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Ultrasound Boat-Monitoring System

Venice Canal Boat Traffic and Damage Monitoring System

A Major Qualifying Project Report:

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by

Alexander Gomperts

Joseph Lee

Yusuke Tanefusa

Date:

Approved:

Professor Peder C. Pedersen, Major Advisor

Professor Fabio Carrera, Co-Advisor

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Authorship

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Abstract

Boats are the primary means of transportation in Venice. It is believed that there is a direct correlation between the wakes produced by different boats and the deterioration of canal walls. Our project analyzes this relationship, using an ultrasound system to monitor and record a boat's velocity, wake height, and wake pressure on the canal walls.

1.0 Acknowledgements

For the past four terms, the ultrasound boat monitoring team had spent their time and strength, working on this project. Cooperation, Communication and Patience were the main powers pushing the group members to accomplish it. Now, the project is finally done. Firstly, we'd like to thank our advisors, Professor Peder Pedersen and Professor Fabio Carrera. They had given us many designing ideas to inspire our creativity, and provided much help and advice on our designs. Also, we'd like to thank all the members from ECE shop for supporting all the hardware needs of our system, the frame manufacturing in particular. It would be impossible to finish this hard work without them. This project had provided us with an excellent chance to test our ability and consistency and given us more confidence to face our future challenges. We really appreciate that so much.

Thank You.

2.0 Introduction

The city of Venice relies heavily on its canals and boats to provide transportation within the city. It is suspected that there is a correlation between the density and type of this boat traffic, and the damage to the canal walls. There is interest in studying this relationship and determining the extent of the correlation. Our system uses ultrasound to collect data on this boat traffic, such as boat type, velocity, wake and other information that can be used to explore this relationship.

This is essential, as currently the canals of Venice are being destroyed by many human factors including boat traffic. Because of this, the Venetian government is eager to find specifically, what the primary sources of the damage are so that the erosion of the canals may be curbed. Our system measures the forces that boats induce on the walls of the canal and serves as a tool to explore the relationship between the boats and the types of forces they induce. It is hopeful that with the information gathered by our system the Venetian government may enact better, more efficient policies to protect the canals.

3.0 Background

Before technical research began, investigation into the current situation and past projects was performed by our predecessors who began this project. This was done to help achieve a better understanding of the problem and to avoid any duplicate efforts. This chapter is a review of what the previous team found in their research as presented by them in their final project report¹.

3.1 Canals of Venice

The city of Venice is located in northeastern Italy, in the north of the Adriatic Sea. It is composed of over 100 different islands in the Lagoon of Venice. The only form of travel, besides walking, is by boat on canals that run between the islands. There are over 170 different Venetian canals, the biggest being The Grand Canal, which snakes its way through the center of the city (see map below²).

¹ Johnson *et al*, Ultrasound Boat-Monitoring System MQP, 2003

² Taken from Lonely Planet at <http://www.lonelyplanet.com/mapshells/europe/venice/venice.htm>



Figure 1: Map of Central Venice

The original Venetian boat is the gondola, however most Venetian residents use motorized waterbuses, called vaporetti, or their own private boats. There are four main types of boats: taxis, cargo boats, pleasure boats, and big taxis. These new motorized boats generate larger wakes than that of a traditional gondola. The canal walls must now sustain greater forces as the size of the incoming wakes grows larger.

The canals are constructed of two different types of materials, depending on location. In the wealthy sections of the city, the canal walls are made of a limestone called Istria, named after the location the stone is quarried from. Underneath this limestone is wood piling, supporting the wall in the earth. The top portion is made of brick. In the poor sections of the city, the walls are made of all brick, because it is

cheaper. The walls are still supported on the same wood piling. The canals are subjected to tidal activity, with a variance of ± 1 meter relative to normal sea level. The average current in the canals is approximately 30cm/s.

3.2 Current Situation

The current problem with the canal system in Venice has to do with the damage caused by boat traffic. Each boat moving in a canal causes disturbances in the water. These disturbances consist of energy in the form of visible wakes or invisible underwater turbulence. This energy can cause damage to the walls of the canals, necessitating repair on a regular basis. This repair is important, as the walls support many Venetian buildings. If they are not cared for, serious wall decay, eventually leading to collapse, can occur.

The only method currently available to monitor boat traffic is by counting boats manually. This involves having a person wait on the side of the canal, counting and classifying the boats as they pass. This is not a very effective or efficient procedure, as it is hard to watch a large number of canals for an extended period of time and tends to be costly.

The current mayor of Venice is in charge of the canal preservation project. This includes determining the cause of damage to the canal walls and implementing measures to minimize this damage. This will in turn reduce the amount of repairs that the canal walls need, as well as preserve the buildings that rest on them. Our project will help in collecting information in order to locate and manage the sources of this damage.

3.3 Completed Work

The previous group working on this MQP completed several tasks towards the construction of this system. As detailed above they have conducted thorough research into the demand for such a system as this and the reasons for it. Upon completing their research they began the design and implementation of their phase of the system. The group partially implemented their system and began testing in on a small scale using an in lab fish tank. They used this scaled down version as a test base, but this proved difficult as they ran into issues relating to the smaller environment and unfortunately spent more time adapting to the smaller environment than testing the system as it would relate to the real world environment. Unfortunately the previous group did not document their work well with respect to presentation of their work to the proceeding group (us), so much of the work they did went for naught. This is where there work ended and where we will pick up.

3.4 Reviews of Previous Research³

This section is an excerpt from last year's ultrasound boat monitoring MQP group's final project report. It provides a background of the work done previously that can be applied to our application.

3.4.1 Analysis of Sewer Holes & Canal Wall Damage in Venice, Italy

Under the advisory of Fabio Carrera, Natalie Mello, and David DiBiasio, WPI students David Chiu, Annand Jagannath, and Emily Nodine completed this

³ Johnson *et al*, Ultrasound Boat-Monitoring System MQP, 2003

Interdisciplinary Qualifying Project during the summer of 2002. This project worked to collect information on boat traffic and relate it to *moto ondosso*, which roughly translates to “wake impact”. They developed a *Moto Ondoso Index* (MOI) based on the energy released into the canal water from the wake of the boat. A greater MOI correlates to more damage being caused. The following table was taken from their report:

Segment	Boat Code	Payload	Summer MOI at 4 km/h	Winter MOI at 4 km/h	Summer MOI at 5km/h	Winter MOI at 5 km/h	Summer MOI at 20 km/h	Winter MOI at 20 km/h	Summer MOI at Avg km/h	Winter MOI at Avg km/h
ALBO	1	High	3.2	2.6	6.0	4.9	100.9	82.2	41.4	33.7
ALBO	1	Low	63.0	51.3	85.4	69.5	625.4	509.2	326.9	266.2
ALBO	1	Medium	10.1	8.2	13.9	11.3	97.6	79.5	29.8	24.3
ALBO	2	High	1.1	0.9	3.0	2.5	204.2	166.3	204.2	166.3
ALBO	2	Low	5.7	4.7	15.2	12.4	1021.2	831.6	968.8	788.9
ALBO	2	Medium	1.0	0.8	2.6	2.1	175.1	142.6	175.1	142.6

Table 1: Moto Ondoso Index

In this table, boat codes 1 and 2 refer to large and small cargo boats respectively, the payload column represents the cargo amounts in the boats measured, and the rest of the numbers represent the calculated MOI for different parameters. The MOI was calculated using the energy released and the wake height. ALBO refers to Rio de l’Aboro, the region of Venice where this data was taken. The MOI index was calculated for a number of regions in Venice. The team combined this data, and produced the following map:

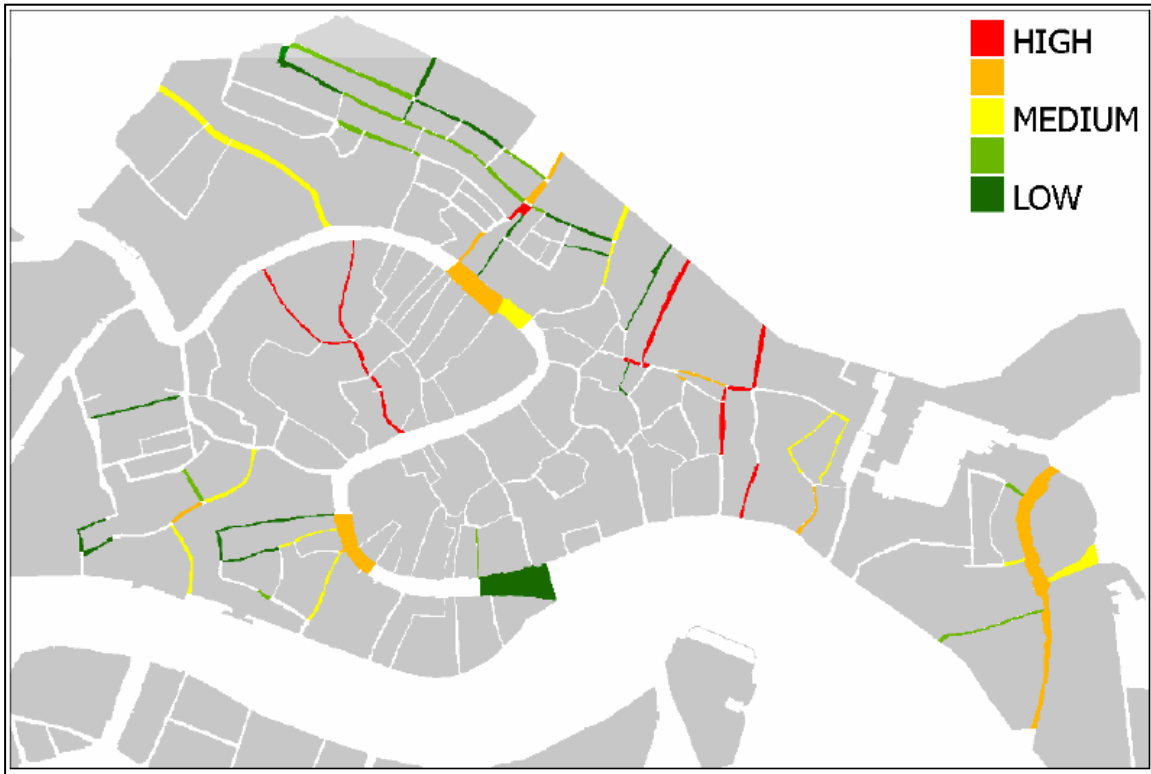


Figure 2: Base MOI for Regions Studied During the Summer

The color of the section correlates to the level of the MOI in that area. They divided the index into two seasons, winter and summer, because of the great fluctuations in traffic caused by tourism. The project gathered data about past traffic trends and projected traffic trends for the year 2007. When they applied the MOI calculation to this, they concluded that the MOI would continue to increase unless something is done. This will cause further canal damage.

