Design and Construction of a Quad Rat Vitals Monitor

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Team Members:

Matthew Bollom – Team Leader

Caitlyn Collins – Communicator

Robert Bjerregaard – BSAC

Derek Klavas – BWIG

Client:

Alex Converse, Ph.D.

Advisor:

Peter Klomberg

Abstract

The design and construction of a rat vitals monitoring system is essential for simultaneously monitoring multiple anesthetized rats. Our client currently runs PET scans on four rats concurrently, and the scans can last up to two hours. During the two hour scans, the rats are under anesthesia and doses of the anesthesia medications must be adjusted based on the rats' vitals. The client desires to have an accurate, reliable, and easy to use rat vital monitoring device to aid in this process. The current design for this monitoring device includes force-sensing resistors (FSR) for monitoring breathing rate, thermistors to monitor rectal temperatures, and pulse oximeters to monitor SpO_2 levels and heart rates. The design also includes an easy to read graphical user interface (GUI) that displays running averages of the four vitals, history graphs of the four vitals, and live traces of heart rate and breathing rate. Data will be stored for later analysis.

Table of Contents

Introduction

Background

The design team's client currently runs positron emission tomography (PET) scans on rats to monitor the location of positron-emitting radionuclides (tracers) within the rats' brains. These scans can last up to two hours, and during the scans the rats are under anesthesia (Figure 1). The client and his assistant must monitor the vitals of the rats during these scans to ensure that they endure no harm while under anesthesia. Currently, the client monitors the rats qualitatively. The skin color of the rats is observed and recorded to ensure that the rats are receiving enough oxygen. The rats' breathing rates are monitored simply by observation, and body temperature is monitored by touch. Currently, heart rate and blood oxygen saturation are not monitored. The client would like to be able to obtain quantitative measurements of multiple vitals of each rat during the PET scans.

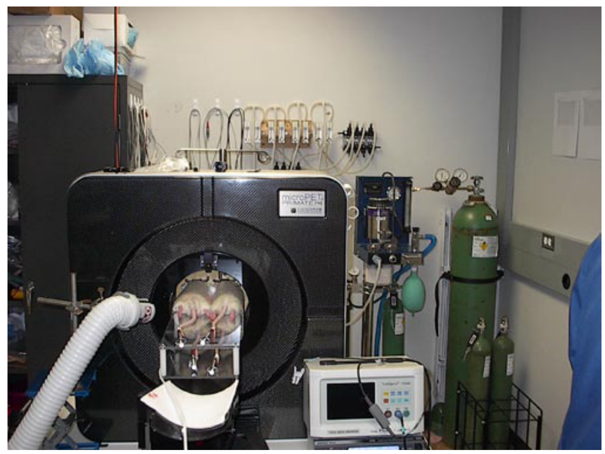

Figure 1: This picture shows four rats in the PET scanner at the client's laboratory. The rats are oriented in a two by two square [1].

Since the PET scanner is designed for monkeys instead of rats, it is large enough to simultaneously scan up to four rats at a time. The client always scans four rats at a time to keep costs down. The radiotracers used in the rats are expensive to produce and decay relatively quickly, so producing a single set of radiotracers for four rats is more cost effective than producing four separate sets for four rats. Due to these restrictions, the vital monitoring device must be able to monitor four rats simultaneously. While under anesthesia, the rats are wrapped in bubble wrap to keep them warm, because the PET scanner is located in a cold room.

Existing Devices

There is currently one device on the market that is capable of measuring the desired vitals of rats and mice (not including temperature). This is a pulse oximeter designed specifically for rats and mice, called MouseOx, produced by Starr Life Sciences (Figure 2). This device is not capable of monitoring four rats simultaneously, and is priced at $7000 for one device [2]. This is not what the client is looking for because of the high cost and the inability of the device to monitor multiple rats. A different pulse oximeter, produced by Nellcor (the Nellcor N-100), was tested for blood oxygen saturation (SaO_2) level accuracy when attached to a rat's tail. When SaO_2 levels were between 75% and 95%, this particular pulse oximeter was capable of measuring SaO_2 levels relatively accurately. When compared to the blood sample analysis, the N-100 measured SaO_2 levels with a standard deviation of ±5.7% [3].

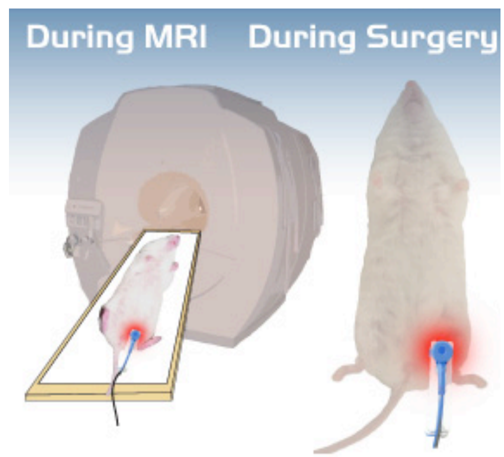

Figure 2: Pulse oximeter produced by Starr Life Sciences capable of measuring heart rate, breathing rate, and SaO2 levels [2].

The client occasionally uses a pulse oximeter designed for small animals, specifically monkeys and dogs, but is unable to consistently obtain accurate data. This is because of the high heart rate and low blood volume of rats. The heart rates of these rats can rise above 300 beats per minute, and this pulse oximeter was not designed with a high enough sampling rate to measure these pulses or the corresponding oxygen saturation. Therefore, the monitoring device must be able to measure vitals outside the normal ranges of small animals or humans.

Client Requirements

The vitals monitor must be able to simultaneously monitor SaO_2 levels, heart rates, respiratory rates, and rectal temperatures of four rats simultaneously. SaO_2 levels must be monitored with an accuracy of ±2%. Heart rates of up to 500 beats per minute and respiratory rates of up to 30 breaths per minute must also be monitored. Rectal temperatures of 33 to 38 degrees Celsius (93 – 100 degrees Fahrenheit) are to be monitored as well. All four vitals of all four rats must be simultaneously displayed in a user-friendly graphical user interface (GUI) on one screen. All probes used to monitor rat vitals must be non-invasive and cause no harm to the rats. Finally, no component of the device can pass the cranial end of the sternum, because the PET scans are focused around the cranial region of the rats.

Motivation

Throughout the duration of the client's experiments, the rats are under heavy doses of anesthesia, which require manual adjustments by the laboratory assistants. The development of a system that readily displays the current values of each vital sign along with the option to view the history of each vital would be extremely beneficial. The laboratory assistants must be informed in a timely manner if any of the four vital signs enter critical ranges, in order that proper adjustments to the anesthesia can be made.

Currently there is no accurate, cost-effective method to monitor and display all four vital signs simultaneously. Since his research is based off of a four-rat setup, the existing devices previously mentioned will not suffice. It would be impractical for him to purchase four of the existing devices that are priced at or above $7000. The total budget of $4000 should therefore be considered throughout the design process and while planning to manufacture four final prototypes. Furthermore, the GUI that is to display the four vital traces must be specifically engineered according to the type of data it will be receiving from the circuit elements and corresponding probes designed to monitor each vital sign. The design team's goal is to design an inexpensive, easily operable prototype that incorporates circuit based monitoring systems along with a LabVIEW GUI to display the signals received from each monitoring system.

Previous Semester's Work [4]

The focus of the previous semester was to finalize the sensors for temperature and breathing rate along with developing algorithms that would accurately interpret the breathing rate and temperature signals. Ultimately, the team chose to utilize the inherent properties of force sensing resistors (FSRs) and thermistors (Figures 3 and 4) to determine breathing rate and rectal temperature, respectively. FSRs alter their internal resistance when pressure is applied, so as the rat breathes its chest will exert various amounts of pressure and the output

Figure 3: Force sensing resistor [4]

Figure 4: Thermistor [4]

voltage will then be proportional to the pressure applied. Thermistors also possess an internal resistance that responds to changes in temperature. Just as in FSRs, the changes in resistance within the thermistor correlate to changes in output voltage.

LabVIEW was used to process all of the analog signals sent to the computer from the FSRs as well as the thermistors. Breathing rate was determined using a signal comparative algorithm. The average voltage received from a given FSR over a period of 10 seconds is compared to incoming raw data. When two sequential time points fall above and below the average value the time gets recorded and stored in an array. The breathing rate is calculated by determining the total time between the past 11 time points within the array, and dividing that value by 10 in order to determine the time between breaths. In order to process the temperature data, LabVIEW simply converts the incoming voltage into a live temperature based on the linear relationship between voltage and temperature within the thermistor.

Along with breathing rate and rectal temperature, steps were taken to develop a pulse oximeter circuit as well as individual pulse oximeter probes (Figure 5) with the help of a graduate student. The probe itself was made up of an assembly of excised components from an existing disposable Nellcor pulse oximeter probe. The harvested LEDs and photodiode were mounted onto a plastic clip opposite one another using a commercially available two-part epoxy. This configuration utilizes transmittance pulse oximetry as

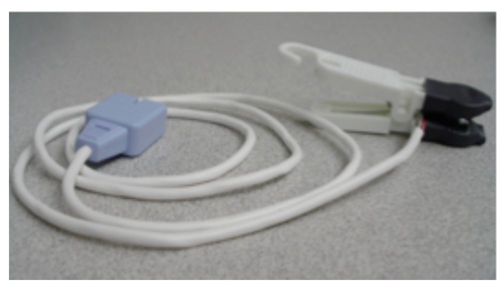

Figure 5: Pulse oximeter probe [4]

opposed to reflectance pulse oximetry. By utilizing transmittance, the output signal is stronger because it is not dependent on the amount of light reflected [5].

Finally, the team was able to program a graphical user interface (GUI). The GUI (Figure 6, next page) displays breathing rate and blood oxygen saturation (SaO_2) as live traces, as well as summary values and history graphs for all four vitals. Although the team was able to integrate the FSR and thermistor signals, work on integrating the pulse oximeter signal was not addressed.

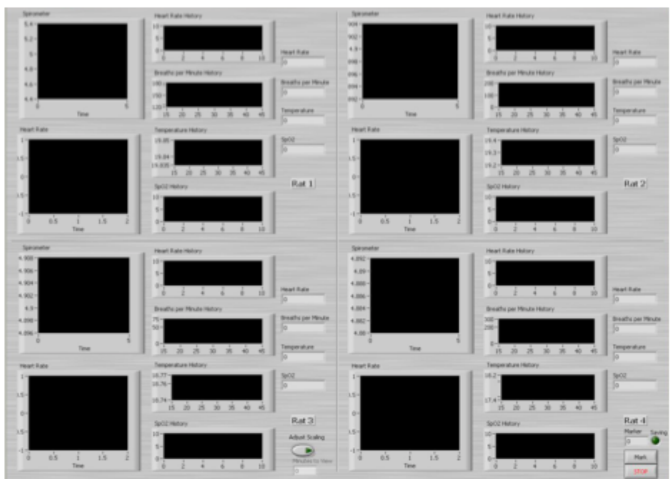

Figure 6: LabVIEW graphical user interface [4]

Midsemester Summary

During the first half of the semester, the team began programming the LabVIEW interface to receive the pulse oximeter data for signal processing. The team also decided to design the circuit boards to contain one pulse oximeter, one thermistor, and one FSR per board so that each rat would have its own board. A method was developed to integrate the signals from each probe into one data stream that would be sent to LabVIEW for processing. Algorithms were developed to process the pulse oximeter data and use calibration curves to calculate SaO_2 values. The calculated SaO_2 values were not accurate using these algorithms because they did not take into account peak-to-peak absorbance changes, which is necessary to calculate SaO_2 of arterial blood and not venous blood. In order to calculate peak-to-peak changes, accurate peaks need to be detected. This was possible with humans, but up until this point the team had not successfully detected peaks using the pulse oximeter on a rat. This is why the team decided to shift its focus to obtaining an accurate pulse waveform using one of the custom pulse oximeter probes on a rat.

Other considerations during the first half of the semester included communication between the circuit boards and LabVIEW, as well as constructing a housing unit for the circuit boards. The team considered using Universal Serial Bus (USB), Wireless Fidelity (Wi-Fi™), and Bluetooth® for sending data from the circuit boards to LabVIEW. Wi-Fi was chosen over the other two options because of its high communication speed and the aesthetics of having wireless data transmission in the laboratory setting. The plan was to have each of the four boards (one per rat) send its data via serial or USB to a 'motherboard' containing a Wi-Fi chip. The 'motherboard' would process these four data streams into one data stream that it would send via Wi-Fi to the laptop and into LabVIEW. In order to do this, the team began working with Wi-Fi data transmission during the remainder of the semester. See the Appendix Communications Summary for more details.

The team also began designing different housing units that could be used after finishing the four circuit boards and the 'motherboard.' The three design options included the Pegged 3 x 3, the Toaster Oven, and the Bunk Bed designs. The Toaster Oven was chosen based on its high scores in ergonomics and durability. This design scored high in ergonomics because it would allow for easy removal of the circuit boards, and the boards would also be very secure once in place. The unit would be durable because the four-piece component is structurally sound and the hinged two-piece component would be very stable when the unit is closed (see Appendix for picture). Since the team could not be sure of the dimensions of the circuit boards until after receiving them, the team decided to wait to construct the housing until the remainder of the project was completed.

Final Design

This semester, progress was made towards a final working prototype in three major areas. A circuit board was designed that contains one pulse oximeter, thermistor, and FSR circuit. Signal processing algorithms were developed to process pulse oximeter data in LabVIEW, as well as transmit data from a board via Wi-Fi. Finally, a new custom pulse oximeter probe was designed and two copies were produced. The final design currently consists of two functioning pulse oximeter boards (also containing the thermistor and FSR circuits), a LabVIEW interface that can read data from all three probes through the printed circuit boards, four thermistors, four FSRs, and two pulse oximeter probes. Very clearly, there is more work that has yet to be done to finish the prototype.

Circuit Boards

Initially the board schematic only included the pulse oximeter circuitry, but the team worked to incorporate the existing FSR and thermistor circuitry to reduce the number of boards to be printed. The team opted to use surface mount parts in order to make the boards smaller. The boards' final physical footprint is an area of 8.75 square inches, much smaller than originally expected. The boards themselves were printed via PCB Express after the Eagle schematic was finalized.

The circuit components (i.e. capacitors, resistors, microcontrollers, etc.) used are surface mount parts, with the exception of the majority of the external connections (i.e. mini circular din connectors, D-sub connector, power jack, etc.). These use a right angle through-hole mounting type.

The communication across the circuit board is regulated by a microcontroller. The microcontroller was initially programmed with PMP, a Pascal editor, and programmed using a meLabs programmer from microEngineering Labs, Inc. In the future, the design team hopes to convert the microcontroller code to C due to its higher degree of flexibility as well as modernization.

The circuit components were soldered in place with relative ease, but some errors within the board were determined after further evaluation. Unfortunately, Eagle made an error during the design of the boards, but with the addition of a small wire, that particular problem was resolved. Another issue discovered after printing was that the pin out for the D-sub connector (pulse oximeter probe receptacle) was flipped so that when mounted on the top next to the other FSR and thermistor receptacles it received improper input. This issue was resolved by mounting the D-sub connector on the bottom of the board. The team desired to maintain uniformity in the front face of the board where the connectors are all mounted, so the D-sub was remounted on top of the board and a crossover cable was created in order to bypass the pin out error. It is also important to note that the board requires a true ground, something the team realized near the end of the semester.

