the receiving end monitor. Other wireless devices, perhaps even other SQUIDs, may be communicating nearby and we need to be sure those signals will not interfere with one another.

Fortunately, we will not need to use a hospital to simulate this environment. Many public places have wirelessly communicating devices broadcasting a bunch of RF signals. A lot of options are available to us for testing in this environment and we can test frequently. The procedure for testing will simply be to communicate simulated signals to our wireless monitor and record the results.

## 7.2 Hardware Specific Testing

We will be running through these checklists throughout construction and will be performing a finalized test on our completed prototypes. More specifications will arise as construction proceeds, but these are the qualities and methods we expect we will need to identify and control.

### 7.2.1 Microcontroller A/D

The MSP430G2 series will be utilized in coding the ADC. **Table 7-5** below shows how the code should be implemented in each scenario of all 4 signals:



**Table 7-5: Analog to Digital Test**

<b>Steps</b>	<b>Process/Question</b>
1	How many signals coming in? Is it 0, 1, 2, etc...?
2	ECG – 0001, SpO2 – 0010, CO2 – 0100, NiBP – 1000, or NONE – 0000.
3	Display LED that a signal was received. Example: Display LED in binary format (1 is on and 0 is off) 0001 or 1000 for ECG or NiBP respectively, etc...
4	Store signal in register(s), like R4, R5, R#
5	Push data in register onto stack, s0, s1, s2, s#
6	Change signal in s# from analog to digital using subroutine
7	Flicker LED for corresponding changing signal. Example, if ECG is changing then 0001 should flicker.
8	Pop data off of s# onto corresponding R#
9	Stop Flickering of LED, to indicate data converted, for approximately 5 seconds until returning to step 4 and completing until all signals converted.

LEDs do not have to be used in order to test if the signal is received, there is also built-in UART, as an option, on the MSP430 and thus a HyperTerminal could also be used to show that the signal is received using the same binary format or using Ascii characters. There are also multiple code templates on Texas Instruments' website to start from as the foundation of the ADC code, and everything is fully open enough to modify all code. Assembly language code may be the best choice for this job because of its direct setup and style of code; however, the C language code is always an option too when using the MSP 430G2 series.

## 7.3 Software Testing Environment

The following sections pertain to properly testing the Simplified Quad-Vitals Integrated Device Intelligent Navigation Controller software and ensuring correct functionality.

### 7.3.1 Proximity to SQVID Connection Box

Due to wireless signal strength variances it is necessary that the SQVID connection box be no more than 100 feet away from the computer running the INC software. This estimate is based on the typical ranges of a standard 802.11b/g/n router's signal strength. This estimate takes into consideration the layout of a typical hospital setting as well as an MRI examination room, as seen in **Figure 7-1a** and **Figure 7-1b**, below. Due to the prototype nature of this project the INC software system is ideally running off of a mobile tablet or laptop, capable of staying within range of the wireless signals being transmitted to the program as the connection box follows its patient. However, if run from a stationary desktop or laptop computer, the scopes depicted in the figures have also been taken into consideration.

**Figure 7-1a: Hospital Setting**

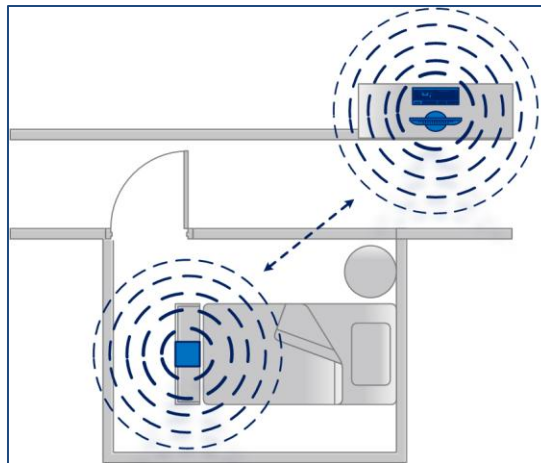
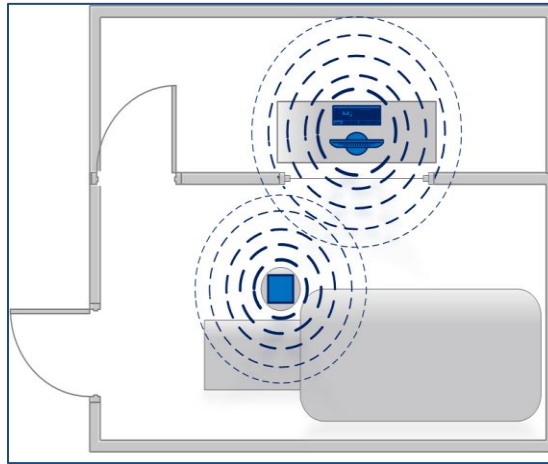


Figure 7-1b: MRI Exam Setting



### 7.3.2 Operating System

The software is to be run from a Windows 8 or Windows 8.1 operating system. The operating system may be on a desktop, laptop, or tablet computer. Only machines with tactile functionality will demonstrate the touch screen capabilities of the software. The INC program has been tested on a Windows 8 laptop, a Windows 8.1 laptop, and a Windows Surface 2 Tablet to ensure proper touch screen behavior.

## 7.4 Software Specific Testing

### 7.4.1 Initial Setup: Configuration Screen

At initial startup of a program the Welcome/Configuration screen is displayed. This screen prompts the user to Add or Edit SQUID connection box profiles, which contain the information necessary for proper connection between the client vital signals and the INC server. This information is summarized in **Table 7-6** below. If any required information is missing or invalid, the user will not be able to proceed to the main screen of the program, and thus the server will not be started. Currently there is only one SQUID box profile, but as described in Section 4.3.2.5, this could easily be expanded upon and improved to serve multiple patients simultaneously.

**Table 7-6: INC Configuration Screen Data**

<b>Information</b>	<b>Description</b>
Name*	This contains the name of the patient for reference purposes.
Age*	This field is the age of the patient for reference purposes.
Gender*	This field must contain the gender of the patient for reference purposes.
Date of Admittance*	Date of admittance helps keep track of how long the patient has been being monitored.
Diagnosis*	This field is used for reference purposes.
SQVID IP Address	This is the IP address of the SQVID connection box. This address will be used as INC's server address for proper communication. There is only one of these per SQVID connection box, and is not configurable from the connection box.
SpO2 Signal Port Number	This is the SpO2 signal's port number, used for connection and recognition by INC's server. It is hard-coded into the embedded systems' module within the connection box and is listed on the outside of the box for easy reference.
ECG Signal Port Number	This is the ECG signal's port number, used for connection and recognition by INC's server. It is hard-coded into the embedded systems' module within the connection box and is listed on the outside of the box for easy reference.
NiBP Signal Port Number	This is the NiBP signal's port number. It is hard-coded into the embedded systems' module within the connection box and is listed on the outside of the box for easy reference.
CO2 Signal Port Number	This is the CO2 signal's port number, used for connection and recognition by INC's server. It is hard-coded into the embedded systems' module within the connection box and is listed on the outside of the box for easy reference.
<i>*These fields are then copied to the Patient Information Window on the main screen.</i>	

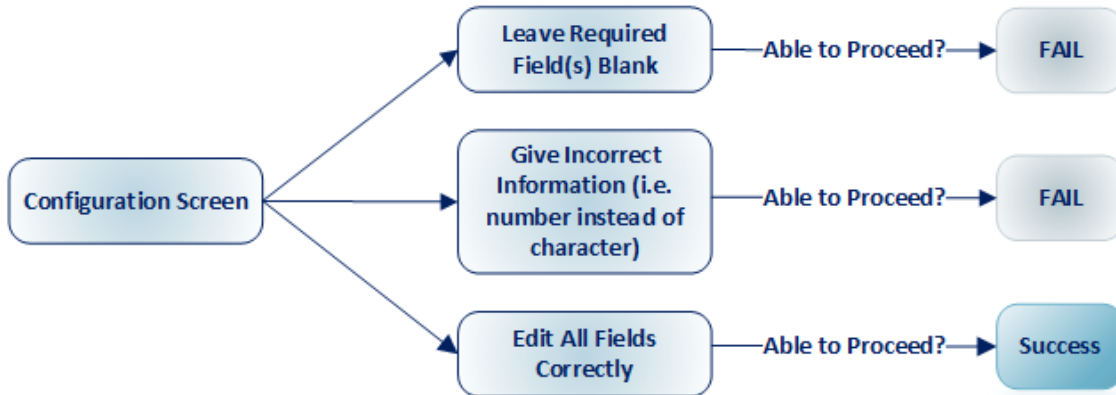
## 7.4.2 Testing Procedures

Testing the software involves testing each signal separately to make sure that its expected data is transferred correctly to the program. The data must then be analyzed as it comes across as a waveform to confirm that it is accurate and proper filtering was effective. In addition, to test the added user features certain steps must be taken to test for bugs in the software.

The main functions and features have been given a testing plan in the form of a flow chart. Each path must be taken to discover any malfunctions and test for proper behavior and each test is dependent on the success of the preceding one. For instance, it is not possible to Record and save waveform data if the Graphing test is not passed; it is not possible to graph data if signals are not being received correctly.

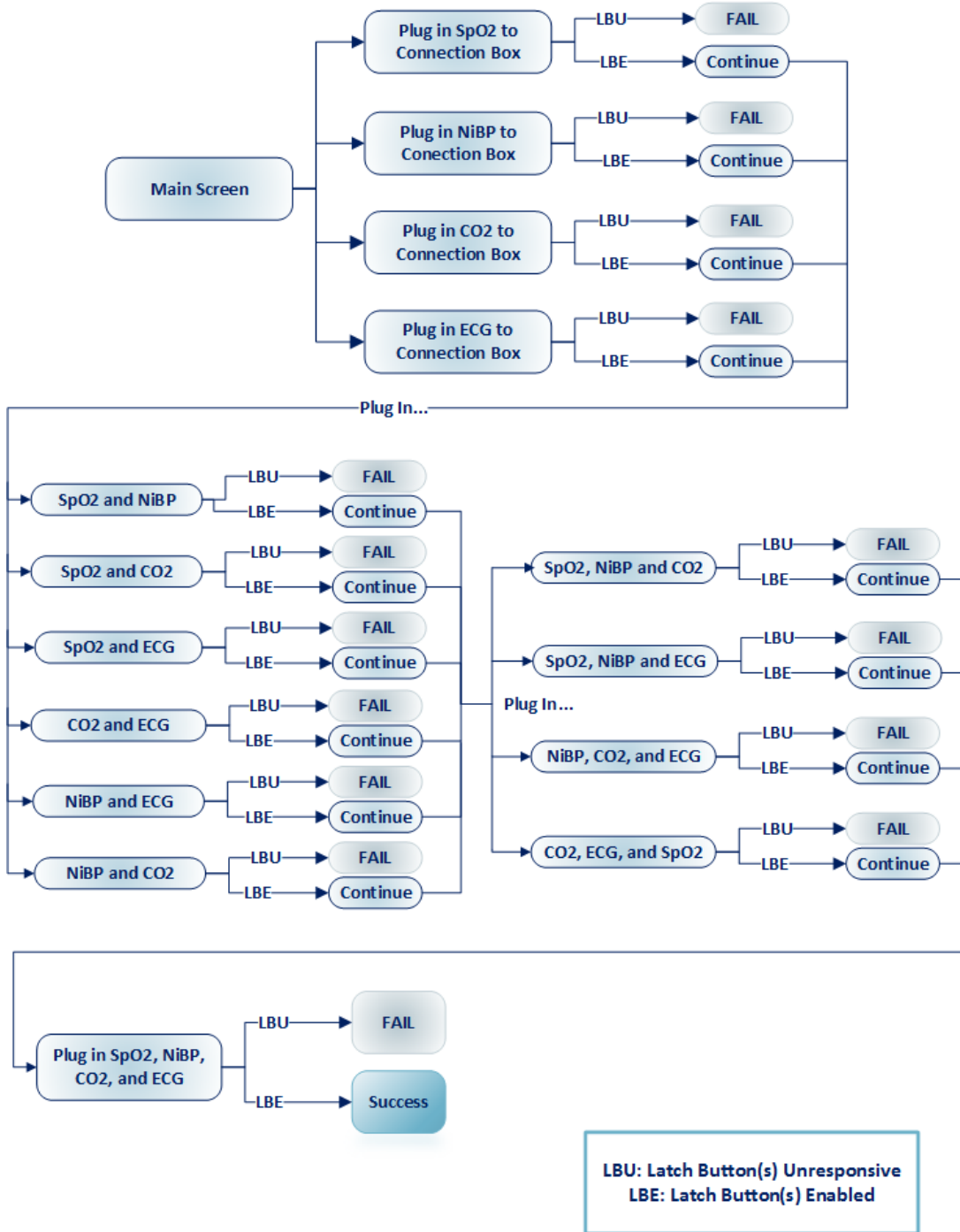
**Welcome Screen/Configuration:** Figure 7-2 shows the testing plan for the configuration window. It is important that the correct data is entered where necessary for proper communication between the INC software program and the vital signals connected to the SQUID connection box.

