April 20th, 2011

Dr. Andrew Rawicz
School of Engineering Science
Simon Fraser University
8888 University Drive, Burnaby, BC
VSA 1S6

RE: ENSC 440 Capstone Project Post Mortem for the HeartMon™, a cardiovascular diagnostic device

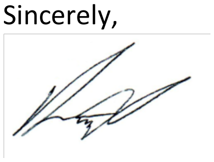
Dear Dr. Rawicz:

Please find attached the capstone project Post Mortem for the product HeartMon™, presented by Biomedical Engineering Solutions. We have designed a heart monitoring system that will be an improvement over the Holter monitor by including diagnostic capabilities and being more portable and accessible. The HeartMon™ is a preventative device, which will keep patients aware of their own health, save doctors time in making diagnoses, and save money in the healthcare industry.

Our post mortem details the current state of the device, deviations from the functional and design specifications, and possible future plans for the device. It also discusses our estimated and actual budget and timeline, group dynamics, and what our team has learned from this project.

Our team is versatile and consists of five innovative and motivated individuals: Amir Kamyabnejad, Bobby Luk, Cheng Zhang, Eric Boyer, and Yash Trivedi. If there are any questions or concerns regarding our proposal, feel free to contact me by phone at 604-617-1478 or by e-mail at aka39@sfu.ca.

Sincerely,



Amir Kamyabnejad
Chief Executive Officer
Biomedical Engineering Solutions

Enclosure: *Post Mortem for the HeartMon™*

Post Mortem for the

HeartMon™

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Table of Contents

1. Introduction 1
2. Current state of device 1
2.1. Hardware 1
2.1.1. ECG Circuit 1
2.1.2. Arduino 3
2.2. Software 4
3. Deviation from functional and design specifications 6
3.1. Hardware 6
3.2. Software 6
4. Future plans 7
5. Comparison of estimated and actual budgets and timelines 8
5.1. Budget 8
5.2. Timeline 9
6. Group dynamics and problems encountered 9
7. What we learned 11
7.1. Amir Kamyabnejad 11
7.2. Bobby Luk 12
7.3. Chen Zhang 12
7.4. Eric Boyer 13
7.5. Yash Trivedi 14
8. Conclusion 15

1. Introduction

During ENSC 305/440, five competent, creative, and motivated engineering students have worked ambitiously to innovate a new heart monitoring system. In this document the current state of the device, deviations from functional and design specifications, future plans, and the budget of Biomedical Engineering Solution's development of HeartMon™ will be assessed. Lastly the individual members' experiences and the team dynamics will be discussed.

2. Current state of device

2.1. Hardware

2.1.1. ECG Circuit

The current state of the ECG circuit is identical to that outlined in our functional and design specifications. A flow-chart of the structure of the ECG circuit is shown in Figure 1.