Pulse Oximeter

The circuit boards that were designed and printed this semester each contain receptacles for one pulse oximeter probe, one thermistor, and one FSR. There is also an input for power and a programming terminal. Since each board is responsible for sensing five different waveforms (red, infrared, ambient, temperature, and respiration) and the analog to digital converter (ADC) is only capable of processing one data point at a time, each waveform must have its own state. The microcontroller controls these states and each state has its own leading character, such as "I" for infrared or "R" for red. Figure 7 illustrates how these different states are read and processed. The "state control" cycles between the five different states. When a state is active, such as pulse oximeter – red, the red LED is flashed on the pulse oximeter probe while the photodiode senses the transmission of the red light, and the ADC reads from its pulse oximeter input and converts the signal to a digital value. This value is then labeled with the leading character "R" (for red) and sent via serial/USB to the computer running LabVIEW. LabVIEW recognizes the signal as part of the red pulse oximeter waveform and processes this signal to produce a graph of pulse and displays values for heart rate and SaO_2. As the microcontroller cycles between five states, each waveform is transmitted to LabVIEW via the ADC.

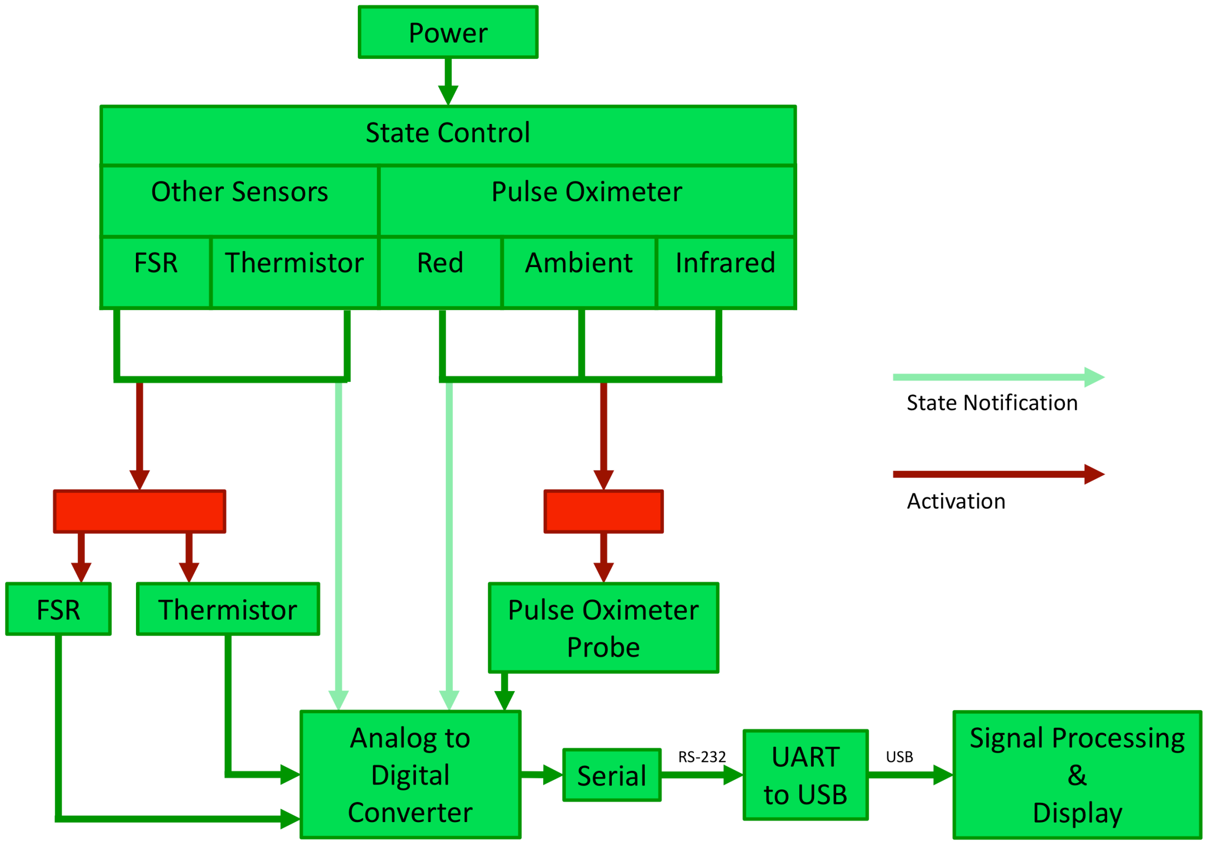

Figure 7: Block diagram of pulse oximeter

The thermistor component of the circuit board schematic was changed so that its output would remain in the acceptable range of 0 to 4.1 V (as specified by the ADC of the microcontroller). The values of R7, R50, and R6 seen in Figure 8 were changed so that with an input of 5 V (VDD), the output will range from 0.5 to 1.5 V over a range of temperatures that the client desires to monitor (32 to 40 degrees Celsius). Extra capacitors (C24 and C37) were added and function as low-pass filters to reduce high-frequency noise and control the bandwidth levels into the ADC.

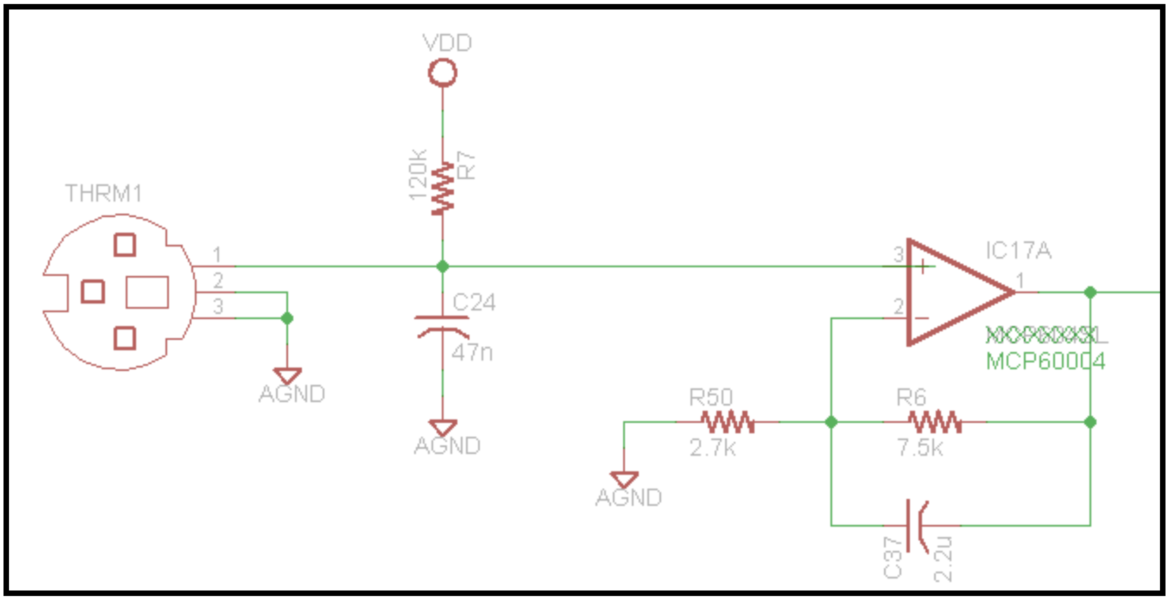

Figure 8. Eagle schematic of thermistor circuit layout

Pulse Oximeter Probe

A new pulse oximeter probe has been designed as an attempt to improve the acquired data for pulse rate and blood SaO_2 levels. This design is fairly robust as it only incorporates a plastic spring-loaded clip with LEDs and photodiodes (excised from an existing Nellcor human pulse oximeter) mounted on it. It is important to note that the spring inside the clip has been altered to assure that the grip does not impede circulation in the rat's hind paw. While last semester's design was able to successfully pick up a signal from the rat's heart beat, the LED and photodiode alignment may have been slightly inconsistent and the probe was not isolating the elements from ambient light. The new design, shown in Figure 9, contains the LEDs and photodiode mounted on the reverse side of the head of the clip, and allows red/infrared light to pass through a ¼ inch hole drilled through the head of the clip. The goal of using this type of design is to ensure that the LEDs and photodiode are directly in line with each other, and to isolate as much ambient light as possible. The shielding that typically surrounds the photodiode was deemed ineffective and was extracted to improve the ease of manfacture.

The manufacturing process started by drilling the ¼ inch hole into the head of each clip. This was accomplished by placing a piece of small wood, roughly the thickness of a rat's hind paw, in between the head of the clip and drilling vertically with a ¼ inch drill bit on a drill press.

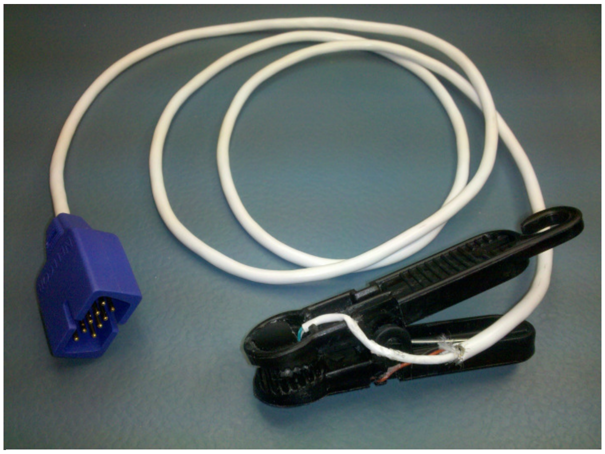
Figure 9: New pulse oximeter probe

Next, the LEDs and photodiode were adhered with two-part epoxy to a small plastic washer that had been sanded down to match the exact shape of the head of the clip. This plastic washer containing the mounted LEDs and photodiode was then adhered with epoxy to the exterior sides of the head of the clip while making sure that the LEDs and photodiode were completely within the ¼ inch hole. Last, grooves were filed into the probe to allow for the exposed wires to be properly secured to the exterior of the probe.

As previously mentioned, the major advantages of this design are the proper alignment of the LEDs and photodiode, isolation of ambient light from the LEDs and photodiode, reduced bulkiness, and simplicity. However, the major disadvantages of this new design are the lack of shielding surrounding the photodiode that may result in increased noise, and the vulnerability of the entire probe if a single wire leading to either the LEDs or photodiode is compromised.

Wi-Fi

After the team toured the client's laboratory, it was determined that wireless data transmission might be desirable because of the setup. USB or serial data transmission would require at least four cables of over 15 feet long (because they needed to be taped to the floor). Wireless would ease the additional clutter this project would add to the laboratory. After some research, a promising option was found – the Gumstix.

The team was able to obtain a Gumstix for a short time. Visual inspection immediately presented a potential problem: there were only two RS-232 (serial) ports available for use. The Gumstix includes three RS-232 ports, but one port is for accessing, controlling, and programming the Gumstix from a remote computer. The other two are available for use with external hardware. In order to pursue the team's initial idea, four available RS-232 ports would be required. Without four ports, the boards would have to be daisy-chained, which would require additional hardware. However, the team was able to connect to the Gumstix and enable Wi-Fi. Problems were encountered when trying to remotely access the Gumstix via Wi-Fi, something that would be essential in the programming of a Wi-Fi server. Unfortunately due to circumstances beyond the team's control, the Gumstix had to be returned.

The team decided to utilize a secondary computer as a Wi-Fi server before the client was asked to purchase an additional piece of hardware. It was necessary that there be a proof of concept to make sure we were on the right track with ideas. A computer was borrowed from the Department of Biomedical Engineering, and Linux (Fedora Core) was installed on it. It was also decided that a further understanding of the Wi-Fi protocol was needed.

Research yielded two protocols the team could consider. Transmission Control Protocol (TCP) is the most commonly used protocol. TCP guarantees delivery of a packet, a small unit of data sent over a network. It does this through a bidirectional communication link between the host and the client. If the client does not receive a packet, the host resends it until it has been received. The second option, User Datagram Protocol (UDP) is unidirectional. The host will continually send data to the client without regard as to whether the client is receiving all the data. Consequently, UDP offers faster transmission times than TCP. UDP is often used for music or video streaming; if some data is not received, that part that is not received will most likely be done with by the time the data could be resent [15]. After considering the options, the team has decided to go forward with TCP because of the transmission guarantee. If some data is missing, the resulting calculations will no longer be accurate, which is important in this project.

During the course of this research, the team encountered several other terms which are important to define. When designing TCP servers, a client makes a request to a host to form a socket. A socket is a constant connection between two computers. The host is listening on a specific port for any client requests. When it receives those requests, it binds the socket and data communication begins. When either the host or the client terminates the connection, the socket is closed. A host can listen on the same port for multiple connections and maintain simultaneous connections if necessary.

The team has developed a TCP server that is accessible via Wi-Fi. The decision was made to use PHP to create the TCP server because one of the team's members was familiar with it. In the future, the team hopes to convert this code to C because C is much more likely to run on a Gumstix or other single board computer. The PHP code for this server can be found in the Appendix. This code opens port 10230 on the host computer and listens for the requests.

When the client makes the request, it binds the socket. Two commands were built into the server: sending *details* to the host will return data about the current device operating and *data* will start transmitting data from the device. In order not to crash the server, data is collected for one second, and is then sent to the client. This process continues for as long as the client is listening for the data. The server currently only accepts one connection at a time for simplicity, but it is a minor detail to add the capacity for simultaneous connections if desired. If configured correctly, this server could be accessible from anywhere in the world due to the unique identifier issued to the host computer when it connects to the Internet.

To receive this data, the team built a LabVIEW VI. LabVIEW has native functions for retrieving data via a TCP connection. After the initial connection, the data was continuously received, and then parsed and displayed. However, because the server is only transmitting data every second, it does not appear as real time as the team desires. This, however, can be fixed by modifying both the server and client software.

The proof of concept has been developed for wireless data transmission using an intermediate computer. Very clearly, such an intermediate computer is not ideal because of its size and additional power consumption. After some more development and porting to a smaller device such as a Gumstix or other single board computer, such a concept can be implemented in the final prototype.

Client Software

Most of the team's focus this semester was on pulse oximeter hardware. The team continued to utilize National Instrument's LabVIEW as the client software. Most client software development was limited to simple interfaces that allowed them to determine if the data that was being received from the pulse oximeter was reasonable. When the pulse oximeter was connected via serial, it was a simple matter to configure the connection, and then read the resulting data. When the circuit boards arrived and were built, the team switched to using USB because of its common use in modern life. To avoid the extra hassle of programming USB, an integrated circuit chip was purchased the converted serial data to USB. This chip helped speed development progress. On the software side, this USB connection was handled exactly like a serial connection.

However, because of practical limitations on LabVIEW, the team also devoted some time into looking into alternative software options. Because a rat's pulse is much higher than a human's, the pulse oximeter must sample and transmit the data at a much faster rate than for human pulse oximeters. LabVIEW has limitations on how fast it can receive data. This also depends on the computer's hardware. During the team's testing, it appears as if LabVIEW cannot receive serial data as fast as it was obtained using other methods, such as a terminal emulation program. LabVIEW probably has some overhead that cannot be minimized and this is causing the performance degradation.

Java, an open source programming language developed by Sun Microsystems, is an alternative option the team considered. For most people, open source equates to free. While that is true, open source software allows anyone to make changes to the underlying code and frameworks and the redistribute those changes. Java includes capabilities to acquire data from a serial port through an additional library – the Java Communication API. However, this library does not include support for Windows, but some developers added Windows support in RXTX [16]. The team has established communication with another undergraduate design team that is utilizing this library. That team has reported great success with using Java and RXTX for serial communication.

Java also includes the abilities to create Graphical User Interfaces (GUI). Such interfaces can be made to appear as if they are native applications and all functionality users have come to expect from interfaces is present. For example, it is possible to minimize the application window and resize it. Java also includes support for threading. Threading allows a program to perform multiple actions at the same time without performance problems. For example, one thread could collect data from the serial port, another thread could perform signal processing, and another thread could update the GUI. All threads operate independently of each other. When the switch to wireless is complete, TCP methods are included in Java. Java is extremely well documented, so it is a simple matter to determine what needs to happen. Finally, a team member has considerable experience with Java, so the team will not have to learn a new programming language.