Figure 7-2: Welcome Screen Testing Procedure



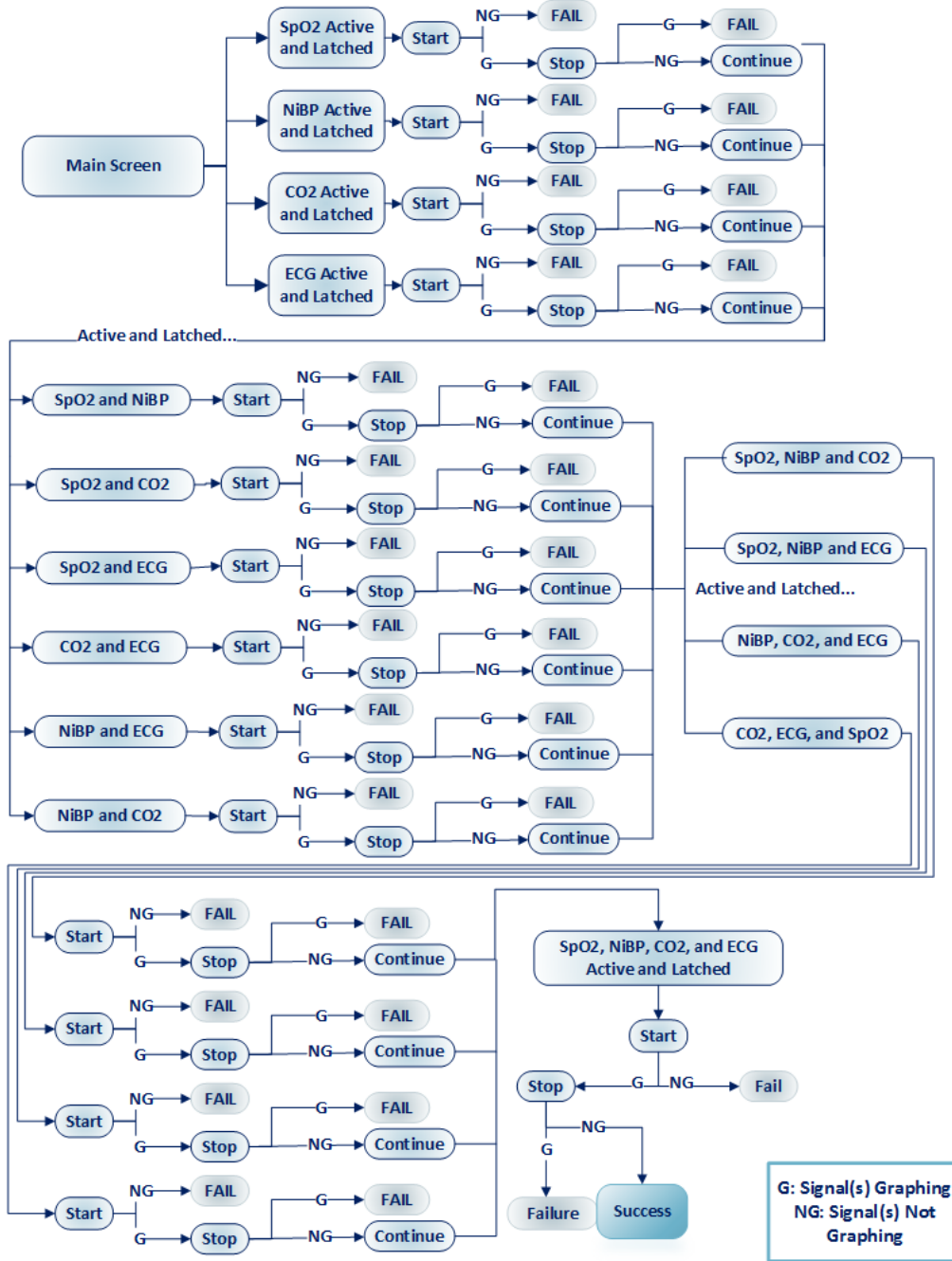
**Vital Sign Signal Acquisition:** Figure 7-3 displays the testing plan for confirming each and every vital sign signal is received by the software program when physically plugged into the connection box. This test cannot be performed until the Configuration test has been passed because each signal is required to have its corresponding port address.

Figure 7-3: Vital Sign Signal Acquisition Testing Procedure



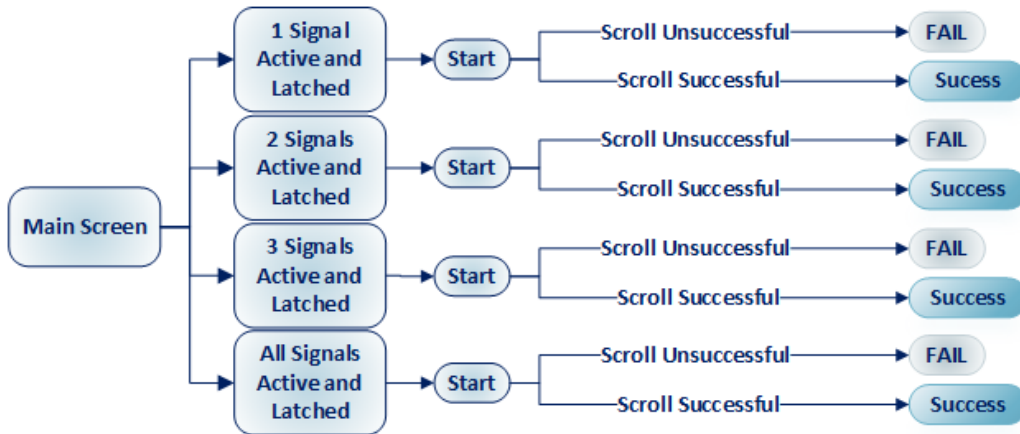
**Waveform Data Display: Figure 7-4** depicts the testing plan to ensure that every signal is displaying correctly in the graph plot. This test assumes that the correct filters have already been applied, but does not test for accuracy of the filtering techniques.

**Figure 7-4: Waveform Display Data Testing Procedure**



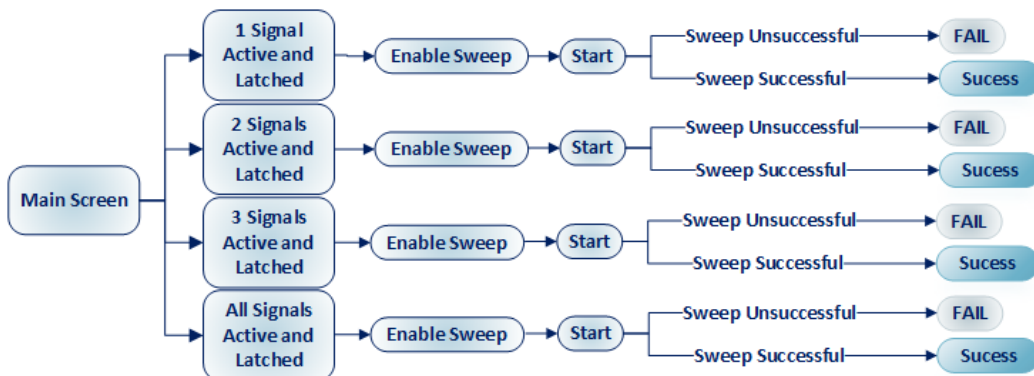
**Scroll Testing:** See **Figure 7-5**. This test can be performed simultaneously with the preceding one. It simply ensures that the graphing plot “moves” to the right to allow for new data to be shown.

Figure 7-5: Scroll Testing Procedure



**Sweep Testing:** **Figure 7-6** illustrates the test that will be used to confirm proper sweep functionality. This test can also be performed simultaneously with the Waveform Data Display test, however because Sweep is not selected by default, a separate test is recommended.

