
Electrocardiogram Demonstration Board

Sponsored By: Texas Instruments – Precision Analog



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Faculty Adviser:

Dr. Rama Mukkamala – Electrical & Computer Engineering

Texas Instruments Contact:

Peter Semig – Applications Engineer

Design Team Members:

Mike Mock
Justin Bohr
Nate Kesto
Chaoli Ang
Xie He
Yuan Mei

Abstract:

The team's design challenge for the semester was to research, design, fabricate, and test the analog circuitry needed to develop an electrocardiogram (ECG) demonstration board for Texas Instruments (TI). The precision analog group at TI sponsored the development of the project at Michigan State University. The group sponsored the project due to their need for another tool to showcase several precision analog components in a biomedical application. Many TI technologies and components are featured using demonstration boards and are put on display at technical trade-shows and other professional events. The defined objective for the design team was to develop the battery-powered analog circuitry needed to interface a Stellaris microcontroller-based oscilloscope with an ECG simulator (CardioSim II). The scope of the project work included the designing of the analog front-end circuitry needed to condition an ECG signal produced by a cardio simulator. The semester's work also included choosing the appropriate TI components to fit the project needs as well as the layout, and fabrication of four printed circuit boards (PCB's). This work was performed to reduce the inherent noise present at the output of the cardio simulator. The simulator generated differential ECG signals with relatively large amounts of noise, which required appropriate signal conditioning to maintain the quality of the output signal at the oscilloscope. To properly condition the displayed signal, the team went through three major iterations in the design of the analog front-end circuitry. Throughout these iterations, the group simulated, tested, and verified the expected results of the circuit operations. The design team exceeded the initial project deliverables by implementing circuitry and hardware needed to handle live ECG measurements from a user's fingertips. The team also implemented the code in the oscilloscope application to display the ECG signal while scrolling in real-time. This was an improvement from the default oscilloscope application and is better suited for the specific application of the ECG demonstration board.

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Chapter 1

Project Background:

The goal for the design project was to develop a demonstration board for Texas Instruments (TI) precision analog group. The team's project sponsor, Pete Semig, works in TI's precision analog group in Dallas, Texas as an applications engineer. The precision analog group sponsored the MSU senior design team's development of an electrocardiogram (ECG) demonstration board. An electrocardiogram (ECG) is a piece of electronic medical equipment that measures and displays the electrical activity associated with the heart. The measured cardiac signals are commonly used for diagnosis and understanding of patient conditions in the medical and research fields. One of the challenges in developing ECG systems lies in the fact that bio-potentials measured at the surface of the skin have low amplitude and are mainly low in frequency (fundamental below 3 Hz with spectral content up to 200 Hz). This requires precise filtering and low-noise amplification. Another challenge lies in the fact that the ECG bio-potentials measured from the heart are differential in nature as they are measured on opposite polarities of the cardiac muscles. A typical QRS complex ECG waveform is a superposition of many physical actions in the body's cardiac muscles (See Figure 1). The composition of these activities occurring in time relate to a variety of valuable ECG frequency spectrum across the lower frequency bands. The usable spectral content in a typical ECG signal falls between 0.3 Hz and 100 Hz. Because of this, most commercial ECG systems are designed with that bandwidth.

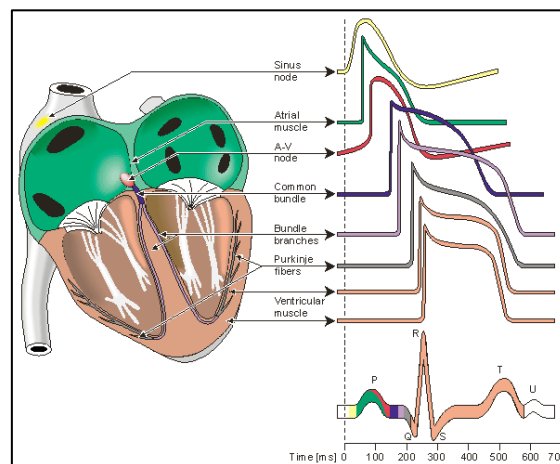


Figure 1: Superposition of action potentials that produce ECG signal

Texas Instruments asked the team to design the ECG demonstration board to replace their current ECG system solution. In recent years, customer interest and design of ECG products has seen noticeable growth, however TI is in need of a portable solution to showcase a mixed-signal ECG system application. In order to provide TI with a functioning and interactive demonstration board, the team was tasked with researching, designing, testing, and fabricating several iterations of board designs.

Project Specifications:

The desired specifications and main objective given to the group was to create a reliable analog-front end circuit to interface a CardioSim II cardiac signal generator (simulator) with a Stellaris EKS-LM3S3748 evaluation board. The board was specified to run from a portable battery as well designing with battery-life in mind. The signal integrity for the output signal needed to be good to have a clear enough ECG signal to show up on the Stellaris' built in 1.5" LCD screen.

Project Development:

The group went through three phases of the design process. The first phase included the research and simulation of the circuitry needed to perform the ECG signal conditioning. The second phase included the layout of two printed circuit boards (PCB's) to confirm practical circuit performance and function. The third phase in the development of the board included the design and fabrication of the final PCB and demonstration board. During each phase, the group learned many things and necessary changes were made to steer the strategy and direction of the project. As requested by the team's sponsor, the group designed the ECG demonstration board using the INA333 instrumentation amplifier and the OPA378 operational amplifiers. The INA333 was chosen by the team to provide high common-mode rejection of noise present in ECG applications. The OPA378 was researched and chosen to fit the necessary SOT23-5 footprint and was desirable due to its low noise and low voltage offset operation. Another feature of the OPA378 is its low power operation, which includes quiescent currents under 150uA. To provide a low power voltage supply for the analog circuit, another TI power management solution was researched and chosen to regulate the 9V battery to a 5V supply rail. During the semester, the team built two power circuits (buck converter and low-dropout regulator (LDO)) and compared their performance in efficiency (battery-life) and noise. The TPS7A4201 (LDO) was chosen as the final power management IC used in the design.

The comparison as well as the rationale used in the decision will be documented in the body of this report. Overall, the design team was able to develop a solution that not only interfaced the analog front-end (AFE) circuit with the cardio simulator, but also allows for a user to measure live ECG signals present at a user's fingertips. This publication has been written for the purpose in documenting the detailed steps taken throughout the design of the ECG demonstration board for the precision analog group at Texas Instruments.

Project Solution:

Throughout the semester, the senior design team met with Peter Semig to discuss the direction and progress of the project. Initial meetings consisted of the team asking many questions to become familiar with the desired deliverables for the demonstration board as well as the final performance desired from TI. It was discussed that, because TI will use the demonstration board to showcase their integrated circuit performance, it was crucial that the demonstration board was reliable and measured ECG signals accurately and clearly. In order for the overall system to work well, the signal integrity needed to be very high as well which required using low-noise components such as the TPS7A4201 linear dropout regulator (LDO) as well as the OPA378 operational amplifiers. Using the OPA378 op-amps in conjunction with best practice PCB layout techniques, and appropriate bandwidth selection, the circuit's output contained very little noise when subsequent testing was performed. Other design considerations for cost optimization were also included while making design decisions for the AFE boards. The main weight of the project cost included the \$33.00 charge for PCB fabrication.

Chapter 2

House of Quality Matrix:

To further help the team breakdown and analyze TI's demands relating to the project solution, a Six Sigma based tool called a "house of quality matrix" was constructed and populated. Shown in Figure 2, the tool shows the correlation of each detailed customer (TI) demand as well as the capability of the potential design solutions for this project. In this diagram, items listed in the rows are the customer's requirements while the columns are populated with the design function requirements. The team then defined the correlation between them using three levels (strong, moderate and weak). The importance and weight of each customer requirement was then addressed accordingly and prioritized.

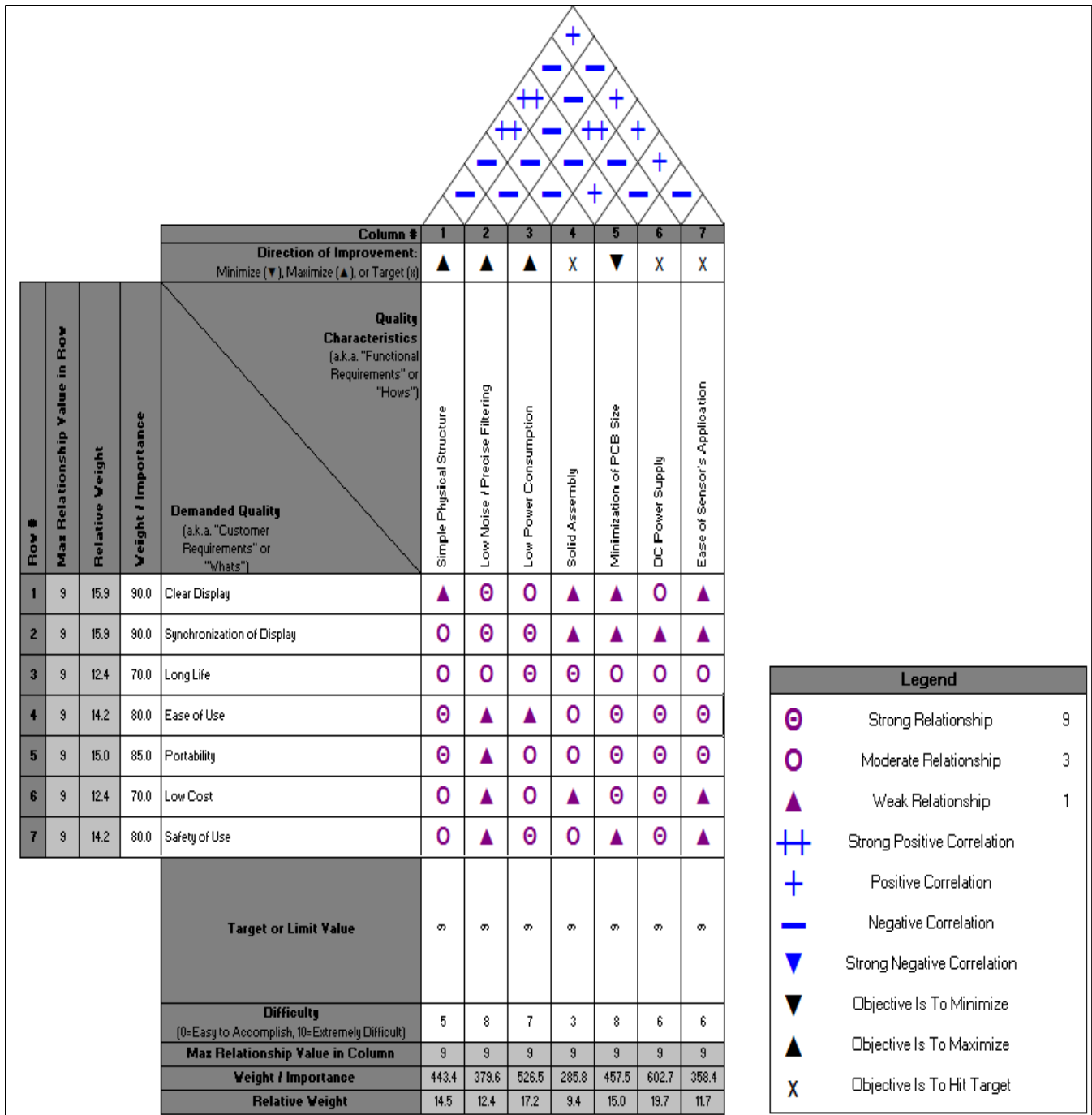


Figure 2: House of Quality matrix used to analyze customer requirements

Project FAST Diagram:

Another tool utilized by the group to analyze the most important functions of the overall ECG demonstration board is called a FAST Diagram. It was developed to understand the functional uses that the demonstration board would provide TI or any user of the board. Figure 3 shows the results of this elementary way of focusing in on the products main functionality. The group analyzed the main function of the demonstration board to be “analyzing an ECG signal.” Sub-functions of the demonstration board included “amplifying analog signals” and “converting analog to digital” and other supporting operations.

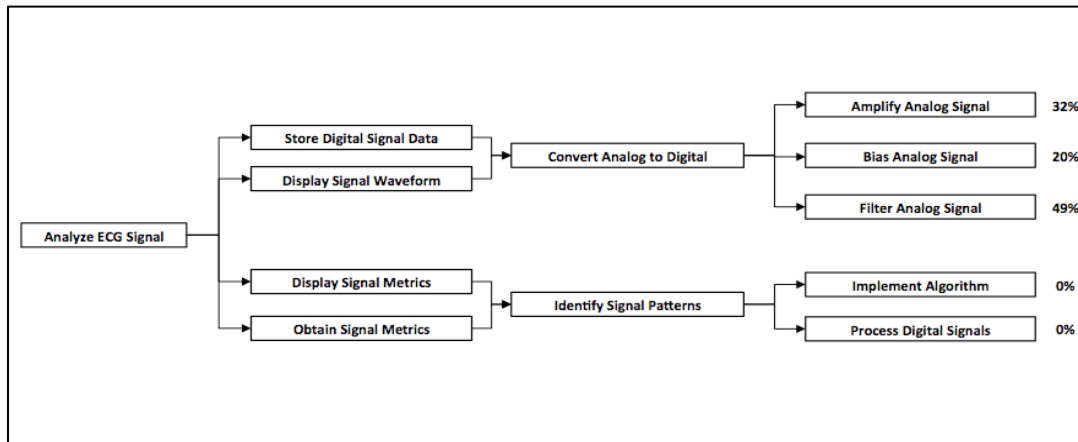


Figure 3: Project FAST Diagram used to break system into basic functions

After researching the project deliverables needed to successfully complete the demonstration board, the group analyzed several PowerPoint presentations provided by TI, which included several reference schematics as well as some general information about ECG signals and their composition. The presentations detailed some theoretical circuit topologies and reference designs for an ECG system developed and analyzed by Matthew Hann, a linear applications engineer at TI. Following the suggestions of Peter Semig, the team spent a few weeks simulating the reference circuits using TINA-TI Spice Software to verify the theoretical operation. The team also built some of the reference circuits and verified live measurements with the simulation results. An example of the reference schematic given to the group is shown in Figure 4. These reference designs helped the group get started in understanding theoretical ECG systems during the development of the phase 1 PCB, however subsequent PCB's were improved upon and re-designed after appropriate measurements and decisions were made.

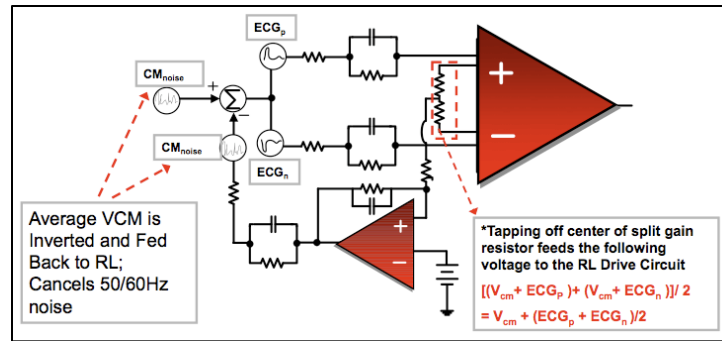


Figure 4: Example reference schematic provided by Matthew Hann at TI

Chapter 3

Circuit Simulations:

After analysis of the critical customer requirements following the team's conversations with Peter Semig, circuit solutions began to develop and the first step in the design process was to simulate the system sub-circuits to understand their function and impact towards the total system behavior. The sub-circuits simulated towards the beginning of the project were the input low-pass RC filter network, the INA333 gain and transient performance, the DC servo-loop, and the output filtering. The integrated circuits used in each sub-circuit were the low-noise OPA378 as well as the INA333 instrumentation amplifier. Figure 5 shows TINA-TI simulation circuit for the input RC input low pass filter network used to bandwidth limit the input signals to the INA333. The function of the circuit was found to include both a common-mode low pass filter as well as a differential mode low pass filter.

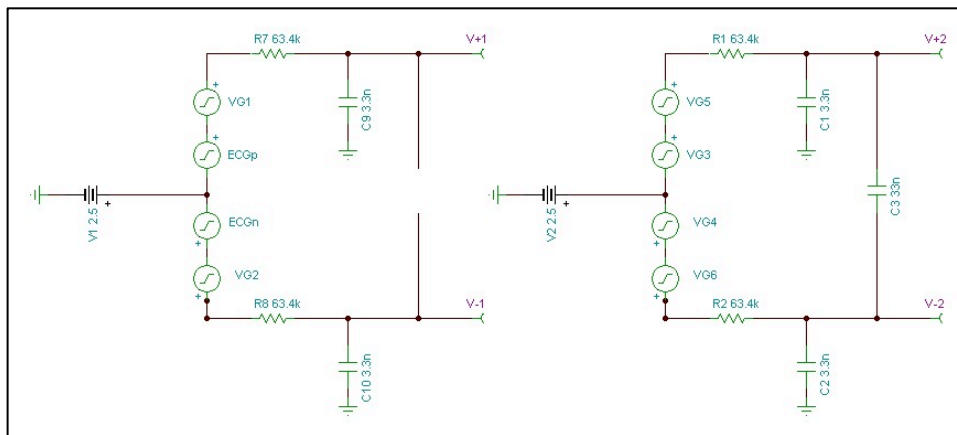


Figure 5: Example TINA-TI simulation circuit of input RC filter network

Another reference circuit explored by the team was the right-leg drive (RLD) amplifier. This circuit works together with the input filter and a DC servo loop to cancel common mode noise as well as set the DC reference for the input signal to be between the power supply (5V) and ground rails. The simulation schematic and results of the DC servo loop is shown below in Figure 5a and 5b. The team was able to input a differential ECG signal using some of TINA-TI's signal source defining tools.