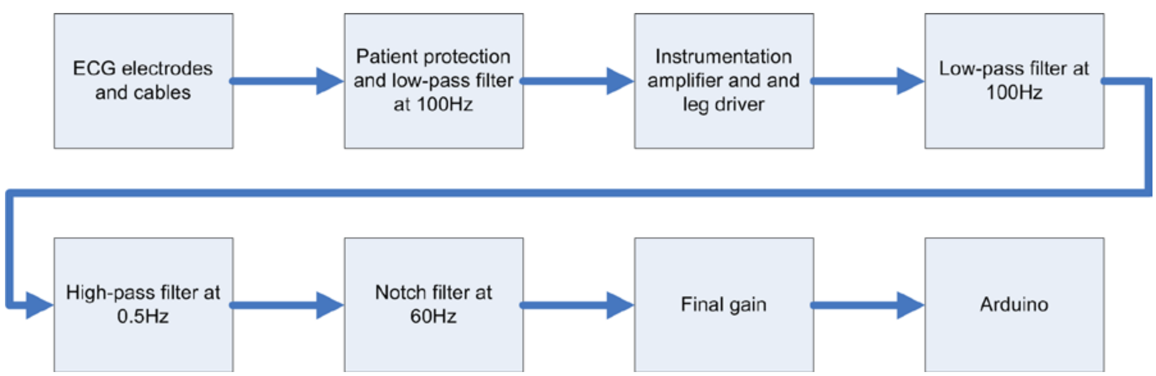


Figure 1: Flow-chart of the HeartMon™'s ECG circuit

Two ECG electrodes obtain the patient's ECG signal: one on the left shoulder and one below and right of the heart. Another electrode is placed on the right leg to cancel out the body's common-mode signal. The two electrodes that obtain the ECG signal are connected to the ECG circuit via shielded ECG cables.

The ECG signal first passes through a 1st-order passive low-pass filter at 100Hz to attenuate electrical noise from muscle movement, RF interference, and EMI. This filter also functions as the patient protection mechanism of the circuit. Patient protection is required because the HeartMon™ is an electrical device that is connected to the body, and thus could produce an electric shock. Because the HeartMon™ is powered by batteries and because the maximum voltage differential in the ECG circuit is only 10V, the patient protection mechanism can be quite simple: high-value resistors in series with the electrodes are sufficient. With these in place, if there is ever a fault in the circuit that causes a voltage differential to develop across the electrode connections, the maximum current that can pass through the body is limited by these resistors to within limits established by the American Heart Association.

Next, the ECG signal passes through an instrumentation amplifier, which amplifies the differential ECG heart signal and rejects most of the common-mode signal. Also part of this section of the circuit is a leg driver, which takes the common-mode signal, inverts it, and applies it to the electrode on the right leg. This has the effect of significantly reducing common-mode noise in the signal.

After the instrumentation amplifier, the ECG signal passes through various filter stages. A 2nd-order low-pass filter at 100Hz further attenuates high-frequency noise beyond what the 1st-order passive filter did, a 2nd-order high-pass filter at 0.5Hz eliminates the DC component of the signal and filters out ultra-low frequency noise resulting from shifts in the body's DC level, and a 60Hz notch filter attenuates interference from household power. With the breadboard version of our circuit we found that the notch filter produced a prominent resonance at 58Hz and only had minimal attenuation at 60Hz, so for our final PCB version we opted to use 1% tolerance resistors for the filters, as opposed to the 5% tolerance resistors that were used in the breadboard circuit, which resolved the issues with the notch filter.

After all the unwanted portions of the signal have been attenuated, a final gain stage can be applied. The full amount of gain could not be applied earlier in the circuit because that would amplify the noise in the signal beyond the limits of the op-amps, and thus would saturate the op-amps, which would produce prohibitive levels of distortion.

After the gain stage, the filtered and amplified ECG signal is sent to the Arduino. The PCB that we made for our ECG circuit is shown in Figure 2.