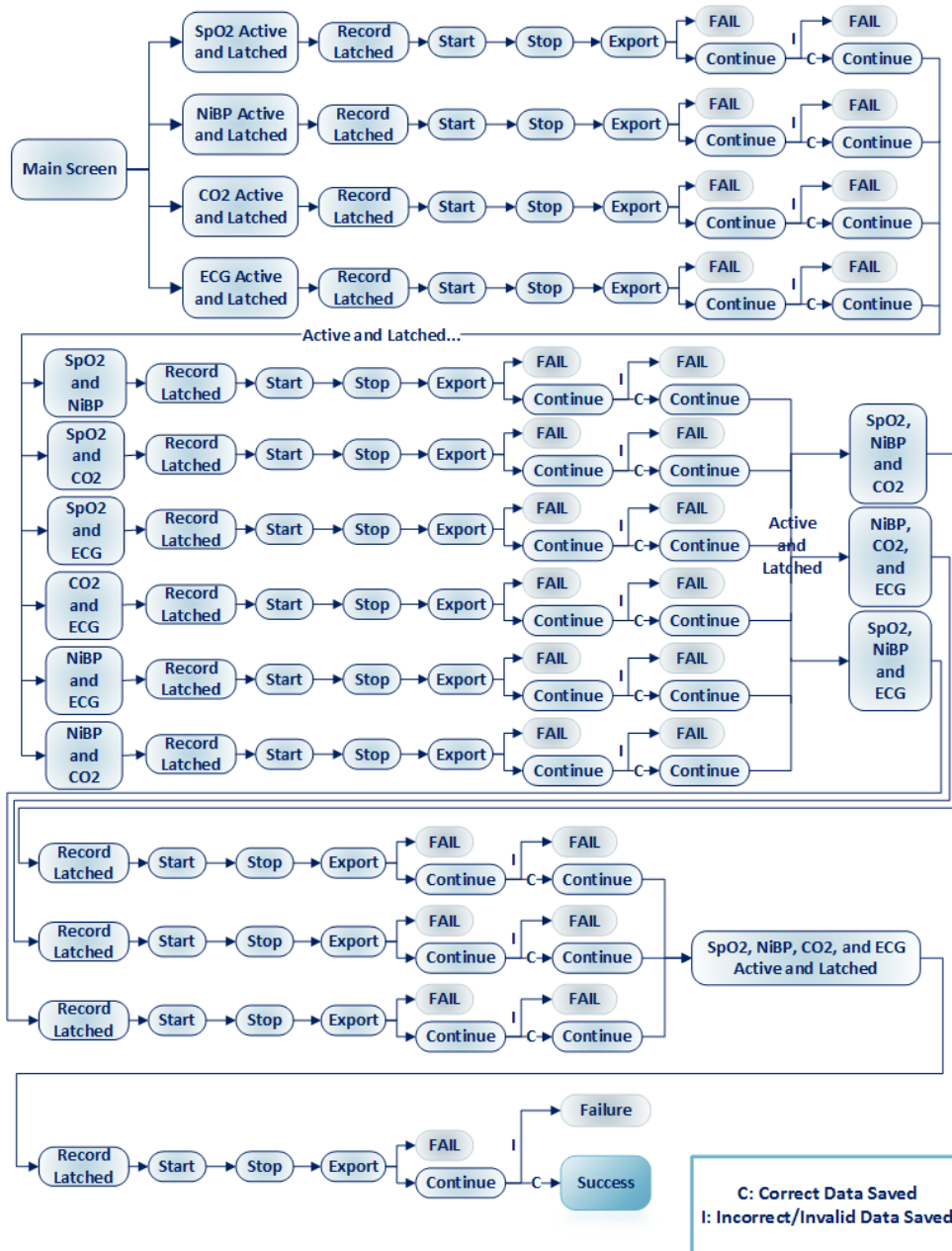
Figure 7-6: Sweep Testing Procedure





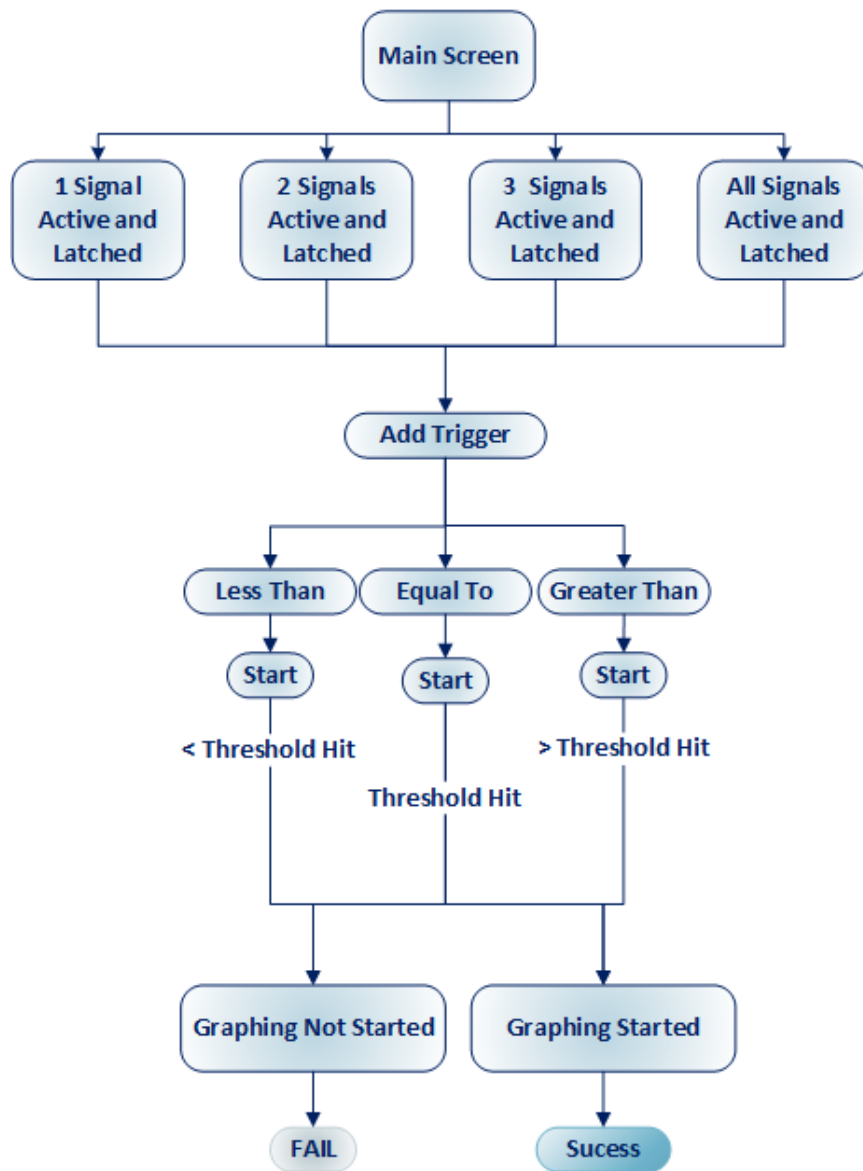
**Record Functionality Test:** The following flowchart (**Figure 7-7**) illustrates the steps taken to ensure that the Record feature performs as desired. Not only does the feature save the waveform values, but it also needs to export a readable .XML file that can be opened using a compatible program, such as Microsoft Excel.

**Figure 7-7: Record Functionality Testing Procedure**



**Trigger Feature Test:** The trigger feature of SQUID INC enables the user to set a threshold value and a relationship to this threshold. Once this relationship is satisfied, the data values of the select signal(s) will begin displaying. This can be useful if, for instance, a patient only needs immediate attention if their blood pressure rises above a certain value. **Figure 7-8** shows how this feature is tested.

Figure 7-8: Trigger Testing Procedure



## 8.0 Administrative Content

### 8.1 Milestone Discussion

#### 8.1.1 Research

The major research milestones for this project came along in the form of component selections near the end of the first phase. The process was chosen based on widely available known resources for the MSP430 architecture and previous experience with the processor in the embedded systems laboratory. The analog filtering and amplification circuits were derived from material covered in the electronics classes as well. The analog to digital conversion was a relatively new concept and specific software for the MSP430 was studied for this end.

#### 8.1.2 Design

##### 8.1.2.1 Hardware

The hardware design of this project was focused mainly on the signal acquisition from the pressure transducer and carbon dioxide sensor along with the amplification and filtering of said signal, and then finally multiplexing and wirelessly transmitting to the base station. This milestone in research focus came along once the decision was made to no longer attempt integration of the two existing wireless systems present for ECG and SPO2 signals. The extent of the integration was to allow for the implanting of the two wireless devices onto the exterior of the SQVID cube, allowing for full functionality as before while still satisfying the requirement of cable management.

The range of options available for this focus was wide, as there are many different processors and wireless boards to choose from on the market. Of the various options which were covered in **Section 4.3.1 Wireless System Materials and Design**, the TI CC3000 was chosen based on its compatibility with the MSP430 architecture, the wide availability of resources for configuring and troubleshooting the device, and most of all because the preferred method for wireless communications in this project as requested by Philips is IEEE 802.11 2.4 GHz WIFI. The major milestone in this selection is the type of wireless communication protocol and the specific board to be used.

The processor selected for this purpose was the MSP430, more specifically the MSP430F5529. This microcontroller was linked to in the cc3000 product page. This not only ensures compatibility with the wireless device, but also the same breadth of resources available for development.

### 8.1.2.2 Software

The software design aspect of this project focused on the program that communicates with each embedded systems board located in the SQUID connection box. Deemed the “Intelligent Navigation Controller” or “INC”, the main milestone with regards to this software system was how it would interface with the embedded system boards and detect which vital signs were connected to the box. Research done into Philips’ current software used by their clients in the professional industry with their current cableless measurement devices led the team to decide on using a TCP/IP communication protocol. This method would allow each microcontroller to possess a unique port number which would then be used by the new program to determine which signal had been connected.

The “plug-and-play” capability with the automatic waveform modifications as per Philips’ healthcare standards can be considered a secondary milestone. This automated functionality serves to assist caring physicians in diagnosing and tending to their patients. It also aids in preventing unintentional human error, either due to negligence or lack of knowledge.

However, the software system’s main objective is to prove that the hardware design is fully functional, as well as accurate and reliable. By achieving communication between the central SQUID box and thus each one of the vital signs connected to it, INC serves to confirm the new SQUID consolidated cable with the integrated wirelessly transmitted signals is an innovative and efficient way to enhance the comfort of a patient facing an MRI scan or undergoing medical observation.

These components have been chosen in order to begin prototyping and testing. Further developments may lead to exchanged boards or components. If time and the board fabrication process allows, integration of both the microcontroller and the wireless board will be attempted on the same platform as the rest of the system.

### 8.1.3 Prototype and Testing

The prototyping and testing schedule is given in a rough form below in **Table 8-1a**, **Table 8-1b**, and **Table 8-1c**.

**Table 8-1a: Prototype and Test Schedule**

<b>Jan. 6 - 12</b>	Receive custom cables from Philips; have them ordered and ready before semester starts.  Have all parts ordered, if not delivered already  Begin programming A/D converter on the MSP430 microcontroller  Begin adapting NiBP and CO2 hoses to sensors.  Test both CO2 and NiBP sensors' functionality.
<b>Jan. 13 – 19</b>	Test both sensors' input/output properties. (lag, max frequency, max input, power, etc.)  Test sensor output with input via hoses.  Begin assembly of power supply unit
<b>Jan. 20 – 26</b>	All remaining NiBP parts acquired  Begin assembly of NiBP rough prototype  A/D conversion program finished  Test microcontroller for proper A/D conversion  Begin programming WiFi module

**Table 8-1b: Prototype and Test Schedule**

<b>Jan. 27 – Feb. 2</b>	<p>All remaining CO2 parts acquired</p> <p>Begin assembly of CO2 rough prototype</p>
<b>Feb. 3 - 9</b>	<p>Rough NiBP prototype assembled</p> <p>Begin assembly of wireless receiver</p> <p>Wireless communication software finished</p>
<b>Feb. 10 - 16</b>	<p>Rough CO2 prototype assembled</p> <p>Power supply unit complete</p> <p>Wireless receiver built</p> <p>Test wireless receiver’s functionality</p> <p>Test power supply separately for stability and proper temperature</p> <p>Test power supply on NiBP sensor, then CO2, and then both together</p>
<b>Feb. 17 – 23</b>	<p>Connection between SQVID and receiver established; test for accuracy and reliability of transmission</p> <p>Test receiver with multiple signals</p>
<b>Feb. 24 - Mar. 2</b>	<p>Begin construction of consolidation shell</p>
<b>Mar. 3 - 9</b>	<p>Flex week - Spring Break</p> <p>Possible Gainesville MRI testing</p>
<b>Mar. 10 - 16</b>	<p>Mount NiBP and CO2 components into consolidation shell</p> <p>Test structural soundness of NiBP and CO2 devices alone and their mounting</p>
<b>Mar. 17 - 23</b>	<p>Mount SpO2 and ECG into consolidation shell</p> <p>Test structural soundness of SpO2 and ECG devices alone and their mounting</p>

**Table 8-1c: Prototype and Test Schedule**

<b>Mar. 24 - 30</b>	Mount power supply into consolidation shell Test structural soundness of power supply
<b>Mar. 31 - Apr. 6</b>	Final Gainesville MRI testing Test complete SQUID on human subject if allowed
<b>Apr. 7 – 13</b>	Complete testing Final product/finishing touches
<b>Apr. 14 – 20</b>	Flex week

## **8.2 Budget and Finance Discussion**

### **8.2.1 Budget Allocation**

The budget allocation for this project is divided in the manner displayed in (**Table 8-2**) below.

