December 18, 2009

Dr. John Bird
School of Engineering Science
Simon Fraser University
Burnaby, British Columbia
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Re: ENSC 440 Post-Mortem for a Qualified Sonar System for the Masses

Dear Dr. Bird:

The enclosed document "Post-Mortem for a Qualified Sonar System for the Masses" details the AquaScan sonar in its completion, and our development process throughout the past semester. The AquaScan includes a testbed for the evaluation of candidate sonar receivers to include in a future sonar system based upon your MASB sidescan sonar technology, as well as a promising receiver we have identified called a Tayloe detector.

This document details the current state of our project, the problems encountered, the proposed and actual timeline and budget, our group dynamics, what was learned, and suggestions for future work in this project.

If any questions or concerns arise regarding our post-mortem, feel free to contact me by phone at (604) 807-9823 or by email at ksw3@sfu.ca.

Sincerely,

Ken Wu
President and CEO
AquaSense System

Enclosure: *Post-Mortem for a Qualified Sonar System for the Masses*

AquaSense

Post-Mortem for a Qualified Sonar System for the Masses

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ABSTRACT

This document details the current state of our project, the problems encountered, the proposed and actual timeline and budget, our group dynamics, what was learned, and suggestions for future work in this project. With respect to the current state of our project, all the functional specifications have been met and exceeded. The noteworthy problems that we encountered were few, and the only problem which remains a concern is noise, although this is due primarily to the limitations of a typical proof-of-concept system. The actual timeline deviated for the proposed in terms of time allotments for individual tasks, although in the end the deadline for this project was met; most notably, things were accomplished in parallel as opposed to being linear in fashion. The actual budget exceeds both the proposed budget and our funding, and this is due mostly to mistakes made in learning how to approach a practical problem; the members of AquaSense Systems are willing to shoulder this expense. Numerous lessons were learned as a group and as a whole, and cannot be done justice here; we refer the reader to section 6 which concerns the individual reflections. Finally, we conclude with the several suggestions for the future direction of this project, and mention briefly the potential for its applications.

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1. THE PROBLEM AND POTENTIAL SOLUTION APPLICATIONS

Sonar systems have numerous military, civilian and scientific applications. Sonar finds much use in navigation as well as target detection, classification, and tracking both in underwater warfare and academia [1]. With respect to civilian applications, commercial fishing vessels rely on sonar to detect fish, navigational guidance systems can be made for the blind, vehicle location systems could allow consumers to find their automobiles in a vast parking lot, and obstacle avoidance systems would give vehicles the ability to look ahead in obscure conditions as well as assist in parking [2]. In both the academic and industrial world, bathymetry (the elevation mapping of the seafloor) also finds much use; the former uses it for a variety of applications – cartography, mineralogy, and the study of underwater faults, volcanoes, and earthquakes – to name a few [3], whereas the latter uses it for navigational safety along trade routes. In addition to this, bottom backscatter plots allow geomorphology, sediment classification, and sonar performance evaluation [4]. These applications are but a subset of those that exist or have been proposed for sonar; however, despite this multitude of applications, the impediment of cost prevents the widespread adoption of sonar technology.

Many existing sonar systems have receivers that are field-programmable gate array (FPGA) or digital signal processor (DSP) based, causing them to be inherently expensive. In the case of FPGA-based designs, redundant components drive up the costs of the device. Another case in point - filters are an essential part of any communications system, not just sonar, and wide-bandwidth digital hardware filters can but must be obtained with fast sampling – which requires expensive analog-to-digital convertors (ADCs), DSPs, or FPGAs [5]; not only so, higher sampling frequencies also increase the digital hardware filter's power consumption and size [6]. Equivalent analog schemes provide a less expensive solution and even excel in some areas, such as in filter performance already addressed in [7], but overall cannot compete with the superior performance of standard FPGA and DSP based designs.

The goal of this project is thus to find an optimal compromise between the cost and performance in sonar system receivers, using modern analog circuit technology, to address the problem of cost-inhibited widespread sonar adoption. To do this, a testbed which is capable of evaluating various receivers will also be developed; the testbed together with its receiver form the complete AquaScan sonar system. The optimal cost target for this project is $300, and performance is defined by the signal-to-noise ratio (SNR) and coherent-to-diffuse ratio (CDR) of the system receiver as a function of distance, as per [8]. A qualified solution for a sonar receiver would open the door to numerous potential applications for military, consumer, academia, and special needs groups alike, as well as providing potentially long-lasting monetary benefit to the inventors. The immediate application of this solution however, would be in 3D multi-angle swath bathymetry (MASB) sidescan sonar technology developed by Dr. Bird of the Underwater Research Lab (URL) at Simon Fraser University (SFU).