Testing

Testing this semester was conducted on a single anesthetized rat under the supervision of Elizabeth Ehlers of the Waisman Center, and on a single anesthetized rat in the lab of Justin Williams from the University of Wisconsin-Madison Department of Biomedical Engineering. The primary focus of all testing was directed towards the pulse oximeter aspect of the design, with the goal of obtaining a pulse waveform from the anesthetized rat.

To simplify the testing trials, a simple LabVIEW GUI was created to display the ambient light signal, red light minus ambient light signal, and infrared light minus ambient light signal. Doing this allows the team to focus on each component of the pulse oximeter individually in order to easily diagnosis the source of any potential problems. For example, initial testing with the pulse oximeter probe manufactured last semester yielded poor results due to the fact that the current running through the LEDs was too high and caused the photodiode to saturate when illuminated by red light. Once the LED current was adjusted to an adequate level, a stream of data was obtained that detected the pulse waveform of the anesthetized rat, shown in Figure 10.

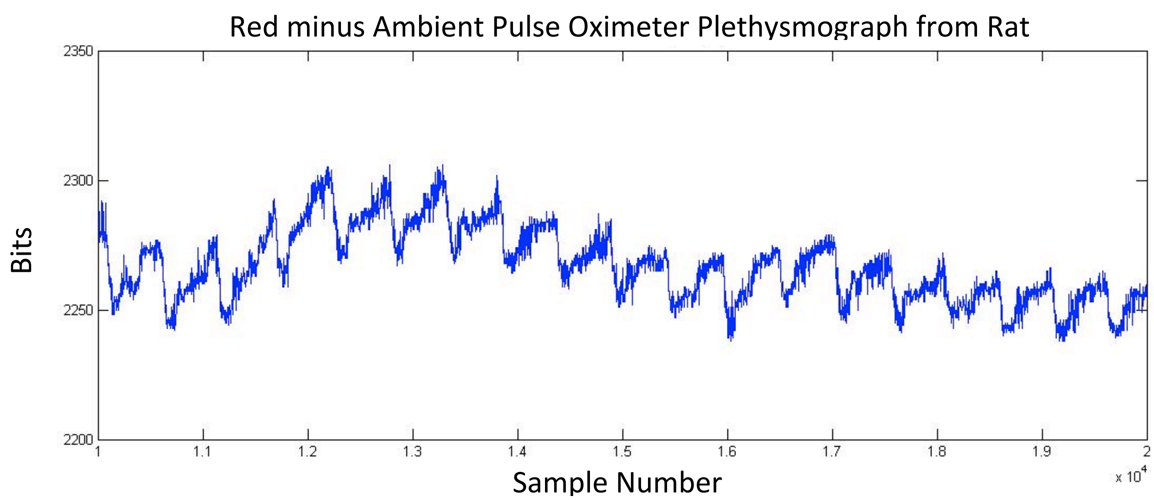

Figure 10: Testing data

Further testing was conducted after the newly designed probes had been assembled. Unfortunately these testing trials yielded poor data because the power supply to the circuit board failed to contain a ground, resulting in extremely noisy and unrecognizable data beyond the point of recovery through filtering (see Figure 11). Nonetheless, because the new probes were able to display a human pulse waveform on an oscilloscope, the team is confident that new probes can indeed obtain a rat pulse waveform if the power supply is properly grounded and the amount of noise (from 60 Hz sources and ambient light) is kept to a minimum.

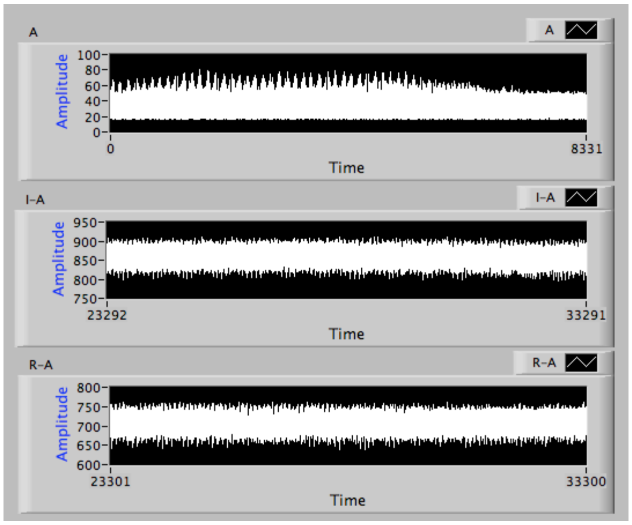

Figure 11: Ungrounded circuit board output

Future testing will continue to work on perfecting the signal obtained from both infrared and red light. After a single rat's pulse can be displayed in LabVIEW, the team will move forward with testing all components of the final design simultaneously in a realistic research setting. This final testing will be the last verification needed before the team can confidently tender a final product to the client that meets each of the specified design criteria.

Ergonomics

When designing the pulse oximeter communication network and the newly designed pulse oximeter probes, human interaction with the vitals monitor was a major factor. The device must be, at a minimum, operable by someone with computer knowledge as their only experience with electronics. The LabVIEW GUI has already been designed to be exceptionally user-friendly, and all measurement probes require minimal setup with respect to each animal, and are simply plugged into the circuit housing unit. As seen in Figure 1 (pg. 5), there already is a significant amount of equipment present in the laboratory setting that our client and his research assistants work in. Therefore, the device should not add any clutter to the research environment. There will already be 12 external wires, one for each probe, and a cord for the power supply, so any additional external wiring should be avoided at all costs**.** This spatial constraint and the user-friendliness requirement are the main reasons why the team used the familiar Wi-Fi option for the method of data transfer (in addition to its high speed).

As previously explained, the pulse oximeter probes have a fairly simple and robust design. This ensures that the research assistants are not required to perform any alterations or extraneous manipulations when applying the clip the hind paw of the rats. Additionally, the probe is easy to clean after each use and the LED/photodiode are not exposed to any cleaning liquids as they are encased within plastic. The spring in each clip has been altered not only to reduce the pressure applied to the rat's paw, but also to ensure that the user does not have to provide a significant amount of force when applying the probe onto the animal. Throughout our testing trials, the person applying the probe to the paw of the rat have confirmed that the application is extremely easy and manageable. After each testing session, the research assistant was able to effectively clean the probe by using a small alcohol wipe.

Ethical Considerations

Animal safety is the main ethical consideration in the design of a quad rat vitals monitor. The client has specified that all probes used in the final design should be non-invasive and cause no harm to the rats. During each test run performed this semester, all governmental and university standards regarding proper animal care were carefully followed [14]. In the future, when a housing device for the circuit boards is manufactured, the animals will be completely isolated from any wiring or circuit elements that could cause harm. To finish, it is important to note that the design of a quad rat vitals monitor is to serve the sole purpose of a diagnostic tool, and should not replace any standard small animal laboratory procedures. The final design will be able to accurately notify the researcher when the vital sign of any rat enters a critical range; however, it is not designed to prevent any rat from entering into such a critical range**.**

Cost Analysis

Funding for Quad Rat Vitals Monitor went towards the circuit boards, power supply, and the laptop that runs LabVIEW. The custom circuit boards were ordered from PCB Express and cost $538 for 20 boards. The client purchased extra boards so that other labs on campus that might want a similar product would not need to order the boards separately (the circuit boards become less expensive as more are purchased). Circuit components, including microcontrollers, resistors, etc., were purchased from Mouser and Digi-Key® costing $26.40 and $371.14, respectively. The variable power supply that supplies 7.5 volts to the boards was purchased from RadioShack® and costs $30.55. The Lenovo® laptop was purchased by the client through the university and costs $660. The total budget for the project this semester was $1626.09. Breakdown of the budget can be seen in Table 1.

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Table 1: Analysis of semester budget

Vendor	Item	Cost
Mouser	Circuit Components	$26.40
Digi-Key®	Circuit Components	$371.14
PCB Express	Circuit Boards	$538.00
RadioShack®	Power Supply	$30.55
Client	Lenovo® Laptop	$660.00
Total		**$1626.09**

Vision for the Project

When this project was first started in Fall 2008, no one could have predicted the turns this project has taken. This is certainly an ambitious project that presents many difficult hurdles, but it also presents the opportunity for learning. After this semester, most of the hardware is in place. Minor adjustments will still need to be made to the pulse oximeter hardware and most of what remains is software. This software includes the microcontroller programming and client software. Client software includes filtering, signal processing algorithms, and a graphical user interface. To guide future design, the team presents their vision for the project.

Mouse Ox is a product that does part of what this project aims to do. It is expensive at about $7000 for one machine, and this does not monitor temperature. For the client to utilize this setup in his laboratory, he would require four of these devices, plus another method to monitor temperatures. The team has aimed to make this project a reasonable expense for him as well as anyone else who may desire such a system. Hardware was designed with extensibility in mind; the system should work as well for monitoring one rat as it does for four rats. While an interface redesign would be needed for a one rat system, such details are trivial and would not require much time and effort to develop once the frameworks are in place.

A major issue facing the team this semester was probe design. It has become readily apparent that a good probe will collect good data. Unfortunately, this was realized too late in the semester. However, some late research turned up differences between the probes designed by the team and professional probes. Most professional animal probes utilize reflectance sensors while the team's utilized transmittance. It should be a high priority to design a probe early in the semester since success will most likely hinge on this. An alternative option would be to obtain a professional animal pulse oximeter probe, determine the proper connections, and build a crossover cable to match the probe to the pinouts of the pulse oximeter board.

After a good signal is obtained on a rat (possibly with some filters applied), the algorithms for pulse and blood oxygen saturation need to be implemented. Temperature and breathing rate have already been implemented, but will need to be ported to the new, final interface. Calculating pulse is simple – find the number of peaks in a set time period (most often the red signal) and divide it by time. Calculating blood oxygen saturation is more difficult. This requires the peak and valley values of the red and infrared signal. When these have been determined, the following equations [5] are used:

$$R = \frac{\ln \frac{R_{peak}}{R_{valley}}}{\ln \frac{IR_{peak}}{IR_{valley}}}$$

$$SaO_2 = \frac{\varepsilon_{Hb}(\lambda_R) - \varepsilon_{Hb}(\lambda_{IR})R}{\varepsilon_{Hb}(\lambda_R) - \varepsilon_{HbO_2}(\lambda_R) + [\varepsilon_{HbO_2}(\lambda_{IR}) - \varepsilon_{Hb}(\lambda_{IR})]R}$$

where ε is the standard extinction coefficient given by

Table 2: Standard Extinction Coefficients

Color	Wavelength (cm)*	ε	
		Hb	HbO_2
Red	660	0.81	0.08
Infrared	940	0.19	0.29

* these are standard wavlengths. These can be measured in a spectrophotometer and ε can be adjusted for those particular wavelengths.

To enable wireless data transmission, a Gumstix would be a viable option. However, since this project's focus is on monitoring four rats simultaneously, the team believes a separate motherboard would be the best option. Four boards can communicate with each other via I^2C. I^2C allows for a unique identifier to be tagged to each board, so it would be easy to determine where the signal came from. The motherboard would take this data, perhaps perform some signal processing if feasible, and then send this data to a Wi-Fi chip. This Wi-Fi would then send the data out to any listening clients. This would require the implementation of the I^2C protocol into the pulse oximeter programming as the hardware for I^2C is already mostly in place.

The team also envisions using Java for the client user interface. This interface would implement data acquisition, digital filtering, signal processing, data saving, and the graphical user interface. Java, as an open source language, is free and is commonly used. Digital filters can be designed using Matlab and then the coefficients implemented into a signal processing routine. A graphical user interface can be easily implemented. In some respects, LabVIEW is specifically designed for engineering use, but this can also be its drawback as it was discovered this semester. Using Java will most likely ultimately give the team more power and freedom to develop and tailor algorithms and an interface to the client's specifications.

When all hardware and software is working, an enclosure for the project is needed. The team suggests a variant of the *Toaster Oven* design as presented in the Appendix, but there is certainly room for improvement. A small footprint of the device is desired, because the entire device should be able to be stored and should remain out of the way during testing sessions.

With all components considered, an individual pulse oximeter board (including FSR and thermistor) will cost approximately $90, plus some additional expenses for the probes, housing, and a computer if necessary. Since Java is open source, it is easy to obtain and is free, and it runs on most computers. When additional boards are coupled together, a multiple rat vitals monitoring system is not financially out of reach for research laboratories around the world. While low cost (compared to competitors) was not an original goal of the project, the team suggests keeping the implications of increasing cost excessively in mind.

Conclusion

This semester, the design team has successfully developed two functioning printed circuit boards that enable the heart rate and blood SpO_2 levels of a rat to be monitored. These circuit boards have been printed with the additional circuitry for measuring rectal temperature and breathing rate. The boards also possess the capability of wirelessly communicating and transmitting data to an intermediate computer, which can then relay the data to a LabVIEW GUI.

A new design of pulse oximeter probe was implemented this semester in an attempt to improve the heart rate and blood SaO_2 data acquired from the hind paw of a rat. Unfortunately, testing indicated that this new design was not more effective than the probe designed in previous semesters. Continued work in this area of the project will strive to manufacture a probe that effectively isolates ambient light and obtains a strong signal.

In the future, the design team will continue to improve the client software to incorporate digital processing/filtering of the data, along with working on an improved communication method of I^2C such that four circuit boards can communicate with each other and eventually with the motherboard microcomputer. Additionally, a housing device will be manufactured that will function to house all the electronics and provide an easy interface to the user for plugging and un-plugging all probes.

References

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Appendix

Product Design Specifications
Quad Rat Vitals Monitor
5/3/10

Team:

Matthew Bollom	Team Leader	mbollom@wisc.edu
Caitlyn Collins	Communicator	cjcollins2@wisc.edu
Robert Bjerregaard	BSAC	rbjerregaard@wisc.edu
Derek Klavas	BWIG	klavas@wisc.edu

Function: A device that is capable of recording and displaying SaO2 levels, heart rate, rectal temperature, and breathing rate of four rats simultaneously. The purpose of this is to help maintain appropriate anesthesia dosage on the four rats.

Client requirements: Accurately record and display SaO2 levels, heart rates, breathing rates, and body (rectal) temperatures of four rats under anesthesia simultaneously.

Design requirements: Build a device that measures and displays the vital readings of four rats under anesthesia. The device must be able to accurately detect heart rates of up to 500 bpm and blood oxygen saturation levels to an accuracy of ±2% so that the anesthesiologist is able to determine the adequate dosage of isoflurane to keep the rats anesthetized. Device will also be designed to monitor respiratory rate (around 20 breaths/min) and rectal temperature (93-100° F).

Physical and Operational Characteristics

1. *Performance requirements:* The device, at minimum, should be able to take the heart rates, breathing rates, and temperatures of four rats simultaneously and display them onscreen. It should also have running graphs showing the vitals of each rat for the duration of the experiment or for a user specified time. It should also display live traces of respiration and heart rate. The software should also record the average values of the vitals to a hard disc every fifteen seconds.
2. *Safety:* The device should be safe for animal use and be consistent with the safety standards of the current rat platform.
3. *Accuracy and Reliability:* The device must be able to accurately detect heart rates of up to 500 bpm, blood oxygen saturations level accuracy of ±2%, respiratory rates of at least 30 breaths/min, and rectal temperatures of 93-100° F.

