SQVID: Simplified Quad-Vitals Integration Device

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Abstract — **The objective of this project is to provide the Philips Company with a consolidated cabling solution to help enhance comfort of patients facing an MRI scan, and assist their caregivers by providing a more streamlined, wireless approach to measuring vital signs. The Simplified Quad-Vitals Integration Device, or SQVID, includes a central hub for vital sign connections, transmitting these signals wirelessly to the necessary system for reading. This project uses two of Philips' existing wireless handheld devices as models for developing an innovative way to transmit non-invasive blood pressure (NiBP) data from patients, taking into consideration the needed safety requirements for equipment residing in a Magnetic Resonance Imaging environment.**

Index Terms — **Magnetic Resonance Imaging, MRI, vital signs, wireless sensor, non-invasive blood pressure, NiBP.**

I. INTRODUCTION

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 alike. In an effort to innovate and ease the stress placed upon patients facing an MRI scan, Philips uses wireless technology to monitor two of the four vital signs typically watched before, during, and after a patients' scan. These wireless handhelds are battery powered, MRI safe, and transmit electrocardiography (ECG) and spot oxygen saturation (SpO2) readings to Philips' sophisticated monitoring software systems, IntelliVue or SureSigns. The two remaining vitals, carbon dioxide (CO2) and non-invasive blood pressure (NiBP) are typically monitored via a complex system of cabling, complicating patient transport and adding to discomfort. All four sensors utilize separate cables, whether they terminate in a handheld or plug directly into a monitoring system.

The Philips Company sponsored the SQVID team, encouraging and assisting them in developing a prototype device capable of transmitting the NiBP signal wirelessly to an accompanying software system. This project aimed to also construct the central housing location for all four vital signs: a small box meant to sit at the foot of a patient's bed and provide the necessary connections for signals being monitored.

Fig. 1. Philips Monitor with SpO2 and NiBP Devices

II. EXISTING SYSTEM

A. Vital Signs and Measurement

The SQVID project takes into consideration two of the four main vital signs of importance during an MRI scan: non-invasive blood pressure and carbon dioxide. Non-invasive blood pressure, or NiBP, is the most commonly practiced category of blood pressure monitoring, in which the patient wears a cuff around his or her bicep. The cuff is first filled with air, cutting off circulation of blood through the brachial artery. The pressure of the cuff is then slowly released and at a certain point blood pushes past the tourniquet. As the blood begins traveling into the artery and the heart pumps, distinct pulses of blood pressure can be measured.

While blood pressure can be determined manually by a trained physician using a stethoscope, it can also be measured by way of a pressure transducer which, in conjunction with proper signal analysis and computation, enables the measurement to be taken remotely and more accurately. The information can be read into a computer and data can be visualized in a much more sophisticated fashion. The SQVID project takes advantage of this technology.

The carbon dioxide, or CO2, levels in a patient's respiration is measured by infrared spectroscopy. Based on the partial pressure of carbon dioxide versus other gases in a patient's exhalation, a reading is taken by way of a cannula placed along the patient's airway, attached to a sample cell. As the patient breathes, an infrared LED passes its light through the exhaled gas in the sample cell and a photodiode picks up the intensity of light that has not been absorbed by the gas. Carbon dioxide is known to absorb infrared radiation, and the partial pressure can be calculated based on the amount of infrared radiation absorbed by the gas.

While both the CO2 and NiBP vital signs were initially considered within the scope of this project, only the NiBP sensor equipment was readily available for the SQVID team to experiment and test with. Therefore, the prototype narrowed its focus to a wireless solution for transferring non-invasive blood pressure data only, with expansion for CO2 readings taken into consideration but left for future development.

B. MRI Environment

Current equipment developed by the Philips Company and utilized in MRI environments are carefully constructed and proprietary in nature, taking into consideration all potential hazards to the patient and built with utmost attention to detail to ensure safety is the number one priority. Due to the dangers associated with the strength of the magnetic field used during the scan, materials such as iron, nickel, cobalt, chromium, steel, and even some non-magnetic forms of stainless steel, can pose deadly risks to patients or any individuals taking part in the procedure. The Philips Company has developed their own "secret recipe" used in patient monitoring equipment to mitigate these risks. All existing sensor equipment as well as vital sign monitoring equipment are proven MRI safe, and all materials used by the SQVID team was subject to the Company's approval to ensure that the prototype developed would fulfill the same requirement.