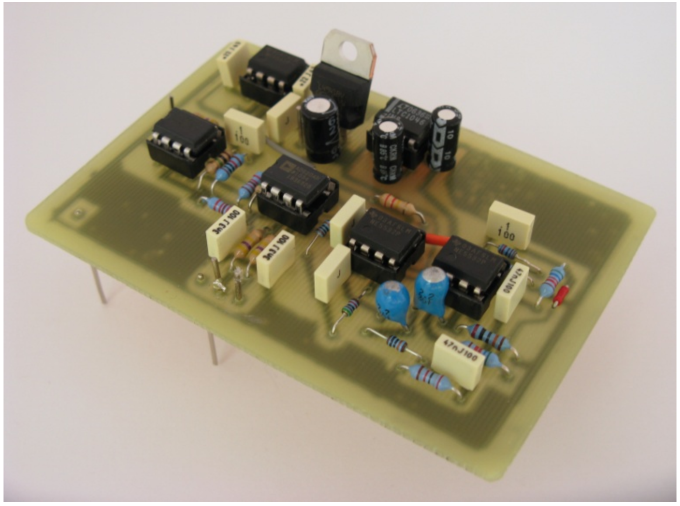


Figure 2: Final PCB version of the ECG circuit

2.1.2. Arduino

The Arduino microcontroller is used to digitize the analog ECG signal from the ECG circuit and transmit the resulting digital signal to the cell phone via a built-in Bluetooth (BT) module. The digital-to-analog converter in the Arduino is a 10-bit device, which provided sufficient precision for our purposes. The BT transmitter was set to a transmission rate of 115,200 bits/second because that was found to be an optimal rate for the HeartMon™.

The built-in voltage converter on the Arduino died partway through our project, which meant that we had to power it with an external regulator. The Arduino requires a regulated voltage of 5V, which is what the ECG circuit is powered by, so to power the Arduino we simply used the power source for the ECG circuit.

2.2. Software

The current state of the HeartMon™ software consists of the functional blocks shown in figure 3 below.

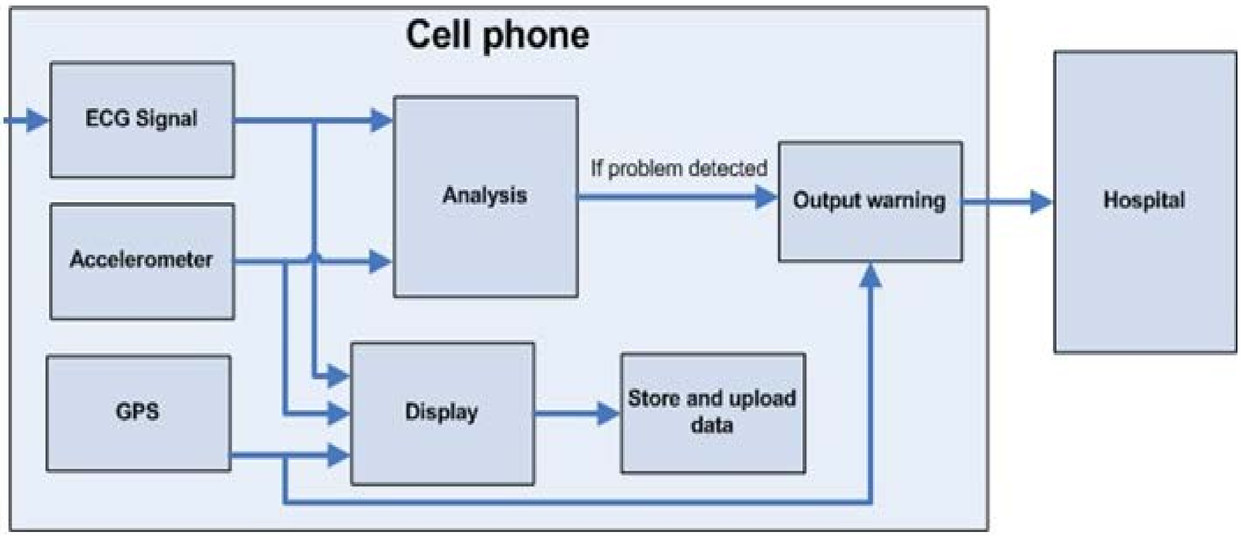
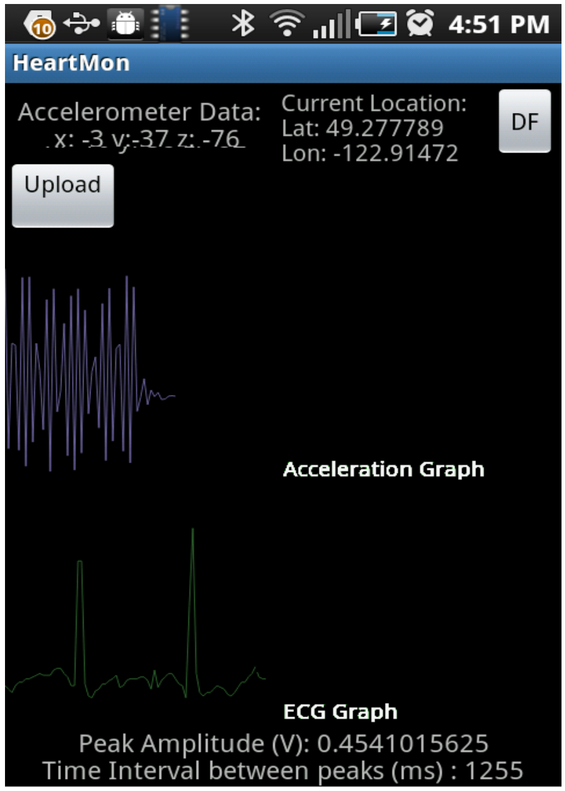