4. *Life in Service:* The device must be functional for at least 5 years, with calibration as needed.
5. *Shelf Life:* The device should be able to go without use for a semester and be put back into use with normal functionality.
6. *Operating Environment:* Will be used in a laboratory environment.
7. *Ergonomics:* The pulse oximeter probe should comfortably fit onto the hind paw of each rat. The probes should not be influenced by the inclusion of bubble wrap during tests. The graphical user interface must be optimized to minimize user interaction. All external probes must be user replaceable with minimal effort.
8. *Size:* Clips must be small enough so that it will not interfere with surrounding sensor and/or devices. No sensors should interfere with the PET imaging, keeping any large components inferior to the base of the heart.
9. *Weight:* The sensor system must not have a mass greater than 1 kilogram.
10. *Materials:* Derived oximeter sensors, converted human oral thermometers, and force sensing resistors. All other materials will not be in contact with the rats.
11. *Aesthetics, Appearance, and Finish:* There must be no exposed circuit components.

Production Characteristics

12. *Quantity:* One.
13. *Target Product Cost:* under $4,000

Miscellaneous

14. *Standards and specifications:* N/A
15. *Customer:* Research organizations working with rats.
16. *Patient-related concerns:* Currently no patient-related concerns.
17. *Competition:* MouseOx produced by Life Starr

Guide to Ordering Printed Circuit Boards from PCB Express

Step 1) Point your web browser to www.pcbexpress.com

Step 2) Click on the yellow *Order* button under the desired layer board (in the case of this project the E4 4-layer was selected)

Step 3) When the first order form page loads enter a name for the project into the *Project Name or Project number box*. Next enter the number of boards desired as well as their appropriate length and width into their individual boxes. The *Board Finishing* is automatically set to Tin Lead and need not change unless the other option, silver, is desired. In order to make later construction easier, check the *BOTTOM Silkscreen* box so that each part is labeled with their respective names. Finally select the program used to design the schematic (Eagle 5.6 was used in generating the board for this project) and select the *Continue to the Next Page* button.

Step 4) The next page will display the information you have entered. If all of the settings are correct select the *Continue to the Next Page* button, if not select the *Back* button and make the required changes.

Step 5) The subsequent page will require you to enter the shipment and payment details including *Name, E-mail, Street Address, Telephone and Credit Card/Account Number*. If the account being used to order the boards is tax exempt or has any special constraints be sure to make appropriate allocations or contact PCB Express directly.

Step 6) The flowing page will ask you to upload a zip folder containing the Gerber layers for the board to be printed as well as to fill out the mapping specs form in to following manner:

- *Top* → .cmp
- *Inner layer1* → .ly2
- *Inner layer2* → .l15
- *Outline* → .mch
- *Bottom* → .sol
- *Silkscreen top* → .plc
- *Silkscreen bottom* → .pls
- *Solder-mash top* → .stc
- *Solder-mach bottom* → .sts
- *NC Drill* → .drd

Step 7) Once all information has been entered correctly select the *Continue to Next Page* button. After viewing the ordering information presented on the final page select the *Order Boards* button and once order is placed be sure to print a copy of the ordering information. PCB Express will send a confirmation e-mail as well as tracking information once the boards have been shipped.

Bill of Materials

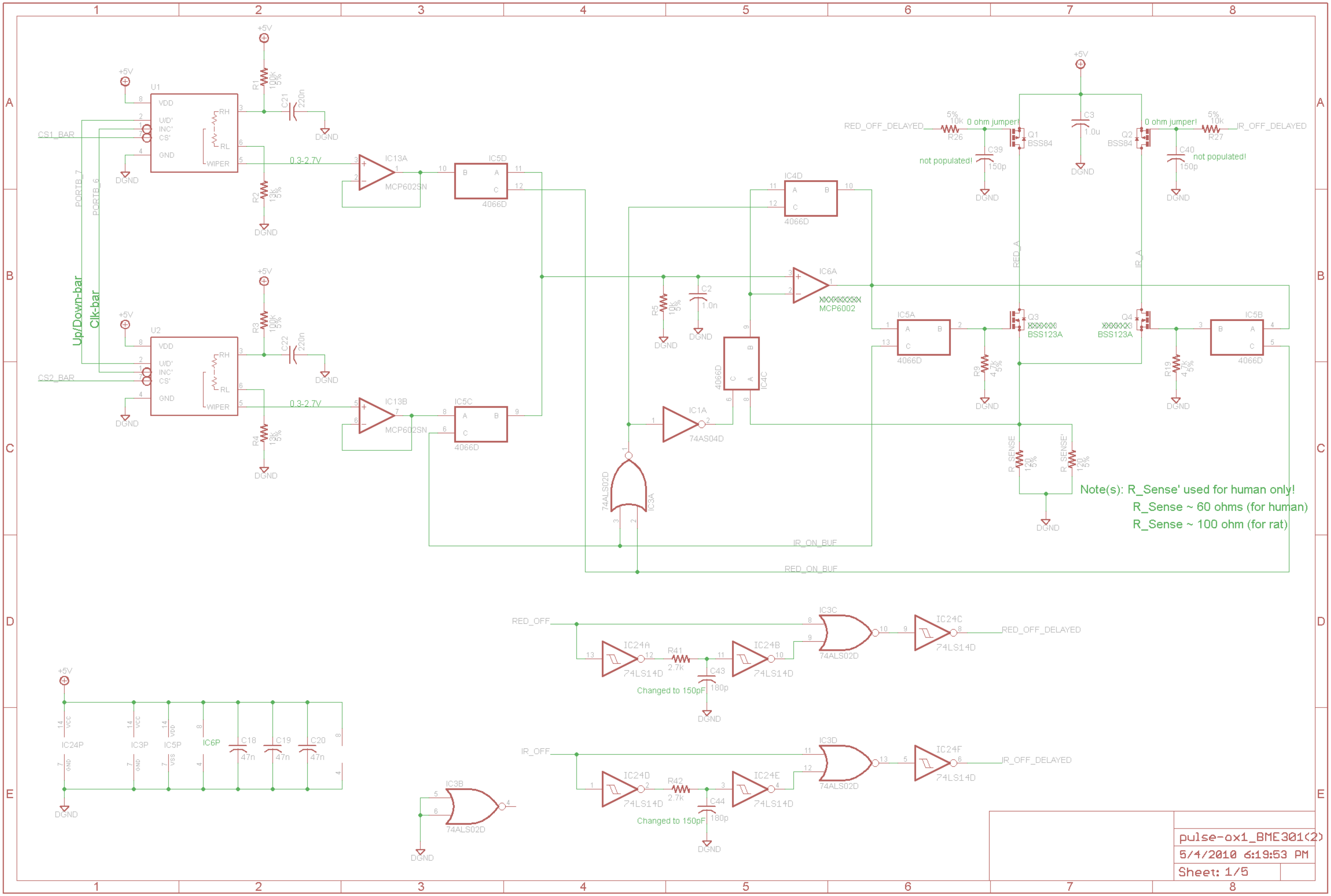
Pulse Oximeter Boards (Quad Rat Vitals Monitor)						Pricing		Ordering Details	
Number of boards ordering for:		4							
Part	Value	Device (Repeat)	Part Number	Quantity	Total Needed	Price	For How Many?	Total Parts to Order	Total Cost
C1	10u		490-3905-1-ND	1	4	$ 8.75	10	1	$ 8.75
C2	1n		445-1347-1-ND	2	8	$ 0.44	10	1	$ 0.44
C3	1u		587-1283-1-ND	4	16	$ 1.21	10	2	$ 2.42
C4	47n		445-2276-1-ND	7	28	$ 1.65	10	3	$ 4.95
C5	4.7u		445-4116-1-ND	2	8	$ 3.30	10	1	$ 3.30
C6	4.7u	(C5)							
C7	100n		587-1279-1-ND	3	12	$ 0.89	10	2	$ 1.78
C8	100n	(C7)							
C9	3.3n		445-2323-1-ND	1	4	$ 2.08	10	1	$ 2.08
C10	220n	(C15)							
C11	1u	(C3)							
C12	220p		478-1318-1-ND	4	16	$ 0.99	10	2	$ 1.98
C13	220p	(C12)							
C14	47n	(C4)							
C15	220n		587-1287-1-ND	12	48	$ 1.10	10	5	$ 5.50
C16	47n	(C4)							
C17	47n	(C4)							
C18	47n	(C4)							
C19	47n	(C4)							
C20	47n	(C4)							
C21	220n	(C15)							
C22	220n	(C15)							
C24	220n	(C15)							
C25	220n	(C15)							
C26	2.2u		587-1286-1-ND	2	8	$ 1.71	10	1	$ 1.71
C27	18p		478-1307-1-ND	2	8	$ 1.10	10	1	$ 1.10
C28	18p	(C27)							
C29	220n	(C15)							
C30	220n	(C15)							
C31	220n	(C15)							
C32	220n	(C15)							
C33	220n	(C15)							
C34	100n	(C7)							
C35	1u	(C3)							
C36	2.2u	(C26)							
C37	1u	(C3)							
C38	680p	(C2)	478-1326-1-ND	1	4	$ 1.43	10	4	$ 5.72
C39	150p	(C12)							
C40	150p	(C12)							
C41	10n		445-1348-1-ND	2	8	$ 0.44	10	1	$ 0.44
C42	220n	(C15)							

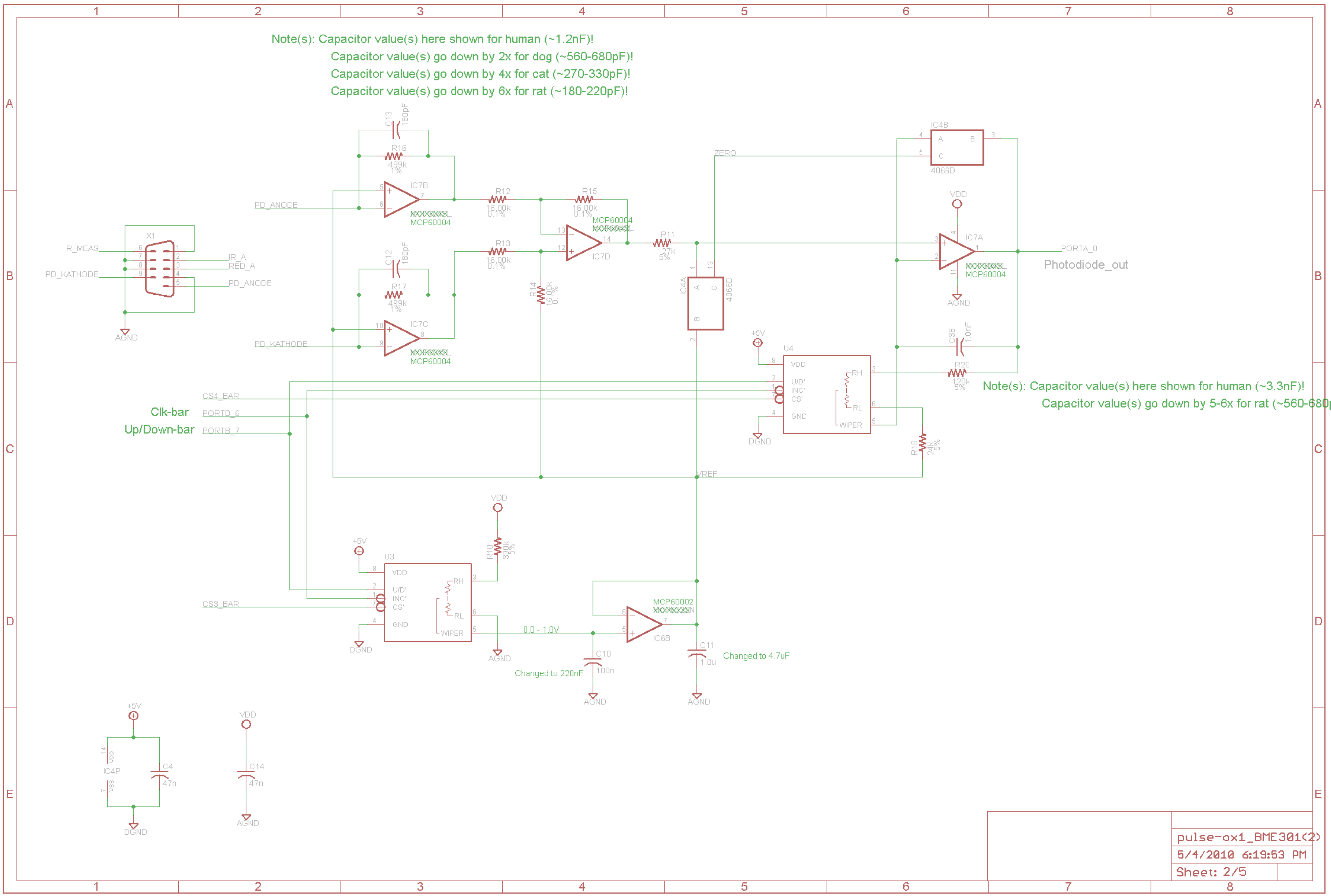
C43	180p		478-1319-1-ND	2	8	$ 1.65	10	1	$ 1.65
C44	180p	(C43)							
C45	10n	(C41)							
FSR1		4pin	CP-2440-ND	1	4	$ 0.81	1	4	$ 3.24
IC1	74AS04D		74HC04DR2GOSC T-ND	1	4	$ 0.53	1	4	$ 2.12
IC2	74LS139D		296-14833-1-ND	1	4	$ 0.50	1	4	$ 2.00
IC3	74ALS02D		296-1188-1-ND	1	4	$ 0.44	1	4	$ 1.76
IC4	4066D		568-1462-1-ND	3	12	$ 0.45	1	12	$ 5.40
IC5	4066D	(IC4)							
IC6	MCP602SN		MCP6002-I/SN-ND	2	8	$ 3.30	10	1	$ 3.30
IC7	MCP604SL		MCP6004-I/SL-ND	2	8	$ 4.40	10	1	$ 4.40
IC8	MAX6520		MAX6104EUR+TC T-ND	1	4	$ 0.80	1	4	$ 3.20
IC9	LD2981A		497-1525-1-ND	1	4	$ 1.03	1	4	$ 4.12
IC10	FT232RL		768-1007-1-ND	1	4	$ 4.50	1	4	$ 18.00
IC11	MCP1804		MCP1804T-2502I/DBCT-ND	1	4	$ 0.86	1	4	$ 3.44
IC12	4066D	(IC4)							
IC13	MCP602SN	(IC6)							
IC14	PIC18F2580-E/SO		PIC18F2580-I/SO-ND	1	4	$ 7.62	1	4	$ 30.48
IC15	74HC02		MM74HC02MXCT-ND	1	4	$ 0.59	1	4	$ 2.36
IC16	MAX232ECWE		MAX232ACWE+-ND	1	4	$ 4.88	1	4	$ 19.52
IC17	MCP604SL	(IC7)							
IC24	74LS14D		296-1212-1-ND	1	4	$ 0.66	1	4	$ 2.64
J1			CP-057A-ND	1	4	$ 0.65	1	4	$ 2.60
JP1			SAM1040-05-ND	2	8	$ 2.01	1	8	$ 16.08
JP2		(Jp1)							
L2	100u		587-2422-1-ND	1	4	$ 0.18	10	1	$ 0.18
LED1		red	160-1422-1-ND	1	4	$ 0.14	1	4	$ 0.56
LED2		yellow	160-1431-1-ND	1	4	$ 0.14	1	4	$ 0.56
LED3		green	160-1423-1-ND	1	4	$ 0.14	1	4	$ 0.56
LED4		blue	160-1645-1-ND	1	4	$ 0.40	1	4	$ 1.60
Q1	BSS84		BSS84PL6327INC T-ND	2	8	$ 3.31	10	1	$ 3.31
Q2	BSS84	(Q1)							
Q3	BSS123		BSS123L6327INC T-ND	2	8	$ 3.16	10	1	$ 3.16
Q4	BSS123	(Q3)							
Q9			300-8446-ND	1	4	$ 0.63	1	4	$ 2.52
R1	100k		RMCF1/10100KJR CT-ND	2	8	$ 0.21	10	1	$ 0.21
R2	13k		RHM13KARCT-ND	2	8	$ 0.34	10	1	$ 0.34
R3	100k	(R1)							
R4	13k	(R2)							
R5	10k		RMCF1/1010KJRC T-ND	3	12	$ 0.21	10	2	$ 0.42
R6	7.5k	(R30)							
R7	120k	(R20)							
R8	750		RMCF1/10750JRC T-ND	1	4	$ 0.03	1	4	$ 0.12