III. PROBLEM FORMULATION

The main objective of this project is to develop a prototype NiBP sensor capable of transmitting data wirelessly to an accompanying software system, taking into consideration MRI safety concerns as well as ease of use, portability, reliability, and accuracy of data. A central connection hub and new cabling system also needed to be prototyped in the hopes of reducing the number of cables currently connected to a patient whose vitals are being monitored.

A. Data Acquisition Hardware

To attain the data from the NiBP cuff provided by the Philips Company, a microcontroller would need to be designed and programmed to retrieve and transmit the pressure transducer data from the cuff. The following requirements were specified with regards to the hardware that would be used in the prototype:

- The unit used to acquire and process the data should be powered by an approved DC supply.
- The unit should perform the necessary analog-to-digital or digital-to-analog signal conversions necessary for proper data acquisition.
- The unit used should not interfere with the clarity or accuracy of an MRI image.
- The unit should be capable of sending the data wirelessly to an accompanying software system.
- The unit should be low-cost and possess a small footprint, being designed to fit in the central connection box.

B. Software

The software system would need to work hand-in-hand with the hardware to retrieve the NiBP signal data and display it in a readable fashion. It would need to be a standalone program capable of residing on a desktop or laptop computer. The following requirements were decided upon to achieve this goal:

- The software system should provide the user with an easy to use graphical interface to view data received from the NiBP signal.
- The software system should handle any conversions or data manipulation necessary to display the data in an understandable fashion.
- The system should display data accurately and reliably, in real time.

C. Connection Box and Cabling

The central connection box needed to be designed to serve as housing for the signal processing hardware as well as to eliminate unnecessary clutter, making patient transportation easier while being monitored. The design took into consideration that eventually all four vital signs would be plugged into this hub which would reside at the foot of a patient's hospital bed. It is imperative that the connection box materials be MRI safe, as well as the cabling used to run from the box to the actual monitoring equipment attached to the patient. Guided by these objectives, the SQVID is designed to meet the following requirements:

- The prototype connection box should be no larger than a 1x1x1 foot cube made of MRI safe materials.
- The box should be lightweight and easily moved from one location to another, without hindering patient transportation.
- The cable used to connect hub-to-patient should not exceed 8 feet in length and cannot bunch, loop, or perform any other unanticipated movement that

would disrupt the clarity of the signal. It should be constructed of MRI safe materials.

IV. DESIGN OVERVIEW

The overall design chosen by the SQVID team uses a Texas Instruments MSP430 microcontroller paired with the TI CC3000 wireless module to perform the necessary data acquisition procedures using the Philips NiBP cuff. A standalone software program, written in the C# language, handles receiving and displaying the data for the user. The connection box prototype houses the microcontroller hardware and possesses two connection ports: one for NiBP and a second left for possible expansion to include the CO2 vital sign.

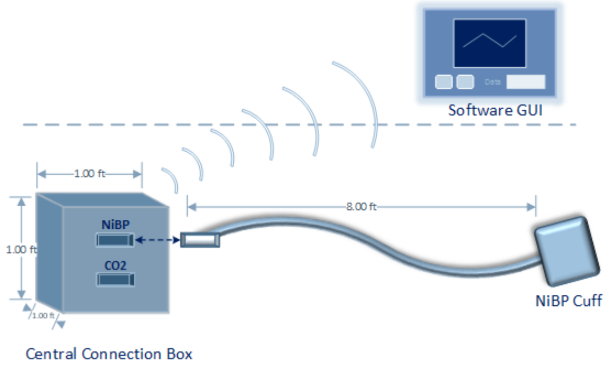


Fig. 2. SQVID Design Diagram

V. HARDWARE DESIGN

The hardware portion of this project refers to the analog circuit design for amplification and filtering of the pressure transducer, the analog to digital conversion of this signal at the microcontroller interface, the serial communication between the microcontroller and wireless processor, the schematic capture and board design of the prototype, and the physical modeling of the connection box. While prototyping this project, the MSP430G2553 Launchpad and CC3000 Booster Pack were used to begin development on the embedded software. One of USCI peripherals on the microcontroller was configured for UART debugging and configuration using hyperterminal on an attached PC. The other USCI module was initialized for SPI communication to the CC3000 wireless processor.

A. *NIBP Analog Circuit Design*

The primary function of the SQVID prototype is to implement the wireless solution for the blood pressure sensor. The sensor must read in an analog pressure signal from a cuff and output an analog electrical signal that has been filtered, amplified, and voltage-limited. The polished waveform is then sent to the microcontroller for A/D conversion.