Figure 3: Block diagram of the cell phone application

The Android phone application for the HeartMon™ receives the user's ECG signal from the Arduino BT board, and plots the data continuously on the graphical user interface (GUI), as shown in the screen capture in figure 4.



Current value (mV): 0.1220703125

Figure 4: Graphical user interface of the application

If a problem is detected in the ECG signal based on the analysis algorithm, the application will warn the user via text message and phone vibration. Also, the application is able to automate phone calls to health professionals when an emergency occurs. For diagnostic purposes, the application has features of data logging and data uploading. The real-time ECG data with other corresponding information such as timestamps will be recorded in a spreadsheet form and stored locally in the phone SD card storage so that either the user or a healthcare professional can view the data any time. In order to let health professionals remotely access and analyze the data, the log files will be uploaded to a chosen server every customizable time interval.

To make the ECG graph more clear and accurate, the application has a built-in digital filtering feature. By enabling the digital filtering on the GUI, the user can see the ECG signal is less noisy and more accurate.

3. Deviation from functional and design specifications

3.1. Hardware

Thanks to careful planning and designing, the ECG circuit is completely identical to what was described in our design specification. It also meets all level I and II requirements from the functional specification.

The Arduino is slightly different from what we described in our design specification. Due to speed limitations of the Arduino's microprocessor we were not able to implement digital filtering. This means that noise in the ECG signal could not be filtered out as well as we had hoped, particularly noise from muscle movement. This results in fairly prominent noise when the patient moves, but when the patient is sitting still we get very good readings because the analog filters are sufficient in this case.

Also, rather than using an accelerometer on the Arduino we decided to use the accelerometer built into the cell phone. This greatly simplified implementation, mostly due to what would have been required to transmit multiple signals over a single Bluetooth transmitter.

3.2. Software

Most of the Category I and II requirements have been met for the software application. The ones that haven't been met are listed below:

[R102-III] The application will work on all Android, iPhone, and Blackberry platforms provided the selected models have Bluetooth capability.

[R110-III] The application's battery usage shall be minimized so that the cell phone can be used for up to 4 days (96 hours) without charging.

[R1-II] The application GUI shall have menus to set the heart rate levels that correspond to normal, irregular, or dangerous.

[R2-I] The application GUI will have a field displaying the patient's health status as normal, irregular, or dangerous.

The functional specifications listed above could not be achieved due to time and budget limitations. However the main features of the project have been successfully implemented within the cell phone application, which include, but are not limited to:

- Displaying the ECG signal in the application
- Performing diagnostics on the signals
- Triggering alarms and alerts in emergency cases in the form of display messages, haptic feedback, sounds, and phone calls
- Logging data in a spreadsheet and uploading it to an online server
- Gathering additional statistics such as location and acceleration

4. Future plans

The HeartMon™ project experienced a very successful completion wherein almost all of the initial expected and additional bonus requirements were fulfilled. Most of the team members are keen on taking the project beyond the scope of the course.