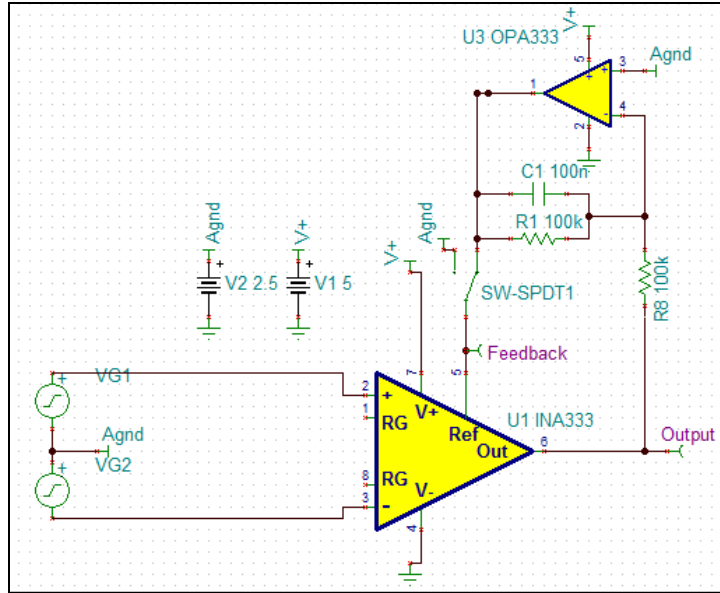


Figure 5a: TINA-TI simulation for DC servo loop circuit

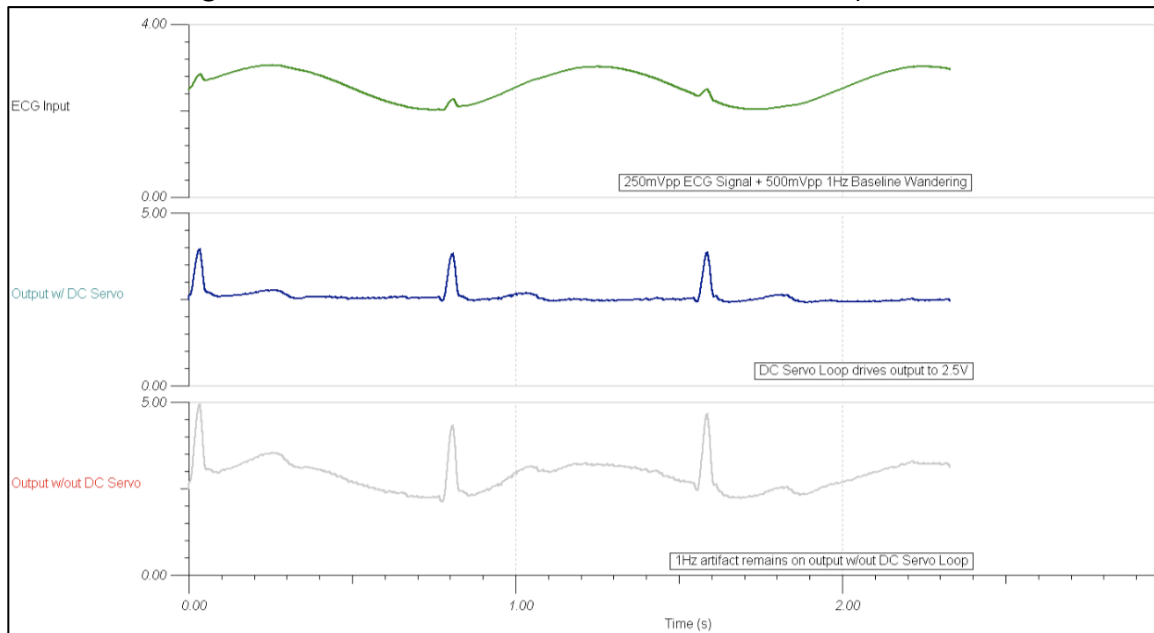


Figure 5b: Results of DC servo loop removing low-frequency drift of input

Other simulations were performed for the right-leg drive circuit. Figure 5c below shows the right-leg drive functioning to remove common-mode signals (60 Hz noise) from the input to the analog front-end.

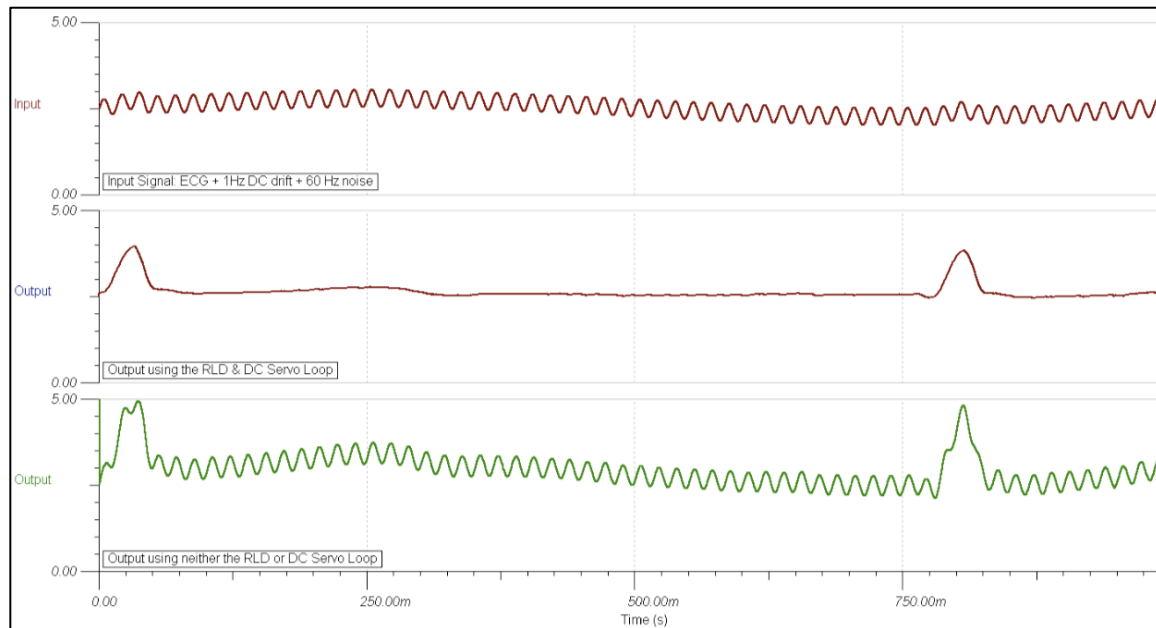


Figure 5c: Right-leg drive circuit simulation removing 60 Hz noise

The power management IC's (TPS7A4201 and TPS62120) were also simulated to confirm the proper voltage regulation and output voltages that would be expected. This helped the team order appropriate parts and confidently layout the power management circuits on the PCB's. The ideal regulated output voltage to run the AFE was (5V). Both the buck converter and LDO were able to regulate a 5V rail from a 9V battery. The layouts for the LDO and buck converter were designed using the reference schematics given in the datasheet's application notes for each device.

Transfer Function Analysis:

To understand the entire system's behavior, the sub-circuits used to piece together the ECG demonstration board's AFE were separated and studied. This was done by the group to piece together their transfer functions into a total system-wide transfer function. As stated previously, the sub-circuits were simulated using TINA-TI spice software and the team was able to confirm each circuit's theoretical transfer function and its corresponding transient behavior. The ultimate goal of this work was to understand each sub-circuits impact on the total system and to work

towards designing the final schematic. The entire circuit can be broken into four main parts that contribute to the differential amplification and filtering of the system. The four main sub-circuits are the input RC filtering, INA333 instrumentation amplifier, the servo loop, and the output filter stage. Figure 6 shows the schematic for the input RC filtering network. It is comprised of a differential-mode low pass filter as well as a common-mode low pass filter. The noticeable contribution to the overall system is from the circuit's differential filtering so this will be included in the following analysis.

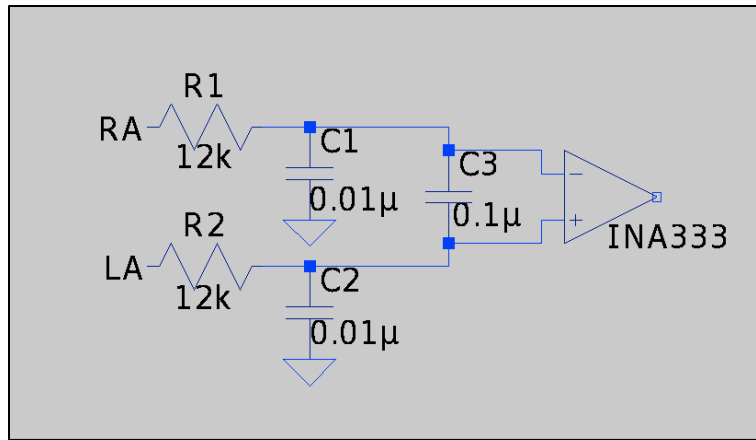


Figure 6: Input RC filter network schematic

The differential corner frequency for the RC input network (low pass filter) can be summarized by Equation 1 below. For the sake of making the analysis easier to understand, the result can be summarized again into a single ended, first order low pass filter transfer function as detailed in Equation 2.

$$\text{Input RC Network Corner Frequency} = \frac{1}{2\pi(R1+R2)(2*C3+C2*C2//C1)} \quad (1)$$

For the later designs, R1 and R2 = 12k, C3 = 0.1μF, and C2 and C1 = 0.01μF as shown above in Figure 6. This provides an input low pass filter with a corner frequency at 32.3 Hz.

$$\text{1st order LP Filter Transfer Function} = \frac{1}{sRC+1} \quad (2)$$

Where the time constant "RC" is equal to 4.92ms

The INA333 provides a differential gain that can be thought of as constant vs. frequency. A resistor placed between pins 1 and 8 for the IC provides the adjustable gain for the INA333. The equation for the gain of the amplifier is found in Equation 3. The circuit block for the INA333 is shown in Figure 7 and was taken from the datasheet developed by TI.

$$INA333 \text{ gain} = 1 + \frac{100k}{R_g} \quad (3)$$

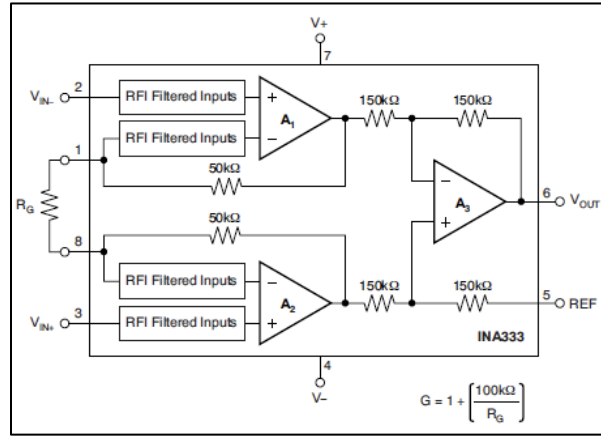


Figure 7: INA333 IC diagram showing R_g (left) as the gain setting resistor

The servo loop schematic can be seen in Figure 8. It effectively creates a high pass filter in the system by inverting and feeding back a low pass signal into the INA333's reference pin 5. This effect is summarized by the transfer function for a first order high pass filter shown in Equation 4.

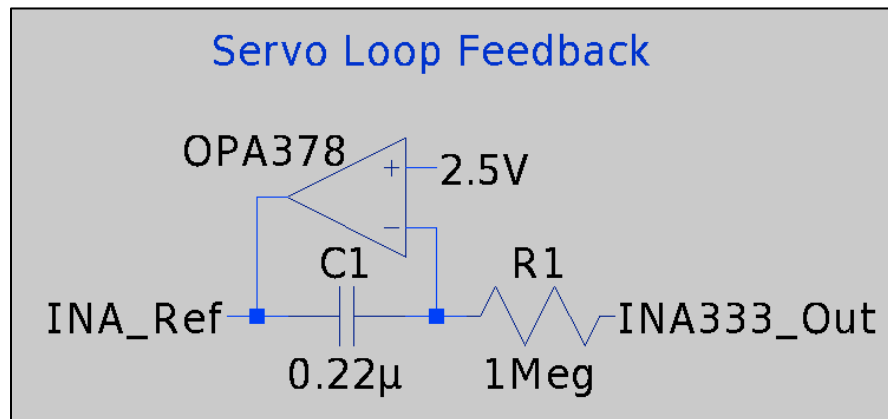


Figure 8: Schematic for system high pass servo loop integrator

$$1st \text{ Order High Pass Filter Transfer Function} = \frac{sRC}{sRC + 1} \quad (4)$$

The output filtering is also can be analyzed using a 1st order low pass filter's transfer function. It has the same form as the transfer function in the input RC network's analysis. The difference between the input filtering RC network and the output filtering is the fact that one is passive and the other is active. The output filtering has a pass band gain greater than unity instead of passive circuit topology used in the input section. Using this analysis and process of piecing together the transfer functions of each sub-circuit the total system transfer function was analyzed using algebraic manipulation and control theory. The resulting total symbolic system transfer function (theoretical) is shown below in Equation 5.

$$\text{System Transfer Function} = \frac{(-16.15 * C3 * R3 * R4 * s)}{(s^3 (C1 * C2 * C3 * R1 * R2 * R3 * R4) + s^2 (C1 * C3 * R1 * R2 * R4 + C2 * C3 * R2 * R3 * R4 - C1 * C2 * R1 * R2 * R3) + s(C3 * R2 * R4 - C1 * R1 * R2 - R2 * R3 * C2) - R2)} \quad (5)$$

The resulting transfer function was analyzed using MATLAB and theoretical component values were plugged into the script. The script used to process the transfer function symbolically is shown in Figure 9. The theoretical bandwidth expected for the MATLAB analysis was from 0.15 Hz to 27 Hz.

```
clc
clear
C1 = 0.05E-6;
R1 = 56E3;
INAgain = 16.15;
C3 = 1E-6;
R4 = 1E6;
R2 = 1E3;
R3 = 100E3;
C2 = 0.047E-6;
num = [-1*INAgain*C3*R3*R4 0];
denom = [C1*C2*C3*R1*R2*R3*R4
C1*C3*R1*R2*R4+C2*C3*R2*R3*R4-C1*C2*R1*R2*R3 C3*R2*R4-
C1*R1*R2-C2*R2*R3 R2];
sys = tf(num,denom);
h = bodeplot(sys)
setoptions(h,'FreqUnits','Hz');
```

Figure 9: MATLAB script written to graph the entire system bode plot

The resulting bode plot was generated from the MATLAB script's symbolic transfer function using theoretical component values. The resulting plot is shown below in Figure 10. As shown, the total system behavior can be summarized as a band pass filter with a bandwidth from 0.16 Hz to 27.04 Hz. The pass band gain of the filter is 64.2 dB (1621.81 V/V). As shown, the theoretical results matched very well with the total symbolic analysis of the system's transfer function.

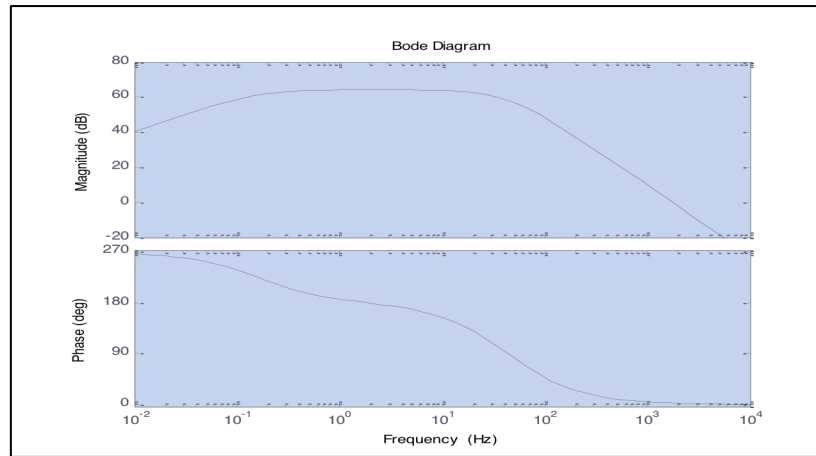


Figure 10: Bode plot analyzed in MATLAB from system transfer function

Breadboarding the Circuit:

Prior to developing the first PCB's for the initial phase of the design project, the group built and tested as much of the analog front-end circuitry (AFE) as possible using a breadboard in the labs at Michigan State University. The INA333 was placed on a DIP-to-MSOP8 adapter to allow the surface mount IC to be placed in circuit and tested using through-hole passive components. In the circuit on the breadboard, the OPA378 op-amps were replaced with readily available LM741 op-amps. The goal in putting the circuit together was to test and confirm the functionality of the reference circuits for the analog front-end system. The circuit was powered using an HP 6216C power supply after being set to 5V. The circuit was tested and measured to confirm the lab measurements with the results and performance seen in the TINA-TI simulations. Figure 11 shows the breadboard test circuit used prior to phase 1 of the AFE development. The sub-circuits placed on the breadboard included the input RC network, the INA333 instrumentation amplifier, the servo loop, and the active low-pass output filter.

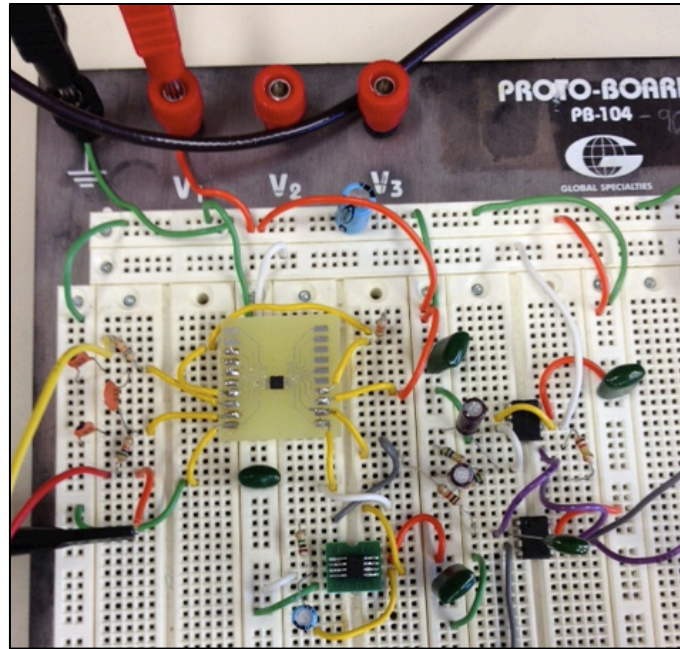


Figure 11: Phase 1 circuit initial testing on breadboard layout

The pass band gain of the analog circuitry as well as the bandwidth was measured, and the signal integrity of the output was observed. A bandwidth from 0.7 Hz to at least 20 Hz was necessary to retain a clear and recognizable ECG output signal. This bandwidth confirmed the theoretical analysis and research of the required bandwidth for the ECG AFE circuit. The gain was also adjusted using the adjustable RG resistor on the INA333 circuit and by adjusting the pass band gain of the active output LP filter. The ECG signal was biased halfway between the 5V power rail and ground to allow for maximum differential “swing” of the ECG signal. To accomplish this on the breadboard, a voltage divider made up of two 560k resistors and two 0.01uF capacitors was used to divide the supply rail to a 2.5 V reference voltage that was used appropriately throughout the circuit to bias the ECG signal correctly. After a clear output signal was found, the output signal integrity was then observed while tuning the gain of the system to approximately 64dB, which allowed the signal to swing fully positive and negative between the rails without saturating the op-amps throughout the signal path. Figure 12 shows the breadboard test setup using the CardioSim II simulator to connect to the AFE. The ECG signal quality is shown on the Agilent 54833A digital storage oscilloscope and the group then began designing and laying out the

phase 1 PCB to include the analog circuitry tested on the breadboard.