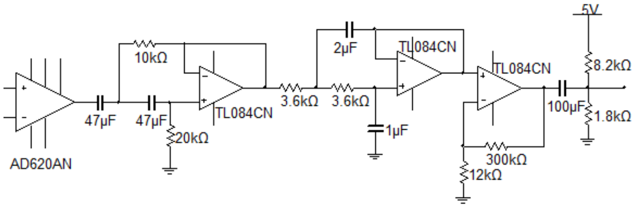


Fig. 3. NiBP Analog circuit schematic (post-transducer)

The transducer used to read the cuff pressure is the MPX2050DP made by Freescale Semiconductor. This particular transducer reads in two pressure signals from two ports on the package and outputs their signals to respective pins. Both signals have baselines at half the DC supply voltage.

To eliminate the relatively large DC offset and accurately measure cuff pressure versus ambient pressure (open-ended port), Analog Devices' AD620 instrumentation amplifier is used. The AD620 is not used as the primary amplifying stage in the circuit, however, because the unfiltered signal is carrying a lot of noise. Amplifying this noise would draw extra unnecessary power, so the signal noise is filtered out before the majority of the amplification takes place. Some amplification from the AD620 is applied to make the signal more readily observable from an oscilloscope and distinguish the signal from potential noise at the op amps. Using the gain equation provided in the AD620 datasheet,

$$G = \frac{49.4k\Omega}{R_G} + 1, \tag{1}$$

the instrumentation stage provides a gain of 10.7 when using the designed gain resistor value of 5.1kΩ. However, a 10kΩ potentiometer is used in place of the gain resistor to allow easy tweaking, if necessary, after the PCB is finalized.

A second-order Butterworth bandpass filter is designed, with corner frequencies at 0.24 and 31 Hz, to isolate the frequency components found in typical NiBP readings, ranging from 1 to 30 Hz. These frequencies are based off human resting heart rates ranging from 1 to 6 Hz and their harmonic components. The highest considered heart rate of 6Hz (360 bpm) has a fifth harmonic at 30Hz. Thus, the corner frequencies of 0.24 and 31 Hz should pass all frequency components attributed to the blood pressure reading we would expect to see from a patient. The use of inductors and electrolytic capacitors near an MRI is not recommended due to the strong magnetic field and RF pulses, so this filter will be strictly RC and use only ceramic capacitors. For the sake of simplicity and tunability, the bandpass is divided into lowpass and highpass stages (as opposed to two cascaded single-order bandpasses) and a Sallen-Key topology is used for both. The Sallen-Key configuration allows corner frequency tuning with the adjustment of only two components (per stage) sharing a common value. However, these filter stages are both unity-gain so another op amp stage is needed to provide sufficient post-filter amplification.

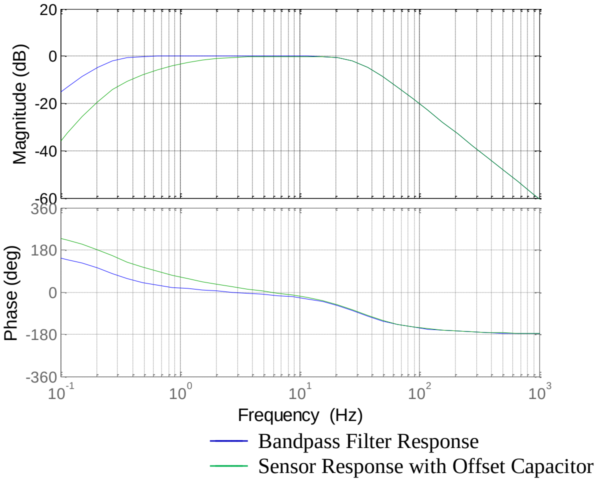


Fig. 4. NiBP sensor frequency response

The filtered analog signal is passed through a non-inverting amplifier stage that brings the signal amplitude to the maximum amplitude desired entering the microcontroller. With the signal's baseline at 0V, the waveform would include negative voltages which the MSP430 microcontroller being used for A/D conversion will not accept. A DC offset of 1V is added to the signal after this amplifier stage and the reference voltage for the A/D conversion is set to 2.5 V, so the desired amplitude should fall just below 1.5V. The negative peaks of the waveform are generally not comparable to the positive peaks so a 1V offset is sufficient to ensure no negative values, though errant negative voltage spikes will not damage the system or achieve high enough potential to cause problems with the microcontroller.