R9	4.7k		RMCF1/104.7KJR CT-ND	2	8	$ 0.21	10	1	$ 0.21
R10	390k		RHM390KARCT-ND	1	4	$ 0.34	10	1	$ 0.34
R11	47k		RMCF1/1047KJRC T-ND	1	4	$ 0.21	10	1	$ 0.21
R12	16k		RHM16KARCT-ND	4	16	$ 0.34	10	2	$ 0.68
R13	16k	(R12)							
R14	16k	(R12)							
R15	16k	(R12)							
R16	499k		RHM499KCRCT-ND	2	8	$ 0.38	10	1	$ 0.38
R17	499k	(R16)							
R18	24k		RMCF1/1024KJRC T-ND	2	8	$ 0.21	10	1	$ 0.21
R19	4.7k	(R9)							
R20	120k		RHM120KARCT-ND	2	8	$ 0.34	10	1	$ 0.34
R21	24k	(R18)							
R22	470		RMCF1/10470JRC T-ND	4	16	$ 0.21	10	2	$ 0.42
R23	15k		RMCF1/1015KJRC T-ND	1	4	$ 0.21	10	1	$ 0.21
R24	20.5k		RHM20.5KCRCT-ND	1	4	$ 0.38	10	1	$ 0.38
R25	270		RMCF1/10270JRC T-ND	1	4	$ 0.03	1	4	$ 0.12
R26	10k	(R5)							
R27	10k	(R5)							
R28	470	(R22)							
R29	470	(R22)							
R30	7.5k		RHM7.5KARCT-ND	3	12	$ 0.34	10	2	$ 0.68
R31	7.5k	(R30)							
R32	8.25k		RHM8.25KCRCT-ND	1	4	$ 0.38	10	1	$ 0.38
R33	470	(R22)							
R41	2.7k		RMCF1/102.7KJR CT-ND	3	12	$ 0.21	10	2	$ 0.42
R42	2.7k	(R41)							
R48	14k		RHM14.0KCRCT-ND	1	4	$ 0.38	10	1	$ 0.38
R50	2.7k	(R41)							
R_SENSE	120		P120ACT-ND	1	4	$ 0.77	10	1	$ 0.77
R_SENSE'	120			(NOT USED)					
SW1	PTS645		450-1132-ND	1	4	$ 0.55	1	4	$ 2.20
THRM1		3pin	CP-2430-ND	1	4	$ 0.78	1	4	$ 3.12
U$1	MMPQ2907A		585-ALD1107SBL	2	8	$ 1.76	1	8	$ 14.08
U$2	MMPQ2907A	(U$1)							
U1			DS1804Z-100+-ND	4	16	$ 3.23	1	16	$ 51.68
U2		(U1)							
U3		(U1)							
U4		(U1)							
X1	Already Have			1	4				
X2			A31725-ND	1	4	$ 1.61	1	4	$ 6.44
X4		8pin	CP-2480-ND	1	4	$ 1.11	1	4	$ 4.44

THRM plug		3pin	CP-2030-ND	1	4	$ 1.29	1	4	$ 5.16
FSR plug		4pin	CP-2040-ND	1	4	$ 1.32	1	4	$ 5.28
Totals								**190**	**$ 262.39**
**Shipping and Handling to cost extra									

The part in grey is ordered through Mouser Electronics. The rest are ordered through Digi-Key.


Up/Down-bar
Clk-bar
CS1_BAR
CS2_BAR
PORTB_7
PORTB_6
U1
U2
VDD
U/D'
INC'
CS'
GND
RH
RL
WIPER
R1 100k 5%
R2 13k 5%
R3 100k 5%
R4 13k 5%
C21 220n
C22 220n
0.3-2.7V
IC13A
IC13B
MCP602SN
IC5D
IC5C
IC5A
IC5B
IC4D
IC4C
4066D
IC6A
MCP6002
R5 10k 5%
C2 1.0n
IC1A
74AS04D
IC3A
74ALS02D
IR_ON_BUF
RED_ON_BUF
RED_OFF_DELAYED
IR_OFF_DELAYED
R26 10k 5%
R27 10k 5%
0 ohm jumper!
not populated!
C39 150p
C40 150p
C3 1.0u
Q1 BSS84
Q2 BSS84
Q3 BSS123A
Q4 BSS123A
RED_A
IR_A
R9 4.7k 5%
R19 4.7k 5%
R_SENSE 120 5%
R_SENSE' 120 5%
Note(s): R_Sense' used for human only!
R_Sense ~ 60 ohms (for human)
R_Sense ~ 100 ohm (for rat)
RED_OFF
IR_OFF
IC24A
IC24B
IC24C
IC24D
IC24E
IC24F
74LS14D
R41 2.7k
R42 2.7k
C43 180p
C44 180p
Changed to 150pF
IC3C
IC3D
IC3B
IC24P
IC3P
IC5P
IC6P
C18 47n
C19 47n
C20 47n
+5V
DGND
pulse-ox1_BME301(2)
5/4/2010 6:19:53 PM
Sheet: 1/5



Note(s): Capacitor value(s) here shown for human (~1.2nF)!
Capacitor value(s) go down by 2x for dog (~560-680pF)!
Capacitor value(s) go down by 4x for cat (~270-330pF)!
Capacitor value(s) go down by 6x for rat (~180-220pF)!
Note(s): Capacitor value(s) here shown for human (~3.3nF)!
Capacitor value(s) go down by 5-6x for rat (~560-680p
X1
R_MEAS
PD_KATHODE
IR_A
RED_A
PD_ANODE
AGND
C13 180pF
R16 499k 1%
IC7B
MCP60004
C12 180pF
R17 499k 1%
IC7C
R12 16.00k 0.1%
R13 16.00k 0.1%
R15 16.00k 0.1%
R14 16.00k 0.1%
IC7D
R11 27k 5%
IC4A
IC4B
4066D
ZERO
VDD
IC7A
PORTA_0
Photodiode_out
C38 1.0nF
R20 120k 5%
U4
R18 24k 5%
VREF
CS4_BAR
Clk-bar
PORTB_6
Up/Down-bar
PORTB_7
CS3_BAR
U3
+5V
DGND
R10 390k 5%
0.0 - 1.0V
MCP60002
IC6B
C10 100n
Changed to 220nF
C11 1.0u
Changed to 4.7uF
IC4P
C4 47n
C14 47n
pulse-ox1_BME301(2)
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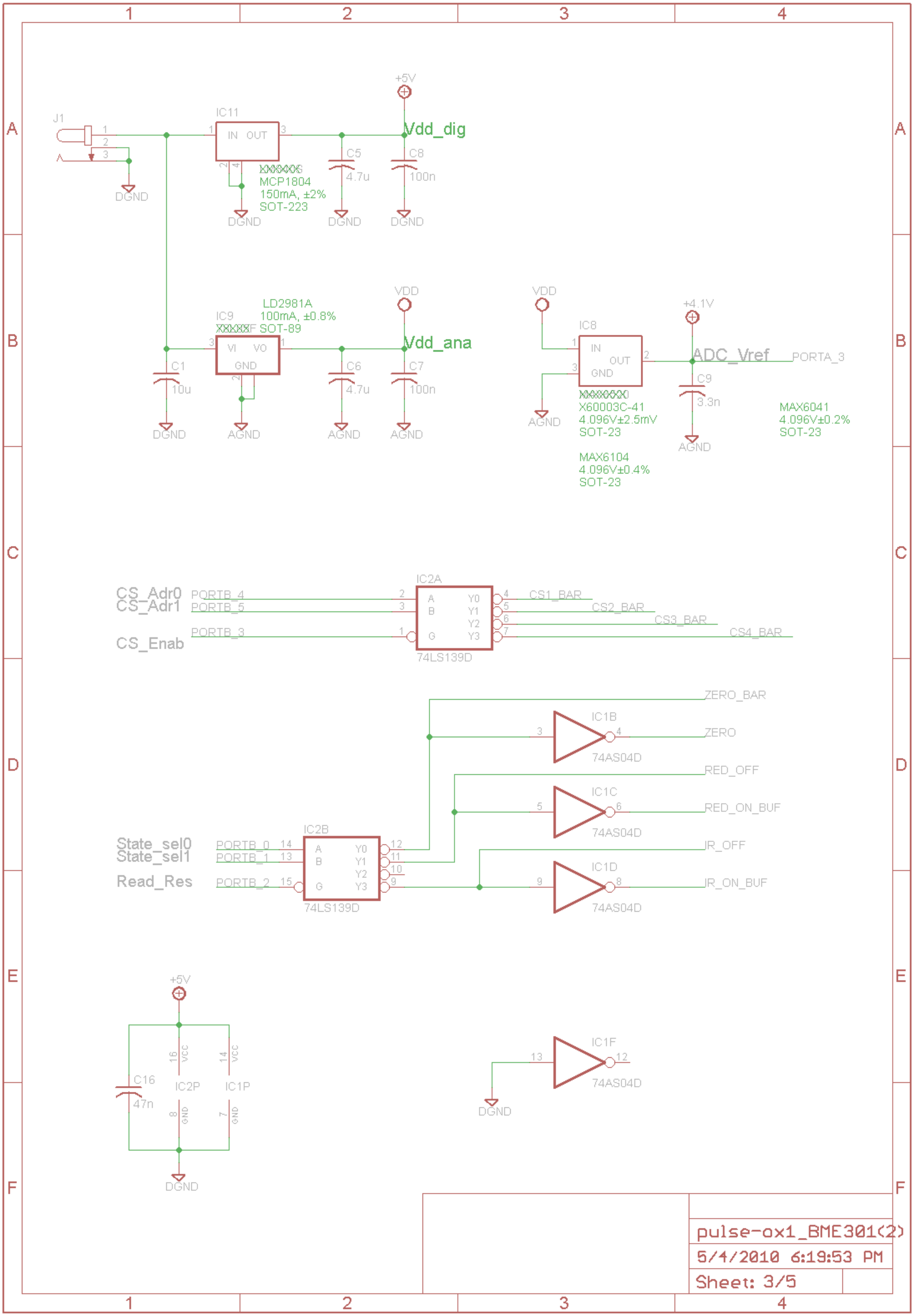
Sheet: 2/5


J1
IC11
IN OUT
MCP1804
150mA, ±2%
SOT-223
C5
4.7u
C8
100n
+5V
Vdd_dig
DGND
IC9
LD2981A
100mA, ±0.8%
SOT-89
VI VO
GND
C1
10u
C6
4.7u
C7
100n
VDD
Vdd_ana
AGND
IC8
IN
OUT
GND
X60003C-41
4.096V±2.5mV
SOT-23
MAX6104
4.096V±0.4%
SOT-23
+4.1V
ADC_Vref
PORTA_3
C9
3.3n
MAX6041
4.096V±0.2%
SOT-23
CS_Adr0
CS_Adr1
CS_Enab
PORTB_4
PORTB_5
PORTB_3
IC2A
74LS139D
CS1_BAR
CS2_BAR
CS3_BAR
CS4_BAR
ZERO_BAR
ZERO
RED_OFF
RED_ON_BUF
IR_OFF
IR_ON_BUF
IC1B
IC1C
IC1D
74AS04D
State_sel0
State_sel1
Read_Res
PORTB_0
PORTB_1
PORTB_2
IC2B
74LS139D
C16
47n
IC2P
IC1P
IC1F
pulse-ox1_BME301(2)
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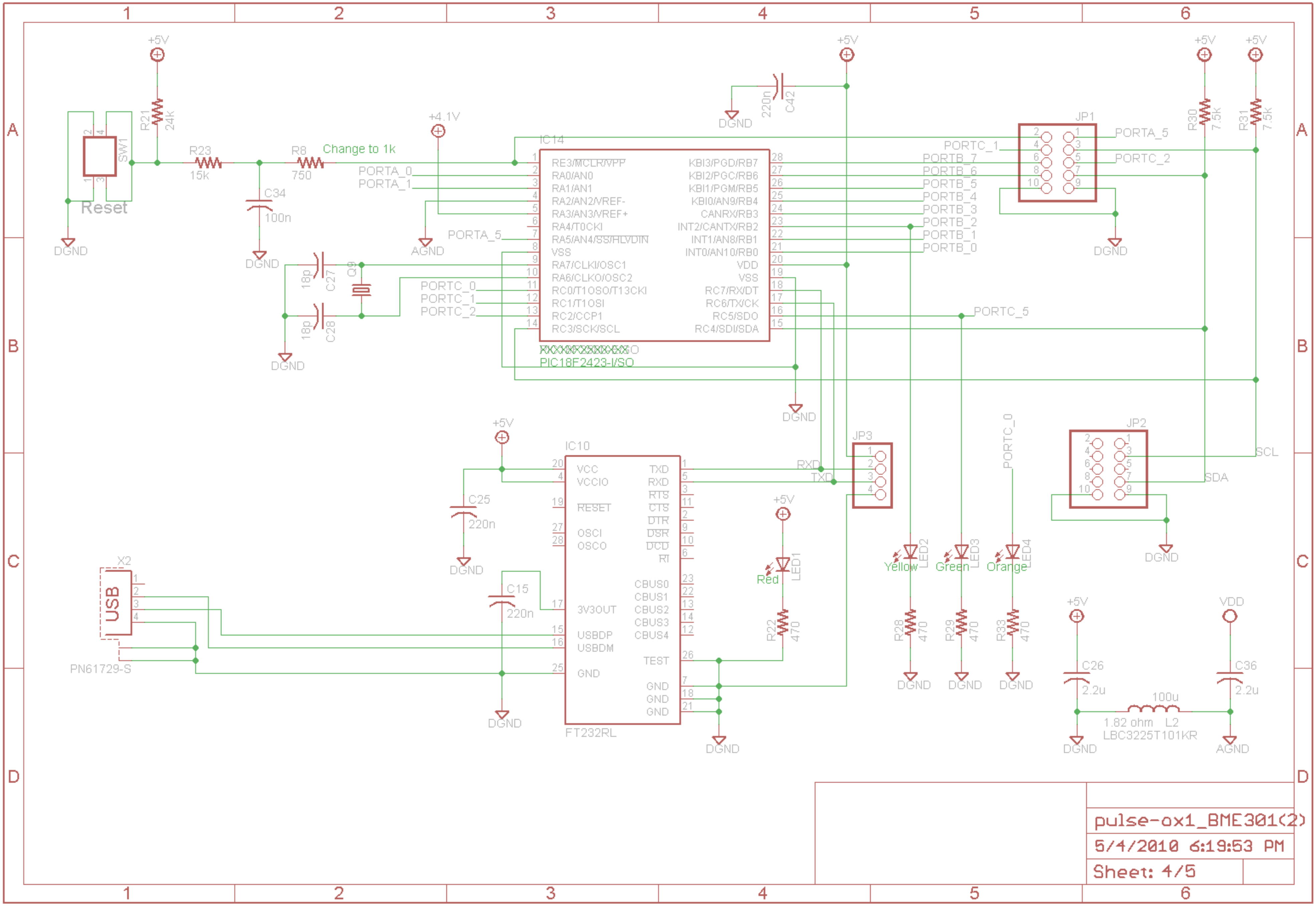