1.1 LIST OF FIGURES

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1.3 GLOSSARY

ADC Analog-to-Digital Convertor
BPF Band Pass Filter
CDR Coherent Diffuse Ratio – the ratio of the power in the coherent part of a signal to the power in the noise part of the signal; for a variable x, this is defined in dB as $20\log(\mu_x / \sigma_x)$
DSP Digital Signal Processor
DAC Digital-to-Analog Convertor
FPGA Field-Programmable Gate Array
GUI Graphical User Interface
LPF Low Pass Filter
MASB Multi-Angle Swath Bathymetry
MCU MicroController Unit
PWM Pulse-Width Modulation
SFU Simon Fraser University
SNR Signal-to-Noise Ratio
URL Underwater Research Lab
UART Universal Asynchronous Receiver/Transmitter
VGA Variable Gain Amplifier

2. CURRENT STATE OF PROJECT

The current state of the project in terms of its major components, as well as the deviations from the original scope of the project, are discussed below.

2.1 TESTBED

The AquaScan testbed provides the foundation upon which candidate sonar receiver circuits may be evaluated. To do this, it must be able to simulate all possible ranges of operating conditions which are of interest, as well as recover and analyze the recovered data to determine the noise performance. The system at present is a complete and fully operational proof-of-concept which is able to simulate the operating conditions beyond the ranges required of us; the operating conditions are maximum range, the duration of a transmitted pulse, and the frequency of the carrier within the transmitted pulse. A noise analysis utility has also been created using MATLAB, which is able to characterize the noise of the system in terms of several measures of interest, namely the SNR, CDR, peak-to-peak noise voltage, and the noise power. Furthermore, our system is capable of recovering the data in real-time. Several other useful features have been included which are beyond the original requirements; these include automatic gain control (which reduces the noise of the system, and maximizes the utilization of the data sampling resolution of the MCU), and tools in the graphical user interface (GUI) which make the analysis of data easier.

2.1.1 Microcontroller and Firmware

As stated in the previous section, the MCU via its firmware is able to simulate the operating parameters beyond the ranges originally required of us, as well as recover the data in real-time for further analysis; the original requirements can be found in section 3.3 of [7]. In order to facilitate these requirements, the MCU is capable of the high-speed data transfer necessary for real-time data recovery, possesses an accurate clock to ensure a stable system and mitigate noise, and includes high-resolution pulse-width modulation (PWM) modules to enable the creation of extremely precise transmitted signals at all operating ranges. That we are able to exceed the operating ranges originally required of us means that the MCU has the potential to further increase the capabilities of the testbed in the future, should this be desired. This is important because it has come to our attention that this project is to be transferred to another student doing his undergraduate thesis, and as an added bonus the firmware is concise, taking up only 360 lines of well-commented code, which should greatly aid in any future development of the platform.

2.1.2 Graphical User Interface

The original goals for the GUI were to allow the user to manage the connection settings, configure the transmitted carrier parameters, display data in a real-time plot, and export data for further processing. The GUI is fully capable of each of these tasks, and addition to this has several useful features to make the analysis of data easier. These include the recording and playback of data, the printing and saving of data plots, the annotation of specific data points, speed control of data playback, real-time zoom, one and two way transmission modes, air and water modes, and support for updating multiple transmission parameters at once (the GUI will respond to these changes after a brief predetermined delay). When recording data, the user can also specify exactly how many pings are to be recorded; when playing data back, the user can also go directly to a specific sonar ping.

2.2 TAYLOE DETECTOR BASED RECEIVER

The Tayloe detector forms the heart of the receiver circuit in the AquaScan sonar, and is also a potential candidate for an analog solution to complement the 3D MASB sidescan technology developed by Dr. Bird.. The receiver circuit with the Tayloe detector is detailed in Figure 1 below:

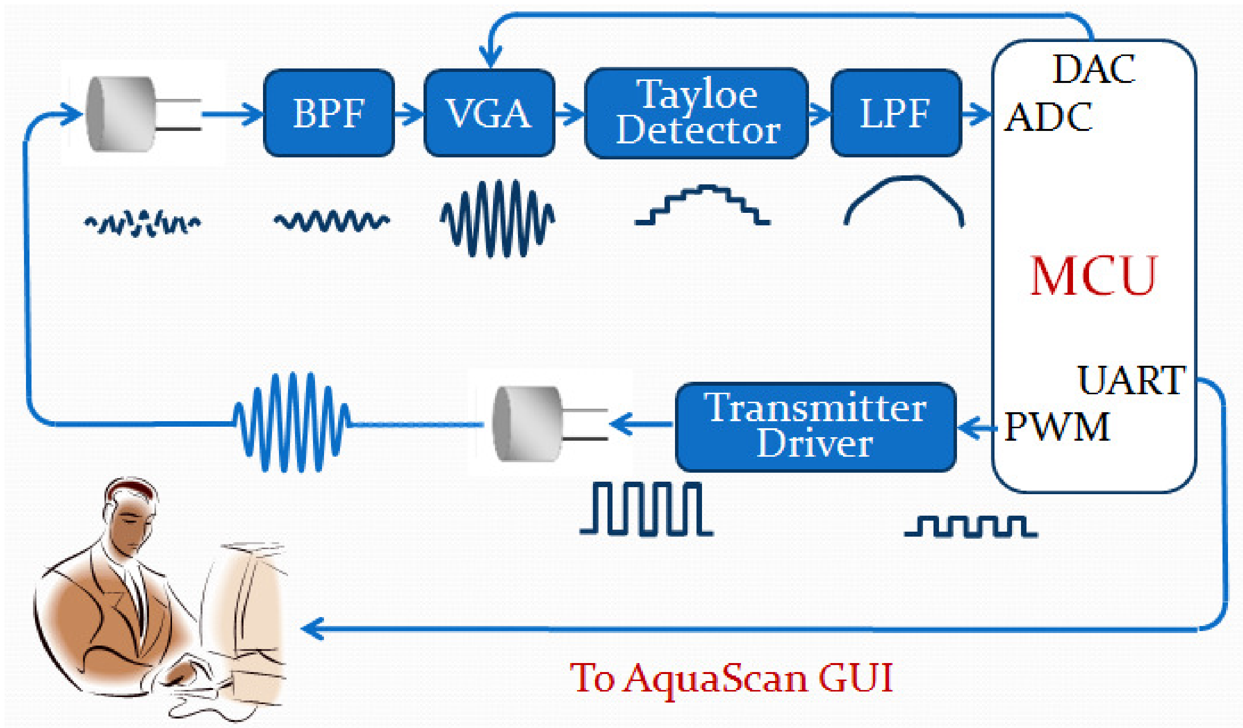

Figure 1: Receiver with Tayloe Detector Circuit

The MCU and its PWM module have already been detailed and will not be mentioned here again; the purpose of Figure 1 is merely to aid in the discussion of the current state of the receiver, whose operation we now proceed to detail. The acoustic signal which is received has experienced both attenuation and some added noise so we use a band pass filter (labeled "BPF") to remove the noise, and then amplify again at a variable gain amplifier (labeled "VGA"); again, this amplification is variable to vary the amplification to a designated maximum value at all possible times, which improves the noise performance of the system and maximizes the utilization of the resolution of the MCU data sampling. The MCU is programmed to provide this functionality automatically using its digital-to-analog convertor (labeled "DAC"); we again point our here that this is a bonus feature beyond the original requirements in [7], and that this feature is typical in sonar systems. After this, we recover the desired signals by running the received signal into the Tayloe detector, which produces a staircase approximation to the desired signal. A low pass filter (labeled "LPF") takes this staircase and gives us back the final signal. The data from this resultant signal is sampled by the MCU at its analog-to-digital convertor (labeled "ADC"), and the information is transmitted to the AquaScan GUI, through the universal asynchronous receiver or transmitter (UART) port of the MCU. The GUI takes the information it receives and displays it in a presentable format to the user.

The Tayloe detector based receiver has been demonstrated to our client in both air and water, and is fully capable of meeting the performance requirements laid out in the functional specifications, including both cost and noise, which as detailed initially in section 1.1 are the two tenets of the AquaScan design philosophy. The per-unit cost of the receiver is detailed below in Table 1:

Table 1: Per-Unit Cost for Single Channel System

Components	**Cost ($)**
MCU	7.00
Amplifiers	64.00
USB-to-UART Module	34.00
Passive Components	20.00
Miscellaneous	30.00
Total Per-Unit Cost	**155.00**

The original cost target was $300 for a single-channel implementation of our system; a channel here refers to an individual receiver module. As can be seen from Table 1, the eventual cost was found to be around half the original cost target. For a six-channel implementation such as that used in Dr. Bird's MASB sidescan sonar technology, the cost was estimated at $548.00; this is because only the receiver components need replication, and a single testbed is sufficient.