They made a number of recommendations to help improve this. First, they concluded that excessive speeding was the primary cause of the wall deterioration.

Although speed limits were implemented in early 2002, only 3% of the motorists obeyed them⁴. Reducing damage meant enforcing stricter speed limits.

Another recommendation they made involved a cargo warehouse proposal. This cargo warehouse would serve as a central distribution center, eliminating 90% of cargo boat traffic, which would in turn reduce the total MOI of all boats in Venice by 68%. This would be a major reduction in canal damage.

Taxis had a very high MOI rating. The group recommended looking at ways to improve the efficiency of taxi routes using Global Positioning Satellite (GPS) and Geological Information System (GIS) to coordinate the shortest routes, routes with the least traffic to reduce congestion, and the fastest routes. In addition, taxis have restricted areas that are not adhered to. Enforcing this restriction would reduce the number of boats in the inner canals, reducing the MOI.



Figure 3: A Parked Venetian Taxi

The final recommendation they made to help reduce canal wall destruction was to improve traffic data. The traffic data they used in their report was incomplete, had gaps, and did not cover enough of Venice. This sets a strong foundation for this boat-monitoring project.

⁴ Moto Ondoso project

3.4.2 Remote Monitoring System

Another project done by WPI students in the past has been an attempt to create an automated traffic monitoring and wake data gathering system. The system was to monitor traffic at different sections of the canals, and measure the amount and level of wake generated by that traffic. Their systems comprised of three devices; a boat identification device, a boat-monitoring device and a wake-measuring device. The boat identification device used in this project made use of a radio signaling technology similar to the highway toll collection systems such as *EZ-Pass* and *FastLane*. The wake measuring device used a pressure sensor in a cylinder immersed into the water. The boat-monitoring device and the wake measuring device were to be installed together in different sections of the canals, and the boat identification devices were to be installed in individual boats in Venice. When a boat with the identification device installed passed through a section of the canal with the monitoring device, the monitoring device recognized the boat and measured the wake created. The collected information was recorded and made accessible for later analysis. The system was completed and functional. However, the city of Venice did not implement it for two reasons: installation difficulty and logistics of the boat identification device. The installation difficulty was on the calibration of the wake measurement system. The wake measurement system required some technical knowledge to install and configure at each installation location before it could gather any useful information. Because the boat-monitoring device was self-contained, installation was easy. However, the city of Venice decided they could not force the device to be installed on boats because it could potentially be used to track movement and issue penalty fines. This would cause a problem with the boat owners.

Currently, Venice has several stations in their canals that could house different equipment for measuring and monitoring the canal usage and its conditions. The stations are currently only equipped with a generic device that continuously monitors the water levels, but there is no system to monitor the traffic at the location.

3.4.3 Waterway Expert Traffic System

Research was done on existing designs of similar products in the market. Although the project team did not expect many findings from a market limited to canal boat-monitoring systems, the research has turned out one very similar product accomplishing the same goal as our project. The project was sponsored by Ocean Systems Development Corporation and was done by the Oceanographic Center at Nova Southeastern University. The aim of the project, named Waterway Expert Traffic System (WETS), was to develop and test new methods to monitor watercraft usage and Sea State in an urban canal. The system is capable of calculating speed, heading and distance of the boats and the calculated data is made available via the web along with the wakes and other monitored data. The monitor unit uses laser traffic counters and several wave sensors to obtain information on traffic. An array of monitoring units is used to obtain information for processing the information regarding the boat's speed, heading, and distance in a real-time manner. The data is recorded and made available through a website. Through the website, it is possible to query the database to look for certain boat traffic meeting different criterion as well as obtain statistical information of overall traffic. A CD-ROM report of the project is made available for free by the research institute and may become a great resource for the project although the project aims to use ultrasound technologies instead.

Although the WETS system provides much of the basic capabilities of our system, there is some lack of functionality for the use in Venice. WETS does not classify the boats automatically, which makes things harder for the researchers to analyze the obtained information. Also, some information such as pressures exerted to canal walls by the boat traffic is not measured or collected in WETS.

3.5 Project Goals⁵

The goal of this project is to develop a system to monitor boat traffic and the wakes generated. The system will log all boats passing a given point with time-stamps and record their type, speed, and the level of wake they leave behind. The data gathered will then be organized into one central database. This data will then be used to assess the sources of destructive wakes and formulate methods to minimize the destruction.

The system will use pulse-echo ultrasound measurements from two ultrasonic transducers to gather information about the boats passing through the canals. A signal-processing unit will interpret this data, and use it to determine the specific characteristics of the traffic at each point of the canal, and to quantify the character of the traffic. This includes type and size of the boat, speed of the boat, wake generated by the boat, and energy discharged to the canal wall by the boat. The signal processing unit is also responsible for rejecting any false echoes from debris and other false signals obtained through the ultrasound receiver. The information gathered will be transferred to a data collection unit. This will organize the data into a database accessible to the officials in charge of maintaining the canals in the form of a database viewable through a computer.

⁵ Johnson *et al*, Ultrasound Boat-Monitoring System MQP, 2003

Upon completion, the system created by this project will be useful for analyzing the traffic in the Venetian canals. This will greatly increase the information gathered about the canals. As mentioned earlier, the canals of Venice are now under direct control of the mayor, who will be in charge of taking any means necessary to improve the conditions of the canals. To assess the most effective measure to improve the canal's condition, and to reduce damage, the mayor and his committee will require a considerable amount of information. By installing the system created by this project, a lot of this data collection process will be automated. This will allow for a larger collection of more complete information. This will in turn help reduce canal damage.

3.6 *Why Use Ultrasound?*

During our work we and our advisors considered several different alternatives in the sensing portion of our system. The possibilities included devices like GPS or RF-ID tags. While these would be easy to implement as compared to ultrasound, they would pose a challenge in public acceptance. The population may suspect that the government would want to use the devices as trackers or to give out speeding tickets. Another option was to use video, but it quickly became clear that far too much processing would have to occur for us to get usable results. In the end we found ultrasound to be the best option we had. Ultrasound gives us a sensing method that is unobtrusive to the population and at the same time, it requires less processing than a method like video. Lastly, ultrasound has been used in underwater applications in the past and has had a successful track record.

4.0 Methodology

The following is a system block diagram of our system. It splits up the system into three logic blocks; echo acquisition, signal conditioning, and decision making. The diagram splits the system further into acoustic, analog, and digital systems and each of the individual components of the system. As seen in the diagram the system begins by retrieving an echo from the canal in the echo acquisition portion. The echo is then passed to the signal conditioning block where the echo is analyzed. Lastly, the analysis gets passed to the decision making block implemented in software that uses the analysis data to decide if the echoes represent a boat or not, and then derives the pertinent information like boat velocity, length, wake height, and wake pressure if it is in fact a boat.

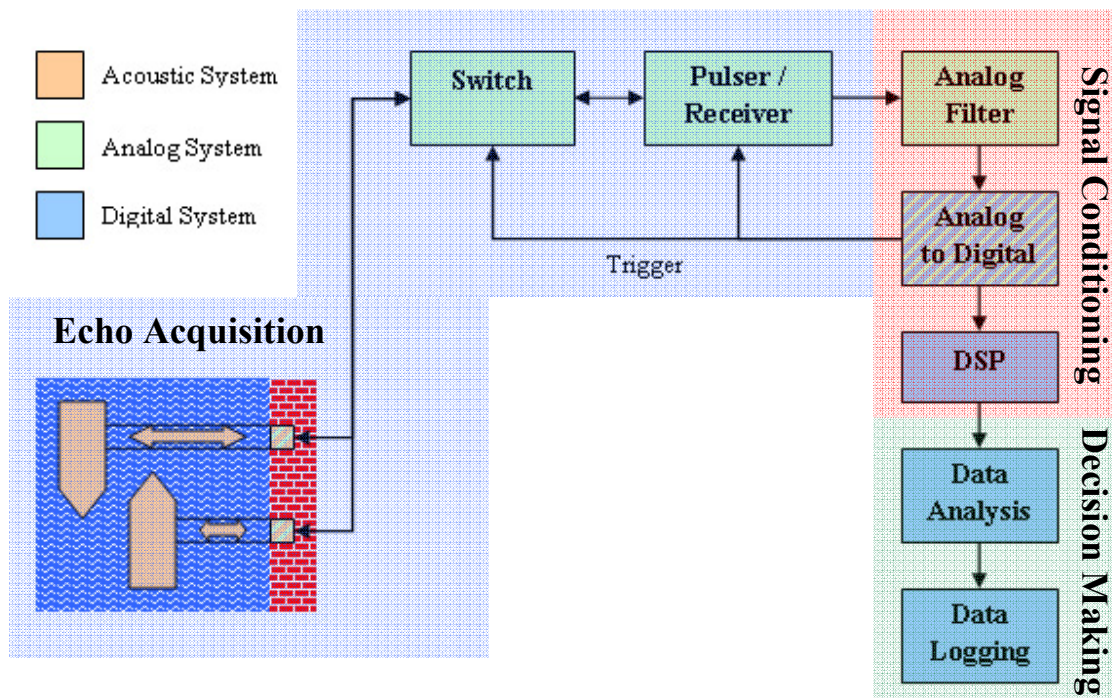


Figure 4: Functional System Block Diagram

The proceeding contents of the methodology chapter will cover the system's subsystems in greater detail. We will explain how the transducers and the rest of the echo acquisition block work together to acquire the signals that are passed through to the signal conditioning block. We will also analyze the tests we have performed on these systems and their integration. Next we will look at the signal conditioning block, following the process that an echo must undergo so that we may obtain usable information. And lastly we will explain how the system makes its decisions in the decision making block.

4.1 Echo Acquisition

As seen below in Figure 5, the echo acquisition block contains the entire acoustic system which includes the transducers, ultrasound waves, boat traffic, and canal debris. Also contained within this block is the portion of the analog system, used to drive the ultrasound transducers; the pulser / receiver and the switch. This block's end purpose is to pass to the signal conditioning block an echo representative of what is in the canal.