The 1V DC offset is implemented using a capacitor and a voltage divider supplied by Vcc at 5V. The filtering effect of the capacitor-resistor configuration imposes a highpass filter with a cutoff at approximately 1 Hz, so it does not significantly affect the passband established by the Butterworth filters. The combined response is shown in Fig. 4.

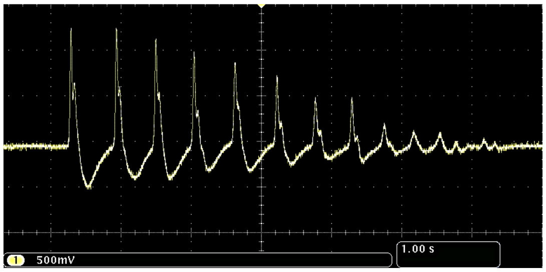


Fig. 5. NiBP sensor output with manual pressure input

The final signal output by the sensor, shown in Fig. 5, gets read into the microcontroller for A/D conversion. It has a baseline at 1V and stays constrained from 0 to 2.5V. All the signal components necessary to read a patient's blood pressure are present aside from the reference pressure the pump is exerting. The implemented sensor can observe the where the systolic and diastolic pressures occur, and referring to the pump pressure at those points identifies the actual pressure values.

B. MSP430 A/D Conversion

After the sensor output has been properly conditioned, the microcontroller must be configured to utilize the ADC10 peripheral. Using EEL 4742C's lab manual as the foundation for the ADC10, the internal clock is calibrated and timers initialized. Then a port and bit must be chosen and initialized in order to receive the analog voltage signal. The control registers must then be configured for utilizing the ADC10. Registers ADC10CTL0 and ADC10CTL1 control how the ADC10 will process the signal. ADC10CTL0 has been configured to compare the incoming voltage signal to 1.5V with a 64xADC10CLKs sample/hold time and a sampling rate limit of approximately 200 ksps. ADC10CTL1's configuration has the ADC10 on Single-channel-single-conversion mode while taking the signal into the port 1 bit 0 (A0 channel) into the form of a 10 bit binary number. ADC10CTL1's sample/hold time has a ADC10 oscillator bit source.

With the control registers configured, then the interrupts must then be implemented by first creating an Interrupt Service Routine (ISR) for them in order to use the interrupts properly. Once an ISR has been established, an interrupt subroutine can be created in order to take in the analog signal, and utilizing ADC10CTL0, take in, convert, and send the signal to whatever viewing terminal used (i.e., UART hyperterminal).

C. SPI Communication to CC3000

The basic wifi application example provided by TI for development with the CC3000 wireless processor was used as a starting point. This package included the application code which provided UART configuration of the processor along with some test utilities. Supplemental configuration code files included the UART driver code, the SPI configuration code, and the host microcontroller driver among others.

The configuration of the microcontroller pins for use with the CC3000 boosterpack were modified for the final design in order to allow use of ADC input channel 0. In particular, the SPI_CS line was relocated from P1.0 (pin 2) of the microcontroller to P2.3 (pin 11). The model for SPI connectivity as referenced from the Texas Instruments CC3000 Datasheet is provided below in **Fig 4**.

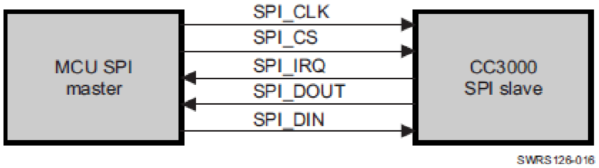


Fig 6. SPI Host Connectivity

The host controller sends the initial configuration data to the CC3000, initializing the smart config feature of the processor in order to connect through a secure wireless network. The IP of the CC3000 device can be displayed over hyperterminal, and the connection can be verified by pinging the CC3000 from any other device on the network.

For further testing of the wireless processor, a jumper is available to move the device into test mode. This allows for a direct serial interface to the CC3000 from the computer. Test pad 1 (TP1) is provided on the board for this purpose. This process also requires the CC3000 radio test tool available on the Texas Instruments website. This is not expected to be required based on the design, utilizing micro strip trace impedance matching and via stitching. Regardless, the capability exists for fine tuning the signal transmission and reception.