In order to detail the noise aspects of the current system, several definitions need to be made. From the glossary, the CDR is given as $20\log(\mu/\sigma)$. The CDR finds use in situations where there is a small target which is slowly moving in the presence of a large background noise; because the target is small, the signal returned from it is likewise small, and thus it is dominated by the large background noise. Typical sonar schemes cannot pick up this target because they require that the returned signal strength be at least comparable to that of the background noise. However, using CDR, a sonar system can still detect such a target; the reason for this in essence is that a target which is slowly moving or stationary has a high CDR, whereas a rapidly moving object has a low CDR. Therefore because the background noise is caused by rapid movement, its CDR is low, and therefore the stationary target stands out because of its high CDR. Typically, a CDR of 40 dB is considered good, whereas a CDR in around 20 dB is acceptable. Figure 2 shows the CDR of our system on the next page in air:

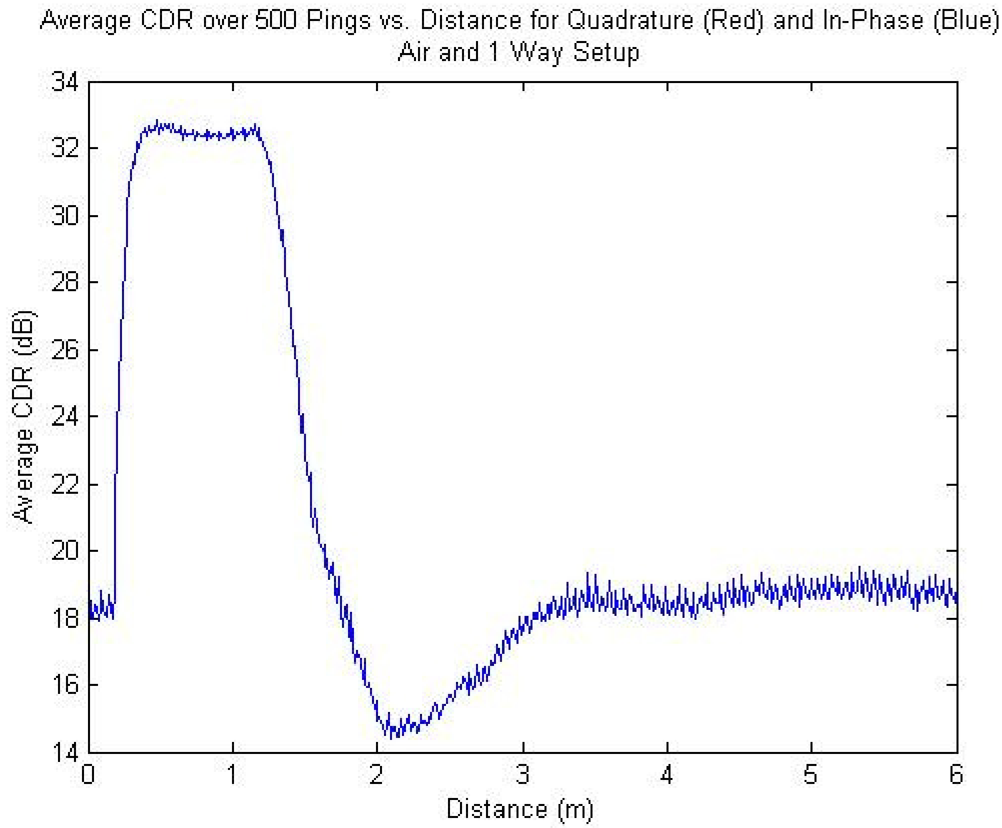

Figure 2: CDR of System in Air

From Figure 2 it is seem that the CDR of the system is about 25 dB, which is acceptable. This is indicated by the jump of about 25 dB from the noise level at the target; the CDR is a relative measure.

The SNR of the system measures how much stronger the signal power is to the noise power, and determines the smallest signal detectable, as well as limits the maximum range of the system. A SNR above 20 dB is desired at all times. Figure 3 presents the SNR for our system in air on the next page:

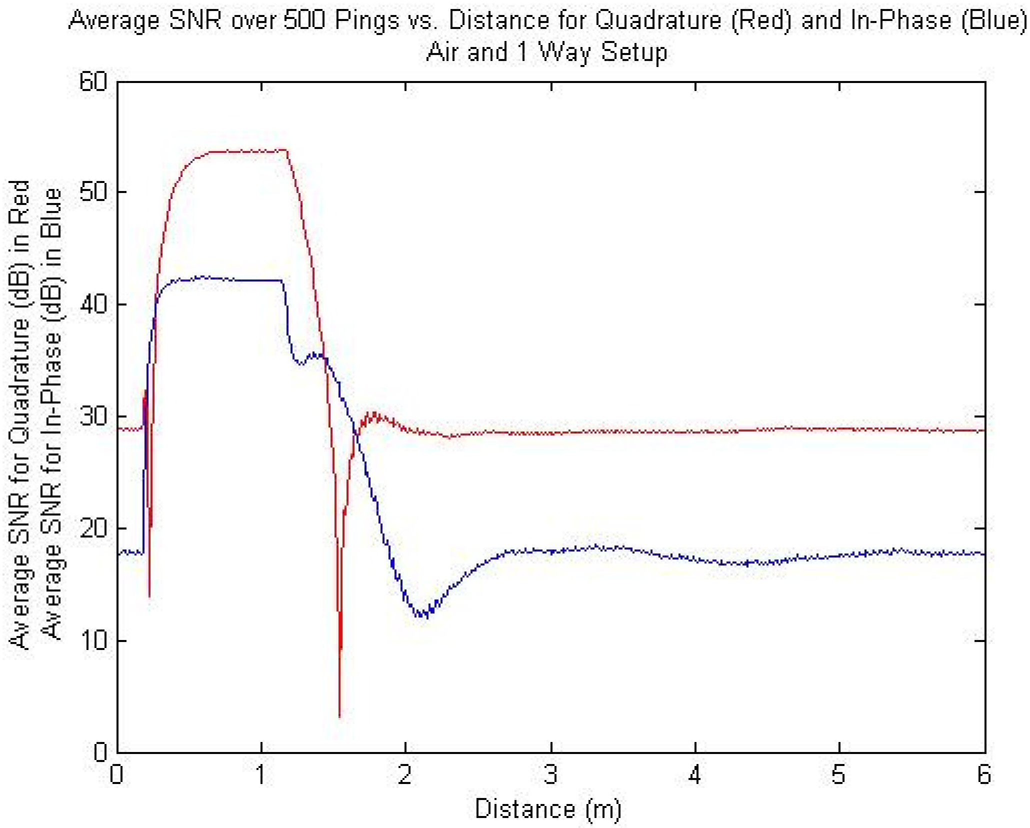

Figure 3: SNR of System in Air

From Figure 3 it is seen that the SNR of the system is about 25 dB for both recovered waveform; again, this is indicated by the jump in SNR at the target, and we also emphasize here that SNR is a relative measure.

Though the noise performance of the Tayloe detector-based AquaScan sonar is acceptable, it is but that of a proof-of-concept system; in an eventual production model, further design optimizations would be made to further improve the noise performance, as will be detailed later in section 7. The system currently also works in water; however, several problems were encountered as will be detailed in section 3.

2.3 DEVIATIONS IN SCOPE

As mentioned in section 1.1, the goal of this project was to evaluate several potential candidate receivers for a future sonar system based upon MASB sidescan sonar technology. However, once the Tayloe detector was successfully implemented, our client suggested that the members of AquaSense Systems instead spend time understanding more of the present system, the significance of the results that were obtained, as well as their potential applications. This would be more beneficial to our learning, and increase our appreciation of the issues pertaining to sonar. Reviewing the weeks that followed the change in scope, the members of AquaSense Systems feel that it was for the best - in the end, we understood more of the issues involved, and unfortunately we also encountered several problems while testing the sonar in water that when combined with our time constraints would have made testing alternative schemes impossible.

3. PROBLEMS ENCOUNTERED

There were few noteworthy problems in the development of the AquaScan – as was mentioned in section 2 on the current system status, the sonar meets and exceeds the functional requirements. Most of the problems that AquaSense Systems encountered during the development of the sonar were due to not understanding the problem before attempting to solve it, and this is detailed thoroughly in the individual reflections. The only issue worth mentioning is noise, which we will proceed to detail briefly.

The problem of noise only manifested itself while we were evaluating the system in the water; the issue was absent during the air evaluation stage. Thus, when we finally moved to the water, we were initially perplexed with the results that we obtained – the results were extremely noisy, and even after a full week of debugging in the URL the noise issues could not be completely solved. Eventually, several conclusions were reached as to the contributing factors:

1. The system was designed to work for variable operating conditions. Because of this, the filters in the system were much wider than they would be for a dedicated system. As a result of this, the noise performance in our system suffered. However, we should stress here that this was acceptable to our client; this variability is inherent to the testbed and part of the functional specifications.
2. The tank of the URL is electrically noisy, and prone to electro-magnetic interference. One of the contributing factors to this was the long wires in the setup that connected our system to the underwater transducers which were loaned to us; these greatly increased the noise picked up by our sonar. For instance, depending on whether the RF communications lab was in use, the noise in our system would increase; we noticed that the noise in our system during the evenings when all the graduate students in the lab went home.
3. Our system, being a proof-of-concept, was developed on a breadboard, which is notorious for its high-frequency performance which is a vital to sonar applications.