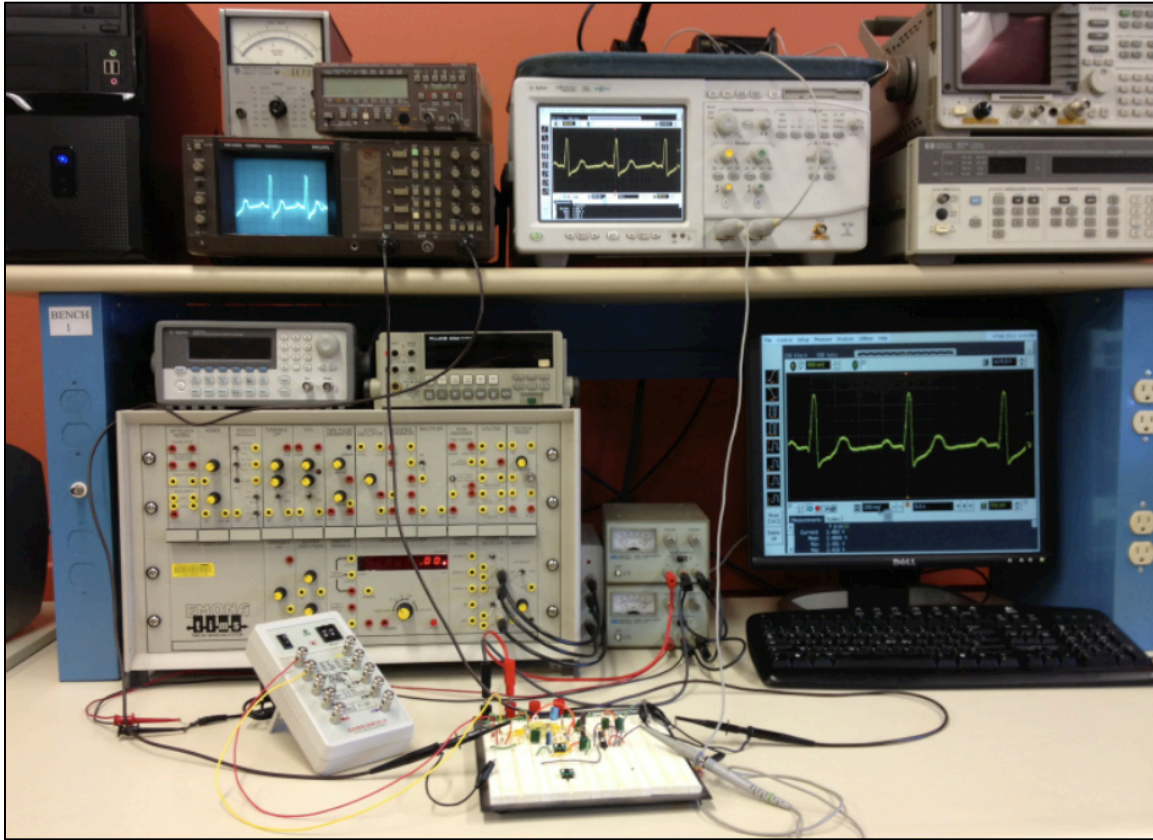


Figure 12: Lab testing showing breadboard AFE and the cardio simulator

Phase 1 PCB Work:

After the AFE circuit operation was confirmed through simulation and breadboard testing, a schematic was created in Advanced Circuit's PCB Artist software for the Phase 1 PCB. The purpose of creating a detailed schematic in PCB Artist allowed for the team to organize and order a professional two-layer PCB. Creating the schematic required the use of components from built-in libraries that come with PCB Artist. For some of the components, custom footprints and schematic profiles needed to be developed. Custom components needed a schematic symbol, PCB symbol, and an overall component that would link the schematic symbol pins and PCB symbol pins together. This process was required for most components used that did not fit a 1206 surface mount pad layout. This included the INA333 instrumentation amplifier, OPA378 op-amps, test

points and TPS62120 switch converter IC. PCB Artist has a simple wizard for creating schematic and PCB symbols for op-amps and almost any IC. Using the wizard shortened the time taken to create the custom components. Components that could not be created with the wizards had to be hand drawn in the editor, which required more precision and patience to complete. Using the datasheets for each of the components and IC's, accurate dimensional measurements allowed these PCB symbols to be drawn by hand and the accuracy was verified using measurement tools in PCB Artist. Since the phase 1 board was developed mainly for testing purposes, several test points and jumpers were placed at appropriate places in the schematic. Figure 13 below shows the Phase 1 schematic used to design and layout the PCB.

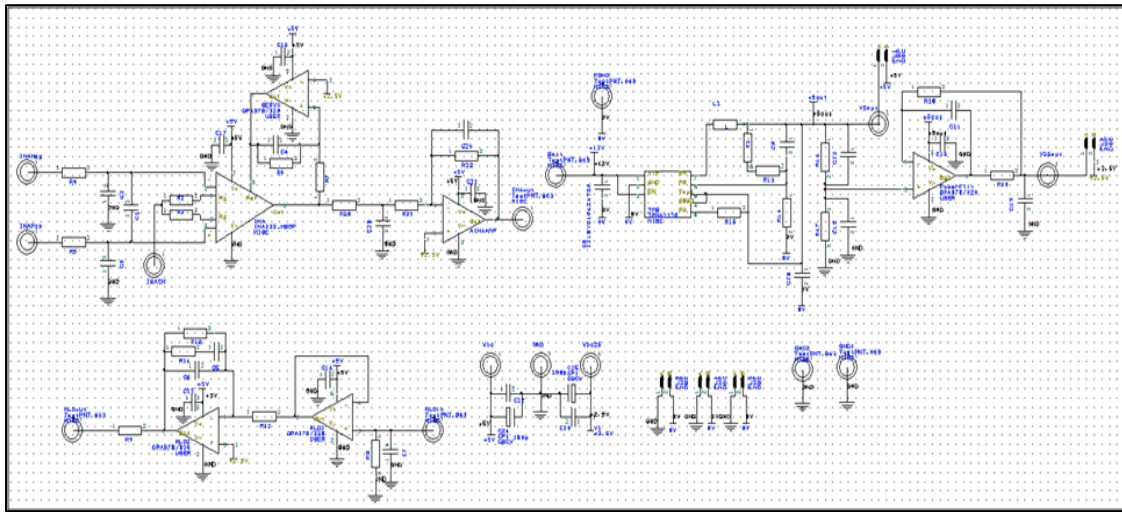


Figure 13a: Phase 1 schematic of AFE and TPS62120 circuit

When laying out the PCB design for Phase 1, a high priority for the team was in minimizing interference through the power circuit's ground plane and sensitive nodes of the circuit. The power circuit used was a TI integrated switcher/buck converter (TPA62120), which bucked a 9V battery supply to the required 5V chosen to power the board. The ground plane for the power circuit was separated due to the noise generated by the internal MOSFET switching in the power IC. To protect the noise from coupling into the high-impedance input pins on the op-amps, the ground plane was also cut out from under to reduce EMI from fast-switching ground-return currents. When using the power circuit, a jumper was placed over the 2-pin headers, which connected the power ground

plane and the rest of the circuit ground. This ultimately reduced the interference from the power circuit to the rest of the circuit. Figure 13 shows the PCB layout fabricated for Phase 1 including the test points, separated ground planes, and jumper pins.

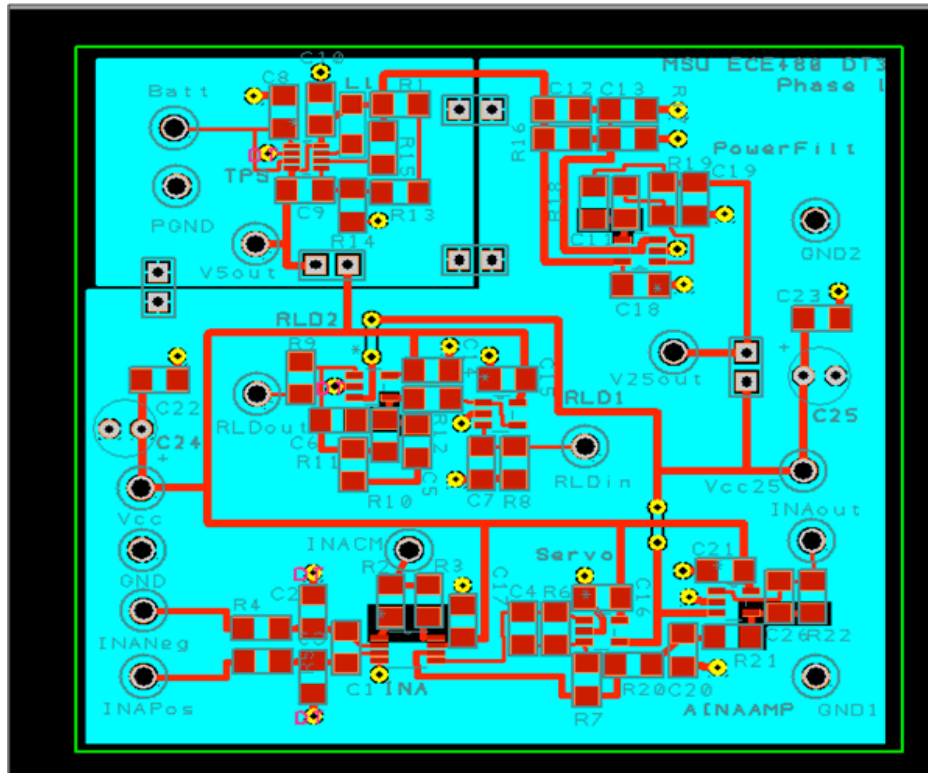


Figure 13b: Phase 1 PCB layout

After initial tests were performed on the phase 1 PCB, the output was saturated at the 0V ground reference. This was unexpected and after further troubleshooting the group discovered that a mistake had been made in the schematic/layout. The non-inverting and inverting pin connections to the servo loop feedback op-amp were switched around which resulting in unwanted positive feedback (saturation). The group was able to temporarily fix this issue by bending the input pins on the op-amp up off the board and small gauge wire was soldered in to reverse the input pin wiring. After rectifying the positive feedback problem, the board operated properly and further testing was performed to confirm correct operation (gain, bandwidth, etc.). The group learned from the wiring

mistake in phase 1 and the servo-loop wiring error was corrected during the development of the phase 2 PCB.

Phase 2 PCB Work:

Phase 2 was created with further circuit testing in mind. Switches were added to turn on/off appropriate circuitry, and a space for a 9V battery connector was created. To test the proof-of-concept in measuring an ECG signal from a person's fingertips, large copper pads (electrodes) were added on the surface of the board. A double-pole double-throw (DPDT) switch was added to allow the selection of two power management circuits. The noise and efficiency metrics were taken and two devices were compared. The two power management solutions tested were both packages in TI's power management portfolio. Circuits for the TPS62120 integrated switch converter and the TPS7A4201 linear dropout regulator were developed on the phase 2 board for comparison. A second switch allowed the user to select between a 2.5V reference and the RLD output to the body (common mode cancelation). A third SPST switch was added in the power circuit to turn on/off the connection to the battery. Figure 14 shows the schematic for Phase 2.

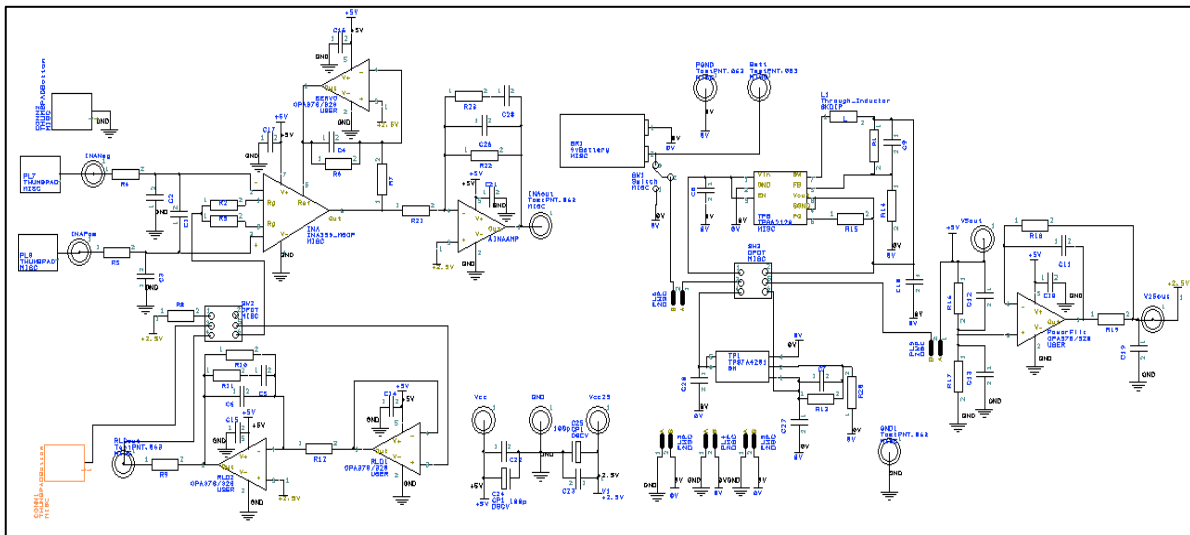


Figure 14: Phase 2 schematic developed and fabricated in PCB Artist

The PCB layout of the phase 2 PCB became more complicated than the phase 1 PCB, due to the addition of the switches and additional components. Because of the additional features and the design for

of two system bandwidths (50 Hz and 100 Hz). Another feature added to the final Phase 3 PCB was an LED indicator light to alert the user when the circuit was being powered. Adding the LED reduced the battery-life of board, however with the LED drawing only 1.5mA, the AFE final board still has a sufficient battery life of 211 hours of continuous operation. Figure 16 below shows the schematic for the phase 3 board including the additional circuitry and features.

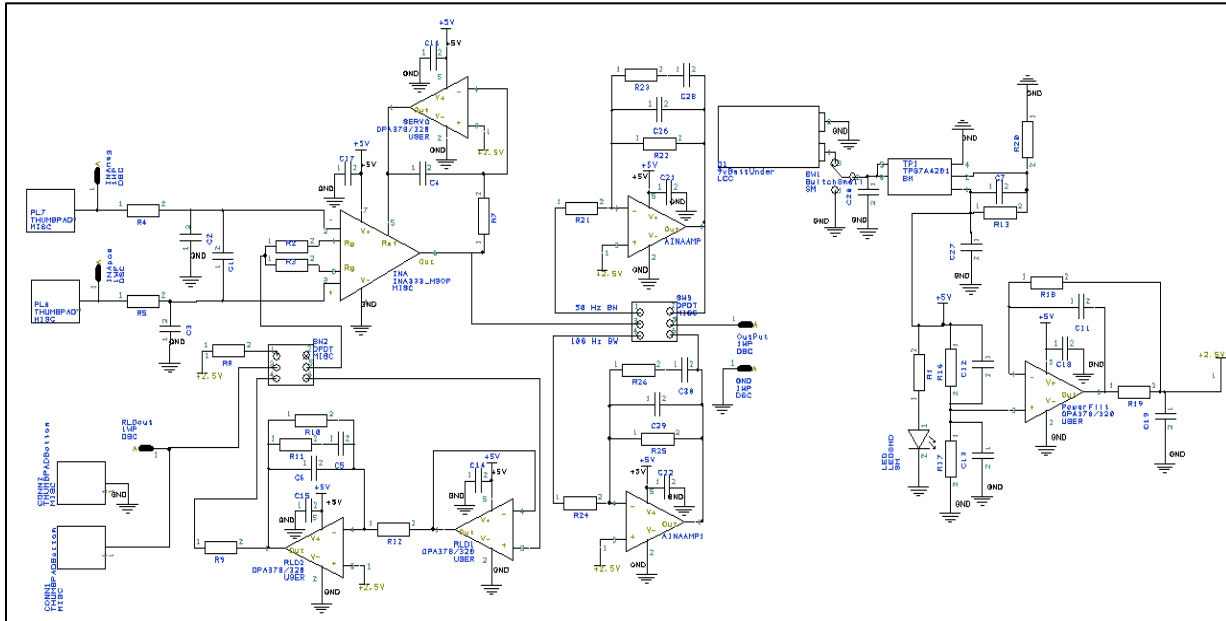


Figure 16: Phase 3 schematic (with switches) developed in PCB Artist

Keeping the same sub-layout of each individual circuit element (servo loop, LDO, output filter, etc.) the layout of phase 3 was spread out to allow for labeling. The precision analog group requested this for the purpose of allowing customers an ability to easily recognize the circuitry used in the board as well as to highlight the components featured in the circuits. The thumb pads were separated to either side of the board to make it easier to grasp when the board is mounted on a display. This was done to make it easier for the user to grip the AFE board and move as little as possible (reduce DC drift and offset). Slight movements in the electrode (finger) connection were researched and found to create artifacts in the ECG signal. The inputs and outputs were also grouped together (100 mil spacing) to allow Molex connectors and custom cables

to connect the CardioSim II and Stellaris board with the AFE PCB. Figure 17 shows the phase 3 board with switches PCB layout.

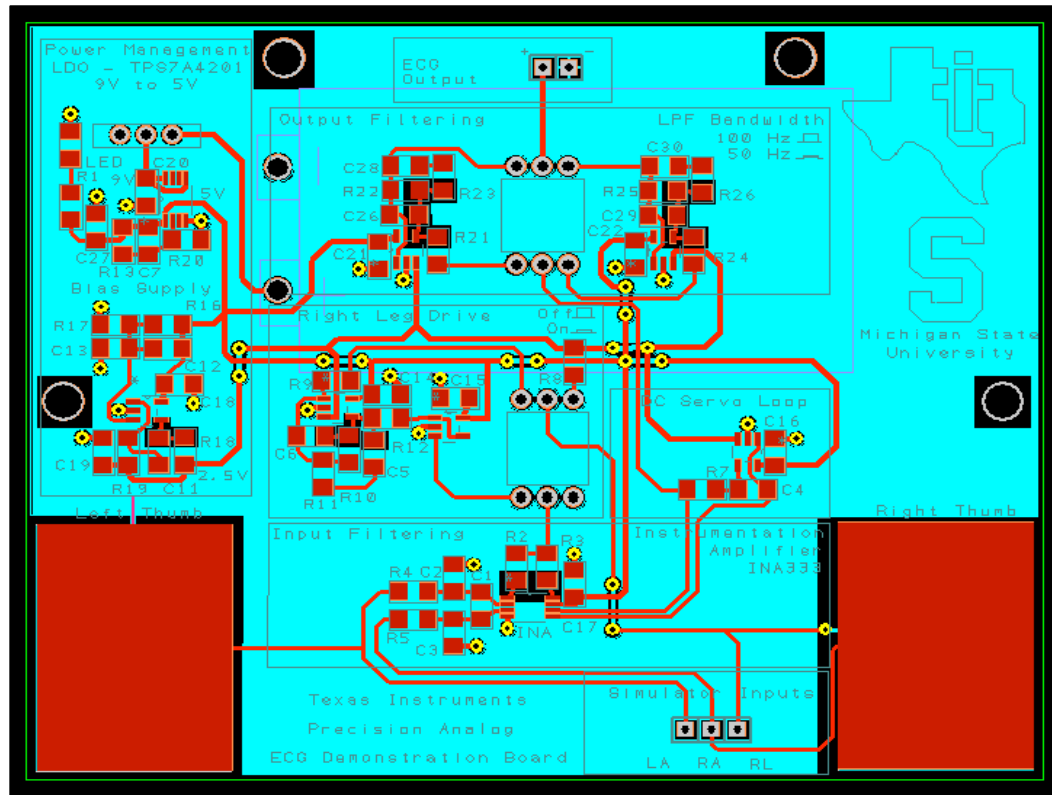


Figure 17: Phase 3 with switches PCB layout

Stellaris EVB Code Modification:

For displaying the conditioned ECG signal a Stellaris LM3S3748 Evaluation Board was used while running a 2-channel oscilloscope program. Although the default oscilloscope program is robust and reliable, it did not meet all the needs of the specific ECG application. Modifications were made in the source code to better suit the needs of the project. In order to make the modifications, the source code that make up the oscilloscope application were studied and better understood. After the basic operation of the programming and structures were laid out, the first objective was to extend the time base of the oscilloscope program. The time base is the amount of time per division (s/div) on the LCD screen. The maximum setting available with the default oscilloscope program was 50ms. After testing, this was found to only allow one period a typical ECG waveform. To extend the time base and allow several periods of ECG signal to be displayed (better visual results), the menu-controls.c file had

to be altered to include new menu selections. The file has a data structure called `g_psTimebaseChoices[]`, which holds all the options available for calculating the time base. This is used by the other functions such as the renderer function that actually updates the waveforms to the screen. This data structure contains entries with names that would show in the menu on the left and the value of the menu item in microseconds for each division of the screen on the right. Five entries were added for 100ms, 200ms, 500ms, and 1s. This allowed the oscilloscope to be set in a time base to show multiple QRS complex waveforms throughout one screen update. Figure 18 shows the data structure used.

```
tControlChoice g_psTimebaseChoices[] =
{
{ "2uS",    2 },
{ "5uS",    5 },
{ "10uS",   10 },
{ "25uS",   25 },
{ "50uS",   50 },
{ "100uS",  100 },
{ "250uS",  250 },
{ "500uS",  500 },
{ "1mS",    1000 },
{ "2.5mS",  2500 },
{ "5mS",    5000 },
{ "10mS",   10000 },
{ "25mS",   25000 },
{ "50mS",   50000 },
{ "100mS",  100000 },
{ "200mS",  200000 },
{ "500mS",  500000 },
{ "1s",     1000000 }
};
```