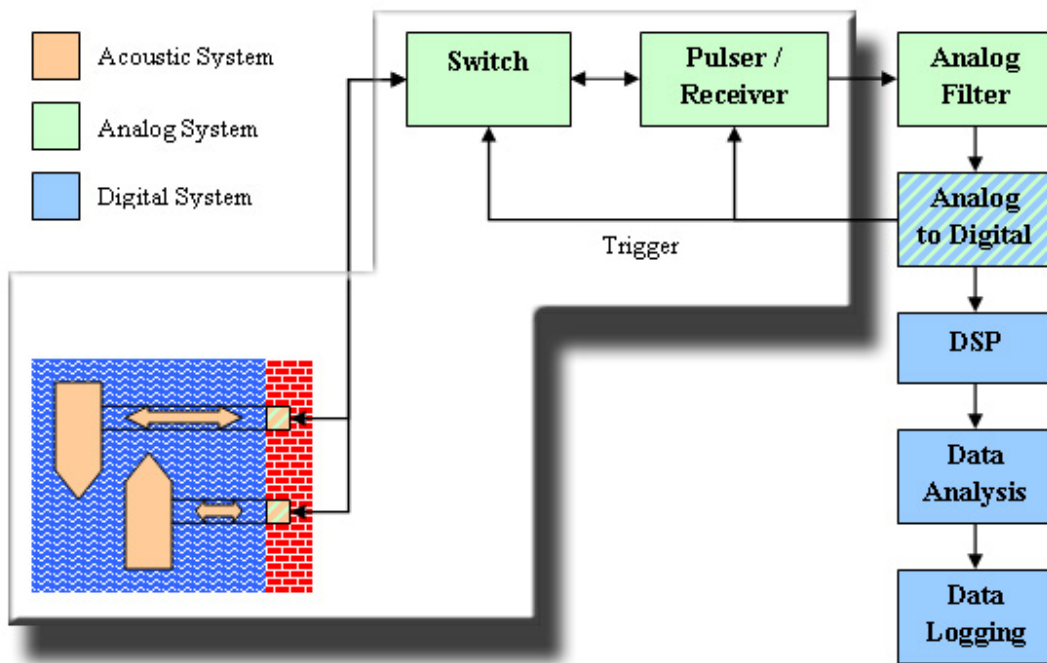


Figure 5: Echo Acquisition Block

To obtain an echo, the Pulser / Receiver (P/R) must first be triggered. In response to this trigger, the P/R will emit a short -200V pulse to the transducer and immediately switch to receive mode where it will wait for a returned echo from the transducer. This high voltage pulse is necessary to drive the ultrasound transducer. Now that it has been

driven, the transducer will convert the electric energy of the pulse into ultrasound energy, emitting a 500 kHz ultrasound pulse. After an amount of time related to the distance of the boat from the transducer, the transducer will receive a returned echo which it will pass back to the P/R which if set to, may apply a gain to the signal and then allow the signal to travel onward through to the rest of the system. Upon completion of this process the switch is triggered and the active transducer is switched. This process of signal acquisition is explained below in Figure 6.

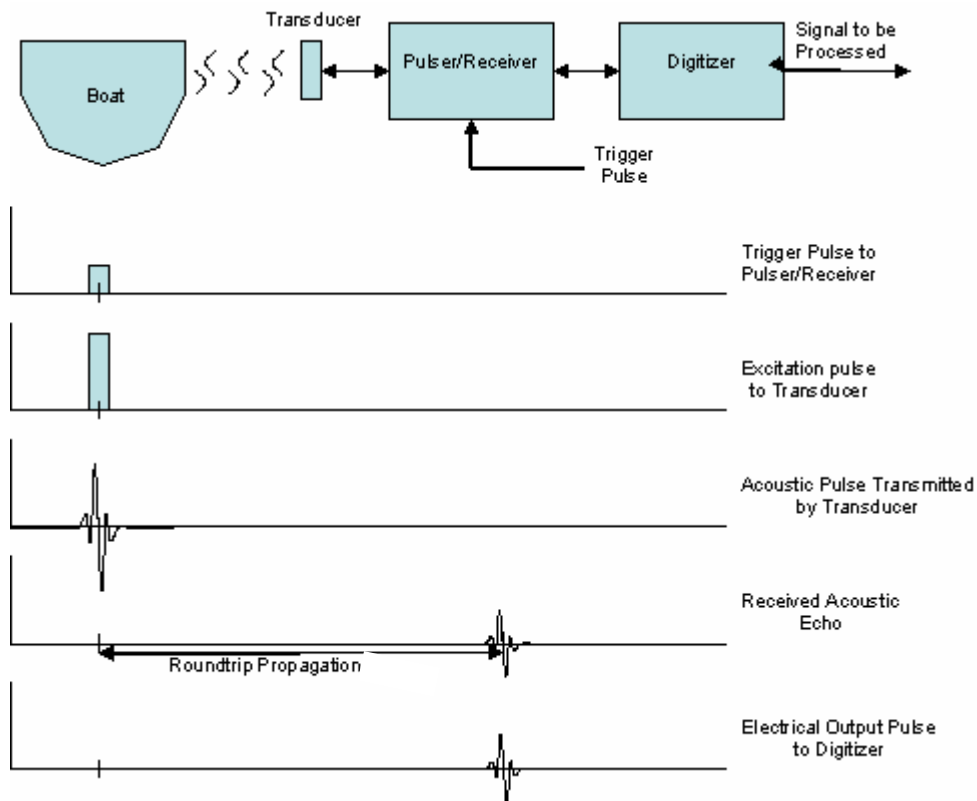


Figure 6: Signal Acquisition Process Diagram

4.1.1 Ultrasound

Ultrasound is a high frequency sound wave, which is reflected when it contacts an object. By gathering and analyzing numerous returned echoes we are able to derive the information that we need such as, distance and velocity of the object, as well as wake properties like height and pressure.

Basic Properties:

In order to produce ultrasound wave, we use a device called a transducer. A transducer is a component that converts an electrical impulse into another form of energy and vice-versa; in this case we convert between electricity and ultrasound energy. Ultrasonic transducers are frequently operated at their resonance frequency to maximize output power. The transducer is a passive device to which must be driven by our P/R. When the P/R emits its high voltage pulse which causes the transducer disk to move, which in turn creates a sound wave pulse much like a speaker would. The higher the voltage of the electrical pulse the shorter the duration ultrasound. The P/R then switches to receive mode where it will pass the electrical signals produced by the transducer when a sound wave impinges on it much like a microphone. These received echoes are then passed on to the signal conditioning block where they will be analyzed and processed.

When receiving echoes an ultrasound transducer produces electrical signals in response to incoming acoustic signals like a microphone does. However, a big difference between our transducer and a typical microphone is that the transducer is a microphone tuned specifically to receive high frequency sound waves. Because different materials have different acoustic properties the echoes vary in shape and amplitude between

surfaces. Therefore depending on the characteristics of the material in the ultrasound wave's path, the parameters of the reflected wave, such as the amplitude, energy, shape, or phase of the wave vary. These variations are used to aid us in the derivation of useful information such as the composition and shape of the impinging object. This information helps us to weed out stray objects that are not boats.

The Cons of Ultrasound:

In the ideal case, our ultrasound wave will be reflected perfectly from a somewhat rough perpendicular surface. However, in the real case, the hull of the boats may be rough or smooth and angled in different ways, so the receiver may not get the perfectly reflected signal. Therefore, we have to determine an angle for the transducer that will maximize signal return.

In general, a high frequency transducer will produce a compact beam and a lower frequency transducer will produce a beam that tends to have greater spread. This spreading can be influenced somewhat by the construction of the transducer's barrel, but is primarily dominated by the frequency of the wave. We would like the ultrasound wave to spread enough so that we can receive a readable echo from a rough or angled surface despite the fact that the majority of the echo would be reflected away from the receiver. Although, if we use too low of a frequency and cause the spread to be too great we run the risk of getting echoes that are too weak to be usable. The optimum frequency for our application can be found by simply varying the transducers from low to high frequency while monitoring the echo strengths being returned.

For getting maximum signal return, the transducer should be at a normal incidence to the surface being examined. Our transducer mounting frame currently allows for only minimal angle adjustments to achieve a normal incidence with the boat hull surface.

4.1.2 Transducers

Our transducers convert a pulse of electrical energy into an ultrasound pulse then act as a microphone returning any impinging ultrasound waves in an electrical form. The transducers we use emit 500 kHz ultrasound waves. This frequency strikes a fair balance for our application between the narrow cone, fast attenuating high frequencies and the high spread, slow attenuating low frequencies.

We use two transducers in the acoustic system in order to give the intelligent decision making block a better view of what is occurring in the canal and because more than one is necessary to calculate necessary data such as boat velocity and length. We chose to separate these two transducers by one meter since this distance offers simplification of the calculations and keeps the transducers far enough apart that they do not both pick up junk at the same time while still keeping them close enough that any boat will eventually be in front of both transducers at the same time. However, this separation is alterable in the frame and software for testing purposes in which the scale may be smaller.

4.1.3 Switch

Below in Figure 7 is a basic functional description of how the switching circuit works. The circuit receives a trigger from the analog to digital converter (ADC) located in the laptop. This trigger is sent to the J/K flip flop which causes the relay that was

previously on to turn off and the relay that was previously off to turn on. Once this has been done the P/R pulse has been routed to the appropriate active transducer.

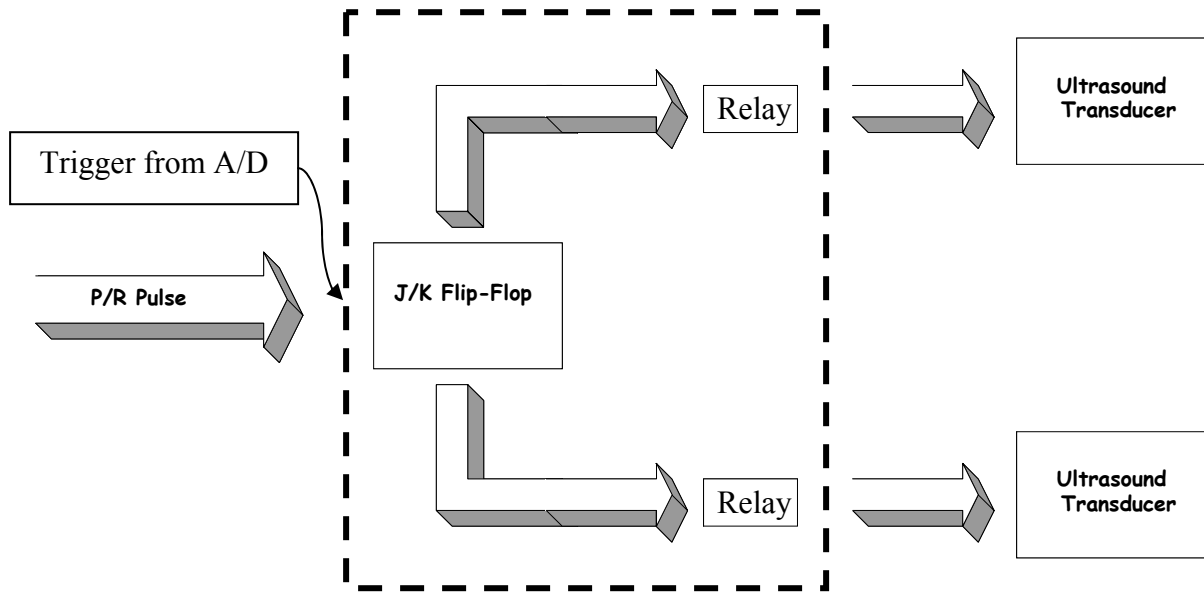


Figure 7: Switching Circuit Block Diagram

This circuit must open and close the relay switches such that the switches are never both closed. The toggling between switches will be controlled by a trigger produced by the analog to digital converter. Because relays are used within this circuit it is essential that we allow these mechanical devices time to settle in their respective states. This makes it important to have precise timing of the toggling and delays between toggling and pulse emission to send and receive useful signals to and from the transducers.