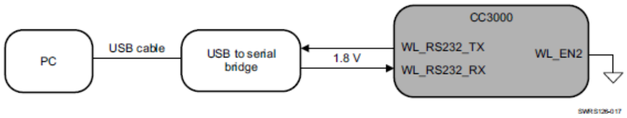


Fig 7. CC3000 Test Mode Serial Interface

Finally, once the CC3000 has been initialized and its IP configured, a socket open command is sent. The microcontroller then sends ADC data via 2 byte packets over the network continuously using UDP protocol. The UDP listener on the user interface end receives these packets and displays the data in two different formats.

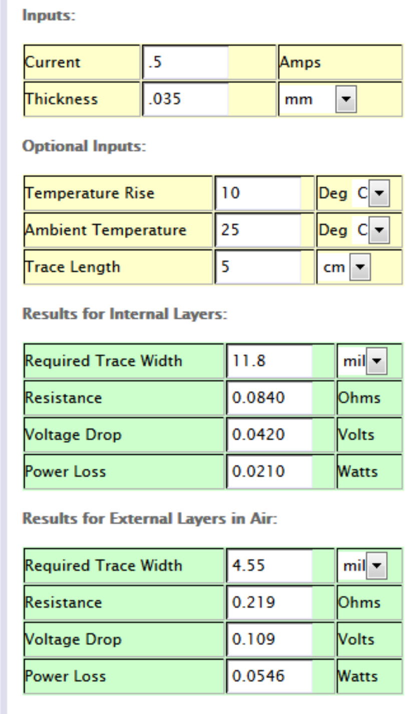
D. Schematic Capture and Board Design

The schematic capture and board design for the SQVID project was performed using Eagle CAD software. Our analog circuit was implemented using the AD620 instrumentation amplifier, and TL084 op amp. The instrumentation amplifier utilizes a 10kΩ potentiometer as its gain resistor to allow for fine tuning the amplitude of the filtered signal.

In an effort to reduce the effects of noise, unused op amp pins were biased at 0V using the dual power supply and resistor pairs. Bulk capacitors were added at the battery terminal, and bypass capacitors were utilized on the power rails of every IC on the board. Via stitching throughout the board was utilized to provide many paths to ground and improve thermal dissipation.

Special attention was given to the CC3000 module and accompanying antenna design. Using miscrostrip trace impedance calculations, the ideal trace width was determined to be 34 mils for 50Ω impedance matching based on other board design criteria including substrate thickness, relative permittivity, and trace thickness.

As suggested by Philips, the board was designed with four layers. This allowed for greater ease in routing the traces and arranging the components, leading to a relatively small overall design. Power calculations were performed to determine the minimum trace width assuming a maximum current much higher than expected (500mA) and the trace width of 12 mils was chosen for all general purpose traces on the board. Nets in the "power" class are given a minimum trace width of 16 mils, and the battery terminal traces are 32 mils.



Inputs:

Current	.5	Amps
Thickness	.035	mm

Optional Inputs:

Temperature Rise	10	Deg C
Ambient Temperature	25	Deg C
Trace Length	5	cm

Results for Internal Layers:

Required Trace Width	11.8	mil
Resistance	0.0840	Ohms
Voltage Drop	0.0420	Volts
Power Loss	0.0210	Watts

Results for External Layers in Air:

Required Trace Width	4.55	mil
Resistance	0.219	Ohms
Voltage Drop	0.109	Volts
Power Loss	0.0546	Watts

Fig. 8. Minimum Trace Width Cacluations

Due to the fact that both positive and negative linear voltage regulators are used, two batteries are required to power the system. 9V batteries were decided upon as the best option for providing the necessary input voltage while maintaining as small a footprint as possible. If the op amp filters had been designed in a single-sided configuration, the second battery requirement may have been avoided. However, the benefit of the dual rails is evident in the versatility of the amplifier/filter. In future development, the pressure transducer may be replaced with other types of sensors. The variable gain on the instrumentation amplifier provides the ability to tune the circuit within the known input limits of the MSP430.