**Table 8-2: Project Budget Allocation**

Sensor Leads	25%	All cables used on patients to monitor vitals are manufactured and supplied by Philips.		
SQUID	55%	The allotted percentage of Total Budget is broken down as follows		
		ECG	15%	Provided by Philips. Known to be slightly more expensive than other sensors.
		SpO2	10%	Provided by Philips.
		NIBP	10%	Custom built.
		CO2	10%	Sensor may be provided by Philips. Integration into wireless solution is our responsibility.
		MCU	5%	Microcontroller purchased from third-party. Relatively low required processing power is expected to greatly reduce the cost.
		Wireless	5%	Wi-Fi module purchased from third-party.
		(percentages here are in reference to the total budget):		
Miscellaneous	20%	Entails small components (resistors, capacitors, etc.), gas used in trips to Gainesville MRI center for testing, materials used in SQUID casing, cable adaptors, etc.		

### 8.2.2 Parts List

The parts list is a work in progress, and the currently selected components are subject to change at any time. The final documentation for this project will include a complete and accurate list of parts. See **Table 8-3** below.



Table 8-3: Parts List

	<b>Part</b>	<b>Qty.</b>	<b>Price (USD)</b>	<b>Link</b>
<b>ECG</b>	Expression MRI Monitoring System - ECG component	1	(Provided)	<a href="http://www.invivocorp.com/monitors/monitorinfo.php?id=7">http://www.invivocorp.com/monitors/monitorinfo.php?id=7</a>
<b>SpO2</b>	Expression MRI Monitoring System – SpO2 component	1	(Provided)	<a href="http://www.invivocorp.com/monitors/monitorinfo.php?id=7">http://www.invivocorp.com/monitors/monitorinfo.php?id=7</a>
<b>NiBP</b>	Pressure cuff	1	(Provided)	<a href="http://www.healthcare.philips.com/main/products/supplies/Products/patient_monitoring/">http://www.healthcare.philips.com/main/products/supplies/Products/patient_monitoring/</a>
	MPX2050 Pressure Transducer	1	12.20	<a href="http://www.digikey.com/product-detail/en/MPX2050DP/MPX2050DP-ND/2186536">http://www.digikey.com/product-detail/en/MPX2050DP/MPX2050DP-ND/2186536</a>
	AD620 Instrumentation Amplifier	1	9.43	<a href="http://www.digikey.com/product-search/en?wt.z_cid=ref_hearst_0211_buynow&amp;site=us&amp;mpart=AD620AN&amp;v=505">http://www.digikey.com/product-search/en?wt.z_cid=ref_hearst_0211_buynow&amp;site=us&amp;mpart=AD620AN&amp;v=505</a>
	TL084 Operational Amplifier	2	0.68	<a href="http://www.digikey.com/product-detail/en/TL084CN/296-1784-5-ND/277429">http://www.digikey.com/product-detail/en/TL084CN/296-1784-5-ND/277429</a>
<b>CO2</b>	CAPNO2 mask	1	(Provided)	<a href="http://capno2mask.respironics.com/default.asp">http://capno2mask.respironics.com/default.asp</a>
	CAPNOSTAT CO <sub>2</sub> Sensor	1	(Provided)	<a href="http://capnostat.respironics.com/">http://capnostat.respironics.com/</a>
<b>Microcontroller</b>	MSP430F5529	1	12.99	<a href="http://www.ti.com/tool/msp-exp430f5529lp">http://www.ti.com/tool/msp-exp430f5529lp</a>
<b>Wireless</b>	SimpleLink Wi-Fi CC3000	1	9.99	<a href="http://www.ti.com/product/cc3000">http://www.ti.com/product/cc3000</a>

## List of Tables

Table 2-1: Cable Fabrication Objectives .....	4
Table 2-2: Connector Choice Objectives .....	5
Table 2-3: Connection Box Objectives.....	6
Table 2-4: Embedded System Objectives .....	7
Table 2-5: Software Objectives .....	8
Table 2-6: Hardware Requirements and Specifications.....	9
Table 2-7a: Software Requirements and Specifications .....	10
Table 2-7b: Software Requirements and Specifications .....	11
Table 3-1a: Potential Hazards .....	18
Table 3-1b: Potential Hazards.....	19
Table 3-2a: MRI Incidents .....	20
Table 3-2b: MRI Incidents.....	21
Table 3-3: MRI Exposure Levels.....	22
Table 3-4: NiBP Wireless Features.....	25
Table 3-5: NiBP Other Features .....	26
Table 3-6: Philips NBP Intellivue Features .....	27
Table 3-7a: MRI Safe Qualification .....	29
Table 3-7b: MRI Safe Qualification .....	30
Table 3-8: Cable Requirements .....	32
Table 3-9: Material Requirements .....	33
Table 4-1: Sensor Signal Acquisition .....	34
Table 4-2: SQUID Cable Requirements .....	40
Table 4-3: Connector Options.....	41
Table 4-4: Cable Risk Factors.....	42
Table 4-5a: Voltage Regulator Options .....	45
Table 4-5b: Voltage Regulator Options .....	46
Table 4-6: Microcontroller Options .....	47
Table 4-7: Microcontroller ADC10 Benefits .....	48
Table 4-8a: ADC10 Features .....	50
Table 4-8b: ADC10 Features .....	51
Table 4-8c: ADC10 Features .....	52
Table 4-9: ADC10 Conversion Modes .....	53
Table 4-10: ADC10 Registers.....	54
Table 4-11: Microcontroller ADC12 Benefits .....	54
Table 4-12a: ADC12 Features .....	56
Table 4-12b: ADC12 Features .....	57
Table 4-12c: ADC12 Features .....	58
Table 4-12d: ADC12 Features .....	59

Table 4-13: ADC12 Conversion Modes .....	60
Table 4-14: ADC12 Registers.....	61
Table 4-15: Blood Pressure Classifications .....	65
Table 4-16: Key Sensor Outputs.....	65
Table 4-17: Estimated Heart Rate Values.....	67
Table 4-18a: Wireless Modules .....	72
Table 4-18b: Wireless Modules .....	73
Table 4-19: ISM Frequency Bands .....	75
Table 4-20: IntelliVue Guardian vs. SQVID INC .....	77
Table 4-21: Additional Feature Requirements.....	82
Table 6-1: Coding Plan Objectives .....	86
Table 6-2: Functions of SQVID INC.....	88
Table 6-3a: Features of SQVID INC .....	89
Table 6-3b: Features of SQVID INC .....	90
Table 7-1: MRI Testing Considerations .....	93
Table 7-2a: MRI Force Test.....	94
Table 7-2b: MRI Force Test .....	95
Table 7-3a: MRI Torque Test .....	96
Table 7-3b: MRI Torque Test.....	97
Table 7-3c: MRI Torque Test .....	98
Table 7-4a: MRI RF Heating Test .....	99
Table 7-4b: MRI RF Heating Test .....	100
Table 7-4c: MRI RF Heating Test .....	101
Table 7-4d: MRI RF Heating Test .....	102
Table 7-4e: MRI RF Heating Test .....	103
Table 7-4f: MRI RF Heating Test.....	104
Table 7-4g: MRI RF Heating Test .....	105
Table 7-4h: MRI RF Heating Test .....	106
Table 7-5: Analog to Digital Test .....	108
Table 7-6: INC Configuration Screen Data .....	111
Table 8-1a: Prototype and Test Schedule .....	120
Table 8-1b: Prototype and Test Schedule .....	121
Table 8-1c: Prototype and Test Schedule .....	122
Table 8-2: Project Budget Allocation .....	123
Table 8-3: Parts List.....	124

## List of Figures

Figure 3-1: Sample NiBP Signal .....	12
Figure 3-2: Sample ECG Signal .....	14
Figure 3-3: SpO2 Sensor.....	15
Figure 3-4: Philips NBP Pod .....	28
Figure 4-1: System Interconnect Diagram.....	35
Figure 4-2: System Design Tree .....	36
Figure 4-3: Hardware Block Diagram .....	37
Figure 4-4: Software Block Diagram.....	38
Figure 4-5: Op-Amp Circuit .....	39
Figure 4-6: TI ADC10 Block Diagram.....	49
Figure 4-7: TI ADC12 Block Diagram.....	55
Figure 4-8: NiBP Sensor Circuit.....	62
Figure 4-9: MPX2050DP Package.....	63
Figure 4-10: MPX2050 Output Voltage vs. Input Pressure.....	64
Figure 4-11: AD620 Instrumentation Amplifier.....	66
Figure 4-12: First Stage of Band Pass Filter.....	68
Figure 4-13: Second Stage of Band Pass Filter .....	68
Figure 4-14: IntelliVue Bedside Monitor .....	78
Figure 4-15: User Interface Design for SQVID INC.....	79
Figure 6-16: SQVID INC Program Flow.....	91
Figure 7-1a: Hospital Setting.....	109
Figure 7-1b: MRI Exam Setting .....	110
Figure 7-2: Welcome Screen Testing Procedure .....	112
Figure 7-3: Vital Sign Signal Acquisition Testing Procedure .....	113
Figure 7-4: Waveform Display Data Testing Procedure .....	114
Figure 7-5: Scroll Testing Procedure.....	115
Figure 7-6: Sweep Testing Procedure.....	115
Figure 7-7: Record Functionality Testing Procedure.....	116
Figure 7-8: Trigger Testing Procedure .....	117

# Appendices

---

## Appendix A – References

- [1] <http://science.howstuffworks.com/mri6.htm>
- [2] [http://www.mrisafety.com/safety\\_article.asp?subject=17](http://www.mrisafety.com/safety_article.asp?subject=17)
- [3] [http://www.biac.duke.edu/research/safety/tutorial.asp#RF\\_2](http://www.biac.duke.edu/research/safety/tutorial.asp#RF_2)
- [4] <http://www.fda.gov/MedicalDevices/DeviceRegulationandGuidance/GuidanceDocuments/ucm107721.htm#general>
- [5] [http://www.biac.duke.edu/research/safety/tutorial.asp#SF\\_1](http://www.biac.duke.edu/research/safety/tutorial.asp#SF_1)
- [6] <http://www.swinburne.edu.au/lss/bpsyc/neuroimaging/documents/MRI-09.pdf>
- [7] [http://enterprise.astm.org/filtrexx40.cgi?+REDLINE\\_PAGES/F2503.htm](http://enterprise.astm.org/filtrexx40.cgi?+REDLINE_PAGES/F2503.htm)
- [8] [http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?REDLINE\\_PAGES/F2052.htm](http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?REDLINE_PAGES/F2052.htm)
- [9] [http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?+REDLINE\\_PAGES/F2213.htm](http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?+REDLINE_PAGES/F2213.htm)
- [10] [http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?+REDLINE\\_PAGES/F2182.htm](http://enterprise.astm.org/SUBSCRIPTION/filtrexx40.cgi?+REDLINE_PAGES/F2182.htm)
- [11] <http://www.biopac.com/Noninvasive-Blood-Pressure-MRI>
- [12] <http://incenter.medical.philips.com/Default.aspx?tabid=729> (publication #: 453564219221)
- [13] <http://www.ti.com/product/msp430g2553>