Figure 18: Time base data structure

When selecting the time base, the oscilloscope application uses that value for the basis of most of its operations, including how long it takes to update the screen. It was analyzed that the larger the time base, the longer it takes for the screen to update. When setting the time base to 200ms, since there are 12 divisions on the screen, the application will take

2.4 seconds between each update, and when it is updated, the entire screen would refresh at once. When viewing an ECG signal it is best to have the signal displaying in real time, instead of a static screen that updates on large intervals of time (every 2.4 sec). Changing this required calling the UpdateWaveform function more often than the original application was defaulted to call the function. The UpdateWaveform is a function that refreshes the LCD screen with the new data digitally sampled from the analog inputs. In the defaulted programming, this function was being called only when the entire 12 divisions worth of data was collected. It was then programmed to wait the entire 2.4 seconds (time base at 200ms). To increase the rate at which UpdateWaveform was called, an IF statement was created in the infinite while loop the application used to run continuously. This IF statement is conditional on whether or not a variable called g_ulSysTickCounter is at a multiple of ten. The variable g_ulSysTickCounter is similar to a timer that continuously counts up while the application runs and updating the screen it every time g_ulSysTickCounter changes would be unnecessary. The resulting code to update the screen and display the signal in real-time is shown in Figure 19 below.

```
if( g_ulSysTickCounter%10==0)
{
    UpdateWaveform(g_bMenuShown, g_bShowingHelp,
    true);
}
```

Figure 19: Code to update screen more rapidly

Another implementation the group made with the oscilloscope application code was by changing the default settings. For the ECG demonstration an offset of -2.5 volts was needed along with turning off channel 2 and turning off channel 1 voltage metrics that cluttered the screen. The default settings were changed, because the manual selection of the settings became a hassle with the small joystick on the board. It was also performed to eliminate the necessary process of adjusting the display settings every time the board turned off or reset. These issues were fixed by setting the default values in the code to the optimal settings for the ECG demonstration. First in Figure 20, to turn off channel 2, the second value

was changed to false, indicating the second channel should be turned off.

```
tBoolean g_pbActiveChannels[2] =
{
    true,
    false
};
```

Figure 20: Default active channels

The default scale for the oscilloscope was 1V/division with 10 divisions, which is too large for the ECG signal with a magnitude of around 2.5 Vpp. The default time base was also set to 100 us, another setting that would have to be changed on startup. Both of these values were set with default variables defined in a header file, and therefore to change the default values, all that was needed was to change the defined value. The variables DEFAULT_SCALE_MV, and DEFAULT_TIMEBASE_US were set to 200 and 200000 respectively. This sets the scale to 200 mv/div and the time base to 200ms/div. Setting the default offset for channel one was not as easy solve. Instead of being set through a default defined variable, it is set through a data structure that is used by many functions in the code. This data structure is then interpreted by a function and passed to the correct places with correct values. This allows a negative value for an offset to be represented with a negative sign in front of the number. Figure 21 shows the data structure and where the -2600 was placed to achieve a -2.6V offset.

```

tRendererParams g_sRender =
{
    true,                // bDrawGraticule
    true,                // bDrawTrigLevel
    true,                // bDrawTrigPos
    true,                // bShowCaptions
    false,               // bShowMeasurements
    true,                // bDrawGround
    {DEFAULT_SCALE_MV, DEFAULT_SCALE_MV},
                        // ulmVPerDivision
    DEFAULT_TIMEBASE_US, // uluSPerDivision
    {-2600, 0},          // lVerticalOffsetmV
    0,                   // lHorizontalOffset
    DEFAULT_TRIGGER_LEVEL_MV
                        // lTriggerLevelmV
};

```

Figure 21: Data structure that holds the channel one offset

Overall the group was able to successfully implement appropriate changes to the function and operation of the Stellaris EVB oscilloscope program. The final display board functions more efficiently because of the changes made to the board's source code.

Display Stand:

A display stand was constructed not only for aesthetics but also for the protection of the board. The demonstration board alone is somewhat prone to damage when being moved around. To prevent damage to the board, an acrylic stand was designed and fabricated to keep the board stationary while also keeping it comfortable for the user to use and see their results. The final design consisted of two pieces of acrylic along with eight standoffs allowing for a comfortable yet safe design for the ECG demonstration board. The team chose to use standoffs with lengths of 1.25" and 3". This allowed for a comfortable viewing angle of the top acrylic sheet to be at approximately 45 degrees for the Stellaris microcontroller. The display was modeled in SolidWorks and the dimensions were also calculated by hand before fabrication. Figure 22 shows the SolidWorks drawing developed to mock-up the team's design.

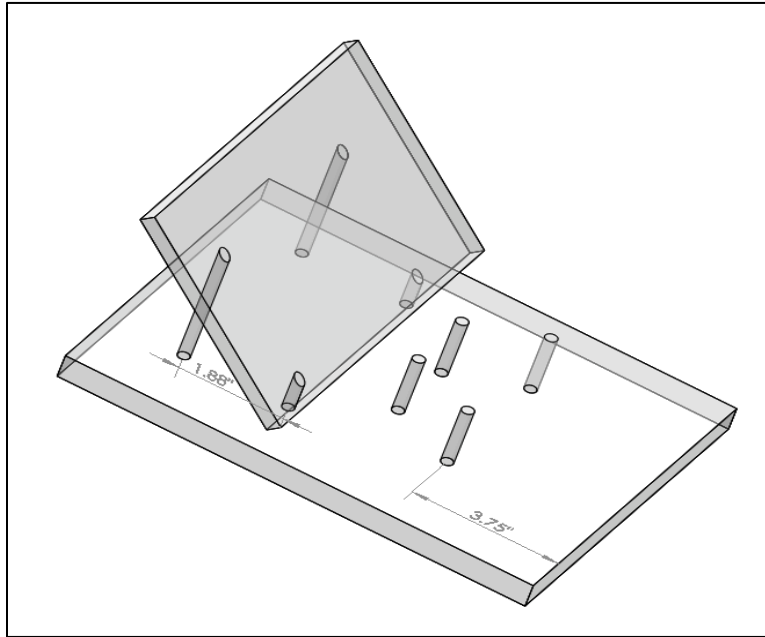


Figure 22: SolidWorks 3D model to assist in fabricating acrylic display

The first four standoffs are positioned to fit the PCB through-holes and are located 3.75" from the bottom of an 8"x10" acrylic piece. All four are 1.25" in length to ensure that the PCB is level and is appropriately spaced far enough to allow the user the ability to rest their hands comfortably on the display. The next four standoffs were positioned towards the rear of the board. The spacing distance was chosen to create a 45-degree angle for better front-side viewing of the Stellaris screen. The 3" standoffs were positioned approximately 1.88" from the 1.25" standoffs to ensure the 45-degree angle thus making it comfortable for a user to read the oscilloscope. After the display was modeled in SolidWorks, a few modifications were needed. It was not feasible to fit the angled acrylic into standoffs. Instead, countersunk holes were drilled and 10-32 and 8-32 screws were used to hold the acrylic in place. The final display board features the Stellaris EVB secured using Velcro as well as a battery pack to power the Stellaris. The final display can be seen in Figure 23 and provides an aesthetically pleasing yet safe method of demonstrating the ECG demonstration board.

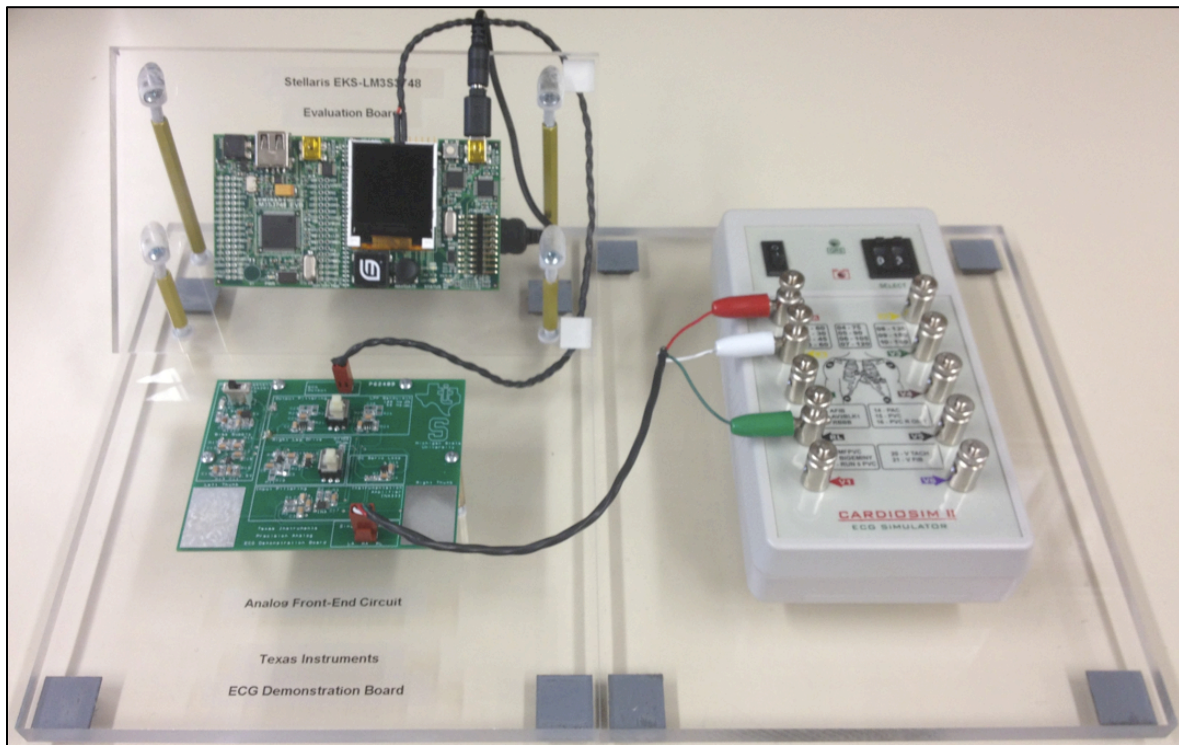


Figure 23: Final solution mounted securely on the custom acrylic display

Chapter 4

Project Testing:

During the design, planning, and development of the ECG demonstration board for Texas Instruments (TI), three major design iterations were performed. The following section will detail the work and steps taken to test and verify each design before re-work and improvements were made. The major learning from each phase of the project designs will also be covered to clearly communicate the group's process of learning from each printed circuit board's (PCB) failures and successes. At the beginning of the design process measurements were taken from the CardioSim II (ECG simulator) to understand the signal amplitude and noise levels present at the differential output from the simulator. Once the group began to design and print the circuit boards, metrics were taken and observed for each phase of the design process. The major tests and verification work done following the population of each PCB was to

measure system bandwidth, gain, and signal integrity. Specific measurements for power efficiency and noise were also taken during the second iteration of design to guide the team to choose an optimal power solution for the specific ECG application. The measurements taken and observed allowed the group to effectively shape the performance and success of the final solution.

Testing the CardioSim II:

After the design project was initially given to the team, the major goal of the project was to design and develop the analog circuitry required to interface a cardio simulator with a Stellaris evaluation board (EVB) portable oscilloscope. Figure 24 shows the simulator that was provided to the group to use for the project. The lack of documentation and the ambiguous “black-box” operation of the cardiac simulator (CardioSim II) inspired the group to immediately test and measure the signals present at the output of the CardioSim II simulator. Due to the differential nature of ECG signals, the group decided to build a 3 op-amp instrumentation amplifier.

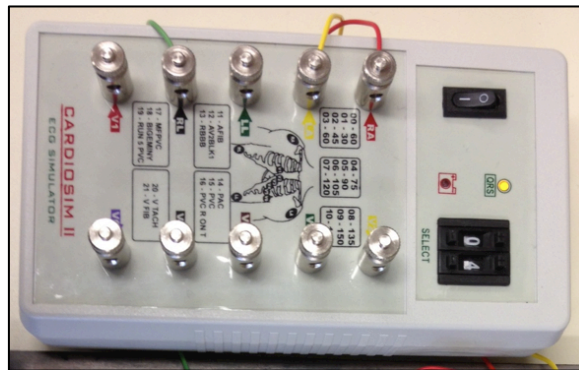


Figure 24: CardioSim II ECG simulator provided by Texas Instruments

Using the electronics parts readily available to the group in a nearby lab, an instrumentation amplifier circuit was constructed using a small breadboard, three LM741 operational amplifiers, and several other passive components (resistors, capacitors). The instrumentation amplifier topology was chosen to measure the simulator's differential output signals. The exact circuit schematic that was designed is shown in Figure 25 and an image of the test setup is showcased in Figure 26. The additional 1 μ F capacitors were added in parallel with the 10k Ω resistors to

add a pole in the circuit's transfer function, which would roll off high frequency spectral content above 16 Hz (estimated bandwidth needed). The addition of the capacitors (poles) dramatically improved the signal to noise (S/N) ratio at the output of the test circuit by attenuating high-frequency noise.

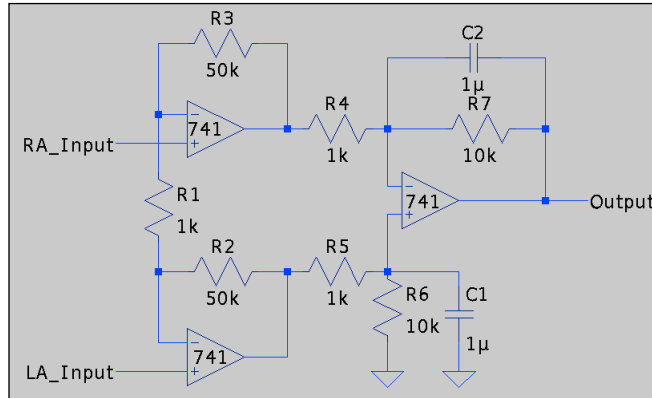


Figure 25: Instrumentation amplifier circuit used to test simulator

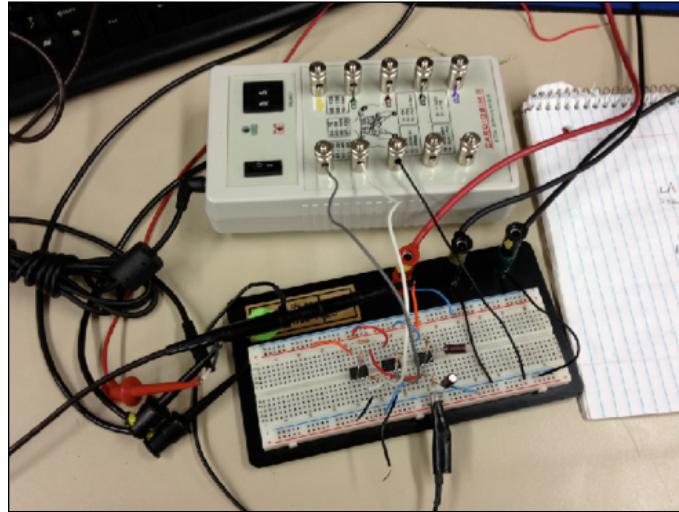


Figure 26: Breadboard testing setup used to measure the CardioSim II

Analyzing the schematic topology and component values in Figure 25 results in a pass band gain defined by the analysis below. The resulting pass band gain is shown in Equation 6 below.

$$\text{Pass band Gain} = \frac{V_{out}}{(RA - LA)} = \left(1 + \left(2 * \frac{R1}{R_{gain}} \right) \right) * \left(\frac{R3}{R2} \right)$$

Where $R1 = 50k\Omega$, $R3 = 10k\Omega$, $R2 = 1k\Omega$, and $R_{gain} = 1k\Omega$.

$$\text{Pass band Gain} = V_{out} * (RA - LA) = 1010 \quad (6)$$

Knowing the pass band gain of the test circuit, the output signal amplitude (V_{out}) needed to be found in order to calculate the differential signals present at the output of the simulator ($RA-LA$). The output of the test circuit was measured using a Philips PM 3365 100 MHz analog storage oscilloscope. The ECG simulated waveform in Figure 27 was measured at the output of the test circuit and the amplitude of the signal was found to be 1.48Vpp (peak-to-peak). Using this information, the differential signals present at the output of the simulator were conservatively estimated to be between 1-1.5mVpp. This amplitude seemed realistic and matched the amplitude ranges that were researched during the first weeks of the project. The correct range for typical ECG signals measured from the skin was researched to be (0.05-3 mVpp). As shown in Figure 27 and was later verified, the lower bandwidth limited the spectral content needed for higher definition of certain components of the QRS complex signal.

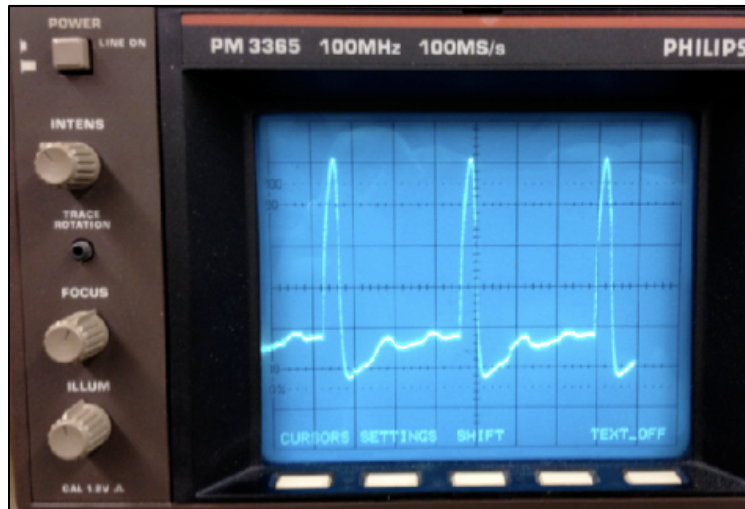


Figure 27: ECG signal measured at test circuit output (16 Hz bandwidth)

The current draw was also tested and measured for the CardioSim II. A Fluke 8840A digital multi-meter was connected in series with a power supply set to 9V DC and the DC current was measured. The current draw for the simulator was measured to be approximately 21.8 mA. A 9V

battery portably powers the simulator and each battery typically is rated for 580 mAh. The simulator's estimated battery life is therefore approximately 26 continuous hours of operation. Although, the large-scale operation of the CardioSim II is still heavily undocumented and slightly ambiguous, the signal amplitude and noise levels were very close to representing the ECG signals that could easily be measured at the surface of a patient's skin. This discovery helped the group design and define the analog front-end circuitry with the intent of preventing the operational amplifiers from operating in their non-linear regions where the output signals would experience rail-to-rail saturations. The knowledge of the battery life of the simulator helped the team make decide on a final power management solution to use for the last two demonstration boards that were fabricated.