Reset
SW1
R21
24k
R23
15k
R8
750
Change to 1k
C34
100n
C27
C28
18p
Q9
+4.1V
+5V
DGND
AGND
PORTA_0
PORTA_1
PORTA_5
PORTC_0
PORTC_1
PORTC_2
IC14
RE3/MCLR/VPP
RA0/AN0
RA1/AN1
RA2/AN2/VREF-
RA3/AN3/VREF+
RA4/T0CKI
RA5/AN4/SS/HLVDIN
VSS
RA7/CLKI/OSC1
RA6/CLKO/OSC2
RC0/T1OSO/T13CKI
RC1/T1OSI
RC2/CCP1
RC3/SCK/SCL
KBI3/PGD/RB7
KBI2/PGC/RB6
KBI1/PGM/RB5
KBI0/AN9/RB4
CANRX/RB3
INT2/CANTX/RB2
INT1/AN8/RB1
INT0/AN10/RB0
VDD
VSS
RC7/RX/DT
RC6/TX/CK
RC5/SDO
RC4/SDI/SDA
PIC18F2423-I/SO
C42
220n
JP1
PORTB_7
PORTB_6
PORTB_5
PORTB_4
PORTB_3
PORTB_2
PORTB_1
PORTB_0
PORTC_5
R30
R31
7.5k
JP2
SCL
SDA
JP3
RXD
TXD
IC10
VCC
VCCIO
RESET
OSCI
OSCO
3V3OUT
USBDP
USBDM
GND
TXD
RXD
RTS
CTS
DTR
DSR
DCD
RI
CBUS0
CBUS1
CBUS2
CBUS3
CBUS4
TEST
FT232RL
C25
C15
X2
USB
PN61729-S
LED1
Red
R22
470
LED2
Yellow
R28
LED3
Green
R29
LED4
Orange
R33
C26
C36
2.2u
100u
1.82 ohm
L2
LBC3225T101KR
VDD
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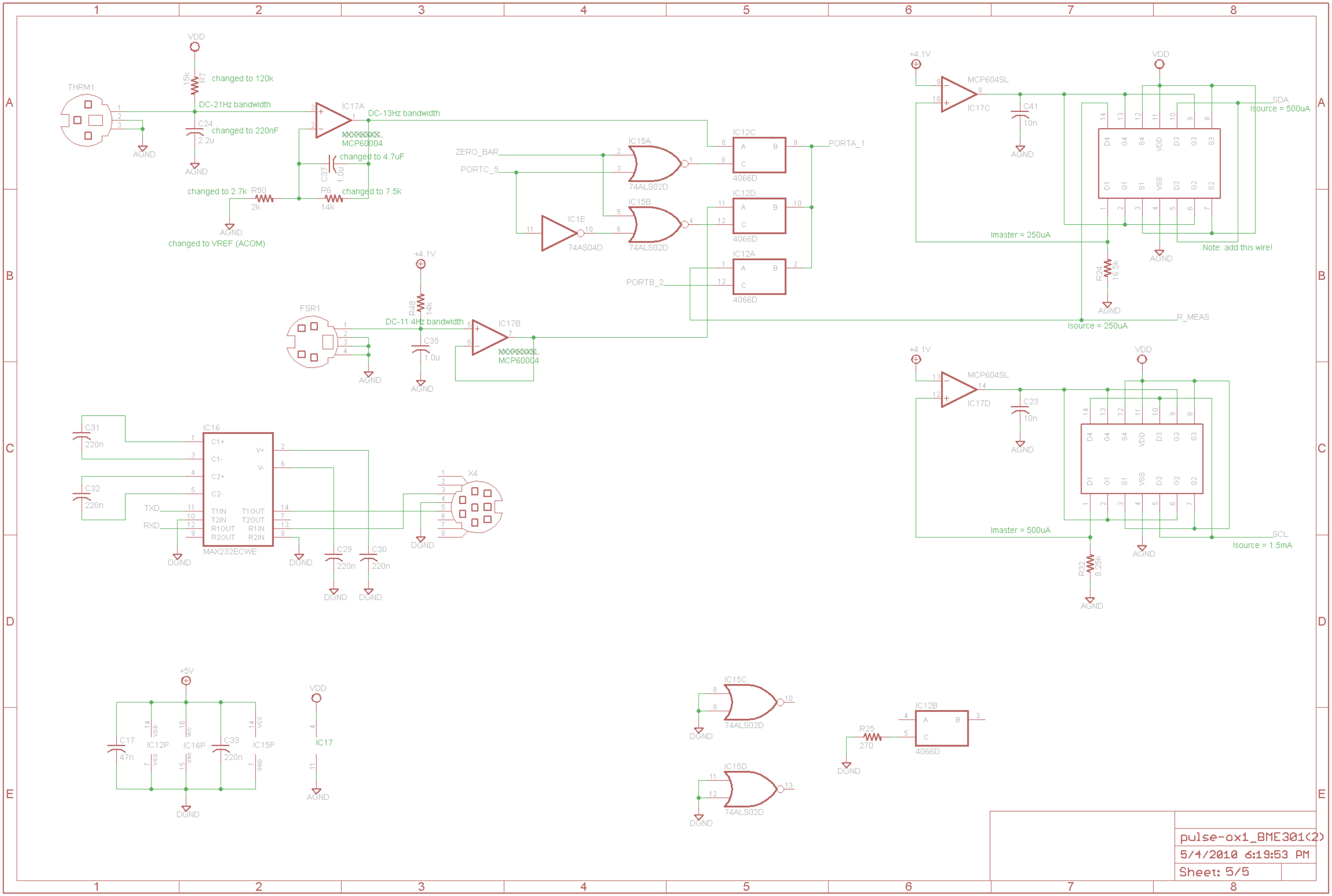
THRM1
VDD
R7
15k
changed to 120k
DC-21Hz bandwidth
C24
2.2u
changed to 220nF
AGND
IC17A
MCP60004
DC-13Hz bandwidth
C37
1.0u
changed to 4.7uF
R50
2k
changed to 2.7k
R6
14k
changed to 7.5k
changed to VREF (ACOM)
ZERO_BAR
PORTC_5
IC15A
74ALS02D
IC15B
IC1E
74AS04D
IC12C
IC12D
IC12A
4066D
PORTA_1
PORTB_2
FSR1
+4.1V
R48
14k
DC-11.4Hz bandwidth
C35
IC17B
R_MEAS
Isource = 250uA
MCP604SL
IC17C
C41
10n
Imaster = 250uA
R24
16.5k
SDA
Isource = 500uA
Note: add this wire!
IC17D
C23
Imaster = 500uA
R32
8.25k
SCL
Isource = 1.5mA
IC16
MAX232ECWE
C31
C32
C29
C30
220n
TXD
RXD
X4
DGND
+5V
C17
47n
IC12P
IC16P
C33
IC15P
IC17
IC15C
IC15D
R25
270
IC12B
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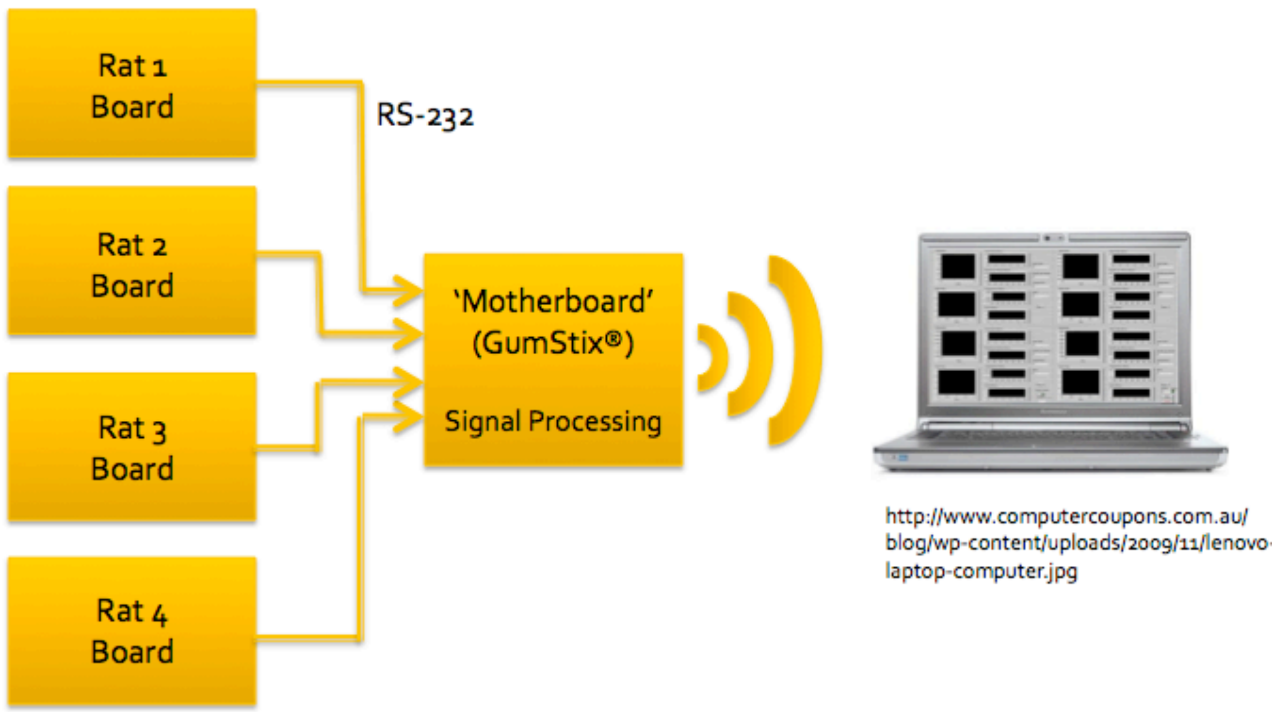
Communications Summary

During the semester, the team's client asked for summary of what options were being planned in regards to communication. That document is included here for reference.

System Communications

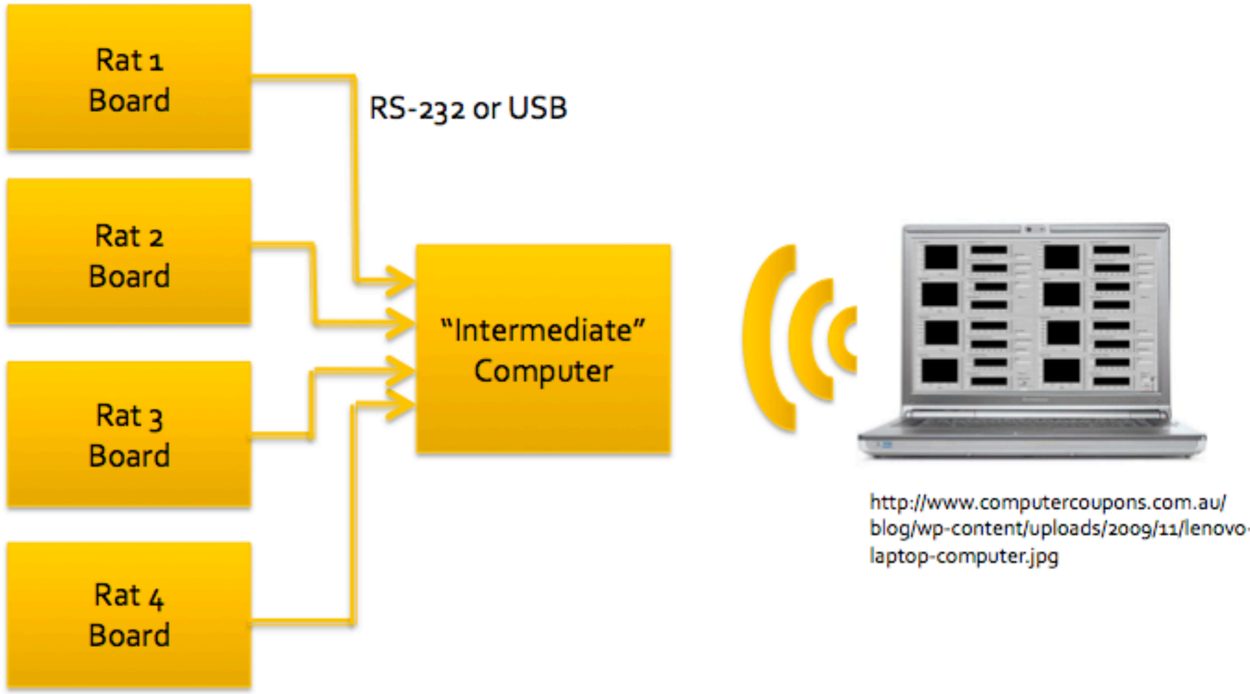
Initial Plan



The team's initial plan will no longer work. The GumStix only has two RS-232 (serial) ports available, so some additional work and programming would be needed in order to allow all four boards to communicate with the GumStix. Also, the team is no longer sure such a powerful device is needed. Essentially, the motherboard's function is to push the data coming from the boards to the receiver computer.

This document continues on the next page.

Revised Plan



After evaluating some of the flaws of the initial plan, the team has developed a new plan that has been implemented. Instead of a motherboard, the team has decided to use an intermediate computer that all the boards will connect to. This intermediate computer will do nothing but make the data coming from the boards available for use. The receiver computer will make a request to the host server and if data is available, it will continually pull that data.

Benefits

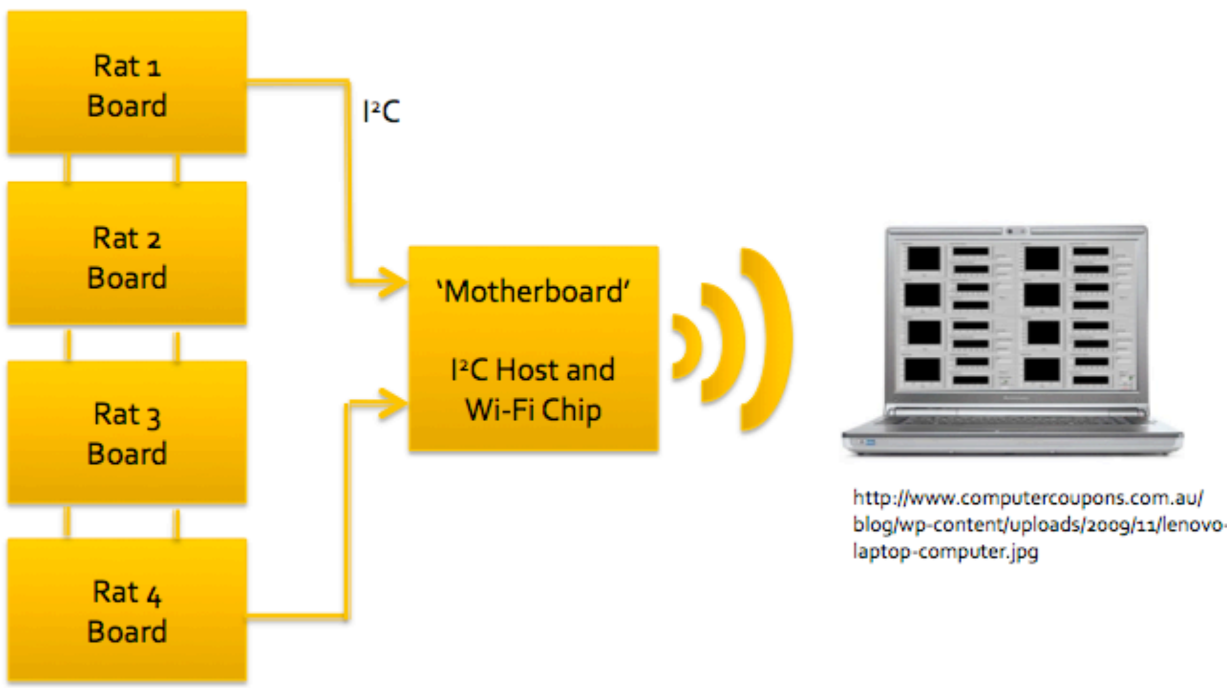
- No additional cost at this time. The team has borrowed a computer from the department and installed Linux on it as that is the preferred operating system for transmission control protocol (TCP) socket programming.
- Each board can be connected individually to the intermediate computer. The boards and parts that were ordered gives the team the capability to use RS-232 (serial) or USB in order to interface with the computer.
- This plan will serve as a proof of concept.
- LabVIEW has functions that allow virtual instruments (VI) obtain data from TCP servers.
- Multiple devices (in theory) could be obtaining this data at the same time. This might not be useful for this project.