# Appendix A – Datasheets

-MPX2050

## Operating Characteristics

**Table 1. Operating Characteristics**

( $V_S = 10$  Vdc,  $T_A = 25^\circ\text{C}$  unless otherwise noted,  $P_1 > P_2$ )

Characteristics	Symbol	Min	Typ	Max	Unit
Pressure Range <sup>(1)</sup>	$P_{OP}$	0	—	50	kPa
Supply Voltage <sup>(2)</sup>	$V_S$	—	10	16	Vdc
Supply Current	$I_b$	—	6.0	—	mAdc
Full Scale Span <sup>(3)</sup>	$V_{FSS}$	38.5	40	41.5	mV
Offset <sup>(4)</sup>	$V_{off}$	-1.0	—	1.0	mV
Sensitivity	$\Delta V/\Delta P$	—	0.8	—	mV/kPa
Linearity <sup>(5)</sup>	—	-0.25	—	0.25	% $V_{FSS}$
Pressure Hysteresis <sup>(5)</sup> (0 to 50 kPa)	—	—	$\pm 0.1$	—	% $V_{FSS}$
Temperature Hysteresis <sup>(5)</sup> (-40°C to +125°C)	—	—	$\pm 0.5$	—	% $V_{FSS}$
Temperature Effect on Full Scale Span <sup>(5)</sup>	$TCV_{FSS}$	-1.0	-	1.0	% $V_{FSS}$
Temperature Effect on Offset <sup>(5)</sup>	$TCV_{off}$	-1.0	-	1.0	mV
Input Impedance	$Z_{in}$	1000	-	2500	$\Omega$
Output Impedance	$Z_{out}$	1400	-	3000	$\Omega$
Response Time <sup>(6)</sup> (10% to 90%)	$t_R$	—	1.0	—	ms
Warm-Up	—	—	20	—	ms
Offset Stability <sup>(7)</sup>	—	—	$\pm 0.5$	—	% $V_{FSS}$

1. 1.0 kPa (kiloPascal) equals 0.145 psi.

2. Device is ratiometric within this specified excitation range. Operating the device above the specified excitation range may induce additional error due to device self-heating.

3. Full Scale Span ( $V_{FSS}$ ) is defined as the algebraic difference between the output voltage at full rated pressure and the output voltage at the minimum rated pressure.

4. Offset ( $V_{off}$ ) is defined as the output voltage at the minimum rated pressure.

5. Accuracy (error budget) consists of the following:

Linearity: Output deviation from a straight line relationship with pressure, using end point method, over the specified pressure range.

Temperature Hysteresis: Output deviation at any temperature within the operating temperature range, after the temperature is cycled to and from the minimum or maximum operating temperature points, with zero differential pressure applied.

Pressure Hysteresis: Output deviation at any pressure within the specified range, when this pressure is cycled to and from the minimum or maximum rated pressure, at 25°C.

TcSpan: Output deviation at full rated pressure over the temperature range of 0 to 85°C, relative to 25°C.

TcOffset: Output deviation with minimum rated pressure applied, over the temperature range of 0 to 85°C, relative to 25°C.

6. Response Time is defined as the time for the incremental change in the output to go from 10% to 90% of its final value when subjected to a specified step change in pressure.

7. Offset stability is the product's output deviation when subjected to 1000 hours of Pulsed Pressure, Temperature Cycling with Bias Test.

## Maximum Ratings

**Table 2. Maximum Ratings<sup>(1)</sup>**

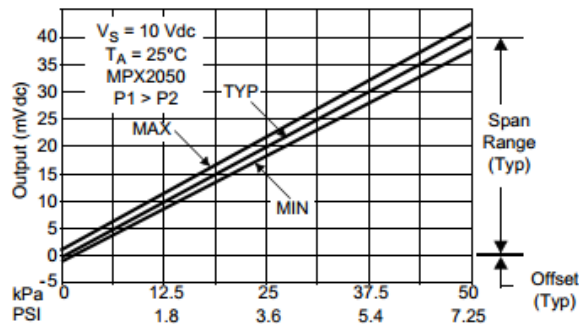
Rating	Symbol	Value	Unit
Maximum Pressure (P1 > P2)	$P_{max}$	200	kPa
Storage Temperature	$T_{stg}$	-40 to +125	°C
Operating Temperature	$T_A$	-40 to +125	°C

1. Exposure beyond the specified limits may cause permanent damage or degradation to the device.

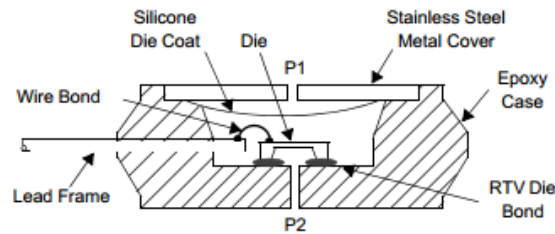
## On-Chip Temperature Compensation and Calibration

Figure 3 shows the minimum, maximum and typical output characteristics of the MPX2050 series at 25°C. The output is directly proportional to the differential pressure and is essentially a straight line.

The effects of temperature on Full-Scale Span and Offset are very small and are shown under Operating Characteristics.



**Figure 3. Output versus Pressure Differential**

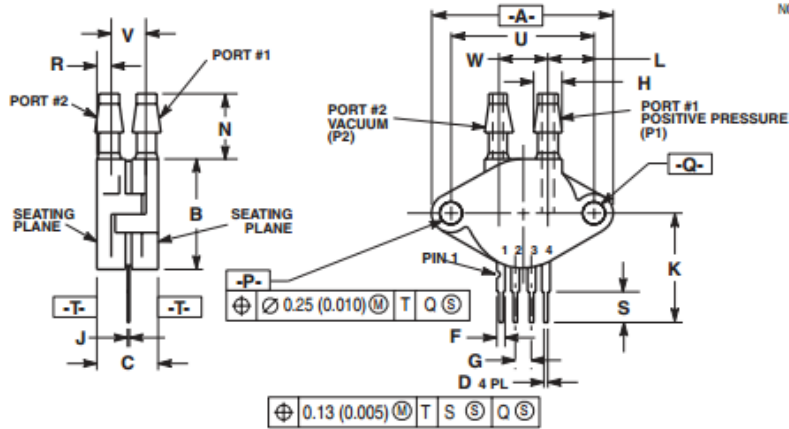


**Figure 4. Cross-Sectional Diagram (not to scale)**

Figure 4 illustrates the differential or gauge configuration in the basic chip carrier (Case 344). A silicone gel isolates the die surface and wire bonds from the environment, while allowing the pressure signal to be transmitted to the silicon diaphragm.

The MPX2050 series pressure sensor operating characteristics and internal reliability and qualification tests are based on use of dry air as the pressure media. Media other than dry air may have adverse effects on sensor performance and long term reliability. Contact the factory for information regarding media compatibility in your application.

## PACKAGE DIMENSIONS



- NOTES:  
 1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.  
 2. CONTROLLING DIMENSION: INCH.

DIM	INCHES		MILLIMETERS	
	MIN	MAX	MIN	MAX
A	1.145	1.175	29.08	29.85
B	0.685	0.715	17.40	18.16
C	0.405	0.435	10.29	11.05
D	0.016	0.020	0.41	0.51
F	0.048	0.064	1.22	1.63
G	0.100 BSC		2.54 BSC	
H	0.182	0.194	4.62	4.93
J	0.014	0.016	0.36	0.41
K	0.695	0.725	17.65	18.42
L	0.290	0.300	7.37	7.62
N	0.420	0.440	10.67	11.18
P	0.153	0.159	3.89	4.04
Q	0.153	0.159	3.89	4.04
R	0.063	0.083	1.60	2.11
S	0.220	0.240	5.59	6.10
U	0.910 BSC		23.11 BSC	
V	0.248	0.278	6.30	7.06
W	0.310	0.330	7.87	8.38

- STYLE 1:  
 PIN 1: GROUND  
 2: + OUTPUT  
 3: + SUPPLY  
 4: - OUTPUT

**CASE 344C-01  
 ISSUE B  
 UNIBODY PACKAGE**



## **How to Reach Us:**

### **Home Page:**

[www.freescale.com](http://www.freescale.com)

### **Web Support:**

<http://www.freescale.com/support>

### **USA/Europe or Locations Not Listed:**

Freescale Semiconductor, Inc.  
Technical Information Center, EL516  
2100 East Elliot Road  
Tempe, Arizona 85284  
1-800-521-6274 or +1-480-768-2130  
[www.freescale.com/support](http://www.freescale.com/support)

### **Europe, Middle East, and Africa:**

Freescale Halbleiter Deutschland GmbH  
Technical Information Center  
Schatzbogen 7  
81829 Muenchen, Germany  
+44 1296 380 456 (English)  
+46 8 52200080 (English)  
+49 89 92103 559 (German)  
+33 1 69 35 48 48 (French)  
[www.freescale.com/support](http://www.freescale.com/support)

### **Japan:**

Freescale Semiconductor Japan Ltd.  
Headquarters  
ARCO Tower 15F  
1-8-1, Shimo-Meguro, Meguro-ku,  
Tokyo 153-0064  
Japan  
0120 191014 or +81 3 5437 9125  
[support.japan@freescale.com](mailto:support.japan@freescale.com)

### **Asia/Pacific:**

Freescale Semiconductor China Ltd.  
Exchange Building 23F  
No. 118 Jianguo Road  
Chaoyang District  
Beijing 100022  
China  
+86 010 5879 8000  
[support.asia@freescale.com](mailto:support.asia@freescale.com)

### **For Literature Requests Only:**

Freescale Semiconductor Literature Distribution Center  
P.O. Box 5405  
Denver, Colorado 80217  
1-800-441-2447 or +1-303-675-2140  
Fax: +1-303-675-2150  
[LDCForFreescaleSemiconductor@hibbertgroup.com](mailto:LDCForFreescaleSemiconductor@hibbertgroup.com)

Information in this document is provided solely to enable system and software implementers to use Freescale Semiconductor products. There are no express or implied copyright licenses granted hereunder to design or fabricate any integrated circuits or integrated circuits based on the information in this document.

Freescale Semiconductor reserves the right to make changes without further notice to any products herein. Freescale Semiconductor makes no warranty, representation or guarantee regarding the suitability of its products for any particular purpose, nor does Freescale Semiconductor assume any liability arising out of the application or use of any product or circuit, and specifically disclaims any and all liability, including without limitation consequential or incidental damages. "Typical" parameters that may be provided in Freescale Semiconductor data sheets and/or specifications can and do vary in different applications and actual performance may vary over time. All operating parameters, including "Typicals", must be validated for each customer application by customer's technical experts. Freescale Semiconductor does not convey any license under its patent rights nor the rights of others. Freescale Semiconductor products are not designed, intended, or authorized for use as components in systems intended for surgical implant into the body, or other applications intended to support or sustain life, or for any other application in which the failure of the Freescale Semiconductor product could create a situation where personal injury or death may occur. Should Buyer purchase or use Freescale Semiconductor products for any such unintended or unauthorized application, Buyer shall indemnify and hold Freescale Semiconductor and its officers, employees, subsidiaries, affiliates, and distributors harmless against all claims, costs, damages, and expenses, and reasonable attorney fees arising out of, directly or indirectly, any claim of personal injury or death associated with such unintended or unauthorized use, even if such claim alleges that Freescale Semiconductor was negligent regarding the design or manufacture of the part.