Testing the Stellaris Oscilloscope EVB:

The Stellaris evaluation board was provided to the design team to utilize as the output display of the ECG signal. The design customer (precision analog group) shipped the board to the group during the first four weeks of the project development. It's small platform and miniature LCD screen fits perfectly with the project goal to be small and portable. The Stellaris EVB used for the project is shown in Figure 28. When paired with the cardiac simulator and the analog front-end interface, it allows the entire system to easily travel to trade shows and customer locations to demonstrate the capability of the integrated circuits (IC's) used in the application.

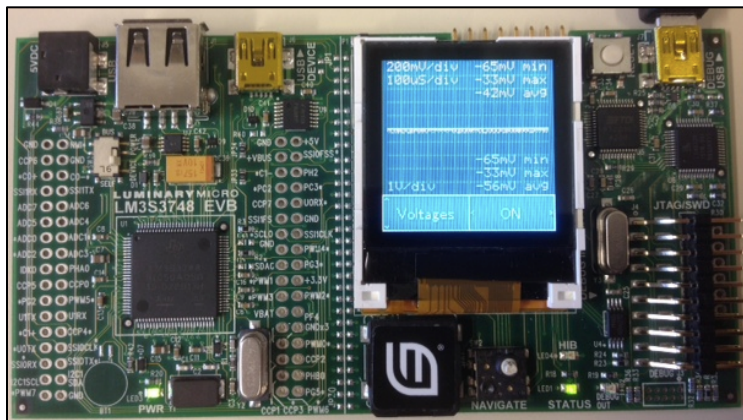


Figure 28: Stellaris EVB oscilloscope displays ECG signals for system

The first step in testing of the Stellaris EVB consisted of becoming familiar with the technical documentation and user manual. After this was achieved, the board's display options and menu were understood. The team then generated a 100 Hz, 1 Vpp sine wave to test the accuracy of the analog-to-digital (ADC) and LCD display used for the board. An Agilent 333250A function generator setup in high-z (high impedance) mode was the source of the test signal. This reference signal allowed the group to confirm the operation and calibration of the display. The appropriate next step in the testing for the Stellaris board was to connect it to display the ECG signals from the Phase 1, 2, and 3 analog front-end PCB's. For each case, the analog-front end circuitry was able to correctly connect with the EVB and the ECG signals were correctly displayed on the small LCD screen as shown in Figure 29.

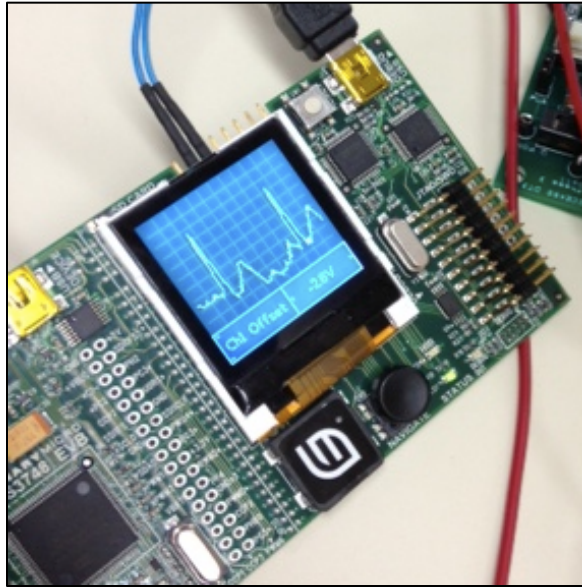


Figure 29: Stellaris EVB oscilloscope displaying the conditioned ECG signals

Testing System Gain & Bandwidth:

Two main system metrics were measured and tested once the PCB's were fabricated and populated. The system bandwidth and the pass band gain were both measured by the group to confirm the theoretical design with the actual boards produced. The system bandwidth was an important measurable feature that directly impacted the ECG signal integrity present at the output of the analog front-end circuitry. The ECG

analog filtering used in the circuitry created the total system effect of a band pass filter. The three main sub-components, that created the poles and zeros required to roll off the frequency content outside the desired pass band, were the input RC network filtering, the servo loop, and the output filtering. The desired bandwidth of the ECG demonstration board was researched and defined to be from 0.3 - 100 Hz. After experimenting with the bandwidth on the breadboard circuit by altering the corner frequencies of the three circuits, acceptable signal integrity was found when using a bandwidth of 0.7Hz - 15 Hz. It was later decided that increasing the bandwidth above 50 Hz increased noise levels present on the signal but also included meaningful spectral content present in the faster occurring events such as the very recognizable R wave ECG spike. After determining the desired system bandwidth, the first ordered PCB was populated with the parts chosen and taken to the lab for testing. The system's bandwidth was measured to compare the actual board measurements with the theory used to select the circuit components. The technique for measuring the bandwidth was to use an Agilent 33250A function generator to generate a 2 mVpp input sine wave. Because of the differential nature of the inputs to the board, one lead (RA) was connected with the signal generator, while the other (LA) was set to a DC level that matched the level of the RA signal (2.5VDC). This eliminated the common mode offset between the two inputs from being amplified by the INA333 instrumentation amplifier. The signal was placed at 2.5 V to allow maximum signal swing between the 5V power supply rail and the ground reference. The output amplitude (peak-to-peak) was measured using an Agilent 54833A digital storage oscilloscope and the gain (dB) was calculated and recorded. The input signal frequency was swept from 100 mHz to 100 Hz and the gain was recorded at intervals along the sweep. Figure 30 shows the bode plot (logarithmic x axis) of the gain (dB) vs. the frequency swept and Table 1 shows the data recorded during the experiment and. As shown in Figure 30, the -3dB corner frequencies were measured to be 0.7 Hz and 15 Hz. This was a success in confirming the theoretical system design with the actual results of the first board measured.

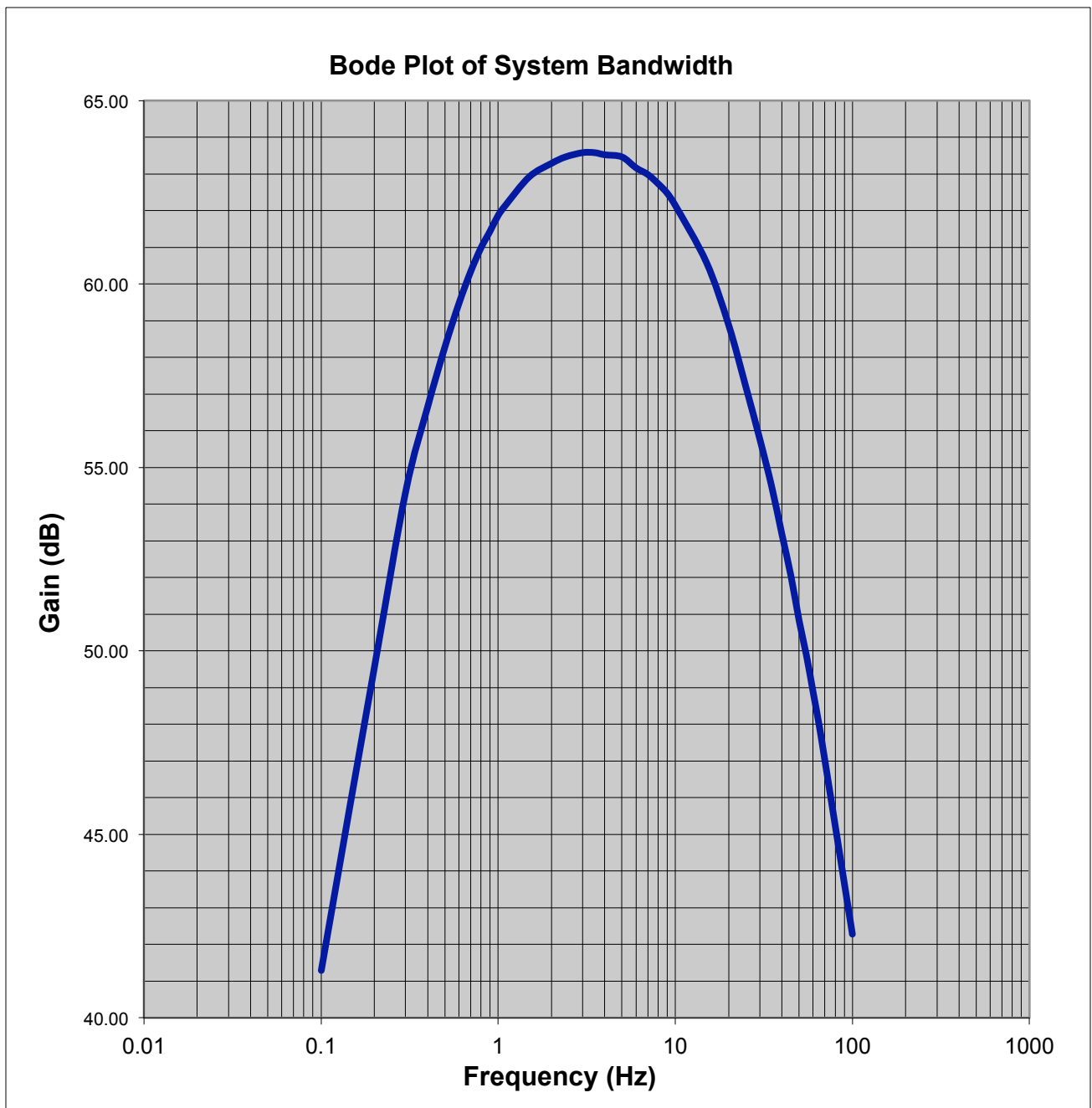


Figure 30: Bode plot of phase 1 system bandwidth (0.7-15 Hz Bandwidth)

Table 1: Recorded data for first PCB gain vs. frequency

Frequency (Hz)	Input (Vpp)	Output (Vpp)	Gain (dB)
0.1	0.002	0.232	41.29
0.2	0.002	0.6	49.54
0.3	0.002	1.0	54.32
0.4	0.002	1.4	56.65
0.5	0.002	1.6	58.28
0.6	0.002	1.9	59.46
0.7	0.002	2.1	60.34
0.8	0.002	2.2	60.98
0.9	0.002	2.4	61.44
1.0	0.002	2.5	61.87
1.1	0.002	2.6	62.14
1.5	0.002	2.8	62.92
2.0	0.002	2.9	63.29
2.4	0.002	3.0	63.46
3.0	0.002	3.0	63.58
3.5	0.002	3.0	63.58
4.0	0.002	3.0	63.52
5.0	0.002	3.0	63.46
6.0	0.002	2.9	63.17
7.0	0.002	2.8	62.98
8.0	0.002	2.7	62.73
9.0	0.002	2.7	62.48
10.0	0.002	2.6	62.14
15.0	0.002	2.1	60.59
20.0	0.002	1.8	58.89
25.0	0.002	1.5	57.21
30.0	0.002	1.2	55.78
35.0	0.002	1.1	54.49
40.0	0.002	0.9	53.18
45.0	0.002	0.8	52.04
50.0	0.002	0.7	50.83
55.0	0.002	0.6	49.88
60.0	0.002	0.6	48.88
65.0	0.002	0.5	47.96
70.0	0.002	0.4	47.00
100.0	0.002	0.3	42.28

The pass band gain of the first PCB measured can also be obtained from the data in Table 1 as 63.58 dB (1510 V/V). The group theoretical gain of the first PCB designed was set by the gain of the INA instrumentation amplifier (set by an external resistor) and by the output filter gain. The gain setting resistor for the INA333 on the first PCB was $6.6\text{k}\Omega$ and the pass band gain of the output filter was set to be 100 V/V. This yielded a total theoretical gain of 1615 V/V. The gain was set to this value to set the amplitude of the output signal. The voltage bias (2.5 V) set the ECG signal at the correct half-supply reference to conservatively allow the appropriate signal swing. The measured input signal amplitude (1.5 mVpp) was used to choose the gain to provide the output amplitude a value of 2.42 Vpp. This allowed a cushion of approximately 1.28 V between the maximum and minimum expected peaks the output signal amplitude. The actual vs. theoretical produced an error of -6.5% but yielded good results at the output.

Power Management Solution Testing:

The team was given the design goal of making the final demonstration board portable and ultimately battery powered. The first revision and board layout was populated with a buck regulator circuit using the Texas Instrument TPS62120 integrated switching converter. This device was chosen and designed in the first board because of its flexible (adjustable) design and high efficiency. The circuit was designed to output a 5V reference that would power the analog circuitry needed to condition the output ECG signal. After populating the first PCB, the reference design for the TPS62120 worked very well and provided the desired 5V DC signal. It was then decided to compare the TPS62120 (integrated switcher) with another power management solution to make a better decision for the power circuit used on the final demonstration board. The two parts chosen to be measured against each other were the TPS62120 integrated switcher and the TPS7A4201 linear dropout regulator (LDO). The second PCB included the power circuitry for both integrated circuits as well as a DPDT switch to allow appropriate selection between the two circuits. Other features included in the second board were test points and shunted jumpers to allow for input and output current measurement. This made for easy measurements in the power efficiency for both circuits. The testing schematic used to measure the input and output current is shown in

Figure 31. Figure 32 shows the jumpers used to shunt the currents through a multi-meter connected in series. A Fluke 8840A digital multi-meter was connected in series across the jumpers for each measurement of input and output current. The input voltage, output voltage, input current, and output current measurements were taken for the TPS7A4201 LDO and the TPS62120 integrated switch converter. The results of these measurements are shown in Table 2.

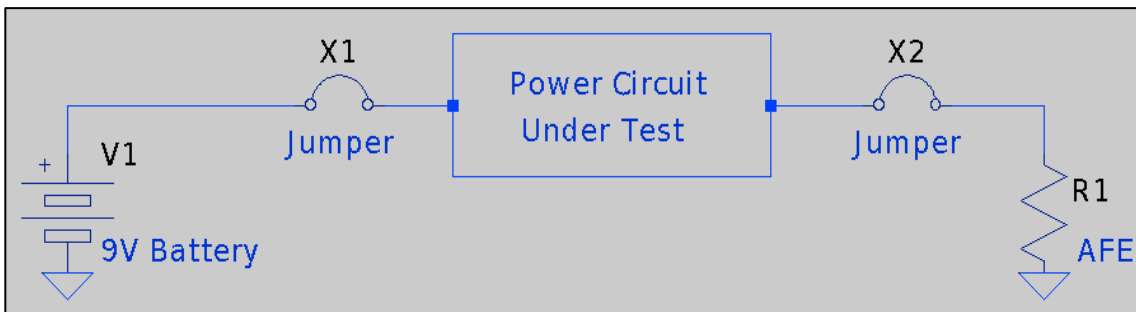


Figure 31: Testing schematic used to measure the input and output current

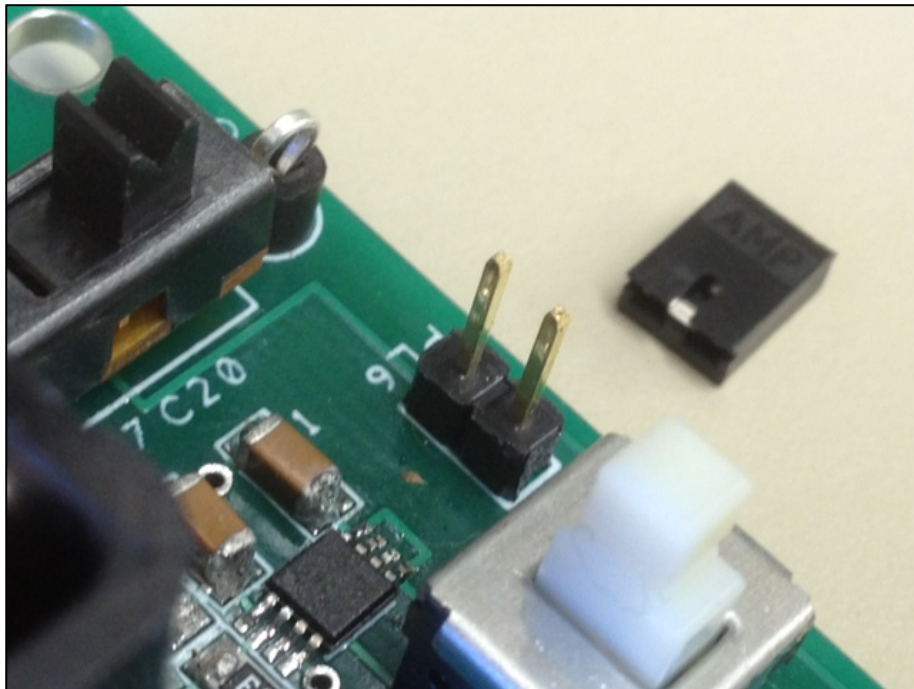


Figure 32: Jumpers allow shunted current measurements with Fluke 8840A

Table 2: Results from measurements of power efficiency for both solutions

	TPS7A4201	TPS62120
Input Voltage (V)	9.5	9.5
Input Current (mA)	0.74	0.43
Input Power (mW)	7.03	4.08
Output Voltage (V)	4.93	5.12
Output Current (mA)	0.67	0.71
Output Power (W)	3.30	3.63
Efficiency (%)	47.00	88.98

As shown in Table 2, the results of the measurements showed that the TPS62120 operates at 88.98% efficiency (matches with datasheet specifications for range of operation) and the TPS7A4201 operates at 47% efficiency. Although the efficiency for the integrated switcher was much higher, the noise levels and larger PCB layout (additional components) were decided to be unnecessary for the specific portable ECG application the team was developing for TI. Using the LDO provided a simplified layout and smaller board footprint and the battery's current draw of 740uA still provided an adequate 783 hours (32 days) of continuous board operation. The power efficiency and noise measurements taken allowed the design team to make a well-informed decision for the final power circuit used in the analog front-end demonstration board.

Testing the Input Finger Sensors/Pads:

The team was given the initial challenge to interface the CardioSim II ECG simulator with the analog circuitry needed to output a clean signal to the Stellaris EBM oscilloscope. A way that the team went above and beyond the initial scope of the design was by implementing input sensors to allow a user's ECG signals to be measured from the fingertips. Two methods were experimented with and tested. Figure 33 shows the breadboard circuit using the Plessey Semiconductor PS25253 ultra high-impedance active sensor.

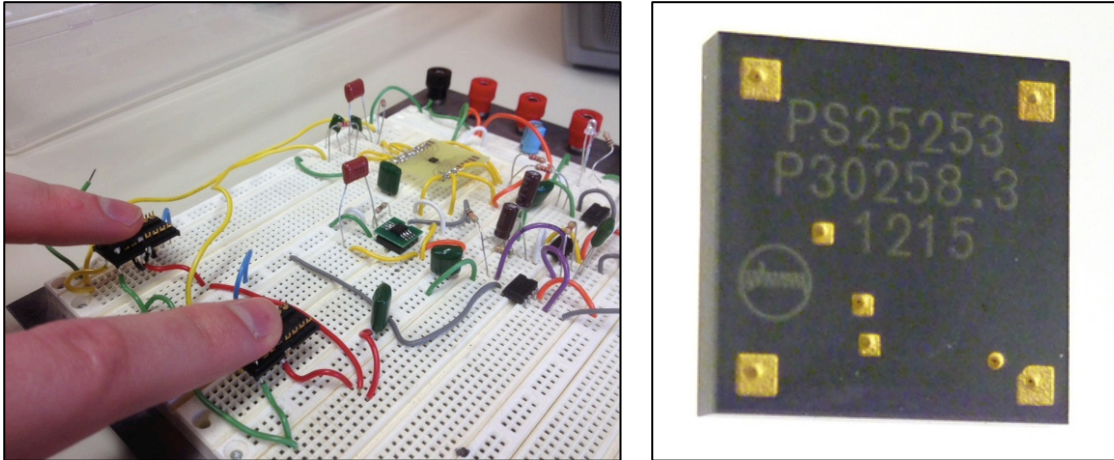


Figure 33: Plessey Semiconductor sensors tested on breadboard

The PS25253 is an active sensor with a built-in voltage gain of 10 V/V. This required adjustment of the gain of the INA333 circuit as well as the output filter gain to eliminate saturation of the outputs of the IC's. An example of the ECG signals at the output of the proto-board, while using the Plessey Semiconductor Epic sensors, is shown in Figure 34.