Relay Switch

Because we must transport the 200V P/R pulses we were unable to use a simple digital switch. Instead, we used a mechanical relay switch. As switches, these

components perform their function well with the exception that because they are electro-mechanical devices they require a nontrivial amount of time to switch and settle. This bouncing property is shown below in Figure 8. The effect of this characteristic is a relatively small slowing of the system's overall sampling rate and the addition of a trigger that takes into account the delay that the relays require. The relay's inherent characteristics also present us with another problem. That is that the TTL J/K flip-flop we are using can only source 0.4mA; not nearly the 27mA switching current required by the relay when it switches.

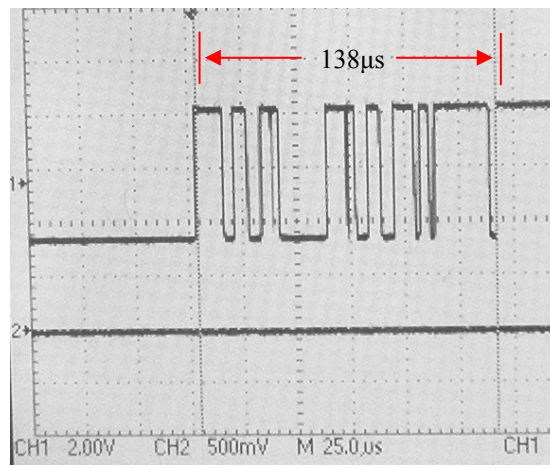


Figure 8: Relay Bouncing

Our solution is seen in the schematic below in Figure 9. To source the current required we connected a 5V source through a 100Ω resistor to the source of a transistor.

This gives us a $\frac{5V}{100\Omega} = 50mA$ source when the flip flop outputs a high; the 50mA is

more than sufficient to drive the relay now.

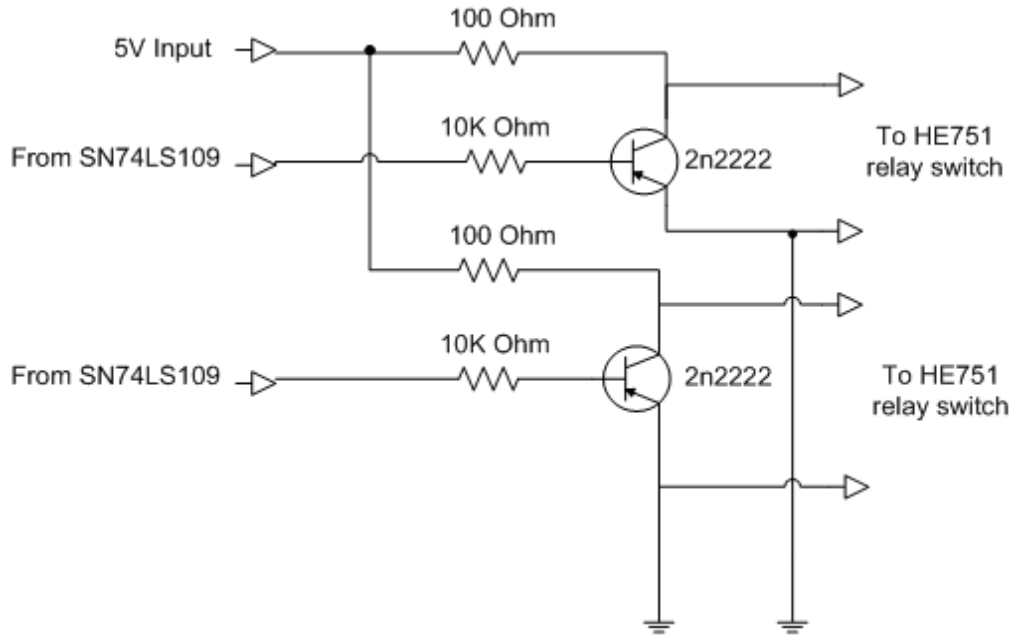


Figure 9: Signal Amplifier Schematic

Below in Figure 10 is the full switching circuit schematic. At every trigger pulse from the digitizer this circuit will switch the connection to the pulser / receiver from one transducer to the other without ever allowing both transducers to be connected at the same time.

The SN74LS109 IC is a J/K flip-flop. This IC will pass a logic high voltage (+5V) to either relay alternating between the relays each time the trigger appears. Because the J/K flip-flop is unable to source all the current needed to drive a relay we use transistors to provide current to the relays as discussed above.

These relays are the actual switches for our switching circuit. We cannot use a typical transistor or MOSFET switch because of the high voltage being sent through by the P/R. The disadvantage of using relays is that they are mechanical. This means that they are subject to far more wear and they introduce a substantial delay in the act of

switching the contact plate between contacts and the bouncing that occurs once contact has been made. Also, they sink a large amount of current when switching relative to digital circuits. This means we had to implement a current amplifier as an adapter between the digital and electro-mechanical devices. However, we must use these relays since they are our only means of switching between ultrasound transducers on a line that must conduct both large voltages and much smaller signals with minimal signal loss and distortion.

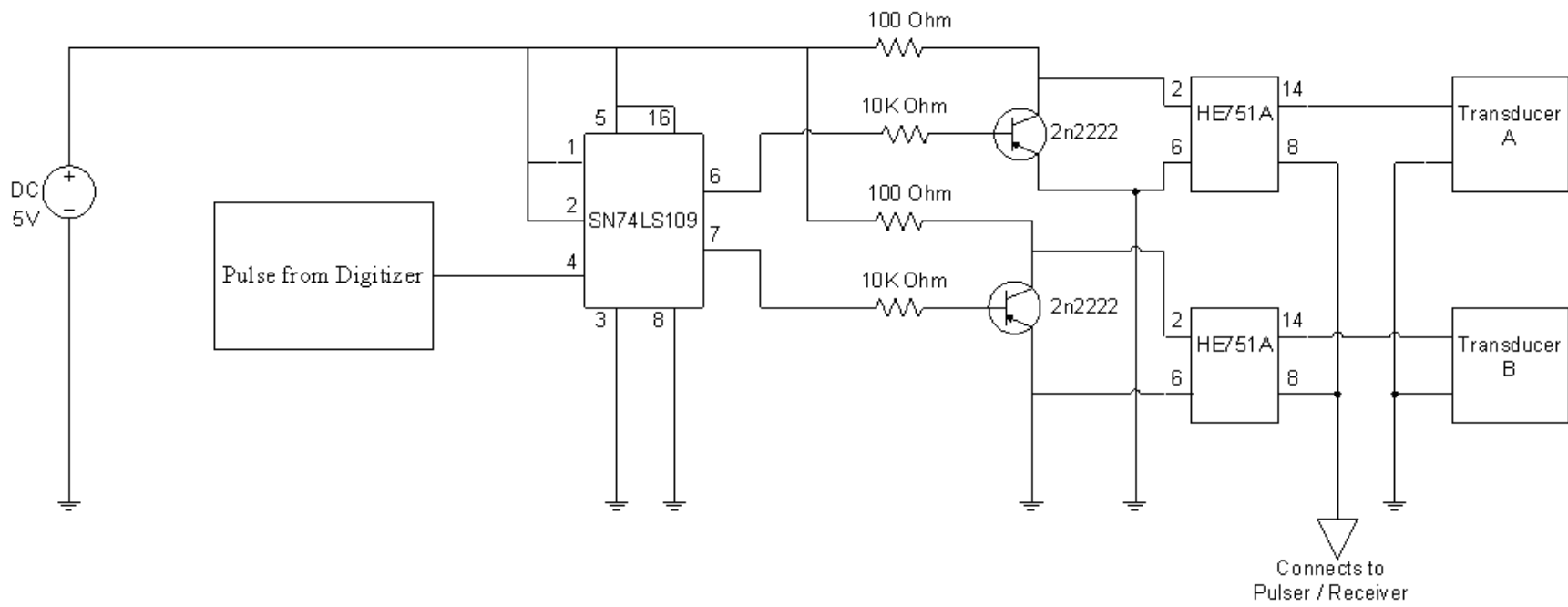


Figure 10: Switching Circuit Schematic

4.1.4 Pulse Generator / Receiver

The Pulse Generator / Receiver's function is found simply in its name. When triggered, this device will emit a -200V pulse for 2 μ s and then immediately switch to receive mode in which it will receive and pass relatively small signals to the bandpass filter. The P/R may also apply a gain to the output if needed. This device is necessary to provide power to the transducers so that they may emit a strong and brief ultrasound pulse. The device we use must be able to source enough power within a span of time on the order of microseconds to the transducers. Currently, we are using the Panametrics 5077PR square wave pulser / receiver which meets our needs for now. But more research needs to be conducted in order to find what component should be implemented in the final system since this component is not very portable and could prove impractical in the Venetian canal environment.

4.1.5 Triggers

The two system triggers are sent by the ADC. The first of these triggers is sent to the P/R causing it to emit its pulse. This occurs whenever the ADC begins a new acquisition of an echo. The second trigger is sent to the switch which causes the switch to switch the active transducer. This occurs whenever the ADC finishes an acquisition after $\frac{2w}{c}$ seconds where w is the canal width and c is the speed of ultrasound (~1500m/s). The next trigger to the P/R must then wait until the relays have settled. This delay has been implemented by simply allowing the software to perform its post processing during the switching, which in its best case takes approximately 30ms,

depending on the number of samples it must process. The best case processing time leaves more than a fair margin of time for the relays to switch and debounce since the worst case time for that to occur is about $200\mu\text{s}$.