The effect of this noise was to decrease our SNR and CDR beneath the acceptable margin. However, the issues above are not caused by any failure on the part of the members of

AquaSense Systems, they are externalities and limitations which must be dealt with outside the scope of our proof-of-concept system; future work is discussed in section 7.

4. ACTUAL AND ESTIMATED BUDGETS

The actual and estimated budgets are detailed below in Table 2:

Table 2: Actual and Estimated Budgets

Expenditure	**Estimated Cost ($)**	**Actual Cost ($)**
MCU Development Kit	100.00	0.00
Electronic Components – Sonar	100.00	155.00
Electronic Components – Research	150.00	440.00
Case	30.00	0.00
Contingencies	100.00	See Above
Total	500.00	595.00

As can be seen from the above table, there is much discrepancy in our actual and estimated budgets. The MCU development kit didn't end up as an expend because we were able to borrow an kit from another student. The case was deemed unnecessary this was merely a proof-of-concept, and also we were already over budget, having exhausted the allocated contingencies. This was because the components for the sonar cost $55.00 more than expected, while those for research cost $290.00 more than expected. Here we would emphasize again that the overall per-unit cost for the sonar is within the $300 target, and the gross underestimation is due to not understanding the problem before attempting to solve it, which is also the reason the research cost is far above its allocated budget; as one can see, the members of AquaSense Systems learned a rather expensive lesson. However, it would be better to learn this lesson now as opposed to on the job, where the consequences would have been much more dire. Unfortunately, the actual budget exceeds the funding received by our group; we have $300.00 from our client Dr. Bird, and an additional $50.00 from the ENSC department. This was because originally, our group presumed that this would be sufficient given that the microprocessor development kit had already been borrowed. The rest of the costs will be shouldered by the members of AquaSense Systems.

5. ACTUAL AND ESTIMATED TIMELINE AND GROUP DYNAMICS

During the initial stages of the project, we did not have enough knowledge to plan an accurate timeline. Nevertheless, we tried to roughly estimate our schedule; however, soon after starting the project, we realized that because of the unique interests and expertise of each group member, we would best achieve our goals by dividing the project into 3 segments, namely hardware design, MCU firmware, and GUI programming. Figure 4 shows a comparison of the planned and actual timelines below:

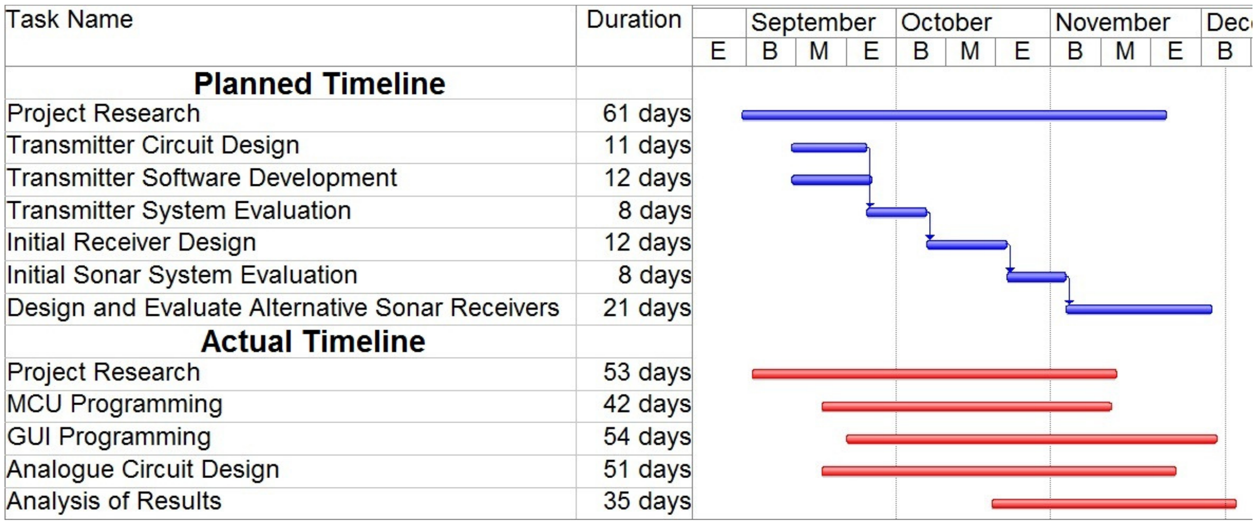

Figure 4: Comparison of Planned and Actual Timelines

As shown in Figure 4 our original timeline is rather linear. For example, we initially planned to all work on the transmitter circuit design, and then proceed to evaluate our system. The actual timeline reflects what actually happened during the course of our project, due to the aforementioned reasons.

While working on our individual parts of the project, we realized that we could potentially encounter many issues during the integration process if we worked in isolation. Therefore almost from the beginning of the project, our team members kept in close contact with each other. We realized that although each one of us was working on a different part of the project, working together would be more beneficial to us, because we could help each other and learn from one another. Eventually, our reasoning proved correct, and we experienced virtually no issues in integration. We also had a lot of fun working together and finally, by working together we learned the importance of accountability, openness, and teamwork.

6. INDIVIDUAL REFLECTIONS

6.1 HAMED

During the course of the past 4 month, I have learned microcontroller programming, C# programming, analogue circuit design and debugging. But most importantly I learned the value of teamwork and accountability. I found my desire for perfection sometimes causes some anguish for myself and group members. I also realized that one of the most important aspects of a successful group is the ability to have fun while committed to meet the deadlines and stay professional. Every time I encountered a problem, the first thought that crossed my mind was that the problem at hand is impossible to solve and our ENSC 440 project is doomed to fail. But then I found if I open my mind and try to fully comprehend the problem, no problem is impossible to solve. I learned to respect my team mate ideas while not giving up my own, and to open my mind to different ways to tackle the same issue. Working everyday for sixteen to eighteen hours for many days and nights I found myself exhausted and tired. Eventually I learned that sleeping and resting is as important as working hard towards achieving our goal.

I truly enjoyed working with my group members on this project. I learned a lot, but I wish ENSC 440 was a two semester course so I could learn and achieve more.

6.2 JOSEPH

I learned a lot from the mistakes I made in the course of this semester. I was the person primarily responsible for the hardware, which means that I made the decision to purchase just about everything. As alluded to earlier, many of the problems our group encountered were because we didn't take the time to adequately understand the problem before attempting to solve it. In my case, this involved failing to understanding the problem itself as well as the tools that would be applied to the problem. With regards to the former, a detailed understanding of the physical phenomena involved and a thorough mathematical analysis are essential; this is the entire point of what has been learned in the past several years – to apply what you've already learned – although I would also say that a willingness to continue to learn is essential (in fact, in applying what you've already learned there is a great deal of reviewing or "relearning" involved). This willingness to learn is particularly relevant in the case of the latter as well; without the detailed reading of the datasheets and manuals, one cannot expect to adequately understand the capabilities and limitations of the tools available. Thus, the main recommendation I have with respect to ENSC 440 and engineering in general is to be willing to pay the price to learn. Reflecting back, had I handled the problem with such a willingness, a lot of time and money could have been saved, and perhaps this project could have even evolved further (or we could have finished our work earlier and have more time to do other courses).

Another lesson I learned was how to work together as a team. In our group, Hamed played the role of devil's advocate, and I was not always that appreciative of the criticisms that he had with respect to my circuit. Also, the way Hamed operates is completely different from the way I do – he thinks outside the box, and at times his suggestions seem arbitrary; I am on the complete opposite of the spectrum – I don't want to try anything that doesn't seem to make immediate sense. We got into at least one argument, and almost a few others because of this; however, I recall numerous times where Hamed saved the day with the somewhat arbitrary suggestion, we solved the problem, and then upon solving it we realized the underlying issue. This leads to my other recommendation – be more open minded.

All in all, I had a great time. The members of AquaSense Systems are an extremely dedicated group of individuals and we had a lot of fun together. I also learned a lot about how sonar works, as well as the previously mentioned lessons that will be applicable to both my future work experience as well as to life in general.

6.3 KEN

Before taking ENSC 440, I heard a lot of rumors about the difficulties of this course, and thus I was somewhat apprehensive. Even so, I underestimated the level of the difficulties associated with this course, but luckily I found a team of hardworking engineering students who are very dedicated. I was surprised what my team achieved in this short time frame.