Freescale™ and the Freescale logo are trademarks of Freescale Semiconductor, Inc. All other product or service names are the property of their respective owners.

© Freescale Semiconductor, Inc. 2008. All rights reserved.



MPX2050  
Rev. 9  
10/2008

## Appendix C – Flow Charts and Diagrams

Figure 3-4: Philips NBP Pod

### NBP Pod

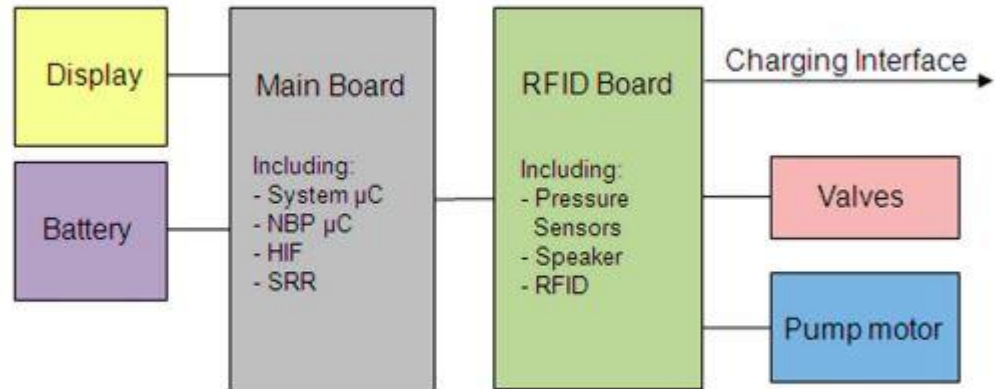


Figure 4-1: System Interconnect Diagram

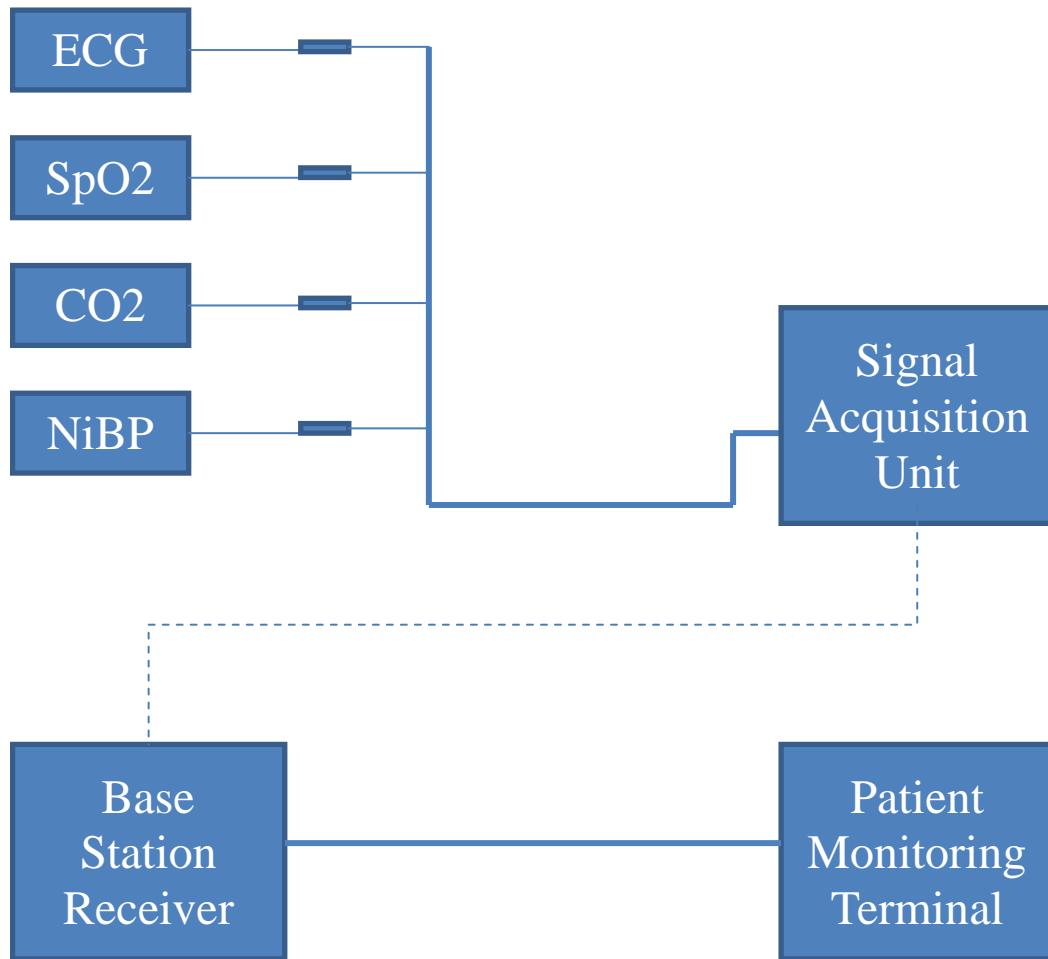
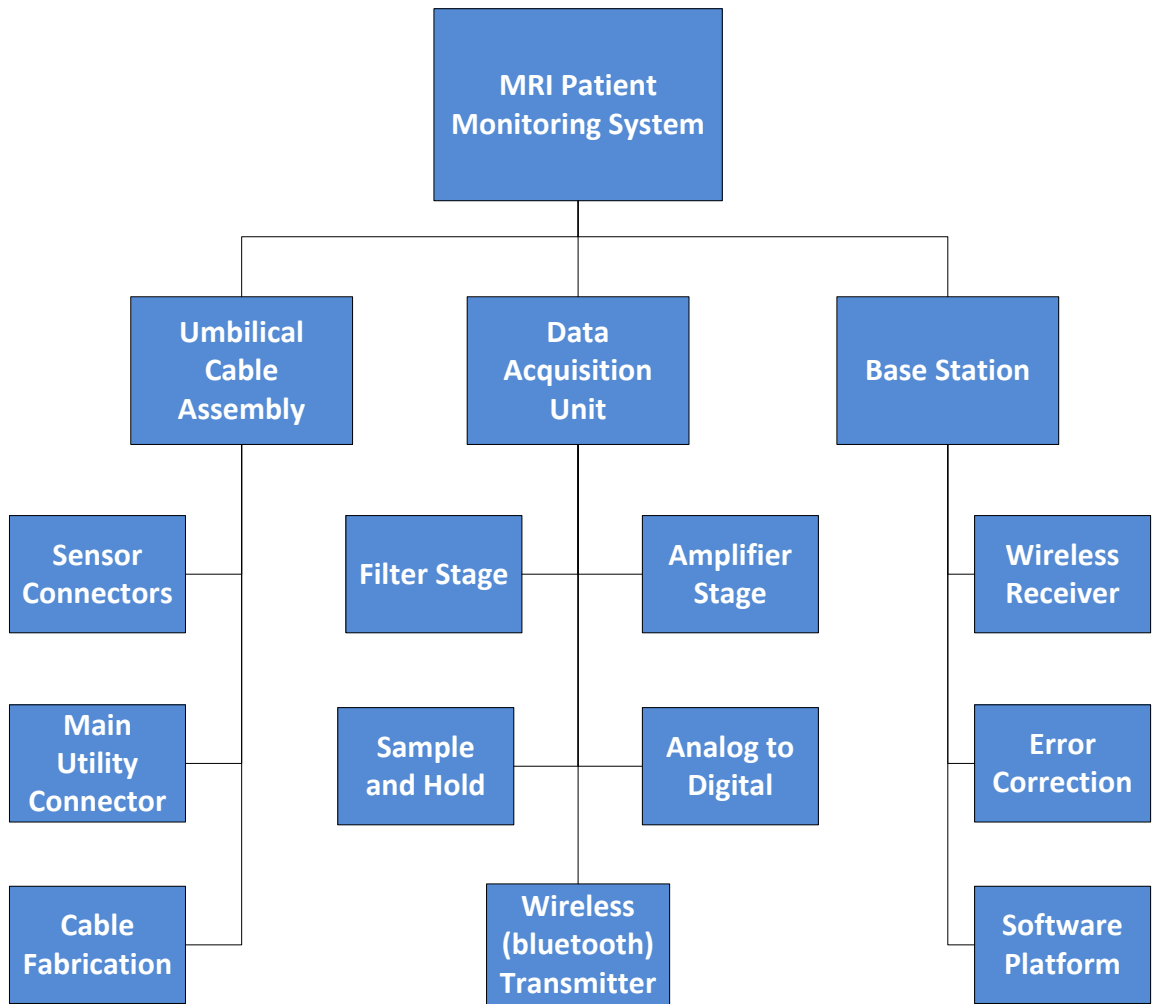