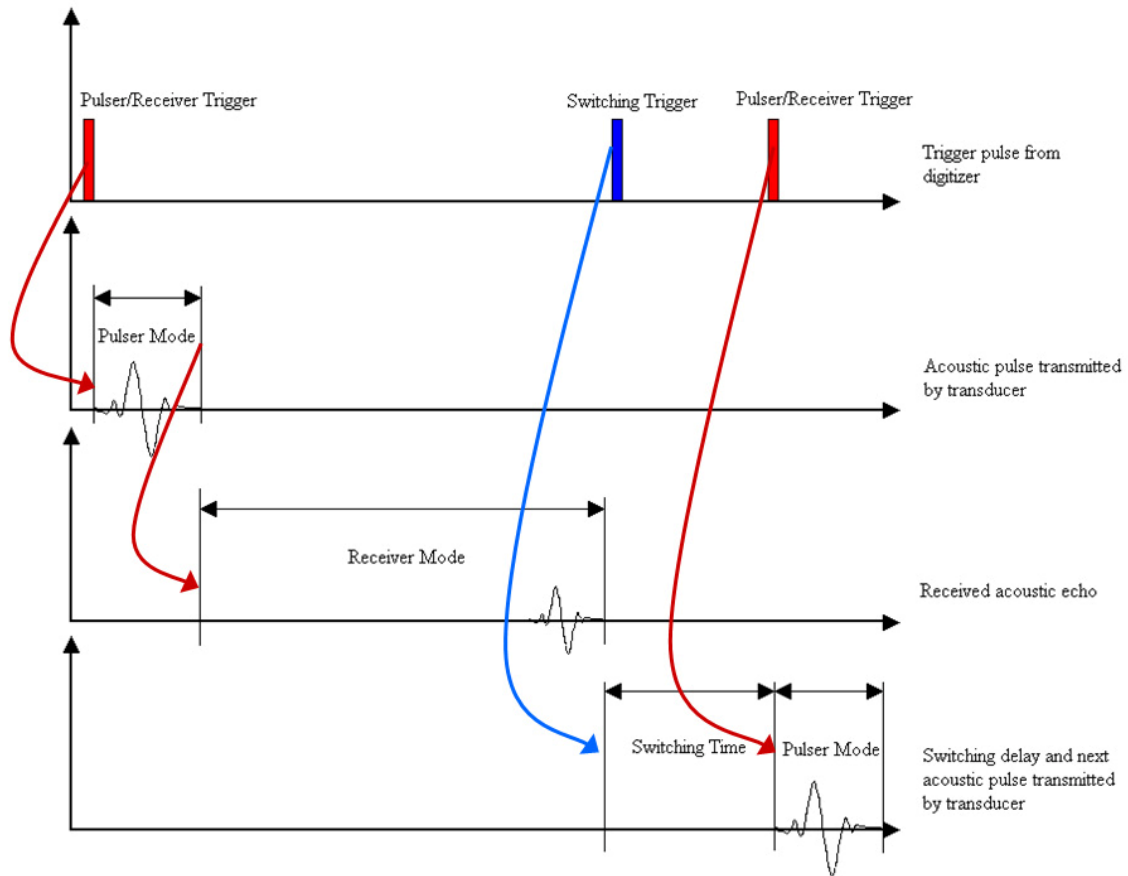


Figure 11: Trigger Sequence

4.2 Signal Conditioning

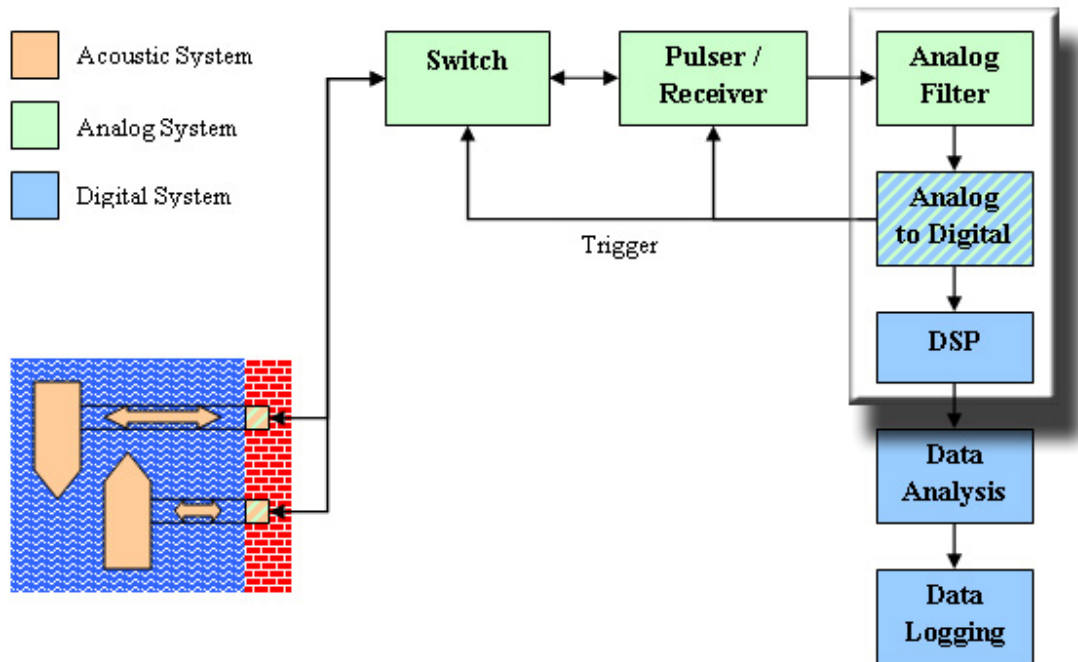


Figure 12: Signal Conditioning Block

The signal conditioning block takes the acquired echo as input. It then performs a series of signal conditioning steps designed to produce data helpful to the determination of what is and is not a boat. Once this data has been collected and organized in software, it is passed on to the decision making block. This block begins with an initial analog filter. The signal is then passed to the analog to digital converter (ADC) where it is converted to a discrete 8-bit digital representation. Lastly, the signal is processed in software before the resulting data is passed out of the signal conditioning block.

4.2.1 Analog Filter

When testing our system within a closed environment, we noticed a couple unwanted anomalies. The first was excessive noise which was not as apparent in the closed environment as it was in the pool. And, the second was the residual capacitance left by the -200V pulse sent by the P/R which drove the first several samples along a negative curve as seen in Figure 14.

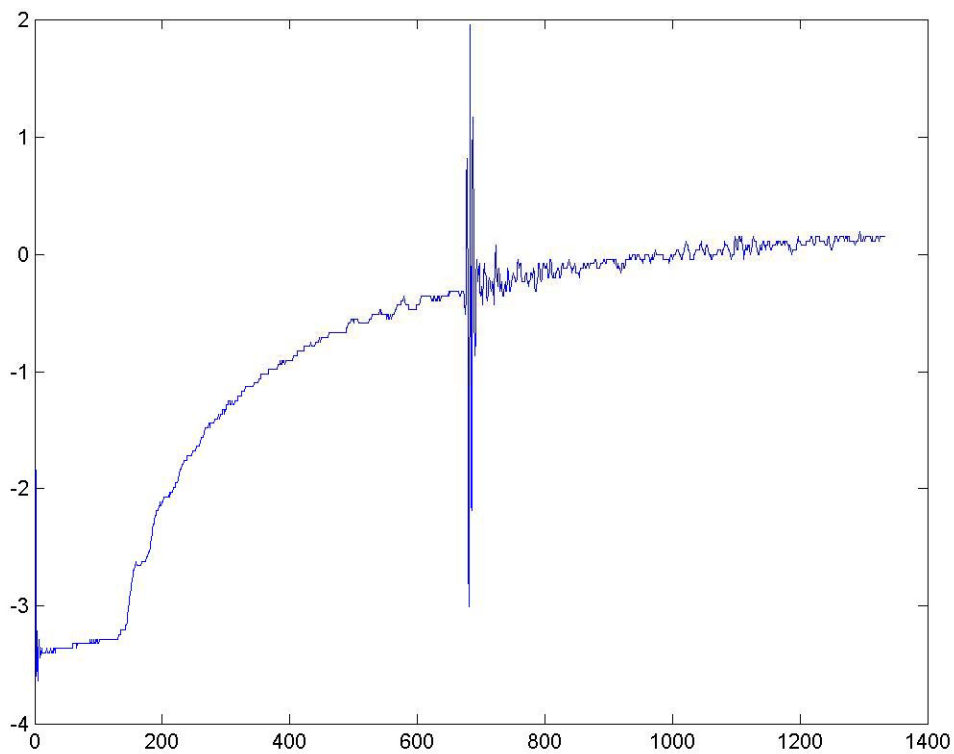


Figure 13: Before Band-Pass Filtering

Even though the system software is capable of processing the echoes; the band-pass filter is a faster more efficient approach in terms of system sampling rate and ease of implementation. Since our transducers are using 500 kHz signal wave, we made a passive

band-pass filter which has 500 kHz center frequency and a bandwidth of 300 kHz. We came up with couple different designs of band-pass filter including active band-pass filter, first order passive band-pass filter, and a second order band-pass filter. In the end we chose to use a first order passive band-pass filter since the active filter would have introduced excessive complexity to the circuit design and the second order passive filter proved to have an unstable center frequency, and because of its steep slope after the pass band it tended to severely attenuate frequencies that it should not. The first order band-pass filter turned out to be more stable and performed satisfactorily as you can see below in Figure 14. Figure 15 shows the resulting filter circuit.

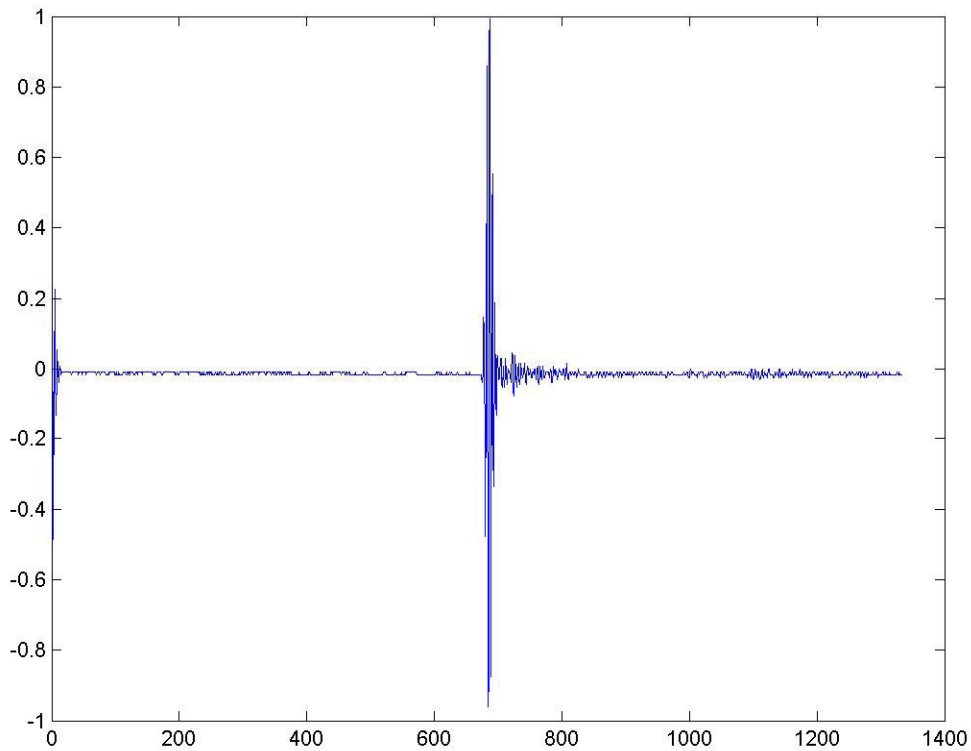
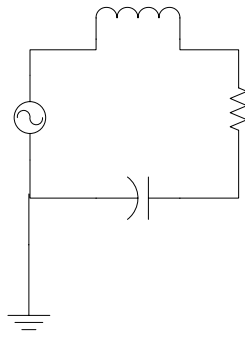


Figure 14: After Band-Pass Filtering



74 μH

Figure 15: 1st Order Passive Band-Pass Filter

Upon testing the filter we derived the proceeding frequency response plot. The ^{AC} plot shows that our center frequency is at about 500 kHz as desired with a wide, 300 kHz bandwidth.