Figure 34: ECG signal measured at the fingertips using Plessey sensors

Another solution designed was to simply have copper squares designed and poured on to the surface of the board. The thought process behind the design was that it would allow the user to comfortably grab and measure directly from the fingertips. Instead of using a high input-impedance (active) Plessey sensor, the group decided to test the simple copper pad. The copper area would provide a dry electrode on the board for the user to touch. The major benefit towards using the copper poured area vs. the Plessey sensors were cost and the simplicity of the

board layout. Each Plessey sensor cost \$5.66 each and the copper patterns placed on the surface could easily be included into any PCB order (free). The group ordered the second PCB and included the copper pads in the layout. One of the goals for the second PCB was to test and verify the proof-of-concept in using the simple copper pads. Figure 35 shows the copper pads and an example of a user placing their fingers for measurement as well as an example of the output signal integrity. Small movements as well as a higher filter bandwidth at 30 Hz, caused the noise seen with the ECG signals.

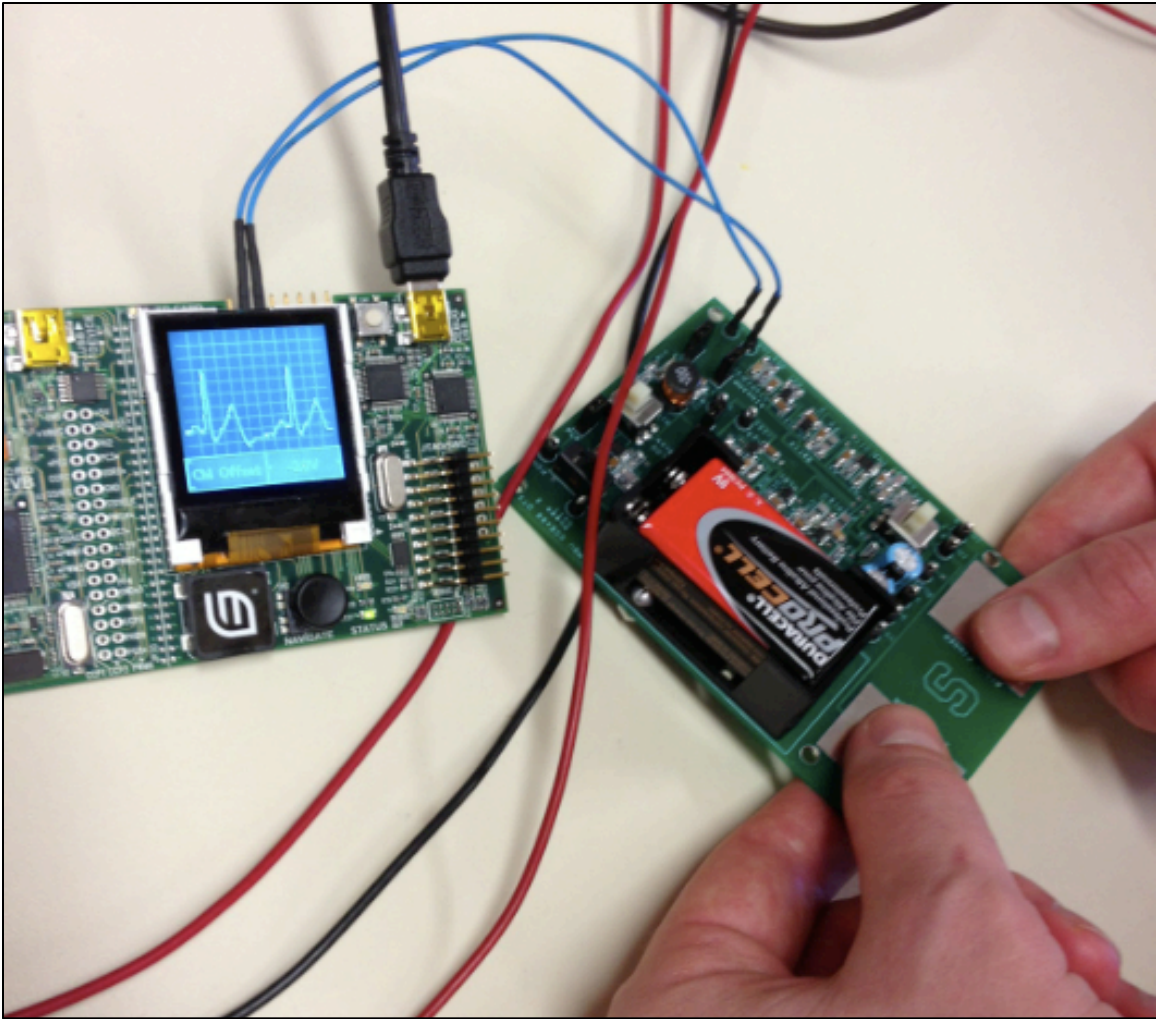


Figure 35: Successful results of live ECG measurements for Phase 2

The copper pads worked very well during the phase II board testing. Because of the success, the copper surface pads were placed in the final Phase 3 design. Pads for the two thumbs, the right-leg drive, and a ground reference were included on the final boards. The finger sensor implementation makes for an excellent feature for the ECG

demonstration board because it allows for live measurements to be made from a user, which improves the experience of the demo. The tests and measurements performed allowed the team to effectively design, layout, and fabricate the final PCB used for the ECG demonstration board. Figure 36 shows the final demonstration board working as intended while displaying a user's live ECG signal. The testing and verification of the final PCB's performance was found to be satisfactory in meeting and exceeding the minimum deliverables for the project. The signal integrity of the output signal when interfacing with the cardio simulator is shown in greater detail in Figure 37. As shown, the final PCB is capable of handling both live signals from a user's fingertips as well as interfacing with the Stellaris microcontroller-based oscilloscope.

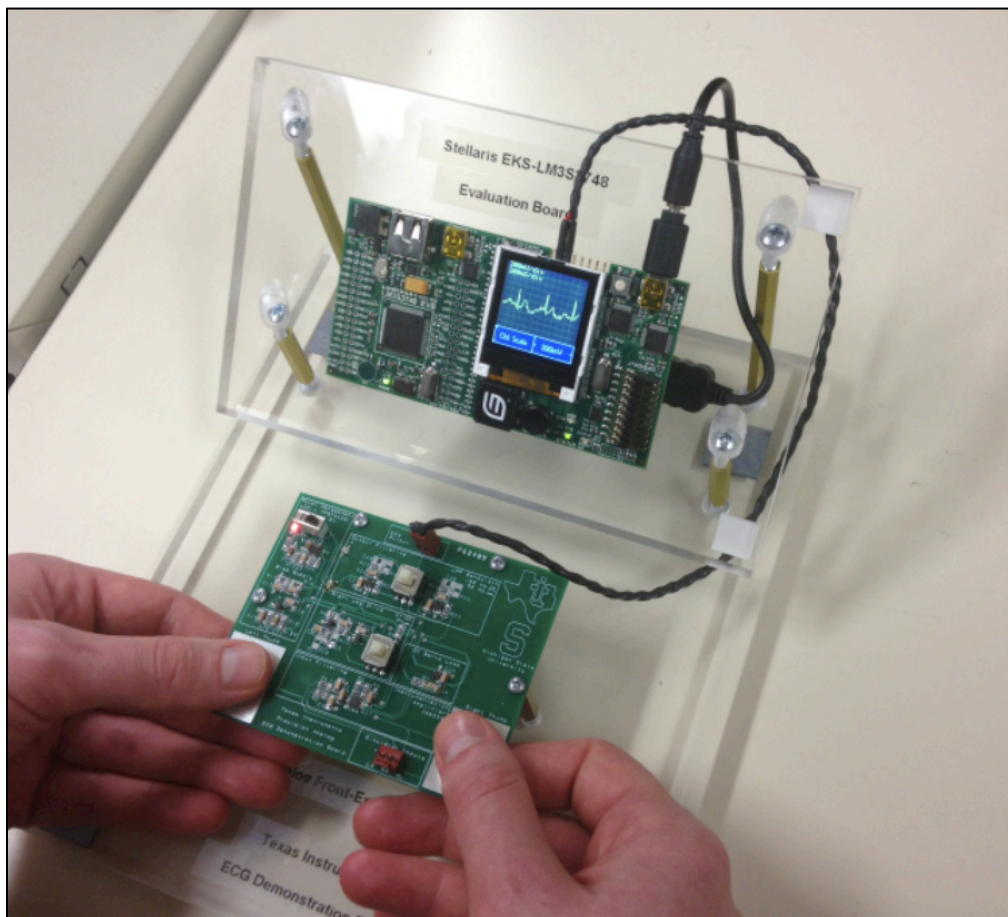


Figure 36: Phase 3 demo board displaying live ECG measurements

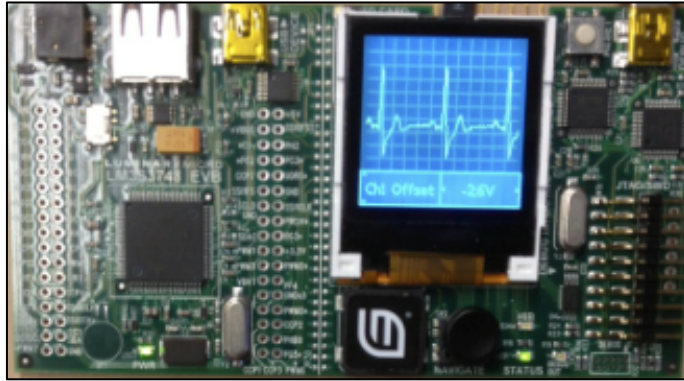


Figure 37: Stellaris displaying the ECG signal using the cardiac simulator

Chapter 5

Project Cost:

The final cost for the final demonstration board was determined to be \$258. This was not the cost that the team paid to develop the board, but represents the cost required to produce the demonstration board from scratch. Some of the parts listed below were provided to the group for the design project. The itemized cost for the entire solution is listed in Table 3 below. A majority of the cost the team paid was in the fabrication of the PCB and acrylic display.

Table 3: Cost summary for the ECG demonstration board

Item	Cost
Acrylic Display	\$30
Battery Pack for Stellaris EVB	\$30
Stellaris Evaluation Kit	\$120
Analog Front-End PCB	\$33
PCB Passive Components	\$25
PCB Integrated Circuits	\$5
Accessory Components	\$15
Total	\$258

The team was given a budget of \$500 to develop the project throughout the semester. The team was able to develop the analog circuitry, four PCB's, and the final solution without exceeding this budget. The ECE shop and technical engineering support at MSU helped with providing some of the smaller components used during the testing and development.

Project Timeline and Schedule:

Throughout the semester, the team was able to research, design, fabricate, and test a functioning ECG demonstration board. The following Figure 38 details the project timeline that the team followed.

Completed Tasks as of Wed 4/24/13 Team3Project							
ID	Task Mode	Task Name	Duration	Start	Finish	% Comp.	Cost
January 2013							
2	Auto Schedul	Meet with Pete Semig	1 day	Wed 1/16/13	Wed 1/16/13	100%	\$0.00
3	Auto Schedul	Meet with Faculty Advisor	1 day	Wed 1/16/13	Wed 1/16/13	100%	\$0.00
5	Auto Schedul	Consolidate Schedules on google	1 day	Wed 1/16/13	Wed 1/16/13	100%	\$0.00
9	Auto Schedul	Research SMD sizes	1 day?	Wed 1/16/13	Wed 1/16/13	100%	\$0.00
4	Auto Schedul	Go over documents from Pete	2 days	Thu 1/17/13	Fri 1/18/13	100%	\$0.00
8	Auto Schedul	Get Schematics from Pete	1 day?	Fri 1/18/13	Fri 1/18/13	100%	\$0.00
6	Auto Schedul	Discuss questions with Pete about	1 day	Mon 1/21/13	Mon 1/21/13	100%	\$0.00
12	Auto Schedul	Decipher analog designs	2 days	Mon 1/21/13	Tue 1/22/13	100%	\$0.00
7	Auto Schedul	Plan goals	1 day	Tue 1/22/13	Tue 1/22/13	100%	\$0.00
13	Auto Schedul	Layout 1 board	8 days	Wed 1/23/13	Fri 2/1/13	100%	\$0.00
18	Auto Schedul	Preproposal	3 days	Tue 1/29/13	Thu 1/31/13	100%	\$0.00
16	Auto Schedul	Order parts	2 days	Thu 1/31/13	Fri 2/1/13	100%	\$0.00
February 2013							
13	Auto Schedul	Layout 1 board	8 days	Wed 1/23/13	Fri 2/1/13	100%	\$0.00
16	Auto Schedul	Order parts	2 days	Thu 1/31/13	Fri 2/1/13	100%	\$0.00
28	Auto Schedul	Oral Proposal presentation	6 days	Fri 2/1/13	Fri 2/8/13	100%	\$0.00
14	Auto Schedul	Fabricate the boards	1 wk	Mon 2/4/13	Fri 2/8/13	100%	\$0.00
17	Auto Schedul	Solder parts	1 day	Mon 2/11/13	Mon 2/11/13	100%	\$0.00
15	Auto Schedul	Test boards using o-scope and flu	1 day	Tue 2/12/13	Tue 2/12/13	100%	\$0.00
20	Auto Schedul	Correct issues from last layout/d	1 day	Fri 2/15/13	Mon 2/18/13	100%	\$0.00
21	Auto Schedul	Design ECG analog front end with	3 days	Mon 2/18/13	Thu 2/21/13	100%	\$0.00
22	Auto Schedul	Simulate circuits	3 days	Thu 2/21/13	Tue 2/26/13	100%	\$0.00
24	Auto Schedul	Order parts	2 days	Thu 2/21/13	Mon 2/25/13	100%	\$0.00
32	Auto Schedul	test plessy sensors/filters/gain	4 days	Mon 2/25/13	Fri 3/1/13	100%	\$0.00
23	Auto Schedul	Layout in PCB Artist	5 days	Tue 2/26/13	Tue 3/5/13	100%	\$0.00
41	Auto Schedul	modify code for stellaris to have	3 wks	Thu 2/28/13	Wed 3/20/13	100%	\$0.00
March 2013							
32	Auto Schedul	test plessy sensors/filters/gain	4 days	Mon 2/25/13	Fri 3/1/13	100%	\$0.00
23	Auto Schedul	Layout in PCB Artist	5 days	Tue 2/26/13	Tue 3/5/13	100%	\$0.00
41	Auto Schedul	modify code for stellaris to have	3 wks	Thu 2/28/13	Wed 3/20/13	100%	\$0.00
34	Auto Schedul	refine filter values according to f	1 day	Fri 3/1/13	Mon 3/4/13	100%	\$0.00
25	Auto Schedul	Fabricate board	1.3 wks	Tue 3/5/13	Wed 3/13/13	100%	\$0.00
26	Auto Schedul	Solder parts	1 day	Thu 3/14/13	Thu 3/14/13	100%	\$0.00
27	Auto Schedul	Test board, both power solutions	2 days	Fri 3/15/13	Mon 3/18/13	100%	\$0.00
30	Auto Schedul	correct issues from last layout/d	3 days	Tue 3/19/13	Thu 3/21/13	100%	\$0.00
Page 1							
Completed Tasks as of Wed 4/24/13 Team3Project							
ID	Task Mode	Task Name	Duration	Start	Finish	% Comp.	Cost
March 2013, continued							
31	Auto Schedul	decide on power solution	1 day	Fri 3/22/13	Fri 3/22/13	100%	\$0.00
33	Auto Schedul	Integrate sensors into design	1 day	Fri 3/22/13	Fri 3/22/13	100%	\$0.00
35	Auto Schedul	layout final prototype in pcb arti	4 days	Mon 3/25/13	Thu 3/28/13	100%	\$0.00
36	Auto Schedul	order parts	1 day	Fri 3/29/13	Fri 3/29/13	100%	\$0.00
37	Auto Schedul	fabricate phase 3 board	1.3 wks	Fri 3/29/13	Mon 4/8/13	100%	\$0.00
April 2013							
37	Auto Schedul	fabricate phase 3 board	1.3 wks	Fri 3/29/13	Mon 4/8/13	100%	\$0.00
38	Auto Schedul	populate board	1 day	Mon 4/8/13	Tue 4/9/13	100%	\$0.00
39	Auto Schedul	test all features of board, power	2 days	Tue 4/9/13	Thu 4/11/13	100%	\$0.00
40	Auto Schedul	fix any issues	3 days	Thu 4/11/13	Tue 4/16/13	100%	\$0.00
42	Auto Schedul	attach to display board	2 days	Tue 4/16/13	Thu 4/18/13	100%	\$0.00

Figure 38: Project Timeline

Project Summary:

Throughout the semester, the group was challenged to design and fabricate a portable ECG demonstration board for the team's sponsor, Texas Instruments. The team was given \$500 to develop the project and was able to finish the project on time without going over budget. The team was able to successfully develop a working ECG demonstration board that meets and exceeds the specified project requirements. The defined project requirements were to develop the battery-powered analog front-end circuitry needed to interface a Stellaris microcontroller-based oscilloscope with an ECG simulator (CardioSim II). The overall scope of the project included precise amplification and filtering of low amplitude and low frequency bio-potentials. The actualized in the design, layout, and fabrication of the analog circuitry needed to do this. The group researched the ECG application, and went on to successfully design, fabricate, and test four iterations of the analog front-end PCB's. The major results, found during this iterative design process, helped the team improve the design throughout the semester and ultimately helped the project to obtain quality ECG measurements. Due to the success of the project, the precision analog group at TI plans to use the team's demonstration board to showcase the instrumentation amplifier (INA333) and op-amps (OPA378) to customers at technical trade-shows. The team was able to take the specifications and list of requested deliverables (provided by TI) development from a theoretical concept to a reliable working product. The major success in the group's results was in implementing the circuitry and hardware needed for the board to take live ECG measurements from a user's fingertips. Figure 39 shows the final solution the group developed for the TI precision analog group.

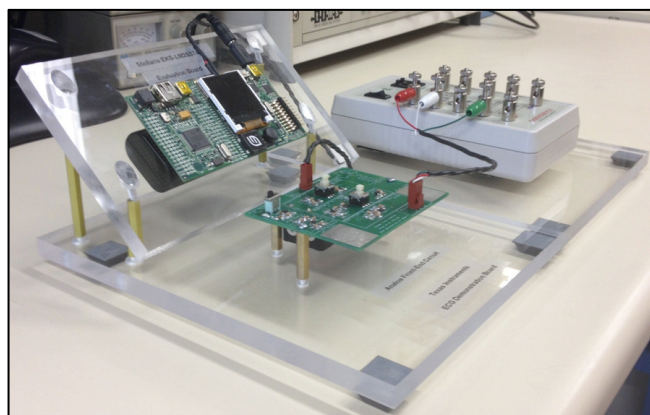


Figure 39: Final ECG demonstration board developed by Team 3

Project Conclusion:

The design team was able to successfully develop an ECG demonstration board for Texas Instruments. The requested functionality of the board was to interface the CardioSim II simulator with the portable Stellaris EVB oscilloscope. The group met this requirement and was able to condition and display the simulator waveforms on the portable display. The group exceeded the requested functionality by implementing a solution to allow live ECG measurements to be taken from a user's fingertips. The group went through several design iterations throughout the semester and as shown was able to successfully simulate, design, test, and fabricate the final demonstration board.