Drawbacks

- The team had no experience initially with TCP socket programming
- The computer that was borrowed is slow.

- There are not enough input devices on this computer for four boards.

Future Plan



The future plan allows for the most expansibility. Additionally, the team would not need an additional computer in order to make the data available since it would be contained all within the final device. This plan would require the development of a motherboard, which is essentially just another circuit board with some circuit components on it. There would also be a WiFi chip built into this board directly, bypassing the need for a GumStix. We would be switching protocols for communication between the boards and motherboard (I^2C instead of RS-232), but the boards and parts that were ordered allows for the use of I^2C. The cable that connects the individual boards to the motherboard is ribbon cable, which is small and flexible. Nothing changes with the receiving computer.

Benefits

- I^2C can be very fast up to 3.4 Mbit/s (although it was first developed for low-speed devices)
- Bidirectional communication
- No strict baud rate requirements
- Each device (ie board) has its own unique address, so the signals can be easily differentiated
- I^2C (in theory) could allow customization of the amount of boards in use. One, two, three, or four boards could be connected together at any time and work, provided there is the appropriate software at the receiving end to accept that amount of boards

Drawbacks

- The team has no experience with I^2C programming
- Another board (the ‘motherboard’) would need to be designed

Wi-Fi Server Code

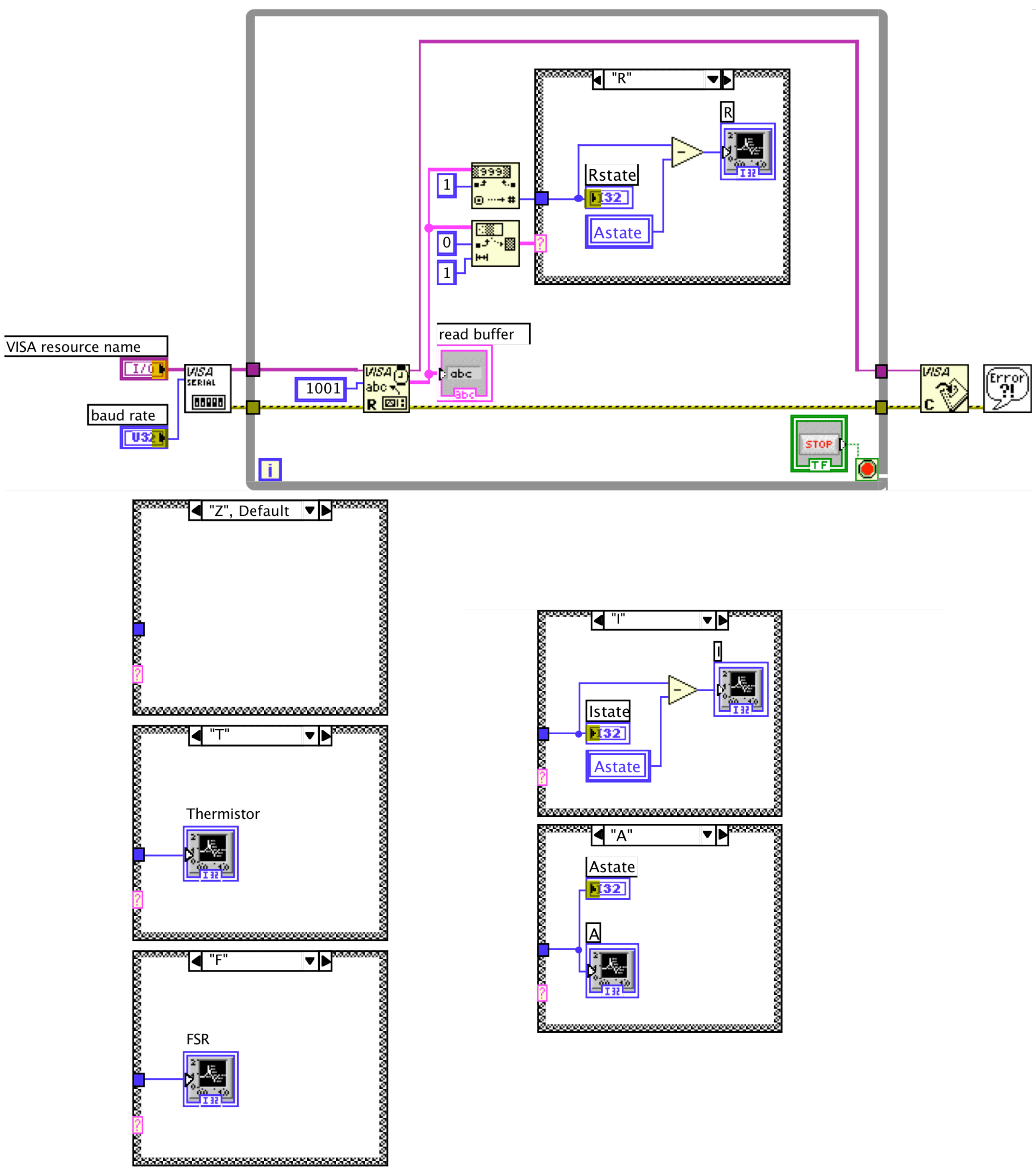
The following is the code for the Wi-Fi server.

```
<?php
include "php_serial.class.php";
     // download from
     //   http://www.phpclasses.org/browse/file/17926.html
$serial = new phpSerial;
$serial->deviceSet("/dev/ttyUSB0");
$serial->deviceOpen();
$serial->deviceClose();
$serial->confBaudRate(115200);
$serial->deviceOpen();

$host ="10.42.43.1"; //adjust to the real ip address
$port = 10230;       //make sure port is opened through firewall

set_time_limit(0);

$socket = socket_create(AF_INET, SOCK_STREAM, 0) or die("Could
     not create socket\n");
$result = socket_bind($socket, $host, $port) or die("Could not
     bind to socket\n");
$result = socket_listen($socket, 3) or die("Could not set up
     socket listener\n");
$spawn = socket_accept($socket) or die("Could ot accept incoming
     connection\n");
$input = socket_read($spawn, 1024) or die("Could not read
     input\n");
$input = trim($input);
if($input == "details") {
     $output = "pulse ox";socket_write($spawn, $output,
          strlen($output)) or die("Could not write output\n");
} else {
     while(true) {
          $read = $serial->readPort();
          socket_write($spawn, $read, strlen($read)) or
               die("Could not write output\N");
          sleep(1);
     }
}
socket_close($spawn);
socket_close($socket);
?>
```

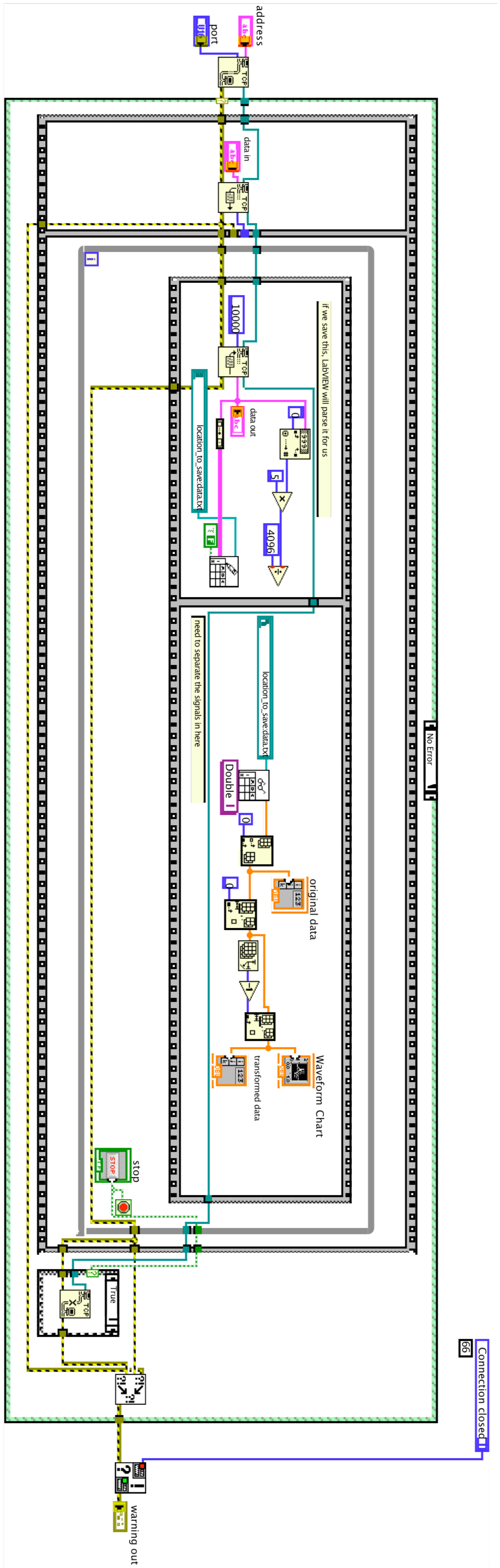
LabVIEW Code

The following is code from the virtual instruments designed by the team this semester.

Serial/USB Version



Wi-Fi Version



Circuit Board Housing

The following is an excerpt from the team's midsemseter paper. The team decided not pursue development of a housing device until the hardware was complete, but those options are included here verbatim for reference.

Circuit Board Housing

One of the main components of the device is the circuit board housing unit. The final design will consist of four identical circuit boards (one per rat) with the additional motherboard Gumstix piece. The housing unit must contain all of these circuit boards, as well as keeping them secure when the device is transported. The team considered three design options: the pegged 3 x 3 design, the toaster oven design, and the bunk bed design.

Pegged 3 x 3 Design

The pegged 3 x 3 design, as seen in Figure 8, is a two-piece rectangular prism. Each piece consists of three sides of the prism, and the two pieces slide vertically into each other. Pegs on the inside of the housing hold the circuit boards. The ports on the front of the housing allow the circuit boards to be connected to the probes. Each row of ports consists of one pulse-oximeter, one FSR, and one thermistor port. There is a fifth

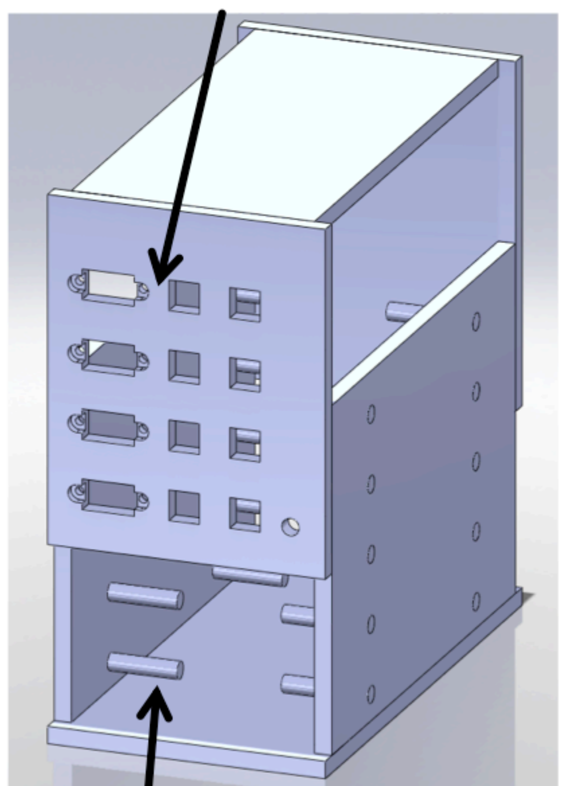


Figure 8: Pegged 3 x 3 Design

level of pegs inside to hold the motherboard.

The advantages of this design include relatively simple construction as well as simple installation of the circuit boards. However, after the circuit boards are installed, they will be difficult to modify. In order to remove the top piece of the housing, all of the ports on the faceplate need to be removed. This design would also be slightly less stable than the other design alternatives, because each of the two pieces could flex inwards and outwards, possibly compromising the integrity of the joints. Also, the boards would require additional support to keep them from sliding around inside the housing after installation.

Toaster Oven Design

The second design option is the toaster oven design (Figure 9). This alternative is similar to the pegged 3 x 3 design in that it is a rectangular prism with roughly the same dimensions and the same faceplate. The difference between the two is how the circuit boards are supported on the interior, along with how the boards can be accessed. As seen in Figure 8, the toaster oven design has grooves in the interior walls that will support the circuit

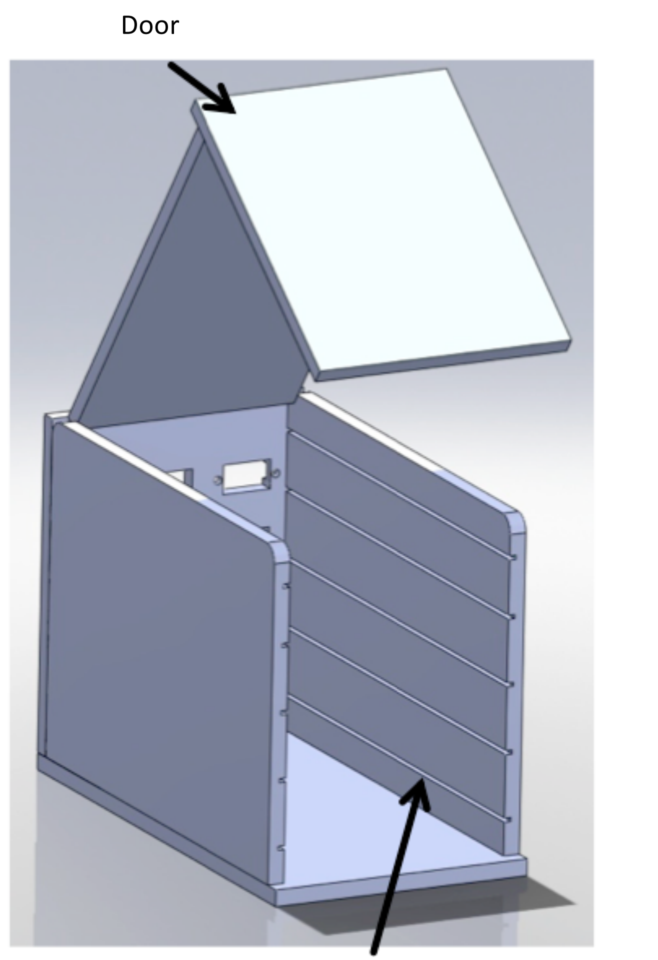


Figure 9: Toaster Oven Design

boards. These grooves allow the circuit boards to be slid in the back of the housing up against the faceplate, where the ports for the probes will be attached. Another difference with this design alternative is the hinged door. This design option allows for simple installation as well as easy modification of the circuit boards. Since the hinged door can be opened without removing any ports, individual boards can be removed without tampering with the rest of the boards. This design option is the most structurally sound because the four-sided piece is more rigid than the three-sided pieces in the pegged 3 x 3 design. Also, the circuit boards are more secure in this design because the grooves provide more of a fixed support than the pegs. However, this design option will be the most difficult to construct because the grooves must be precisely aligned with the ports on the faceplate so there is no stress on the circuit boards or the probe receptacles.