1.1 nF

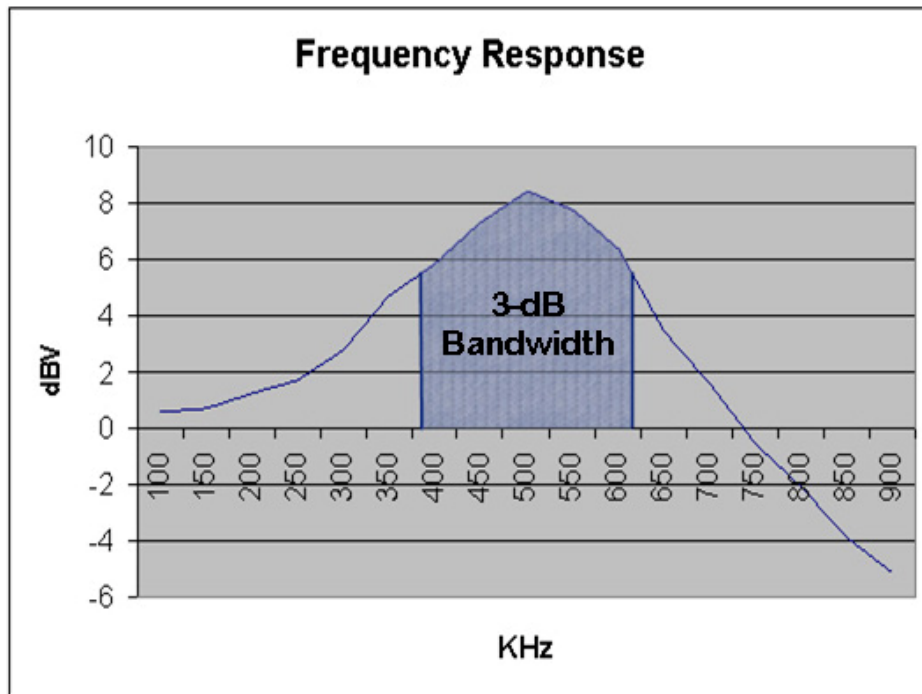


Figure 16: Frequency Response

4.2.2 Analog to Digital Converter

Our analog to digital converter is an 8-bit, 2-channel NI5102 PCMCIA digitizer card. This card simply plugs right into most laptops with accompanying software, making the system far more portable than the previous lab setup that had used a much more substantial device.

The ADC does exactly what its name implies; it converts analog signals into 8-bit digital representation. Using this ADC we may adjust the sampling rate from 1Hz up to 20MHz, we may also adjust the voltage range it will take in so that the 8-bits of resolution may be used optimally. Our system utilizes the ADC at 2MHz, doubling the Nyquist frequency for the echoes of 500kHz. This provided us with enough resolution to successfully process the signal while at the same time keeping the number of samples to process at a manageable level.

The ADC also serves as the trigger source of the rest of our circuit. It is capable of outputting a TTL level trigger output at the start and stop of signal acquisitions. This and other features of the National Instruments digitizer are controlled by its software interface on the laptop.

4.2.3 Digital Signal Processing (DSP)

The DSP portion of the system is implemented solely in software. It receives the echo from the band-pass filter and then applies several of its own filters to the signal before passing the newly filtered echo onto a decision making process. The first filter in this process is called matched filtering.

Matched Filtering

In order to determine whether returned echoes are those of a boat hull we need a way to analyze the signals we receive. Our primary method of single signal analysis is the use of cross-correlation. In essence, cross correlation process compares two signals and returns an amplitude that is related directly to the similarity of the two signals. In our application we will be comparing the returned echo we receive with a predetermined reference echo that is representative of a boat echo. For now, we will cross correlate each the received echoes with a single reference echo, but later on it may be necessary to add different references as different types of boat hulls may produce different echoes. We will now delve into the mathematical details of the function.

When using cross correlation, the echo and reference signals are divided into blocks. Each block in the echo signal is correlated with its corresponding block in the reference signal to produce the cross correlation as a function of time. The continuous cross correlation function is defined mathematically in Equations 1 and 2 below.

$$c_{fg}(x) = f(x) \star g^*(x) = \int_{-\infty}^{\infty} f(u)g^*(u - x)du$$

Equation 1: Cross Correlation

or

$$c_{fg}(x) = f(x) \star g^*(x) = \int_{-\infty}^{\infty} f(u + x)g^*(u)du$$

Equation 2: Cross Correlation

As seen above, the cross correlation function is similar to convolution. The difference between the two is that when performing a convolution one signal is first inverted along its x-axis. This operation is not performed in cross correlation. Thus, for two given signals the results of cross correlation and convolution will only be the same if the first signal is symmetrical along the x-axis (an even function). This function is implemented using the C interface of matlab. Examples of the effect of this function are seen below.

When the received echo is similar to the reference:

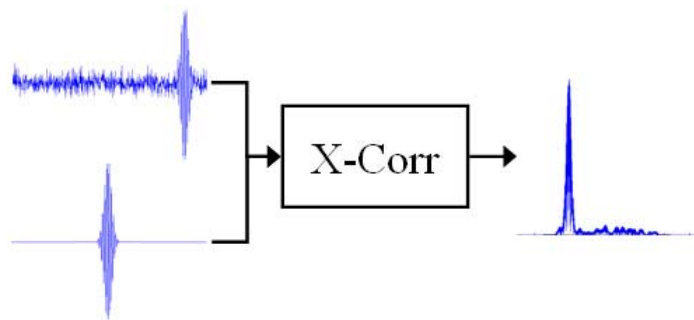


Figure 17: The Cross Correlation of Two Similar Echoes

When the received echo is dissimilar to the reference:

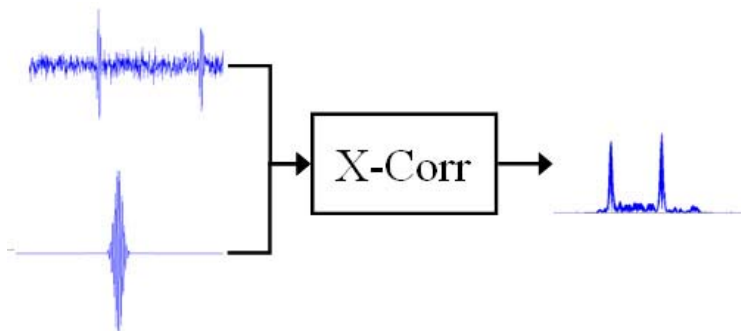


Figure 18: The Cross Correlation of Two Dissimilar Echoes

Attenuation Compensation

As the distance the echo must travel increases so does the amount of attenuation. This relationship between the distance and attenuation is described by Equation 3.

$$a = \frac{1}{d - NF}$$

Equation 3: Echo Attenuation

Where a is the percent attenuation, d is the distance traveled by the echo, and NF is the Near Field characteristic of the ultrasound transducer.

The near field of our transducer is approximately 10cm. In order to compensate for this attenuation, the software implements a smart signal amplification function by applying Equation 4 to the incoming signal.

$$echo[x] = echo[x](1 + \frac{x}{s}) \quad \text{For } x > NF(\frac{s}{w})$$

Equation 4: Attenuation Compensation

Where $echo[x]$ is the x^{th} sample of the incoming echo array, s is the number of samples, NF is the near field distance, and w is the canal width.

First Bang Removal

Whenever a transducer emits a signal it immediately returns a first bang back down the line to the rest of the system. This first bang is in actuality a strong echo appearing at the very start of an acquired echo. Since this is actually a 500 kHz

echo, the band-pass filter does not attenuate it leaving the job up to the DSP process lest the extraneous echo confuse the data analysis process.

To do this the DSP process simply sets the unwanted portion of the echo to 0V. The unwanted portion is determined by the minimum distance configuration setting that defines the smallest distance a boat is allowed to be from the transducer. This configuration setting's purpose is actually part of the reality check of the program in which it will toss unreasonable results (like a boat that is closer than 5cm). So this filter actually performs two functions; it removes the first bang as well as any echoes that appear too close to the transducers. Below you see an example of this function.