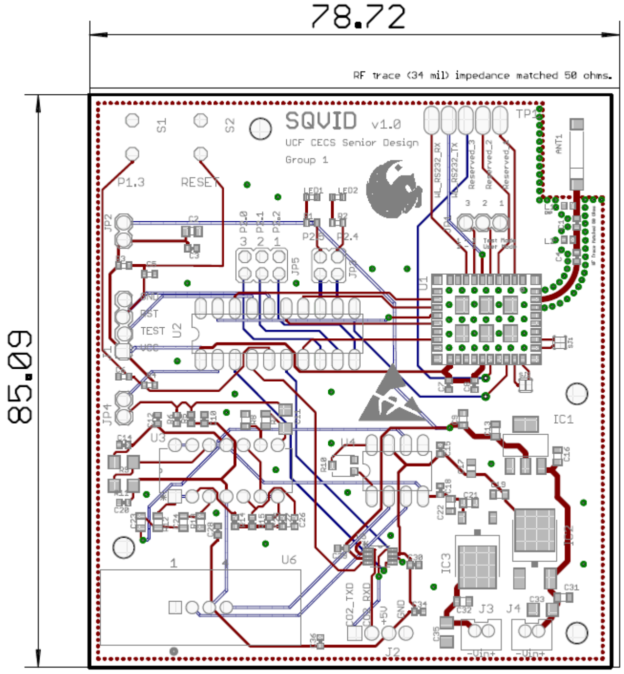


Fig 9. PCB Routing and Dimensions

In the event that the microcontroller is rendered useless, the board contains a 20 pin DIP slot that allows for easy microcontroller replacement. There are also protection schemes in place to prevent the instance of a ruined chip. The is a jumper to break the connection from the analog sensor to the MSP430 in case the maximum output amplitude is not known and the circuit must be tested before connecting to the controller. There is also a serial voltage level shifter in order to facilitate communication between 5V serial devices and the 3.3V microcontroller.

The PCB design also incorporates excess GPIO pins as 2 position headers, allowing for future expansion. A reset switch has been placed on the board, along with a general purpose switch and two general purpose LEDs. The silk screen layer includes a custom UCF pegasus logo, and a static discharge warning logo. The project name and names of each component is present as well.

In sourcing all of the components used for the board, a BOM was updated to include Digi-Key part numbers for each component. Philips was generous enough to produce extra boards, and provided a skilled technician to populate the incredibly small surface mount components in place. The smallest size parts on the board are size 0402.

E. Consolidation Design and Connection Box Modeling

The main concept behind designing a consolidated system is reducing the number parts the user has to manage. So, the ideal system would have all four sensor leads reconstructed into one cable that plugs into a single unit at the foot of the bed. Unfortunately, the reconstruction of MRI-safe sensor leads is beyond the scope of this project. However, the idea of consolidation stays alive with the sensor hub. The case is designed to be as close to one part with one switch as possible.

The general layout of the case and configuration of sensors is to lay the four modules side-by-side and keep the case as flat-packed as possible. Taking the smallest area the sensors could fit into securely and allotting additional space for power supply and miscellaneous electronics (indicator LEDs, switches, etc.) resulted in a case footprint of roughly 12”x10” with a cozy 2” ceiling. For ease of access and assembly, the modules are mounted to a tray that slides into the front of the outer shell and is secured with an external screw.

For the production of the housing, Philips has made available the use of their rapid prototyping lab, complete with a 3D printer. With 3D printing capabilities, the model was designed using CAD sketches and 3D modeling software. The software of choice was PTC Creo 2.0, particularly Creo Parametric.

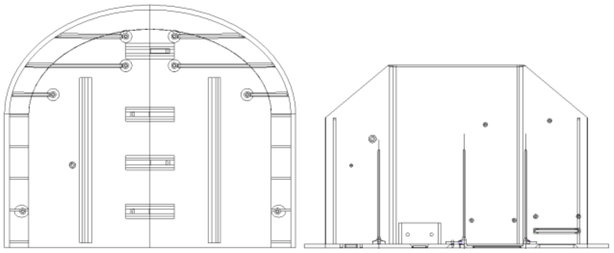


Fig. 10. CAD drawings for case and removable tray (Top view)

Being able to create custom parts contributes greatly to the unifying theme. Though, relying on the use of the 3D printer imposes a few constraints on the model’s dimensions and mechanics. One of which is the printer’s 7.8”x11” printing stage with a 5” maximum height requires the 12”x10”x2” model be split into smaller parts. The case being split into parts, as opposed to a solid single-cut shell, is inherently less structurally sound but this problem is alleviated with extra support bridging the seams along the outermost shell and ribbing throughout the inside (as seen in Fig. 11).