Figure 4-2: System Design Tree



**Figure 4-9: Hardware Block Diagram**

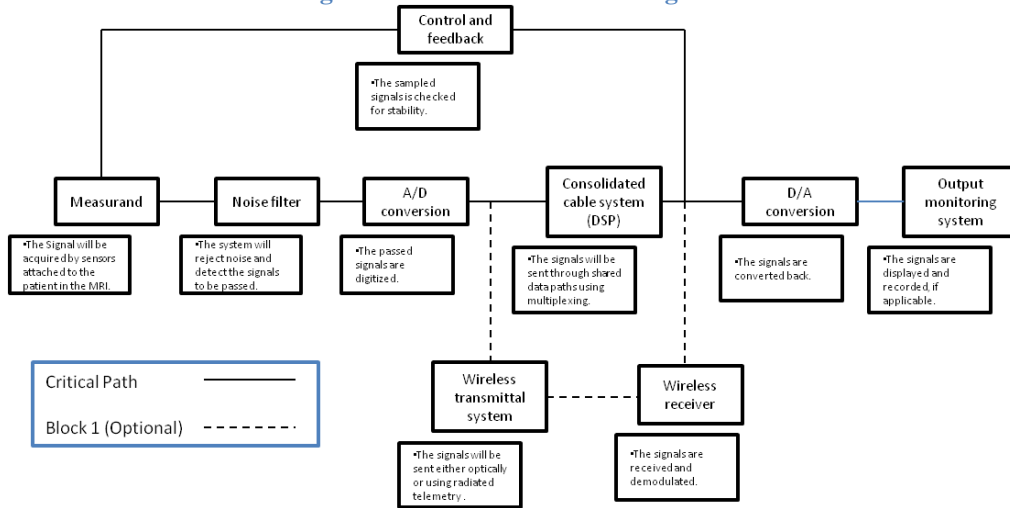


Figure 4-10: Software Block Diagram

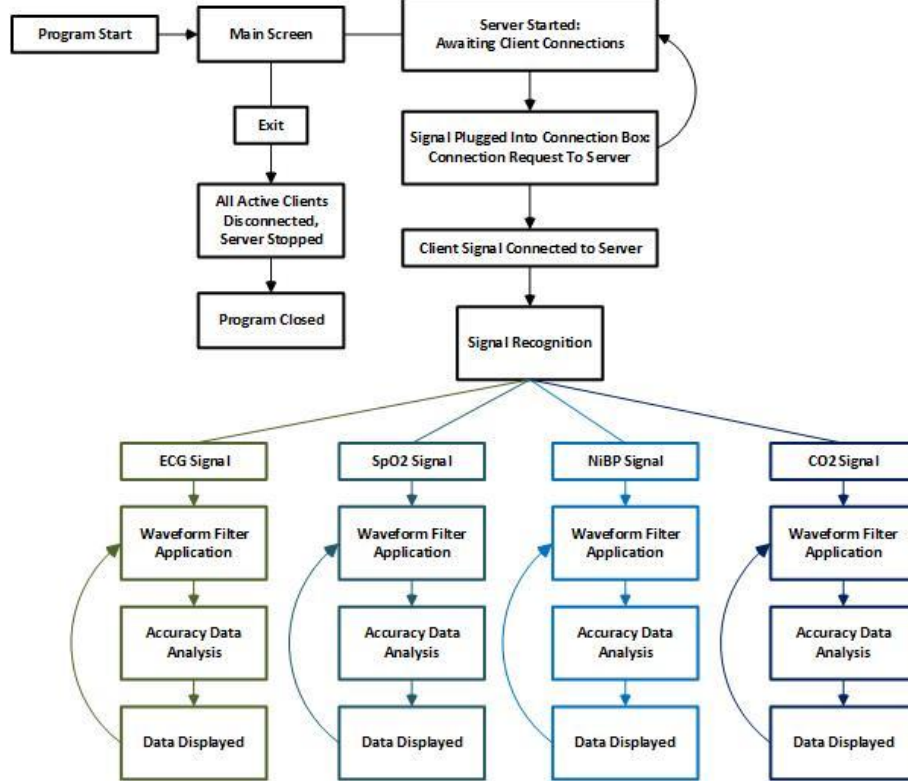


Figure 6-11: SQVID INC Program Flow

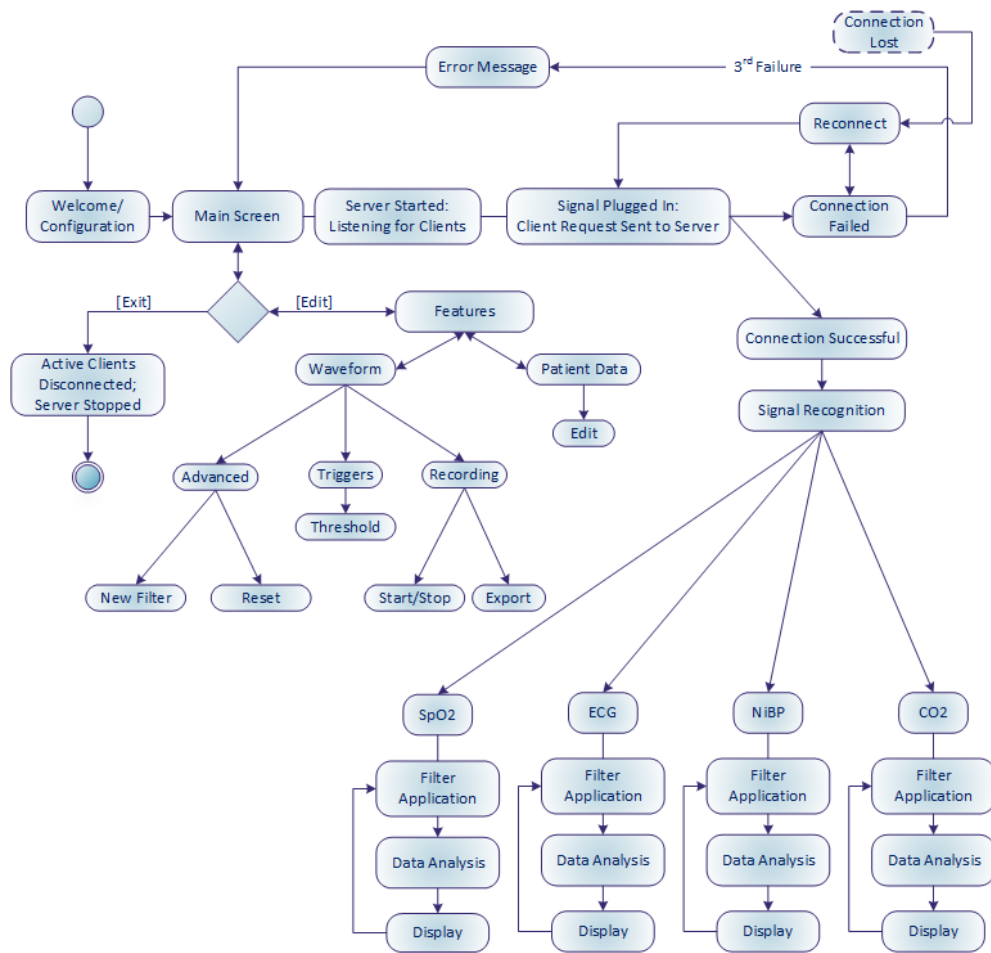


Figure 7-12: Vital Sign Signal Acquisition Testing Procedure

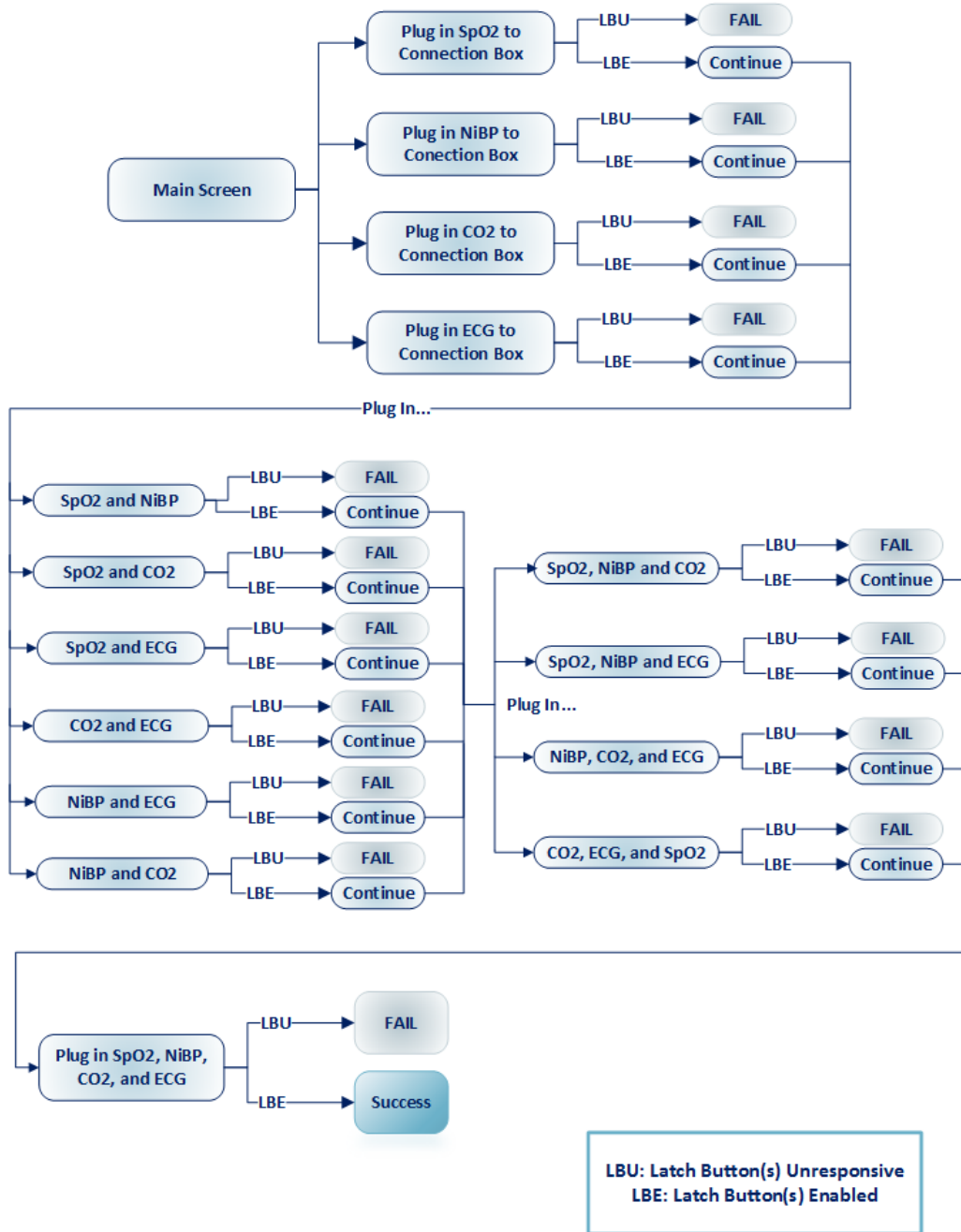




Figure 7-13: Waveform Display Data Testing Procedure

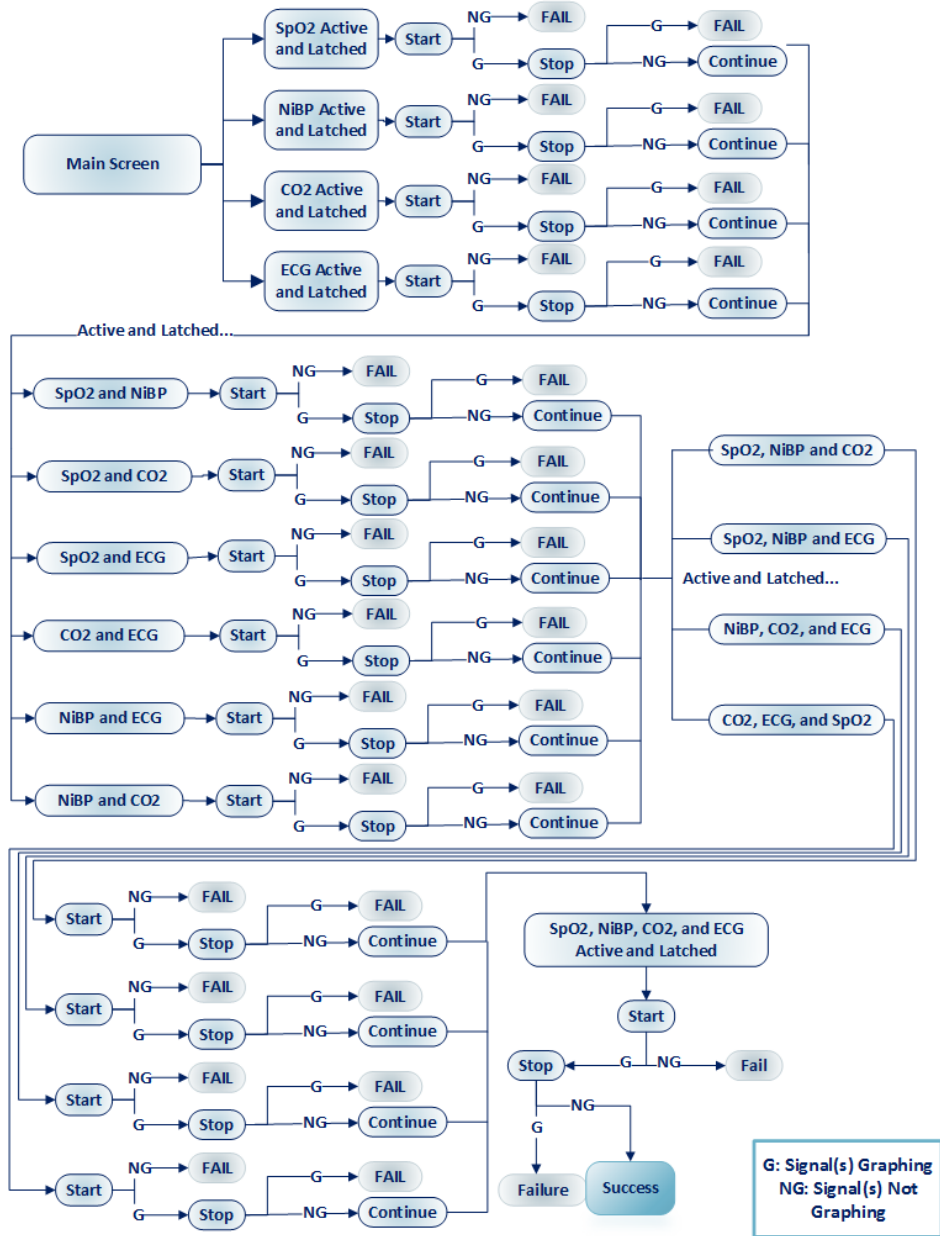


Figure 7-14: Record Functionality Testing Procedure

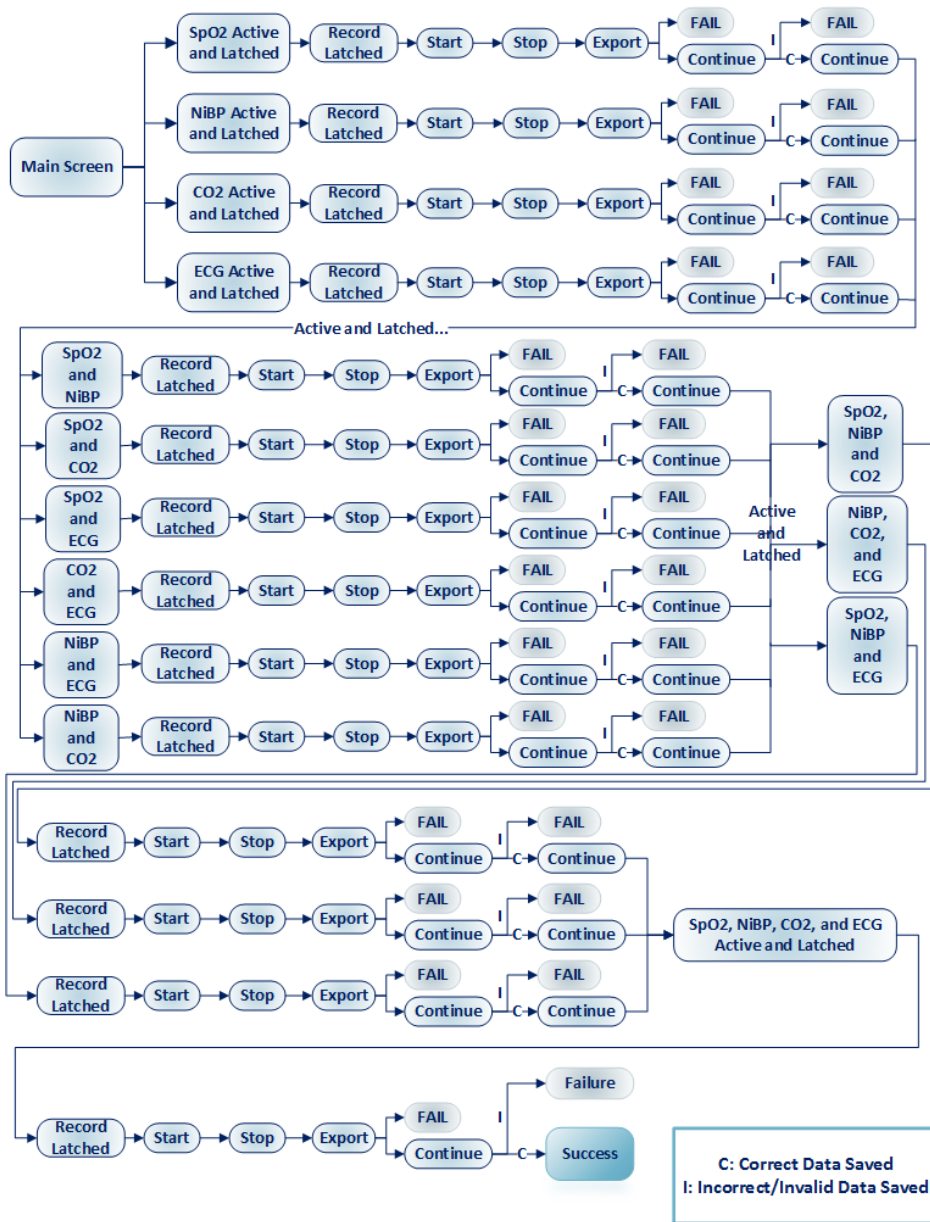