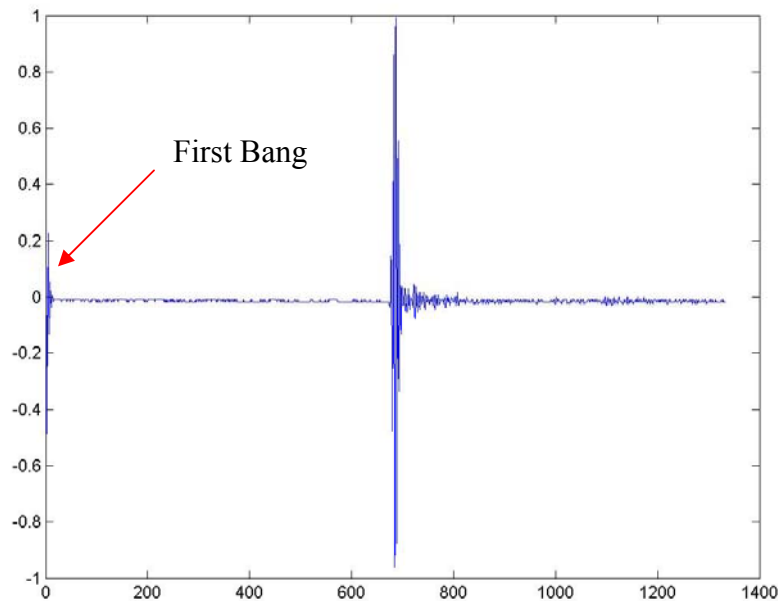


Figure 19: Echo without First Bang Removal

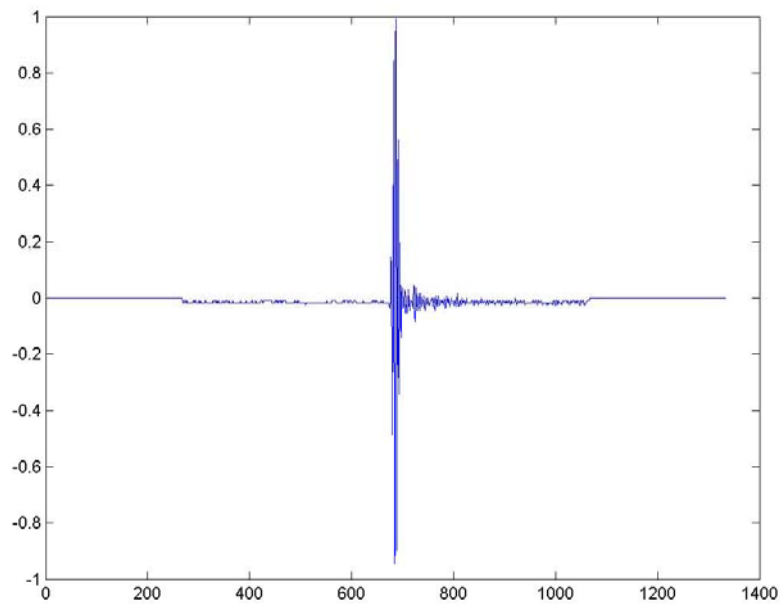


Figure 20: Echo with First Bang Removal

4.3 Decision Making

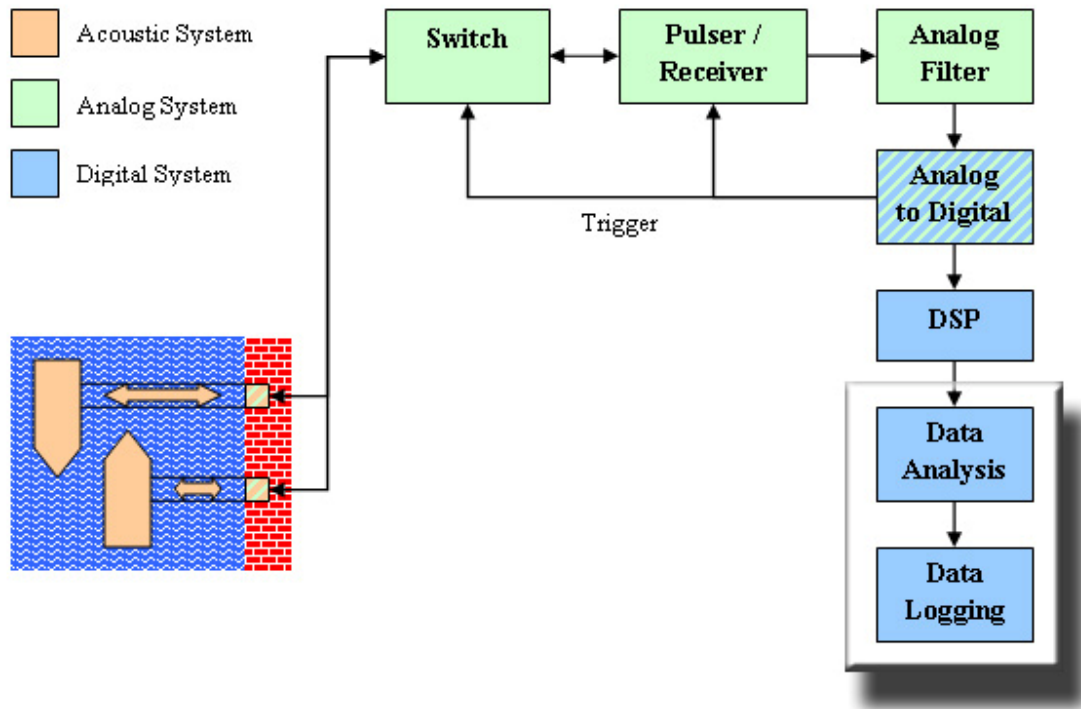


Figure 21: Decision Making

The Decision Making portion of the system uses the data taken from the signal conditioning block to make decisions pertinent to the system's goals. This block decides whether a series of echoes represents a boat or not, how fast the boat is moving, and the length of the boat. Once this information has all been derived it is passed on to a data log where all the boat and system information gets stored.

4.3.1 Data Analysis

In the data analysis portion of the system the software makes several calculations based on the data it is given from the previous block. This process will calculate an

object's velocity, length, and distance from the transducer. It will also make the decision as to what is a boat and what is not a boat.

Distance

The distance of an object from the transducer is easily calculated by multiplying the index of the highest amplitude sample in the echo by the distance per sample. This distance value is used not only in the reality check to rule out false positives, but also as a means of matching signals with boats in the water. The software sees objects in the water as distances, logging boats away after an object has not been seen at a specific distance for a period of time. It is necessary to relate these distances with a threshold since the boat may appear closer or further from the transducer as the hull shape changes in front of the transducer.

Length & Velocity

Using the data gathered previously, the length and velocity of a boat are calculated easily using equations 5 and 6. Figures 21 and 22 show what each value in the equations represents.

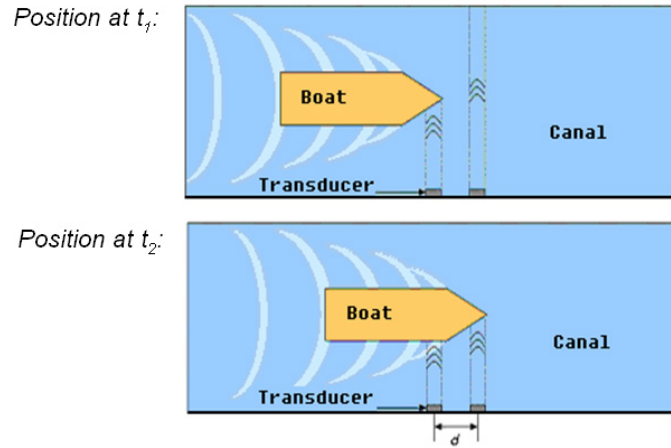


Figure 22: Velocity Calculation

$$v = d / \Delta t_v$$

Equation 5: Velocity

Where $d = 1\text{m}$ (distance between the transducers) and $\Delta t_v = t_2 - t_1$.

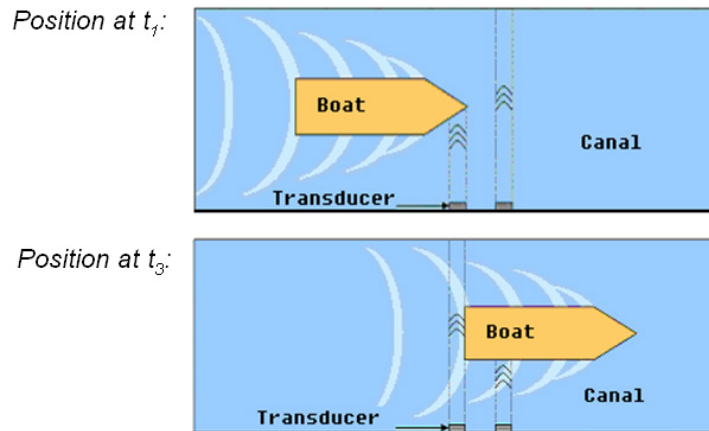


Figure 23: Length Calculation

$$l = \Delta t_l v$$

Equation 6: Length

Where $d = 1\text{m}$ (distance between the transducers) and $\Delta t_l = t_3 - t_1$.

Reality Check

Once the boat's length and velocity has been calculated, these values will be applied to the reality check portion of the decision making block. The reality check will either accept or reject the object based on the length and velocity calculations. If the boat is longer or shorter than a boat should be (for instance, >7 meters or <2 meters), then it is rejected; if the boat is faster or slower than a boat should be (for instance, >30 knots or <2 knots), then it is rejected. These criteria may be set within the software. If the boat passes these criteria, the boat's information is logged in the system's data log, otherwise the boat entry in the software is tossed.

4.3.2 Data Logging

With all the information we need collected, analyzed, and derived the last step is to store it all away and make it available to the people who need it. To do this we simply write out the pertinent data to a text log file on the laptop. The text holds the velocity, length, and passage time and date of the boat as well as the location of the system. Below you see an example of what a single entry in the log looks like.

```
-----  
Location ID:  'canal name'  
Date Stamp:   April 20, 2004  
Time Stamp:   13:45:00  
Velocity:     3.14159 m/s  
Length:       4.2 m  
-----
```

Figure 24: Boat Log Entry

5.0 Testing Procedure

We performed several unit tests in order to verify that each component of the system operates as we expect before we integrate it. Our first unit test was centered on the switching circuit. Next we then tested the band-pass filter. Once these two components were tested we performed an integration test of the system in the closed environment of a bucket of water. Lastly we will move our system into the pool to perform our full system testing.

5.1 Switching Circuit Testing

We connected one input to high (5V) and the other of each relay to ground, and sent trigger pulse to J/K flip-flop. By triggering the J/K flip-flop, the output of the two relays should each go from high to low and low to high while never allowing both relays to output high.

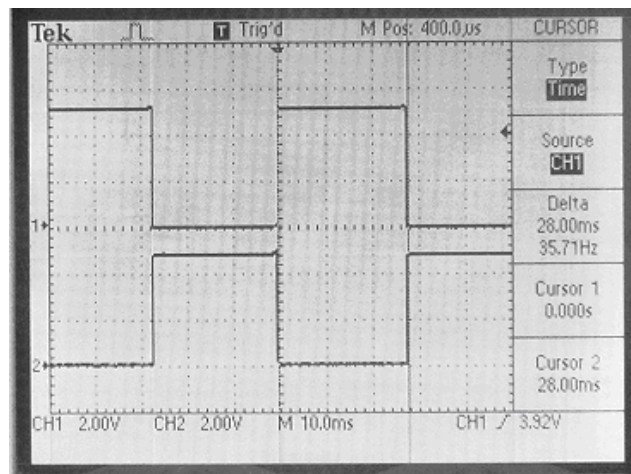


Figure 25: Waveform of Switching Relays

Instead of the software, we implemented a 4-bits binary counter to produce trigger for running the J/K flip-flop for testing. By calculation, there must be a separation of at

least 1.05ms between Trigger A and Trigger B for 2 relay switches. To do this we chose a clock frequency of 500Hz to provide the clock to our 4-bit counter which. This means that every binary count of the counter is worth 2ms (1/f). Using a 4-bit counter we will have 2^4 , or 16 counts per cycle. So each cycle will be 32ms. This is larger than the minimum cycle time of 28ms that we will calculate for you in the timing section. Using AND and NOR gates we set our circuit to output a trigger pulse when the counter reaches “0001” and “0010”. Thereby giving us 2 triggers separated by 2ms every 32ms. Figure 25 shows the schematic of our 4-bits counter with triggers A and B which are output to the P/R and switch circuit, and Figure 26 is the actual picture of our switching circuit.