Bunk Bed Design

The third design option is the bunk bed design. As seen in Figure 10, this design alternative consists of five 'bunks' supported by four rods. The bottom four bunks will hold the four identical circuit boards, and the top bunk will hold the Gumstix board. This design is aesthetically pleasing for the technologically savvy individuals working in the lab setting. It is also

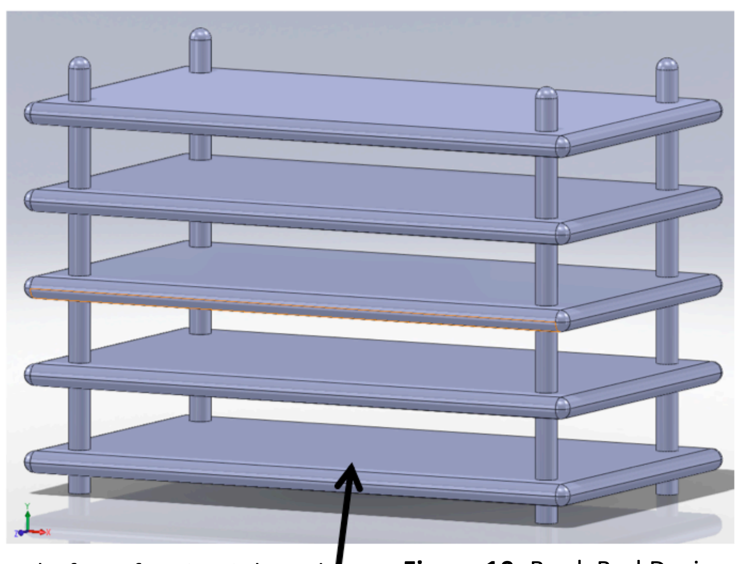


Figure 10: Bunk Bed Design

the easiest to manufacture. Any modifications to the circuit boards while testing the prototype would be extremely simple because of the open design. This open design, however, presents some problems. The circuit boards would be exposed with this design, which could result in damage if extreme care is not taken. Also, communication between the four identical boards and the motherboard would require additional wiring on the outsides of the bunks, increasing vulnerability to damage.

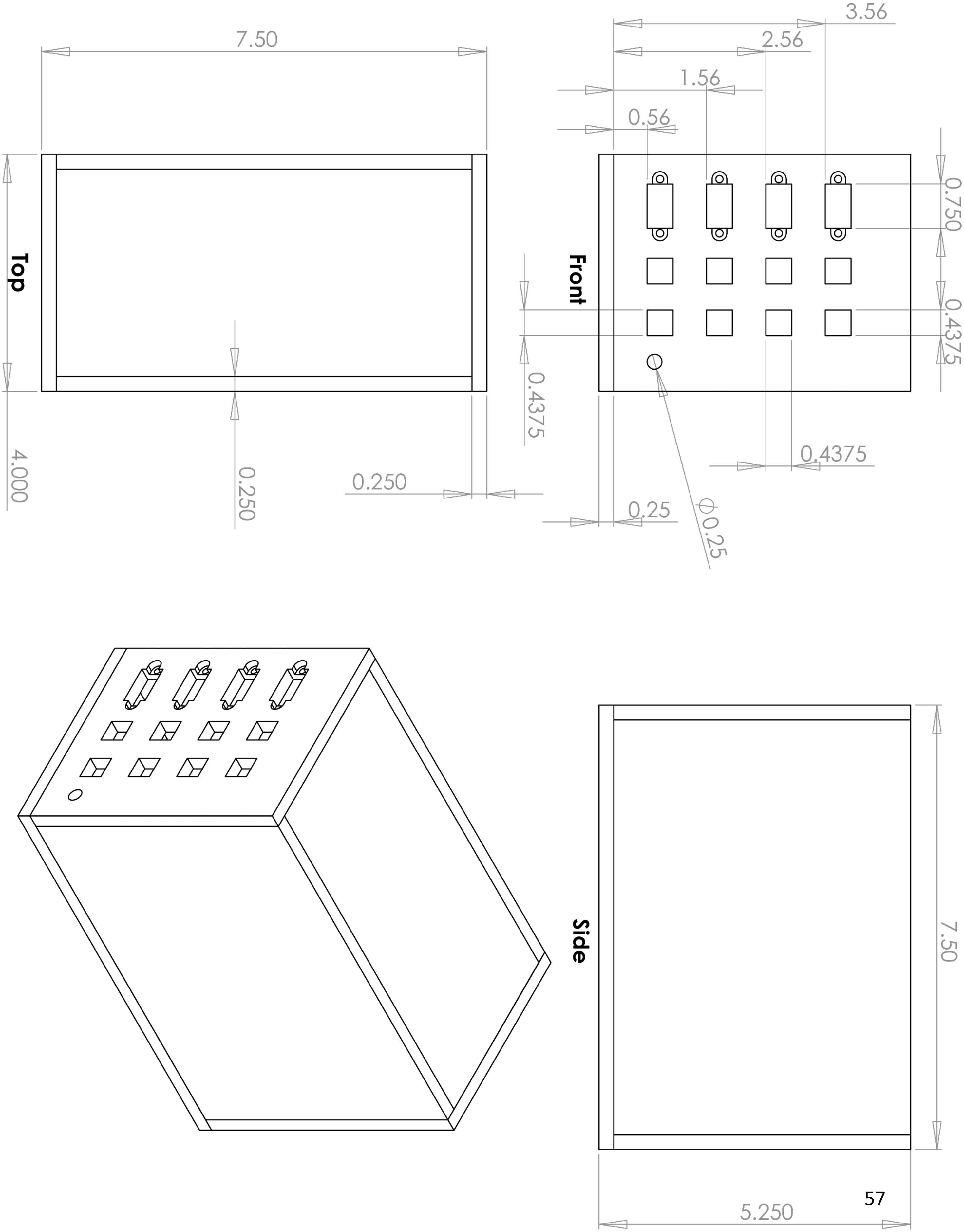
Circuit Board Housing Design Matrix

The circuit board housing design matrix (Table 2) was used to evaluate the three proposed design alternatives. Each option was rated using the following criteria: manufacturing feasibility, ergonomics, durability, and aesthetics. Ergonomics was weighted the highest because this will be the most important aspect of the design for the client. Even though the toaster oven scored lowest in manufacturing feasibility because of the extreme precision needed for the grooved sidewalls, this option scored highest in ergonomics and durability. The

Table 2 – Circuit Board Housing Design Matrix

Criteria (Weight)	Pegged 3 x 3	Toaster Oven	Bunk Bed
Manufacturing Feasibility (30)	26	22	26
Ergonomics (40)	30	35	25
Durability (20)	15	17	14
Aesthetics (10)	7	7	10
Total (100)	**78**	**81**	**75**

bunk bed design received a low score in ergonomics and durability because of the exposed circuitry and wiring. Because of its high durability and high grade in ergonomics, the design team decided to construct the toaster oven housing unit. Proposed dimensions for this design can be found on [the next page].


7.50
Top
4.000
0.250
0.250
3.56
2.56
1.56
0.56
Front
0.750
0.4375
0.4375
0.4375
0.25
ϕ0.25
Side
7.50
5.250

Communication Options

The following is a verbatim excerpt from the team's midsemseter paper. This section should serve as a reference and more details about what the team actually pursued can be found in the paper.

Communication

A major component of this project is to design and implement a method that allows the circuit boards to transmit data to the computer. The chosen method must allow data to be transmitted at a rate sufficiently fast enough so all data is acquired and included in the analysis. Additionally, it must be feasible for the team to complete any programming required. The team has researched and developed three methods that would allow for the communication of data between the circuit boards and the computer.

Universal Serial Bus (USB)

Universal serial bus, more commonly known as USB, is a wired connection directly between the pulse oximeter microcontroller and the computer. Such a connection would allow for data transmission of up to 480 Mbps (megabits per second) [6], well in excess of the requirements of one circuit board (each circuit board will have a data transmission rate of approximately 500 kbps). Because USB is commonly used in many aspects of computing today, using USB would not require users to learn how to interface the device with the computer. An implementation using USB would make the device plug-and-play. After connecting the USB cables to the computer, the computer would recognize the device and the user interface would be able to receive data from the pulse oximeter. Additionally, such cables are relatively inexpensive and would require no additional hardware for the computer or the microcontroller.

In order to make this device plug-and-play, some complex programming may be required. Most microcontrollers have USB libraries that allow for interfacing of USB with the microcontroller. It is unknown if the microcontroller in use on the pulse oximeter is USB compatible because the team is not working with the pulse oximeter hardware. If the microcontroller is not USB ready, additional work must be done to prepare the microcontroller for use with USB. With this method, each board would require one USB cable. As mentioned earlier, these cables are inexpensive ($16.99 for a 12 ft. cable [7]), but our client would require four of these cables at over 12 feet long each. The ideal setup of this device requires that the cables be taped to the floor to minimize tripping hazards.

A second option for using USB is to integrate the signals into an individual data stream using the Gumstix. This data could then be transmitted over a single USB cable. This single USB cable would help keep our client's laboratory cleaner and the overall cost a little less. However, it is unknown if each signal could individually be encoded on the Gumstix before being transmitted over USB. If that is possible, the computer could then separate the individual signals easily. Otherwise, some different method for identifying data must be developed.

Wireless Fidelity (Wi-Fi™)

Wireless fidelity (Wi-Fi™) is another commonly used computer protocol being considered for data transmission in this project. Wi-Fi is well known for allowing users to connect to a network or the Internet wirelessly. Another use of Wi-Fi is an *ad hoc* network. Such a network allows wireless devices to communicate directly with each other eliminating the need for other hardware such as a router [8]. Such a setup would be useful with this project as it would eliminate the cables required for the USB option and allow the users some flexibility with device setup in the laboratory. The Gumstix considered for use supports 802.11g wireless networking [9], which can achieve a theoretical speed of up to 54 Mbps. In practice, most 802.11g devices achieve a speed of 24 – 36 Mbps [10], more than sufficiently fast enough for this device. By setting up an *ad hoc* network between the Gumstix and computer, data can be transmitted between the two devices. Preliminary investigation into the capabilities of the Gumstix indicates that setting up this *ad hoc* network will be relatively easy.

However, this option is the most expensive. Depending on the Gumstix purchased, a separate Wi-Fi chip may need to be purchased. The estimated cost (including a Gumstix) can range anywhere from between $199 – $269 depending on the power of the Gumstix purchased. An Overo-series Gumstix contains a Wi-Fi chip already and is overall less expensive. The verdex pro-series Gumstix would require an expansion board with a separate Wi-Fi chip, but it may offer a little more flexibility with feeding the signal from the pulse oximeter microcontroller into the Gumstix. Some further research is needed in order to understand how to push data from the Gumstix through the Wi-Fi connection and how the computer will receive the data [9].

A final point to be considered with Wi-Fi is the potential for interference. Research indicates that the PET scanner should not interfere with the Wi-Fi signal. Additionally, wireless internet is present in the facility where the scanner is used and no problems have been reported.

Bluetooth®

Bluetooth® is another wireless option being considered. While similar to Wi-Fi in theory, it offers a shorter range, requires less power, and is less expensive overall [11]. One of the verdex pro-series Gumstix includes a Bluetooth chip which has an optimized data transmission rate of up to 3 Mbps, but it allows for individual tagging of signals to be transmitted at that rate [12]. However, it is a concern that the signal transmission speed will lower with multiple connections. Additionally, with lower power and a slightly lower speed, the range of Bluetooth is significantly less than that of Wi-Fi. Estimates of maximal range are between 10 and 33 feet [11]. Since this Bluetooth chip is built into the Gumstix, minimal interfacing should need to be done in order for it to transmit data from the pulse oximeter microcontroller.

The computer our client purchased for use with this project is currently not Bluetooth compatible; an adapter would need to be purchased and the computer configured to use it. Such adapters can be purchased for about $25 [13]. Additionally, some initial pairing of the device and computer will need to be performed and this may be difficult. Once paired, the devices should automatically detect and pair once they are within range of each other.

While this option is feasible, it still requires extensive research because not as much information is known about the Bluetooth protocol.

Communication Design Matrix

The Communication Design Matrix (Table 1) was used to evaluate the various design ideas. Programming feasibility was a major component of the evaluation criteria and USB scored the highest on this. Wi-Fi has a communication speed well in excess of the requirements, so it scored the highest in that category. Aesthetics was a measure of how clean the project would keep the client's laboratory and both Wi-Fi and Bluetooth scored the highest due to the fact they are both wireless. Operability was a measure of how easy it would be for the user to use the project; Bluetooth would require a little bit of setup and thus scored lowest in that category. With all criteria taken into account, the team will proceed with using Wi-Fi technology to stream data from the circuits to the computer.

Table 1 – Communication Design Matrix

Criteria (Weight)	**USB**	**Wi-Fi™**	**Bluetooth®**
Programming Feasibility (35)	29	28	31
Cost (15)	12	9	9
Operability (15)	12	10	8
Communication Speed (30)	25	30	20
Aesthetics (5)	1	5	5
Total (100)	**79**	**82**	**73**

Block Diagram

Figure 7 demonstrates the setup of this device. There will be four boards (one per rat) and each board will contain all the circuits components for the pulse oximeter, FSR, and thermistor. Each of these boards will feed into the Gumstix, which will act as the 'motherboard' to the entire system. Some signal processing may occur on the Gumstix. After signal processing, the data will be transmitted over the Wi-Fi connection where the computer will receive the data and display it in the GUI.

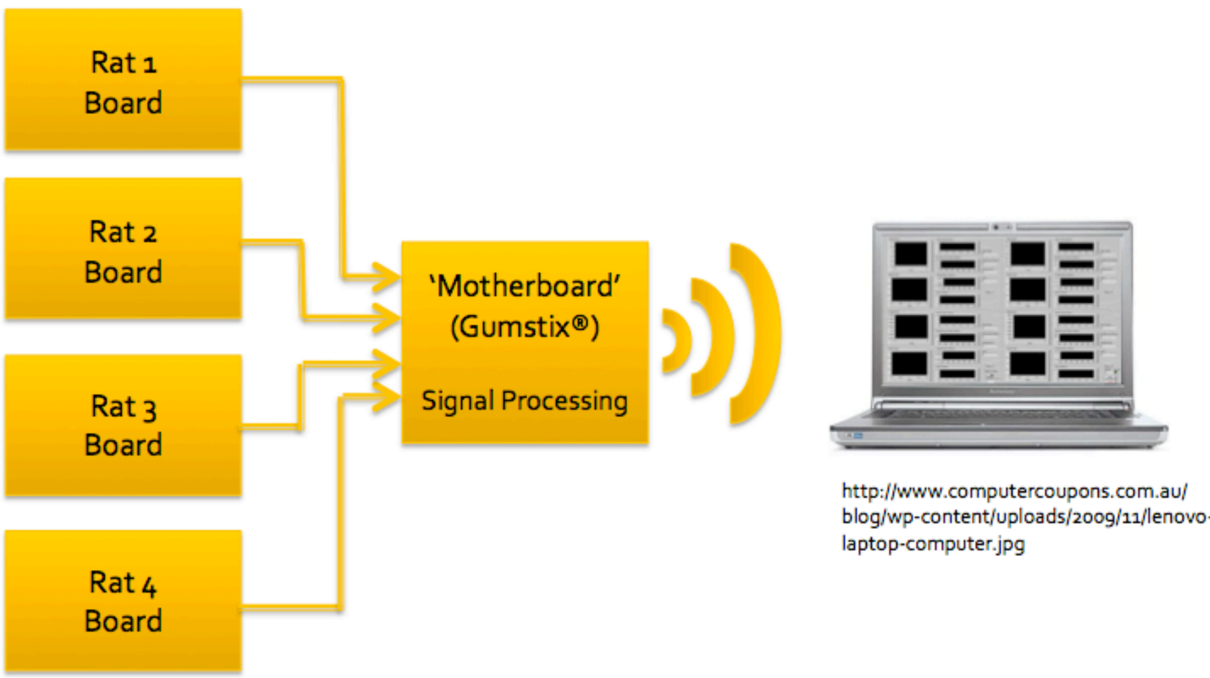


Figure 7: Block diagram of project