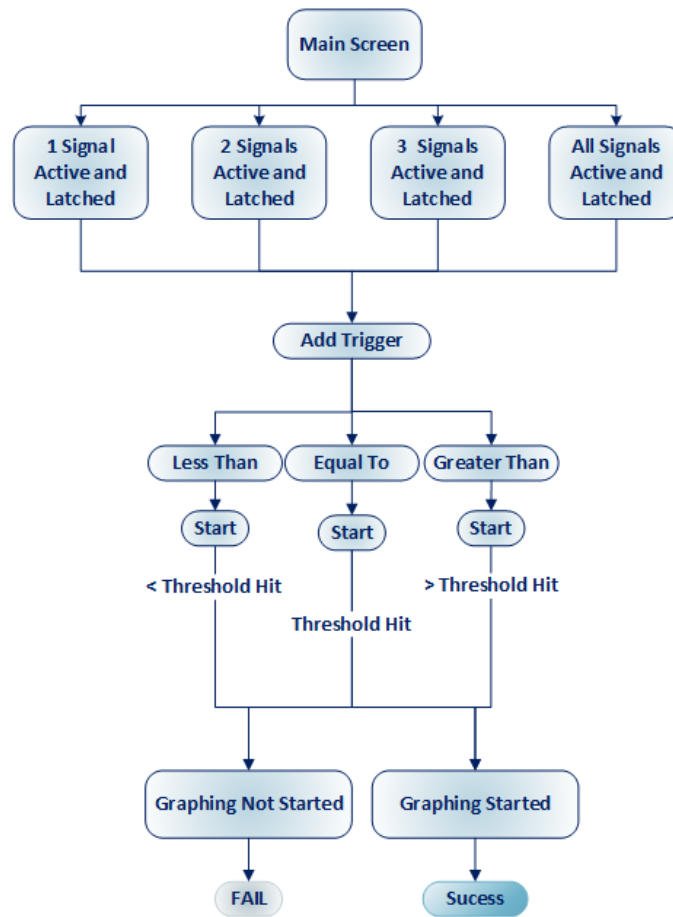
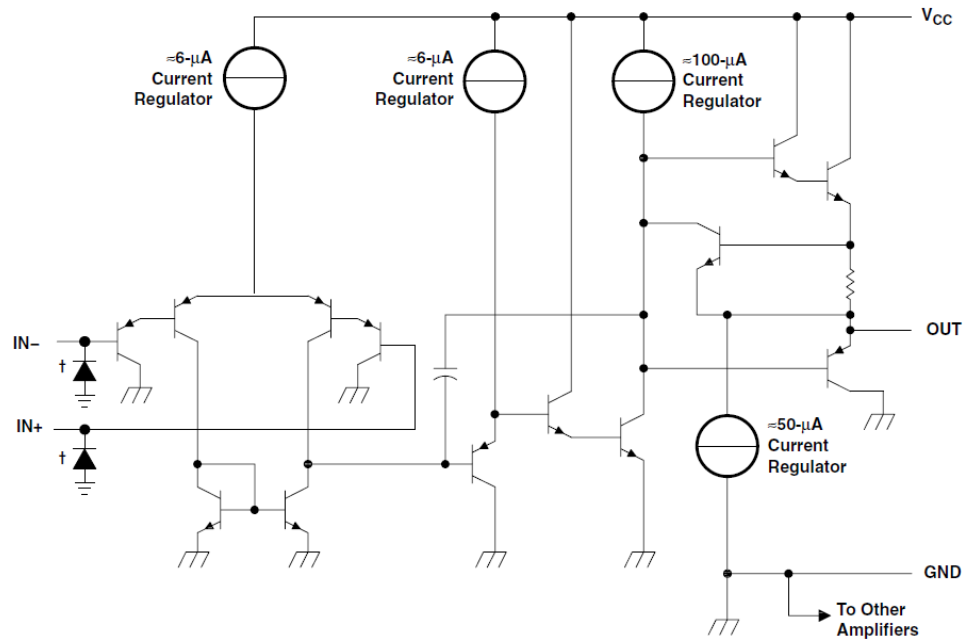


Figure 7-15: Trigger Testing Procedure



## Appendix D – Schematics

Figure 4-16: Op-Amp Circuit



COMPONENT COUNT (total device)	
Epi-FET	1
Transistors	95
Diodes	4
Resistors	11
Capacitors	4

† ESD protection cells - available on LM324K and LM324KA only

Figure 4-17: NiBP Sensor Circuit

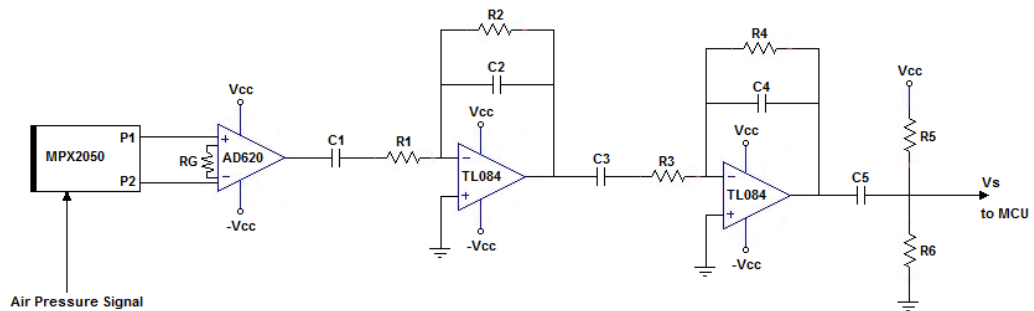


Figure 4-18: First Stage of Band Pass Filter

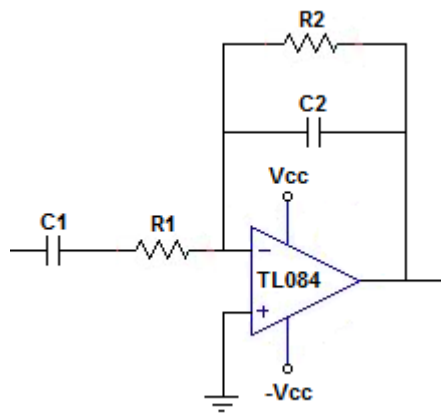


Figure 4-19: Second Stage of Band Pass Filter