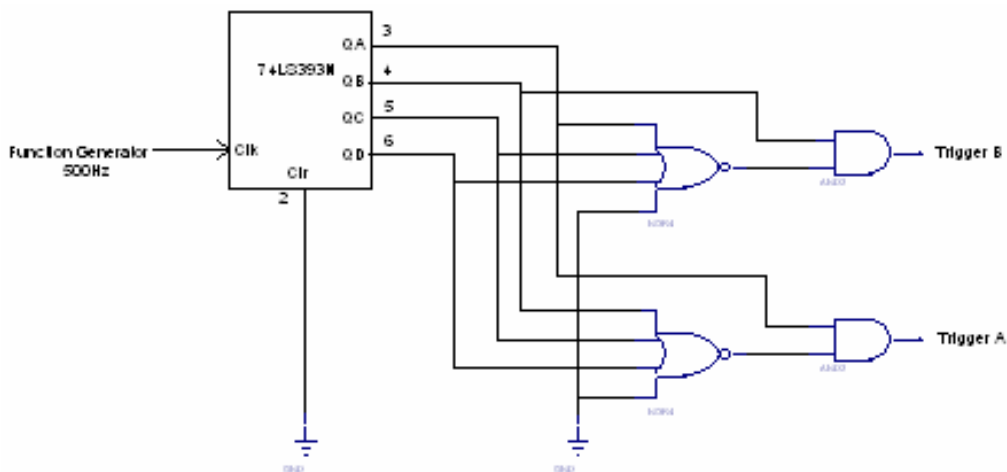


Figure 26: 4-bits counter for trigger generation.

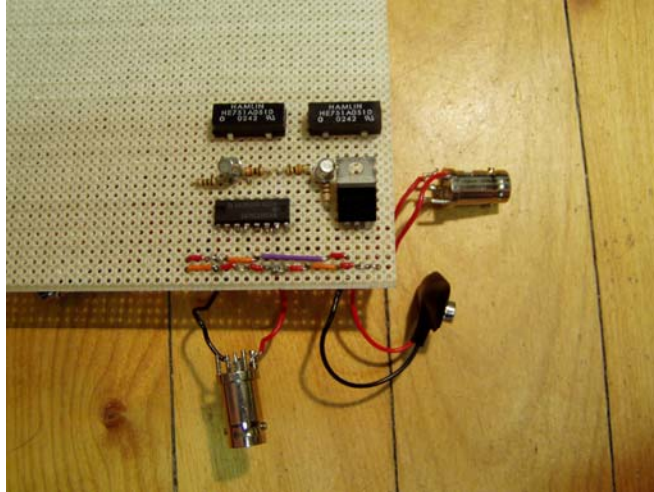


Figure 27: The Switching circuit (including 2 relay and JK flip-flop)

5.2 *Band-Pass Filter Testing*

Since our filter was designed to have center frequency 500 kHz and the bandwidth about 300 kHz, we used function generator to produce input signal from 100 kHz to 900 kHz and see if the attenuation started at about 500 kHz or not. Figure 27 shows the graph of frequency response, as we can see from the graph; the filter is given out the highest dBV at around 500 kHz. Figure 28 is the schematic of our 1st Order Passive Band-Pass Filter.

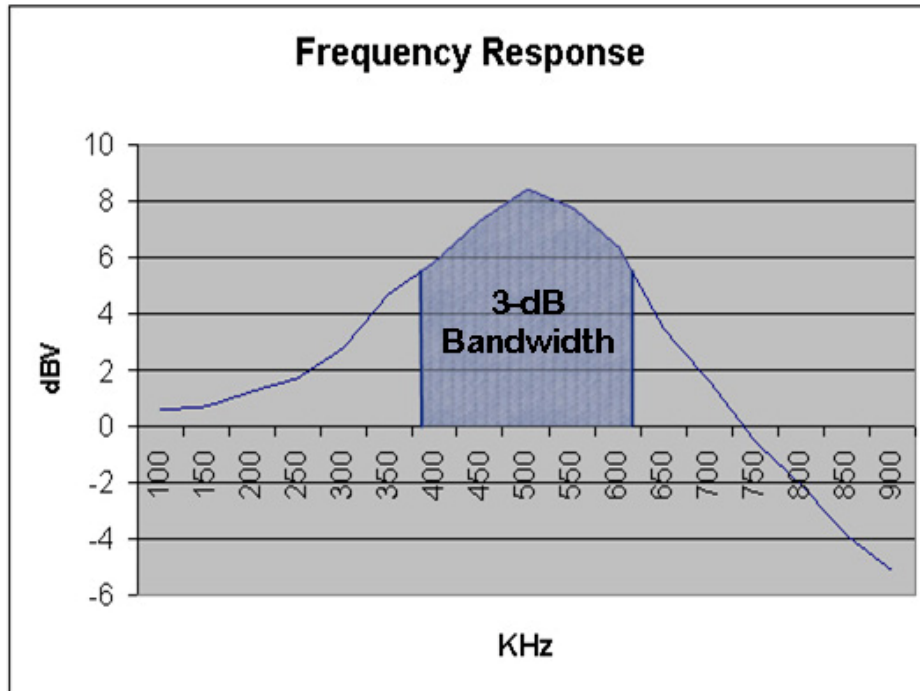


Figure 28: Frequency Response

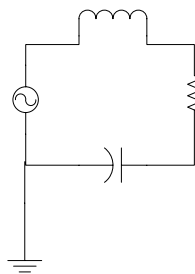


Figure 29: 1st Order Passive Band-Pass Filter.

5.3 Bucket Testing

After we got the switching circuit and filter testing done, we put them together and started the bucket test. First of all, we connected the transducers with 2 relay switches. Put them under water inside the bucket, and we can see the echoing signal by using oscilloscope. Figure 29 shows the testing result without clearing the initial noise, and Figure 30 showed the same signal but the initial signal was ignored.

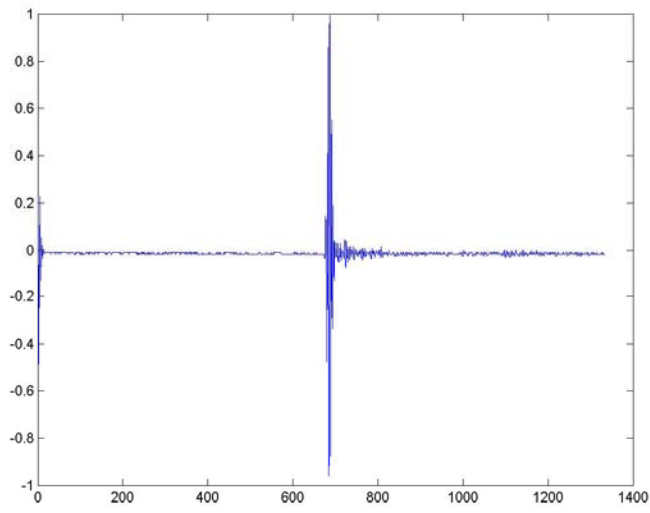


Figure 30: Bucket testing without zeroed start.

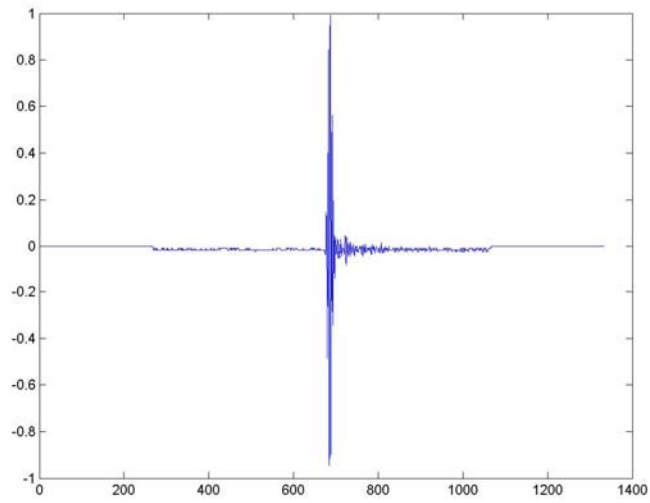


Figure 31: Bucket testing with zero start.

5.4 Pool Testing

The pool testing is the second phase of the project; we changed the location from the lab to the pool. For this part of testing, we had some additional units needed to test; such as, frame, software, and testing object.

5.4.1 RC Boat Object

Different from the lab testing, instead of only using the transducers, we used a RC boat to be our testing object in the pool. The RC boat has to have suitable length and speed; boat hull must sit low enough in the water to be detected consistently by the transducers.

If everything works perfectly, we can run the boat across the sensors at varying distances at relatively low speeds. Use a stopwatch to measure the time it takes for the boat to go from the start point to the end point. Record all system output. Compare the system's length calculation to the actual length. Calculate the boat's velocity and compare to the value returned by the system. Furthermore, beside the normal boat hull testing, we also use sand paper to create a rough boat hull surface to see if it does affect the result or not. However, this part hasn't been done until we can overcome the circuit errors in the pool

5.4.2 Sensor Mounting Frame

Before we test our system in the pool, we created a suitable frame for holding the transducers. Also we should adjust sensors height just to below water level to get the optimum testing result. Figure 31 is the actual picture of our metal frame, and Figure 32 showed the frame setup in the pool.



Figure 32: The frame for holding transducers

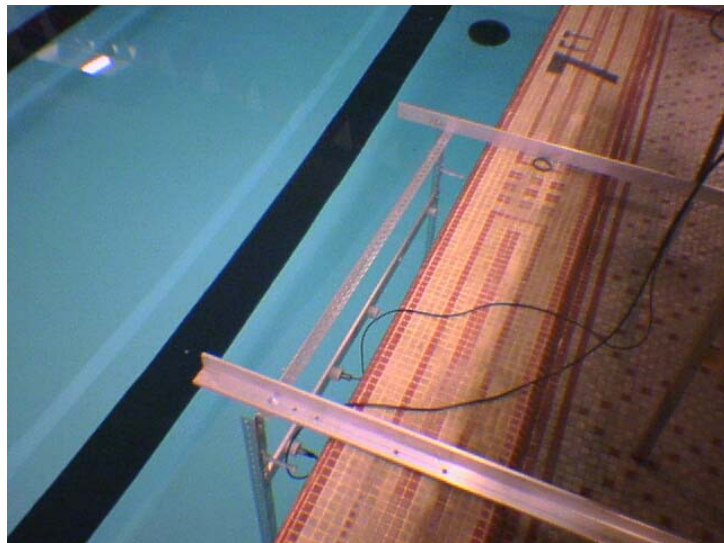


Figure 33: The frame setup in the pool

6.0 Conclusions

The status of this project did not come as far we had hoped. At the inception of this stage of the project we had expected to end the year with a functional pool setup of the system. However due to many delays and obstacles the system did not fully come together at the close of the project year.

What we do have is a working switching circuit and band-pass filter. But, because these two components were not completed in a satisfactory manner until days before the project close the software portion of the system never underwent tests that could measure its ability to recognize boats. This of course was very disappointing.

The next step in the completion of this system is to integrate the analog portions of the system with the software so that the boat detection algorithms can be evaluated. Once the system has been integrated, tested, and debugged we can move on to the next stage of implementation which will implement the project as an embedded system on the true Venice canal scale.

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