Efforts were made to turn the project into a business venture. These efforts are still ongoing and we have discussed possible strategies and methods to take the project further. These ideas are hoped to materialize after the completion of the course. At present, we are conducting market research for feasibility and are studying a list of possible clients and vendors who might show interest in the project. There are also prospects of setting up a small start-up company to promote HeartMon™.

Regarding the project itself, further development may be pursued depending on the result of market research, feasibility study, resources, and business opportunities. After acquiring such information, a decision will be made to whether to sell HeartMon™ as is to a well established company, or implement further development, or abandon the project all together. As to further development, we hope to eventually implement all the requirements listed in our functional specification, especially proper digital filtering, compliance with CSA, UL, and FCC requirements, reduced size and weight, improved diagnostics and reliability, and compatibility with more mobile phone platforms, such as Blackberry and iPhone. Other features that we may include are wireless ECG electrodes, an oximeter, and a thermometer.

5. Comparison of estimated and actual budgets and timelines

5.1. Budget

Table 1 summarizes the estimated and actual budgets for the project.

Table 1: Estimated budget vs. Actual budget

Category	Estimated Amount	Actual Amount
Microcontroller including Bluetooth (Arduino BT)	$168.00	$188.10
Accelerometer	$52.00	$57.12
Power Control (DC-DC converters and batteries)	$20.00	$19.87
Project Case for Arduino	$10.00	$0
ECG electrodes	$65.00	$60.25
ECG circuit components	$50.00	$34.78
PCB Supplies	$30.00	$48.43
Contingency fund	$100.00	$25.04
ESSEF cheque	n/a	$100.00
Expense Subtotal	$495.00	**$533.59**

Our actual total amount is close to our estimated total amount, with a difference of only $33. We underestimated the cost of some of our components such as the microcontroller and accelerometer but also overestimated for other components such as the ECG electrodes and circuit components. A project case was not made for the hardware so the actual cost is $0. With careful handling of our hardware components and along with some fortune, we only needed to use 25% of our $100 contingency fund to replace an instrumentation operational amplifier. Because we acquired funding from the ESSEF and have decided to keep our components, we must pay the ESSEF $100.00 for not returning the hardware.

5.2. Timeline

The Gantt chart shown in figure 5 summarizes the timeline of the project. The red bar is the actual timeline and the blue bar is the planned timeline.

