Sonar Obstacle Detection System for Underwater ROVs

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It is difficult for operators of remotely operated underwater vehicles (ROVs) to navigate through environments where visibility is partially or completely obstructed. One solution to this problem is to attach a video camera to the ROV, and stream video real-time to a computer or monitor on the surface. However, this type of setup can be expensive and cumbersome. This paper considers a simpler and potentially less expensive alternative to visual feedback: sonar. Active sonar, or sound navigation and ranging, uses one or more transducers to reflect sound waves off of potential obstacles in the water. Sonar systems can accurately determine the distance to an object, based on the time it takes for sound to travel to and from the object. Underwater sonar has been used commercially for many years, but there is a distinct lack of inexpensive commercially available underwater sonar systems for small-scale applications. In this experiment, a single ultrasonic transducer was purchased and waterproofed to provide the desired solution. The sensor was tested underwater and was found to be capable of reporting (through the use of colored LEDs) the relative proximity of underwater obstacles to an ROV operator.

Introduction

Researchers use remotely operated underwater vehicles (ROVs) to explore and take measurements in a wide variety of situations. In many locations, such as in lakes or ponds, or at large depths, visibility of the ROV can become severely limited. In these conditions, an ROV operator may be unable to see exactly where the ROV is located, and/or unable to clearly determine a safe path of travel. A forward-facing sonar sensor, mounted on the ROV frame, will help the ROV operator navigate more smoothly through environments with limited visibility.

Sonar, or sound navigation and ranging, uses sound waves traveling through a known medium (this medium is water in the present case) to determine the distance to other objects. Sonar is achieved through the use of transducers, which convert electrical energy (an electrical signal or voltage) to mechanical energy (in this case, a sound wave) and vice versa. A periodic electrical signal causes the transducer to send out a packet of sound waves, known as a ping. When the echoes that reflect off of objects in the path of the sound wave return to the transducer, the vibration of the transducer is converted back into an electrical signal, which can be used to determine the distance to the object. **Figure 1** below illustrates the propagation of sound waves away from and toward a transducer.

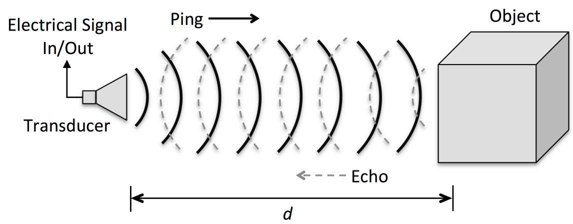

Figure 1 – Propagation of sound waves emitted by a transducer (ping), and reflected off of an object (echo) located at some distance *d* from the transducer.

The time that elapses between the ping and the detection of an echo is related to the distance to an object by the following equation:

$$2d = v_{sound} * t$$

Where d is the distance to the object, v_{sound} is the velocity of sound in water, and t is the elapsed time. It is important to note that the time lapse actually represents the time to travel to and from the object (twice the distance to the object).

The design of a robust sonar system involves many different considerations. These include several of the difficulties inherent in the physics of sonar, such as: sound wave attenuation, temperature gradients, background noise, instrument sensitivity, and many others. Special care must be taken to ensure that the resonant frequency of the transmitting and receiving transducers allows for sufficient wave travel distance, while also remaining minimally susceptible to interference from background noise sources.

Higher frequency sonar devices allow for higher resolution in distance measurements, however, the higher frequency signals also attenuate much more quickly than lower frequency signals [1]. Frequencies in the 30 kHz – 500 kHz range have been used successfully for decades, measuring distances well over 1 km [2]. This means that, for this application, where the distance being measured is on the order of 1 - 10 m, transducer frequency, as long as it is below 500 kHz, is not a limiting factor.

Because of the complexity of sonar systems, purchasing complete sonar solutions can become very expensive. The sensors themselves account for only a small portion of the total cost, the bulk of the cost is likely to support the development of the complex electrical circuits that generate and condition the transducers' electrical signals. These complex circuits may be replicated by an ambitious student or researcher, but require in-depth knowledge of electrical engineering concepts, and debugging them typically requires the use of oscilloscopes and other expensive instruments.