Despite the sleepless nights, my team was able to have some fun while we were working together. This is very important in a team environment, because it motivated us to work together during those rough times, so that we could finish this project on time.

One of the many challenges I had was to find the right parts to implement our designs. For the labs and projects I had done before, we were given the parts we needed in advance, and didn't have to find our own parts, and ensure they would work for a design.

I have also learned the importance of being patient; for example, if you get stuck and become frustrated you won't be able to think properly, which leads to you not getting anywhere. Be patient, go research, ask around for the answer, and you'll find the answer faster in less time. No design problem is simple.

In summary, I have learned to analysis datasheets, choose the right parts for applications, research effectively, build complex circuits neatly, interface hardware with software, and plan ahead. I would say I have learned more practical skills in this course than in any other course.

My overall experience in ENSC 440 is very meaningful to me. We have learned a lot throughout this semester, and we can go on to use this knowledge to our advantage in the work force.

6.4 LOGAN

Since this project began in September 2009, our group mates have been worked pretty closely with each other. I have never enjoyed working in a group as much as in this project. I think that the most unique characteristic of our group is that everyone is so motivated and hard working.

Although the tasks for different members were clearly divided according to our expertise, we have been working together closely throughout the semester. Besides having regular meetings on campus to discuss our progress and future work, we also usually go to the lab to work on our project after classes are over. Many times we planned to work for a set amount of time in the lab, but we ended up staying up in the lab until we had some breakthrough. This is the most dedicated group I have ever worked with.

Our group dynamics have been crucial to the success of our project. They bring together different approaches and opinions to solve the problems we encounter throughout the course of our project. I have learned to be objective and positive whenever new problems happen. In order to be objective, we must trust our group mates and also learn to be more open-minded. We respected others' ideas, were patient, and as a result developed corresponding methods to verify the best candidate solution.

Throughout the project, the GUI has been changed from time to time due to bottlenecks or new requirements from other areas of the project; this is because the GUI has to work together with the MCU and hardware. I also found that the way we expect a program to work may not necessarily be the way it actually works; thus sanity and unity test become the best way to expose the missing cases that we haven't considered, and to ensure the GUI works for all cases all the time. I have also learned a lot about the communication between microcontrollers and the GUI, how to handle fast speed data transmission, and how to plot real-time graphs. My programming and debugging skills have also definitely improved.

All in all, this 440 project is a challenging but rewarding experience for us that could not be gained from other courses. This project also made our team become better friends.

7. CONCLUSION

The project in its current state is more a proof-of-concept than a finished product. We believe that in the design of the AquaScan sonar, AquaSense Systems took a significant step towards creating an inexpensive, yet qualified sonar system that can be adopted by the masses. By extending our work to a six-channel sonar incorporating it with our client's patented MASB 3D sidescan sonar technology, we will be able to open the door to numerous applications in the civilian, military, and academic markets as detailed previously in section 1. The monetary, social, and education benefits of creating such a system are likewise many. With respect to the future direction of this project, the noise performance of our prototype can further be improved by creating a PCB, shielding the circuit from external interference, and narrowing the filter bandwidth to that of a specific transducer. Though this work is to be passed on and no longer remains in the hands of the members of AquaSense Systems, we are interested in the future direction of this project and would like to see what this would eventually manifest into.

8. REFERENCES

[1] F. le Chevalier, *Principles of Radar and Sonar Signal Processing*. Norwood, MA: Artech House Inc., 2002.

[2] O. Tetsuya, K. Kohji, and Y. Hirohiko, "Vehicle parking assist system and method." U.S. Patent 7 272 477, Sep. 7, 2006.

[3] N.C. Smoot, "Multi-beam sonar bathymetry and possible tectonic implications," in *The Journal of Geology*, vol. 91, no. 5, pp. 591-598, Sep. 1983.

[4] University of New Brunswick, "Geodesy and Geomatics Engineering," 2008, www.unb.ca /secretariat/Senate/documents/GGE_2009.doc.

[5] EMCellettronica, "DSP (digital signal processing) on FPGA - advantages and disadvantages," September 26, 2008, http://dev.emcelettronica.com/dsp-digital-signal-processing-fpga-advantages-and-disadvantages.

[6] G. Elamary, G. Chester and J. Neasham, "A simple digital VHDL QPSK modulator designed using CPLD/FPGAs for biomedical devices applications," in *World Congress on Engineering Conference,* Jul. 1-3, 2009.

[7] AquaSense Systems, "Functional specifications for a qualified sonar system for the masses." Canada, October 19, 2009.

[8] J. Bird (private communication), Oct. – Dec., 2009.