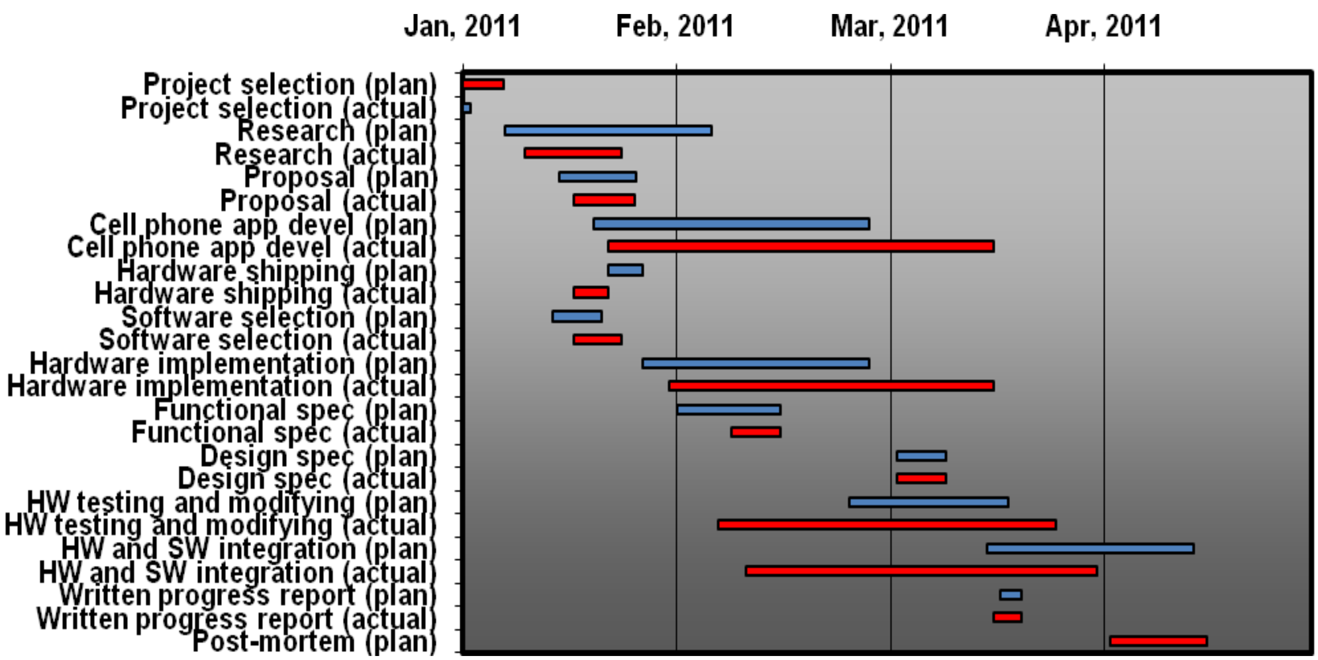


Figure 5: Gantt chart of the project timeline

For the most part, our actual timeline matches our planned timeline. We were able to keep on track, and at times got ahead of schedule, partly by putting in a 40-hour work-week during the reading break in the third week of February. Developing the software application on the cell phone took longer than expected as the group was new to Android development. The hardware implementation also took longer than planned as there was some downtime between building the circuit and testing it as it was dependent on the cell phone application.

6. Group dynamics and problems encountered

We were privileged to have a very diverse team with a wide range of skills to accomplish our ENSC 305/440 course objectives. The team dynamics continuously changed over the course of thirteen weeks, which will be summarized below.

Originally, most of the members did not know each other. The group was formed shortly before the start of the ENSC 305/440 class. We were warned early on that one of the most important factors in the success of our project is the human factor. We were told that technical aspects can be figured out, but the biggest problems for teams from previous years have been team dynamics. Thus, special attention was given to this subject and considered vital to the success of our project.

In the very beginning we recognized the urgency of getting started right away, and not leaving anything for the stressful parts of the semester, such as final exam period. Also, regular meetings were set up to review accomplishments from the previous week, assess current needs, make decisions, and lay out action plans for the upcoming week. These meetings, and the early start of them, kept us on schedule throughout the semester.

Another major contributor to our success was full time attendance of all team members during the reading break. This period turned out to be the most productive portion of the semester, as everybody was present at the same place and the same time, every day for the whole week.

The technical tasks were distributed firstly on a volunteer basis, and thereafter based on competencies and urgent needs of certain skills. This resulted in greater motivation for team members to do what they were familiar with and had an interest in. This motivation resulted in high quality performance and meeting deadlines on time.

We encountered some group dynamics challenges during the course. One of the challenges was different progress rates for different parts of the project. For instance, some tasks progressed faster than expected, some slower, and sometimes members were idle as there were no tasks for them to accomplish. This challenge was overcome by continuously monitoring the overall performance of the team, and adjusting to the needs and challenges by changing members' tasks.

A more challenging aspect of group dynamic was to determine different members' competencies, work habits, and communication styles to establish effective interpersonal communication. Then, members' abilities were to be utilized effectively to successfully accomplish tasks. This was a challenging task to fulfill in thirteen weeks, but got easier as time went by.

Overall, we believe that we worked well together for the purpose of this course, and all of the members are willing to work with each other again in future projects.

7. What we learned

7.1. Amir Kamyabnejad

I feel very privileged to be part of Biomedical Engineering Solutions (BES). I look forward to working again with all BES members in future. The following are my significant contributions to this amazing team.