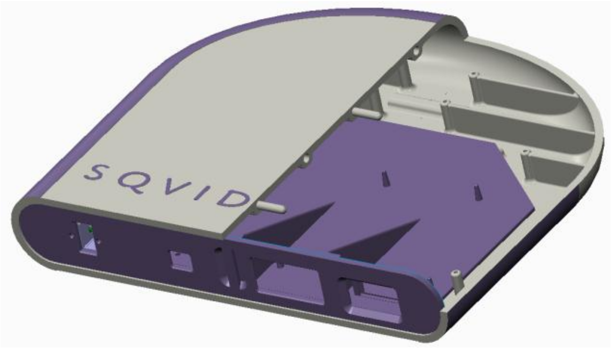


Fig. 11. 3D model of housing (section removed to reveal inside)

The other main factor taken into consideration was the amount of material being used. The plastics used in the printer are a substantial expense, so it is good practice to conserve material as much as possible without sacrificing too much strength. As mentioned earlier, ribbing along the hollow insides is an efficient and sturdy support.

With STEP files containing dimensions for the SpO2, ECG, and EtCO2 sensors and the known dimensions of the PCB and battery packs, the model shown in Fig. 11 was tailored to secure all the parts in as small a space as possible. The STL (stereolithography) files were then sent to the printer and the model was realized.

VI. SOFTWARE DESIGN

The software portion of this project refers to a standalone graphical user interface running on a computer as well as the programming that enables the microcontroller and wireless module to gather and transmit data to the GUI. Nicknamed the Intelligent Navigation Controller (or “INC”), the program allows the user to see the data coming in from the NiBP cuff both graphically and numerically. The two devices communicate using UDP protocol, enabling fast and accurate data exchange.

A. SQVID INC

The SQVID INC software program is written in the language of C#, using Visual Studio 2012 and is designed to run on a standard Windows operating system. This language and IDE were chosen due to the near limitless possibilities that accompany the numerous libraries available for use. The program functions as a simple UDP listener, waiting for socket connections from a second device. The IP address of the listener and the port number are configurable. For the purpose of this project the program listens for any IP address attempting to send data packets on the specified port. UDP protocol was chosen due to simplicity purposes. A handshake is not needed between devices and timing of data delivery was of greater concern than order of packets, as with TCP protocol.

The graphical display of data used in INC is mainly for proof of concept purposes and does not show the typical blood pressure reading in mmHg. The waveform displays the voltage reading similar to an oscilloscope. In order to calculate and display an actual blood pressure reading a pump would have been required to regulate pressure, and several calculations would have had to be conducted to determine both the systolic and diastolic blood pressures. Due to time constraints the team was not able to implement this stage of development.

B. Microcontroller Programming

The microcontroller used for this project was programmed using TI’s Code Composer Studio. Data received from the NiBP cuff sensor comes into the ADC10 memory register and from there is converted into a packet format and sent wirelessly using TI’s CC3000 module. The CC3000 is told which port to send the data to and opens the specified socket to send the packet. This process runs in a continuous loop as soon as the microcontroller receives power. The module is capable of sending up to 8 bytes of data in a single packet. This would make expansion to include other sensors relatively feasible.

C. Networking

In order for both INC and the microcontroller to communicate all were set up on the same wireless network and given specific IP addresses for debugging purposes. Using TI’s SmartConfig process the CC3000 can be connected to any Wi-Fi network, with or without security settings enabled. Due to the prototype nature of this project, security was not a primary concern.

VII. CONCLUSION

The SQVID Project demonstrates the ability to enhance patient comfort by using affordable, easily programmable technology, and generally available “off-the-shelf” equipment to transmit vital signals wirelessly. With the exception of the proprietary materials provided by the Philips Company this project demonstrates the ability to solve a real world problem using everyday materials and a little ingenuity.

The SQVID team learned a great deal about how to cooperate and utilize resources when faced with unforgiving deadlines and unfamiliar scenarios. Working with such a reputable company taught the team how to interact in a professional setting. More importantly, the team learned how to communicate ideas and questions in such a way that feedback became constructive and beneficial.

The research phase that took place prior to prototype development was eye opening and, while not necessarily more difficult than actual development, demanded more discipline from each member of the team than expected. From this experience the team learned the importance of detailed planning and the value of research, which became strikingly apparent when it came time to construct, build, and program the prototype.

From this overall experience the SQVID team feels much more prepared for the “real world”. Having now experienced the difference between scholarly learning and the reality of applying such principles, a career in engineering is not only more tempting but finally attainable.

ACKNOWLEDGEMENT

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