Suggested Future Developments:

Future work that could be performed to improve the functionality of the demo board includes the following:

- Implementing an FFT based beats/minute calculation of the signal
- Implementing digital filtering using the Stellaris microcontroller
- Designing the analog system using higher-order filters
- Integrating the Stellaris display board and AFE board into one PCB

Acknowledgements:

Special thank you to Peter Semig and Collin Wells, from Texas Instruments, for supporting the group and offering your expertise and accountability. It was a pleasure working with Pete and Collin over the course of the semester. Thank you for sponsoring the project.

Special thank you to Gregg Mulder for assisting the group with encouragement as well as some of the soldering for the surface-mount IC's on the PCB's the group developed. The team enjoyed Gregg's personality and professionalism throughout the semester.

Special thank you to the group's faculty facilitator Dr. Rama Mukkamala for meeting weekly with the group and supporting the team throughout the semester as well as providing weekly feedback on the group's progress and results.

Awards/Recognition:

MSU - ECE 480 Senior Design Competition – Spring 2013 – 2nd Place Award

Appendix I: Technical Contributions

Team Members:

Mike Mock:

Mike assisted the technical development of the project by simulating the analog front-end circuits used in the entire AFE system. Taking the results of these simulations, Mike developed the control theory analysis of the system and documented the results of the MATLAB analysis of the system transfer function. Mike developed a technical understanding of the entire system. Mike also contributed by building the breadboard analog front-end circuit as well as implementing the finger sensor pads for testing on the breadboard. After his work with simulations and the breadboard testing, he confidently chose the component values for each PCB layout in phases 1 and 2 as well as for the final phase 3 PCB. Mike was also responsible for ordering the components used for each phase of PCB design. Although rare throughout the semester, Mike contributed at times by aiding in the process of laying out the PCB's. For PCB layouts Mike more actively participated in the decision making for layout arrangements as well as verifying the boards accuracy before ordering them. For the development of the final demonstration board, Mike contributed to the project by driving results in simulating, designing, and verifying proper operation of the entire system for each phase of the design. He also provided a majority of the recorded results documented throughout the semester. Mike selected and analyzed the two power solutions (TPS7A4201 vs. TPS62120) to compare efficiency and noise measurements. Mike also aided in the fabrication of the acrylic display stand for the demo board. Throughout the semester, Mike communicated with Pete Semig (sponsor) and reported the results, successes, and failures. In conclusion, Mike provided technical support throughout the project in all areas of the development of the ECG demonstration board.



Justin Bohr:

Justin assisted technically in several areas of the project including PCB design, code modifications, breadboard testing, and simulations. During the initial project specification and objectives outlining, he helped understand and simulate circuit diagrams given to the team to base the project. The circuits included the servo loop and the Right Leg Drive. He also helped with determining their function in the overall circuit and how they should be modified to suite the specific ECG application. Justin helped determine part values when testing the circuit on the breadboard. Justin then transferred the completed and tested circuit from the breadboard into a schematic using PCB Artist. To accomplish this Justin made the necessary components in PCB Artist using the data sheets of the circuit components to be used including the INA333, OPA378, TPS7A2401 and TPS62120. After the Phase 1 AFE was populated Justin assisted in testing and troubleshooting the boards functionality. A wiring error was identified and then fixed for the Phase 2 layout. He then collaborated with Mike to add features to the schematic such as two power circuits that could be switched between to test efficiency, thumb pads to test the feasibility of using these pads to acquire a live ECG signal, a battery connector, and a switch to turn the battery on or off. A switch was also added to switch the RLD on or off. Justin then made the changes in PCB Artist to the schematic and layout, creating phase 2 of the AFE. After the phase 2 AFE board was populated, Justin aided in testing and troubleshooting the circuit. He then removed all testing components and organized the phase 3 PCB. While developing the Phase 3 board, Justin followed Peter Semig's suggestion to spread out the circuit and showcase each part of the circuit for ease in demonstration. Finally, Justin became familiar with the Stellaris Oscilloscope application code to make modifications so that the oscilloscope would update more rapidly and start with the optimal settings for viewing ECG signals.



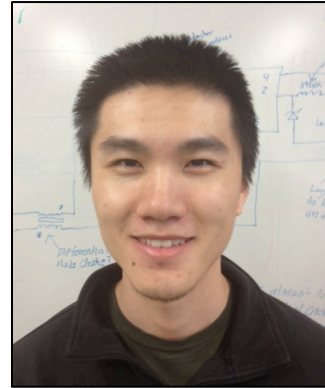
Nate Kesto:

Throughout the semester Nate assisted in many areas of the various phases of the project including practice with PCB Artist, Tina-TI, and filter pro. However, Nate focused more so on various aspects of each phase. Specifically, he performed the filter calculations for the common and differential mode filtering associated in the AFE circuit using prior knowledge of RC networks from previous classes. After the calculations were completed, Nate simulated the filters using Tina-TI by using variations of the filter models obtained from Mr. Pete Semig to assure a high integrity signal. Nate also assisted in the population of each of the PCBs at the different phases of the project. This proved to be a tedious process due to Nate's inexperience with surface-mount components, however it was a great opportunity for him to practice and become familiar with PCB design and population before going into industry. This summed up his work in phase 1. After the PCBs were fabricated and populated, his role in phase 2 was to assist in various testing of the different systems on the boards. Specifically, he and Mike determined the efficiency of the two proposed power chips using the available lab equipment, and he helped decide the best option. Along with the power testing for the chip, Nate also contributed to the calculation of the battery life of the ECG demonstration board itself with the help of Mike and various datasheets. Finally for phase 3, Nate's major contribution was the design and machining of the display. He assisted with the calculations on where to place the standoffs and at what angle. After the calculations were completed, Nate along with Mike and Chaoli machined the display. This proved to be an interesting experience in that it did not associate with electrical engineering.



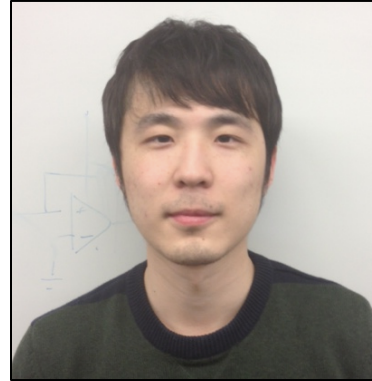
Chaoli Ang:

During the project, Chaoli had been working on different technical processes. During phase 1 and 2, Chaoli simulated the filter, which was later implemented in power management circuitry to reduce the high frequency noise from the DC power supply. During the design process, several attempts had been made to tune the cutoff frequency to get as close as possible to the desired value of 36Hz while demanding a relatively high gain. By trying to have an accurate high frequency performance, Chaoli and Justin picked the OPA333 amplifier as a major component of the circuit. By using the simulation software Filter Lab, the basic schematic of the filter circuitry was generated. The simulation by TINA-TI gave out an unexpected result with large variance. Changing the value of capacitive and resistive components of the circuit did not worked out well for the goal of design. Chaoli and Mike built up the simulation circuit to examine its AC characteristics of it. Problem was narrowed down to the functional frequency bandwidth of the operational amplifier. Chaoli and Mike replaced the OPA333 with LM741 to solve the problem and finalize the design. To test the circuit, Chaoli built up simulation circuits with the parts provided by Texas Instruments. Other than designing and simulation on filters, Chaoli dedicated in testing printed circuit board to achieve the optimization of the output of the Stellaris demonstration board. After the PCB board is ready, Chaoli and Mike populated the board by surface-mount and hand soldering. When testing analog front end PCB, the signal output are so noisy that no clear ECG pulse is displayed. Chaoli and Mike tested sub-parts of the board and found a potential problem with the right leg drive. By looking back into the biomedical theory and analyzing the signal flow, he correct the value of resistive load in the circuit which increases the cut-off frequency of the filtering process, thus eliminated the noises.



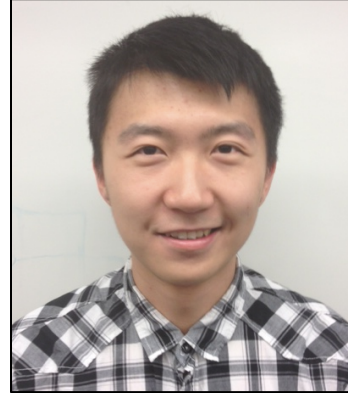
Yuan Mei:

Throughout the semesters, Yuan assisted in many aspects for this project. Sponsor Pete Semig from TI provided the front to end schematic. Justin, Mike and Yuan draw the schematic on the TI Tina and run the transient analysis. Then because the input signal was pretty small, Mike and Yuan designed and built a very basic instrumentation amplifier using three 741 operational amplifiers. Although it had limit, due to the power connection, it's a dual power supply, 9 volt and -9 volt respectively, the amplification yet do help team detect the small ECG signal generated by the CardioSim with gain 1000. In addition, Mike and Yuan made a small sub team to build the prototype of the front to end schematic on the breadboard. After successfully build the prototype, they measured and tested the output data, which verify the analog design and ensure the PCB design. Besides the hardware building and testing, Yuan downloaded the code compiler, installed the code library and worked on the add-on features to Stellaris microcontroller. The initial thought was to change the time base to increase the resolution of the output signal, implement the Fast Fourier Transform and calculated the heart beats per minute. Yuan changed the code and enable the time base large enough for use. Also, Yuan has a excellent skills on soldering, he responsible for the 30% of the soldering part through phase 1, phase 2 and phase 3.



Xie He:

During the designing process of the project, Xie contributed in multiple aspects in various phases. In phase 1 Xie (co-working with Nate) was focusing on analyzing the input RC filtering circuit including common and differential mode filtering associated in the AEF circuit. Specifically, the analysis includes the derivation of transfer functions for various filters, the calculation of time constants and corner frequencies and the stimulation of filtering circuits. In the stimulation of filtering circuits, he stimulated and compared



each sub-circuit contained in the overall filtering circuit in purpose of understanding how each part works separately and assuring an output signal with high resolution. In phase 2, Xie populated 55% of each PCB with the assistance of other teammates and assisted in testing them. The populating process on PCBs is good experience for practicing soldering surface-mount components. After the project had been done, for the enhancement of final product for design day, Xie assisted in testing thumb pads, the sensors used for detecting life signal and worked on digital signal processing. In detail, Xie was assigned to digital filtering programming and beat per minute (BPM) detector programming. For BPM detector programming, Xie looked over Fast Fourier transform (FFT) code on the Internet and designed a signal filtering in MATLAB, which were two essential stages for successfully detecting the impulse of R waves later in envelope detecting process.

Appendix II: References

Software

PCB Artist Software

<http://www.4pcb.com/free-pcb-layout-software/index.html>

TINA-TI Software

<http://www.ti.com/tool/tina-ti>

PCB Artist Tutorial

<http://www.4pcb.com/media/PCBArtistTutorial.pdf>

Datasheets

OPA 378 Operational Amplifier

<http://www.ti.com/lit/ds/symlink/opa378.pdf>

INA333 Instrumentation Amplifier

<http://www.ti.com/lit/ds/symlink/ina333.pdf>

TPS62120 Switch Converter

<http://www.ti.com/lit/ds/symlink/tps62120.pdf>

TPS7A4201 Linear Dropout Regulator

<http://www.ti.com/lit/ds/symlink/tps5410.pdf>

PowerPoint Presentations:

“Analog Fundamentals of the ECG Signal Chain” – Matthew Hann (TI)

“PCB Artist Quickstart Guide” – Peter Semig (TI)

Appendix III: Technical Attachments

Bill of Materials:

ECG Demo Board Bill of Materials					All prices are in US dollars.		
Index	Quantity	Part Number	Manufacturer Part Number	Description	Unit Price	Extended Price	
R19	1	P100ECT-ND	ERJ-8GEYJ101V	RES 100 OHM 1/4W 5% 1206 SMD	0.1	\$0.10	
C29	1	445-6074-1-ND	C3216X7R2E153K115AM	CAP CER 0.015UF 250V X7R 1206	0.34	\$0.34	
C2,C3,C7	3	445-2291-1-ND	C3216X7R2J103K115AA	CAP CER 10000PF 630V X7R 1206	0.216	\$0.65	
C26,C6	2	445-4456-1-ND	C3216X7R2A333K115AA	CAP CER 0.033UF 100V X7R 1206	0.26	\$0.52	
C1,C17,C16,C4,C15,C14,C22 C21,C12,C12,C18,C19 C11	12	445-1378-1-ND	C3216X7R2A104M160AA	CAP CER 0.1UF 100V 20% X7R 1206	0.212	\$2.54	
	1	445-4016-1-ND	C3216X7R1E224K	CAP CER 0.22UF 25V 10% X7R 1206	0.19	\$0.19	
	3	P1.5KECT-ND	ERJ-8GEYJ152V	RES 1.5K OHM 1/4W 5% 1206 SMD	0.1	\$0.30	
	4	P100KECT-ND	ERJ-8GEYJ104V	RES 100K OHM 1/4W 5% 1206 SMD	0.1	\$0.40	
	1	P10KECT-ND	ERJ-8GEYJ103V	RES 10K OHM 1/4W 5% 1206 SMD	0.1	\$0.10	
	2	445-1593-1-ND	C3216Y5V1A106Z/0.85	CAP CER 10UF 10V Y5V 1206	0.18	\$0.36	
	2	P120KECT-ND	ERJ-8GEYJ124V	RES 120K OHM 1/4W 5% 1206 SMD	0.1	\$0.20	
	1	P1.0MECT-ND	ERJ-8GEYJ105V	RES 1.0M OHM 1/4W 5% 1206 SMD	0.1	\$0.10	
	2	P2.2KECT-ND	ERJ-8GEYJ222V	RES 2.2K OHM 1/4W 5% 1206 SMD	0.1	\$0.20	
	R13	1	P300KECT-ND	ERJ-8GEYJ304V	RES 300K OHM 1/4W 5% 1206 SMD	0.1	\$0.10
R18	1	P51KECT-ND	ERJ-8GEYJ513V	RES 51K OHM 1/4W 5% 1206 SMD	0.1	\$0.10	
R16,R17	2	P560KECT-ND	ERJ-8GEYJ564V	RES 560K OHM 1/4W 5% 1206 SMD	0.1	\$0.20	
R4,R5	2	P8.2KECT-ND	ERJ-8GEYJ822V	RES 8.2K OHM 1/4W 5% 1206 SMD	0.1	\$0.20	
Keystone 1294	1	1294K-ND	1294	HOLDER BAIT 9V UNIV PLASTIC PC	1.84	\$1.84	
Red SMD LED	1	516-2825-1-ND	HSMC-C150	LED CHIP ALINGAP RED SMA	0.56	\$0.56	
Advanced Circuits 2-Layer PCB	1				33	\$33.00	
					Subtotal	\$42.00	
					Shipping	Estimate	
					Sales Tax	\$0.00	
					Total	\$42.00	

Project Schematics:

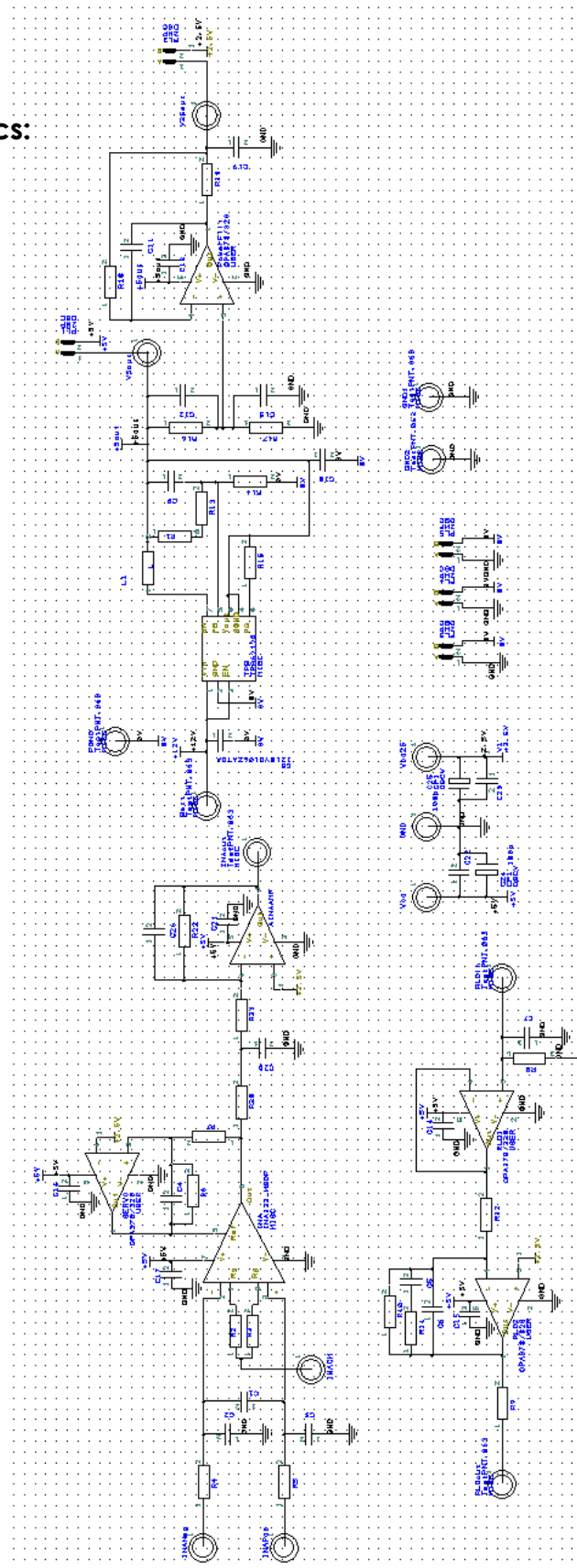


Figure 40: Phase 1 Schematic

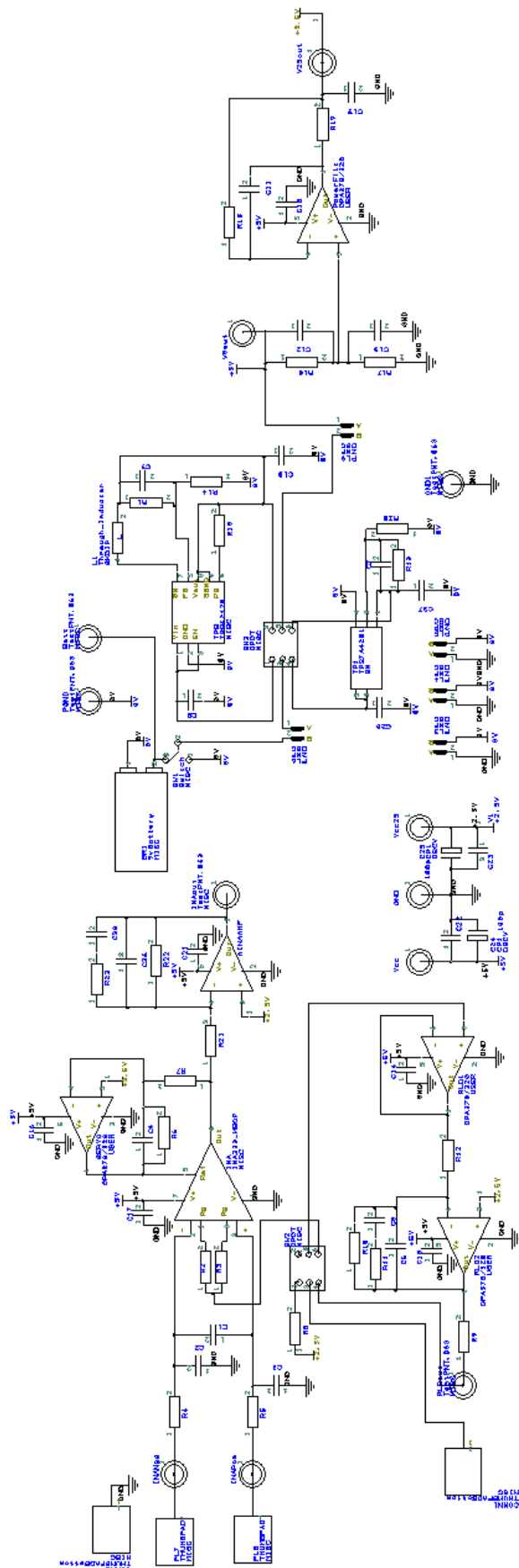
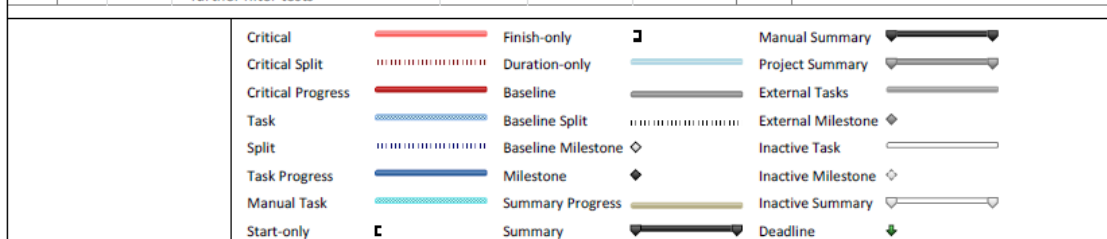
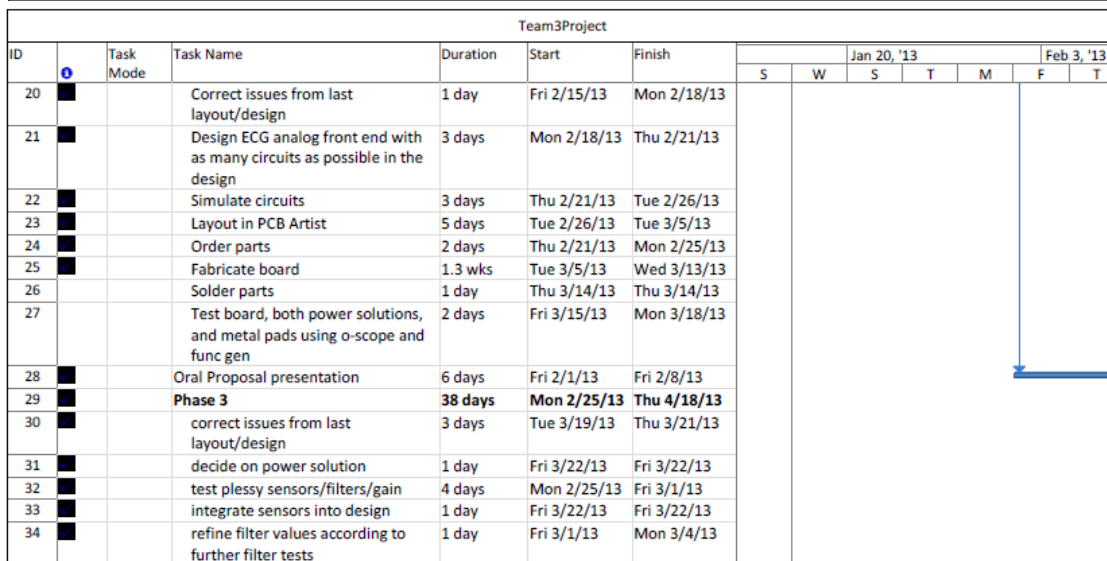
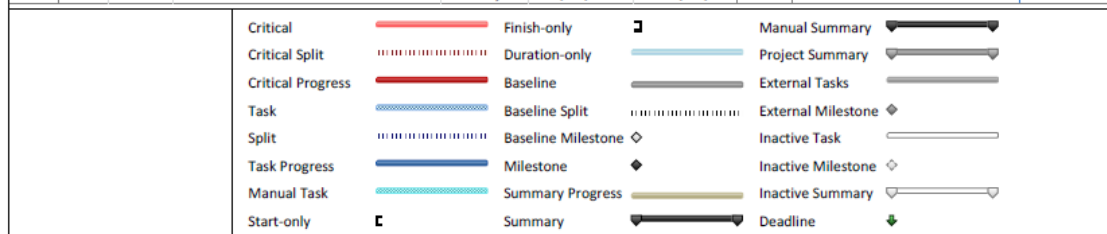
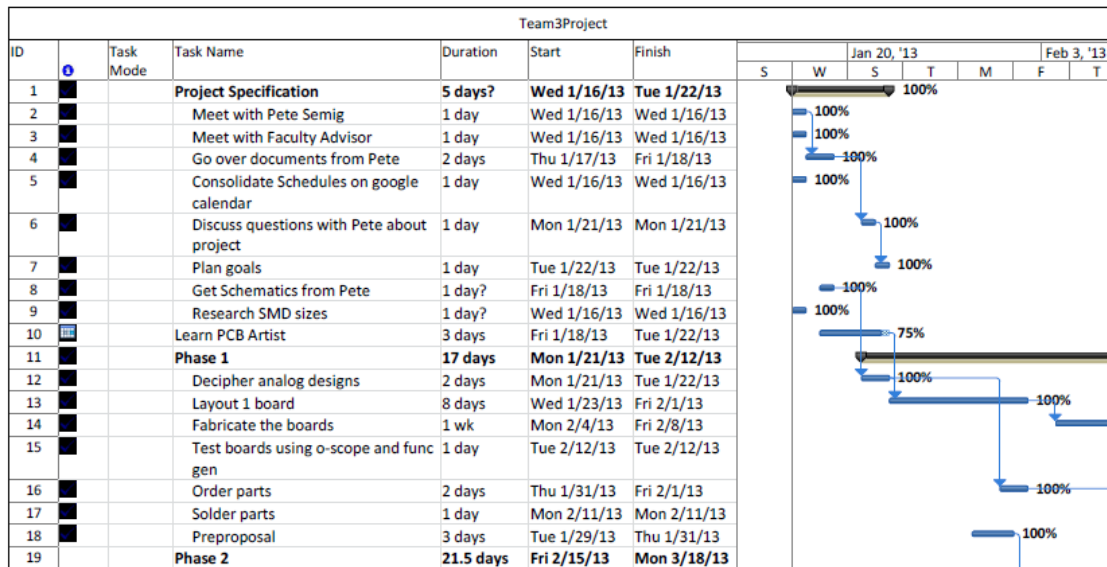


Figure 41: Phase 2 Schematic



Project Gantt Chart:



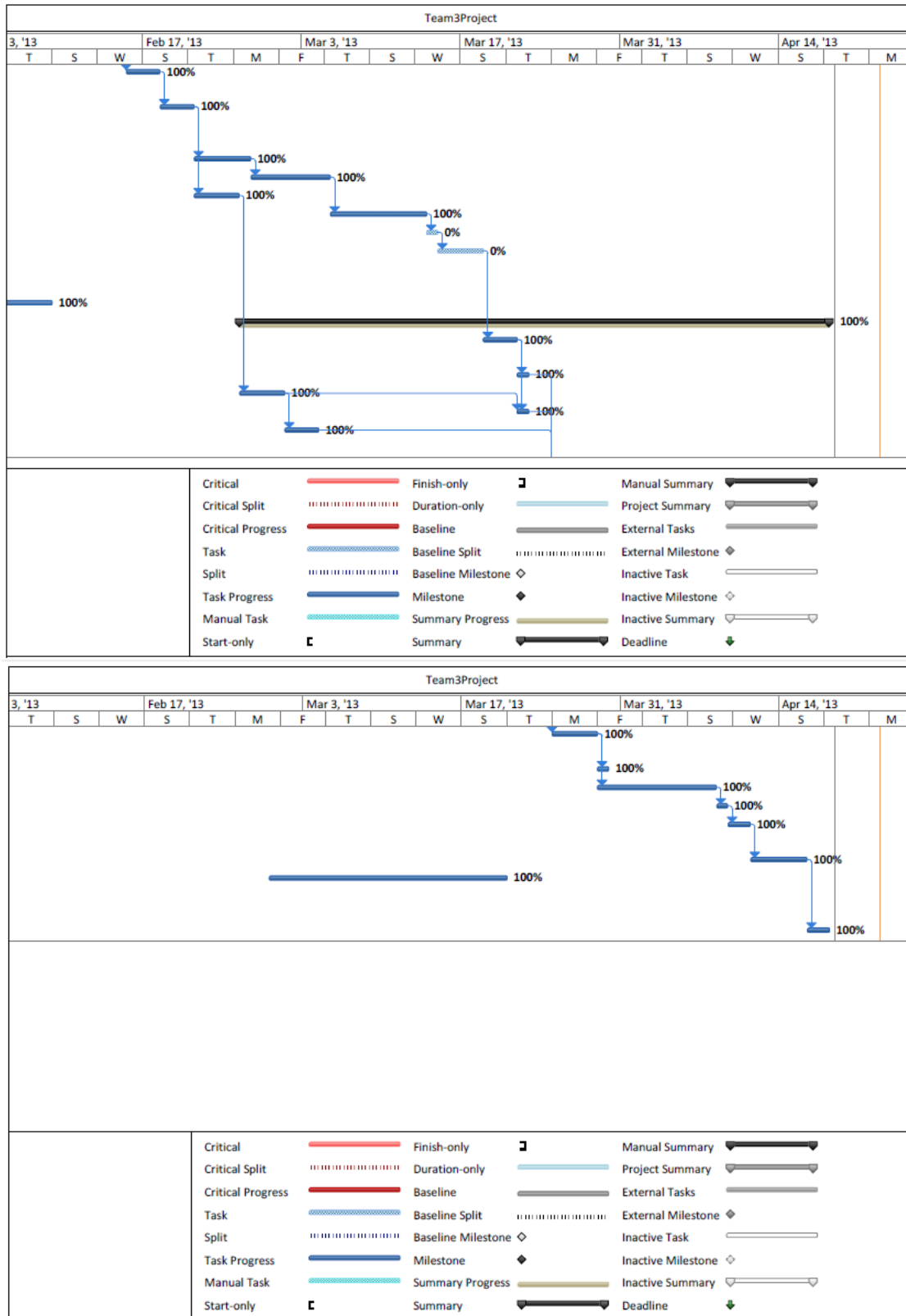


Figure 43: Semester Project GANTT chart

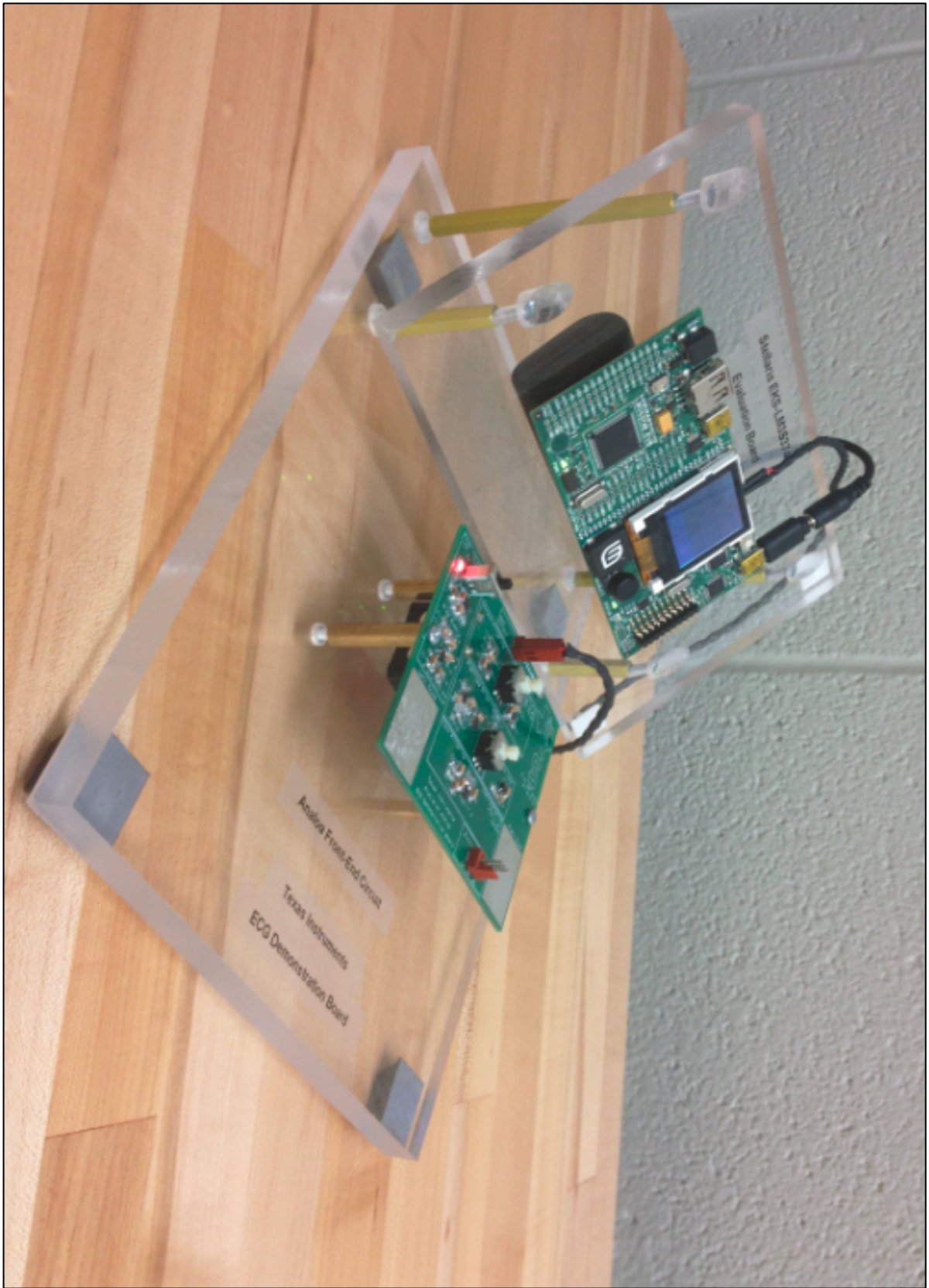


Figure 44: Final ECG Demonstration Board

Electrocardiograph Demonstration Board



Prototype



Phase 1



Phase 2



Phase 3

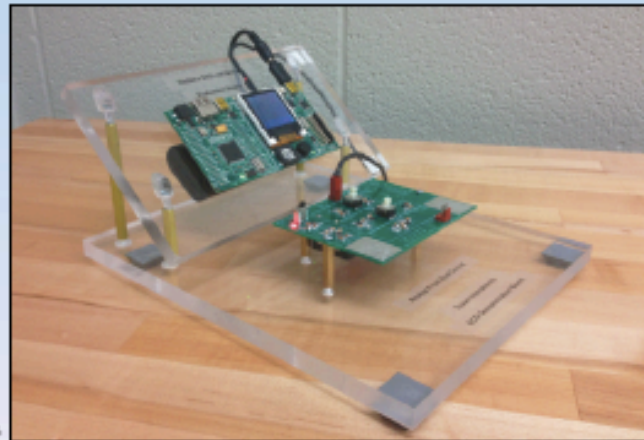
Project Description

The project challenge for the semester was to research, design, fabricate, and test the analog circuitry needed to develop an electrocardiogram (ECG) demonstration board for Texas Instruments (TI). The precision analog group sponsored the project's development throughout the semester. Texas Instruments intends to use the demonstration board to showcase the INA333 instrumentation amp as well as the OPA378 operational amplifier.

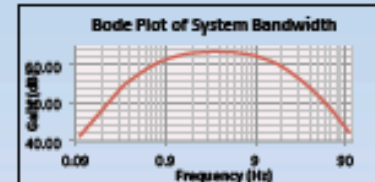
System Block Diagram



Final ECG Demonstration Board Solution



Project Results



System Bandwidth: 0.7 Hz - 50 Hz
Passband Gain: 64.3 dB
Battery Life: 211 hours

Summary of Results

The final PCB combined with the acrylic display fulfills and exceeds the project requirements. The final demonstration board successfully filters and amplifies an input ECG signal from the CardioSim II simulator and can display the signal on the Stellaris EKS-LM3S3748 LCD screen using the oscilloscope application. The design team successfully implemented the analog circuitry needed to capture a live ECG signal from a user's fingers tips. Texas Instruments plans to use the board to showcase the performance of their precision analog components.

Project Requirements

- Design and fabricate the analog front-end (AFE) circuitry
- Select a TI power management integrated circuit to utilize a 9V battery
- Measure the ECG signals from the CardioSim II (simulator)
- Condition the analog ECG input signals for accurate display
- Interface the AFE with a Stellaris Oscilloscope evaluation board (EVB)

System Components

CardioSim II ECG Simulator:



Provides realistic chest electrode ECG signals as inputs to the system

Analog Front-End Circuit:



Amplifies and filters the noisy input ECG signals to output a clean signal for display

Stellaris EKS-LM3S3748:



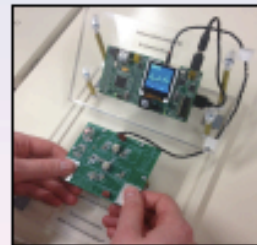
Displays the filtered ECG signals using a programmed oscilloscope application

TI Integrated Circuits Featured:

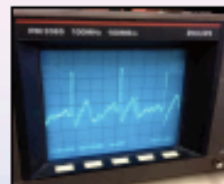
- OPA378 Low-Noise Op-Amp
- INA333 Instrumentation Amplifier
- TPS7A4201 Linear Dropout Regulator

Cost Table

Item	Cost
Acrylic Display	\$45
Battery Pack for Stellaris EVB	\$30
Stellaris Evaluation Kit	\$0
Analog Front-End PCB (4)	\$220
PCB Passive Components	\$96
PCB Integrated Circuits	Free
Accessory Components	\$70
Active ECG Finger Sensors	\$24
Total	\$485



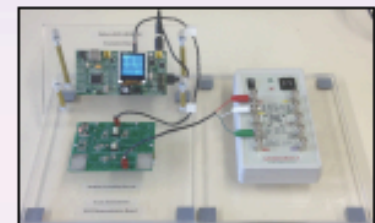
Successful live ECG measurement



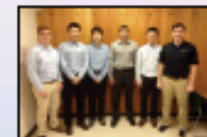
Output from AFE Circuit (Live)



Output from AFE Circuit (Simulator)



CardioSim II output through final AFE system



Design Team 3

Mike Mock Xie He Yuan Mei
Nathan Kesto Chaoli Ang Justin Bohr

Faculty Advisor

Dr. Ramakrishna Mukkamala

Project Sponsor

Peter Semig
Texas Instruments Precision Analog



Figure 45: Final Poster