I started looking for an appropriate project weeks before the start of the semester. I frequently met with SFU faculty Dr. Andrew Rawicz, Dr. Marinko Sarunic and Mike Sjoerdsma to come up with a feasible and innovative project. Eventually the idea of heart monitoring system was formed, discussed with the team, and approved to become the topic of our project.

Moreover, I was the first member of the team and actively looked for engineering students to put in a team together and was involved to bringing in all team members. Decisions on bringing all subsequent members were decided democratically between all existing members.

I took responsibility of team leadership by default, as no one else volunteered for this position. I made sure I studied all team members carefully to become familiar with their work habits, competencies, and effective language to establish communication with. This was a challenging task, as everyone is very unique in their capabilities and ways of communication.

In order to establish an effective leadership role, I setup regular meeting with appropriate meeting agendas and presenting the overall state and direction of the team. I did my best to listen to everyone's needs and opinion and voice them in our meetings and discussions and make everyone feel their inputs are valued and important.

I made sure I was involved in everyone's tasks, knew the state of their progress, their current challenges, required resources, and estimated completion time. I was present at all partial meetings that were technically specific to one or more member's tasks.

I did my best to not allow my personal feelings, and opinions affect my decisions. I made sure that decisions are reflective of the team member's opinion. All major decisions were discussed in a transparent way and voted on by all team members.

Moreover, throughout the semester I frequently met with course instructors to ensure we are on the right track. I also visited health professionals, hospitals, and doctors to make sure we integrate their inputs into our design. I also looked into partnering with business students through a business professor, as well as talking to venture connection to assess the possibility of expanding our project beyond the course objectives.

7.2. Bobby Luk

I've really enjoyed working on this project this last four months with this group. I learned many things regarding technical aspects and group dynamics from working in this project.

My main role was to develop the cell phone application. I was involved in setting up the Bluetooth communication between the microcontroller and Android phone. I also learned a great deal about developing and debugging in the Android environment through reading documentation and learning hands-on from coding and observing the results. I participated and gave my input in team meetings where we developed and integrated algorithms to analyze the ECG signal to detect heart problems. I designed and implemented a log file algorithm to record the ECG, accelerometer, GPS, and warning data that could be later uploaded for health professionals to review. I applied modifications and enhancements to make the source code easier to maintain and expand upon for future purposes.

Having worked on many projects throughout my undergraduate degree along with my three co-op work terms, I have had experience both as a leader and as a follower. Having leadership experience in the past taught me the importance of teamwork, communication, and organization, which was emphasized again for this project. I learned to provide regular updates to the team to keep them in the loop. I also learned how to change my working style depending on who I was working with to maximize efficiency.

In general, regular communication is key. It should be done through different ways, such as e-mails, text messages, and phone calls, depending on who is the contact. Our group was able to do this and it helped everyone remain focused on the tasks at hand.

7.3. Chen Zhang

Working on this 4-month project is a challenging but rewarding experience. Throughout the SFU engineering program, researches and projects we did are mostly course-oriented. But in ENSC 305/440, we have a chance to choose and develop a product/system which can contribute to the society. Although the development consumes time, but the whole process will give us a better insight of how technology turns into a product and dig out our innovative potentials as an engineer.

As the Chief Software Officer of Biomedical Engineering Solutions, my primary responsibility is the development of Android application HeartMon™. During the development of this application, I gained a lot of knowledge of Java language programming and Android application development. I am also exposed to the use of Java web server and Tomcat Servlet since we need to set up a server to remotely receive the data sent from the Arduino BT board and store the data for diagnostic purposes. All these techniques I learned from this project significantly helped me have a better understanding of software development enterprise solutions such as server setup and data management.

Technical knowledge aside, playing the role of software leader improved my interpersonal skills such as leadership, teamwork, time management, and planning techniques, which will help me in my future career. This project experience also taught me that in terms of teamwork diverse skill and experience set in a team can be a significant advantage when it comes to workload division, expertise management and work efficiency. Having different strength in various fields in a team can inspire creative solutions to the problems encountered during development.

7.4. Eric Boyer

As the chief of hardware for this project, I have gained experience and knowledge mainly in two areas: analog circuit design and group collaboration.

Before this project I was already fairly knowledgeable with analog circuits, mostly because of my various personal electronics projects related to hi-fi audio. However, this project brought this knowledge and skill up one level by introducing me to new areas of analog circuit design, and giving me practice with various skills that I had not yet mastered. For example, this project gave me substantially more knowledge on the subject of switching voltage converters because we were required to use them to power our ECG circuit efficiently. In terms of analog filters, although I already had a strong understanding of them from my work with hi-fi audio, I learned more nevertheless. This project introduced me to the problems encountered when filtering ultra-low frequency signals, as well as how strongly component tolerances can affect filter performance, particularly with Sallen-Key notch filters. This project also gave me the opportunity to practice my skills building a PCB using the toner-transfer method, which turns out to be harder than I originally predicted.

In terms of group collaboration, this project has taught me many things. Most importantly, I have learned that the most important thing in a group project is effective communication. Without listening to others or discussing issues properly, group projects simply fall apart. Thankfully, we had excellent communication, so our team worked well together and issues were addressed quickly. This minimized wasted time and stress.

After effective communication, I think that proper planning and organization is the next most important quality in a group project. Our group was quite organized and we had clear plans throughout the semester, which really helped to maximize our efficiency. In fact, I don't think that any of us found this project to be overwhelming (unlike many 440 students in the past) even though it was fairly complicated, and I attribute this to our excellent communication, planning, and organization.

If I were to repeat my experiences in this course, there isn't much I would change. I learned a lot and I feel that I contributed a lot to the team. I think the only thing I would change would be to have a more diverse workload. For this project I worked almost exclusively on the hardware and was barely exposed to the software. I would have liked to work on the software to gain more experience with my programming skills, but unfortunately time constraints did not allow for this.

7.5. Yash Trivedi

My role in the project was that of a Systems Engineer with involvement in both, the Software and Hardware components as required. Initially, I was involved in conducting research for various aspects a such as selecting the microcontroller best suitable for our project, various peripheral circuits, development on the Android platform, the Bluetooth capabilities and compatibilities of the Android SDK along with the phone hardware and microcontroller programming. Once we had finalized on the parts, I came up with a system design to integrate various components. I set up a framework to establish communication between the Android phone and the Arduino microcontroller. I verified that the signals could be sent back and forth after proper processing procedures were implemented within the microcontroller. After this phase was complete, I got involved in software development. I worked on various features on the phone application such as the graphs, phone alerts etc. I was also involved in designing the software architecture and code debugging. During this phase, I came up with algorithms to perform various diagnostics on the signal so as to detect any heart conditions. Additionally, I designed and implemented a digital filter on the phone and had to make calculated decisions affecting the system transients such as response time, signal accuracy, power management etc.

I learnt many things along the way such as the value of teamwork and good communication. The most important factors involved in accomplishing tasks efficiently are communication, organization and planning. Our team met all three requirements and hence we did not face any significant roadblocks or challenges. All of our problems were dealt with at the earliest possible chance in an efficient manner. Overall, I've had a great experience with some very talented and friendly team members.

8. Conclusion

The Biomedical Engineering Solutions team is proud that we have not only successfully completed the proposed product according to our functional and design specifications, but also exceeded our expectations by adding several extra features. Excellent team dynamics made this engineering project course a pleasant and invaluable teamwork experience for all the team members. This unforgettable experience will be taken with us in our future careers and the further development of this product. Finally, we would like to wish all members of our outstanding team the best of luck in their future endeavors.