For this project, a compact sonar system was developed that is simple, robust, and comparatively inexpensive. This system can be assembled and tested without the use of expensive electronic equipment. The sensor itself can be mounted on the front of an ROV to determine the distance to nearby objects. The relative distance to these objects is conveyed to the ROV operator through the use of several LEDs. A green, yellow and red LED light up alternately as the ROV approaches an obstacle in the water. These LED indicators will provide the ROV operator ample time to notice and respond to obstacles in the water.

Methodology

After investigating several commercially available ultrasonic transducers, the MB7062 weatherproof sensor manufactured by MaxBotix, Inc. was selected for this application. The MB7062 consists of a single ultrasonic transducer (with a center frequency of 42 kHz), with a PVC housing. The PVC housing has an IP67 protection rating, which means that it can be submerged in water up to a depth of one meter for 30 minutes without being damaged [3].

This particular model has a cone-shaped housing around the transducer, which works to concentrate and direct the acoustic power of the system, and also helps reduce the amount of interference from other signals or noise [4].

The circuit diagram for the MB7062 can be found in the datasheet provided by MaxBotix, Inc. [5] and is included below in **Figure 2** for reference. The circuit is designed to work off of a low voltage power source (3.0 V - 5.5 V). The circuit generates a 42 kHz signal that drives the transducer, and has several LM324 operational amplifiers, which amplify and filter the signal coming back from the transducer. The sensor reports the distance via the output pins in three different ways: pulse width modulation (PWM), RS232 serial communication, and analog voltage.

The PWM pin outputs a square wave, where the duration in microseconds of the high voltage portion of the wave corresponds directly to the time between ping and echo detection. The RS232 pin outputs standardized serial text with a three-digit representation of the distance in centimeters (see the datasheet for further details). The analog pin outputs a “voltage with a scaling factor of (Vcc/1024) per cm.”

The analog output was used in this experiment, because the value reported on this pin is designed to filter out invalid distance readings that result from noise. The ping/echo/calculate/transmit cycle takes about 100 ms, and thus the device is limited to a maximum of about 10 measurements per second.

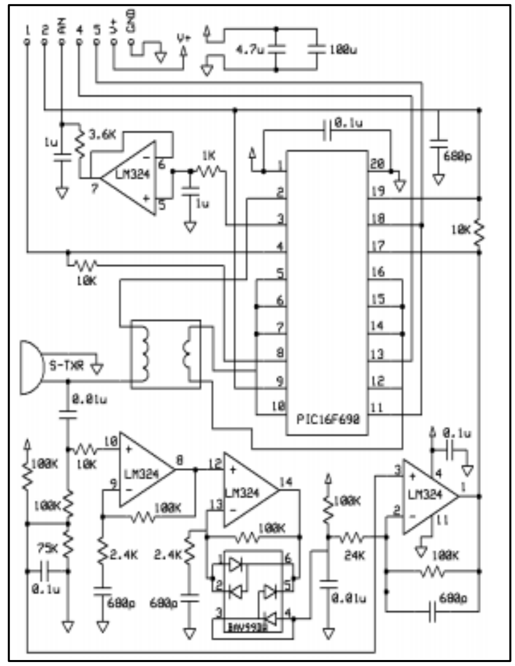

Figure 2 – MB7062 circuit diagram. Several LM324 operational amplifiers are used to filter and amplify the signal received from the transducer.
Source: http://www.maxbotix.com

Because the MB7062, like most other inexpensive sound transducers, is designed for use in air, it had to be completely waterproofed. A small bead of RTV silicone was applied around the outside perimeter of the transducer (to prevent water from flowing through to the electrical circuitry). A flexible silicone was used so that the vibration of the transducer was not inhibited. A harder silicone or epoxy would have firmly bonded the transducer to its PVC housing, which would have caused the transducer to stop working entirely. The wire connections on the back of the sensor were also covered completely with several layers of waterproof liquid electrical tape (see **Appendix A** for product details).

An Arduino Uno microcontroller was used to communicate with and supply power to the ultrasonic sensor. The Arduino microcontroller was selected because it is portable, and the Arduino programming language is simple enough that it can be learned and implemented quickly. The

Arduino program that was used for this project is included in **Appendix B**.

Each of the seven pins on the back of the MB7062 was soldered to a separate wire on an Ethernet cable that matches the length of the ROV tether cable (50 feet). An RJ45 keystone jack was used to break out the wire connections on the male end of the Ethernet cable and connect into the Arduino board. The V+, GND and Analog pins on the MB7062 were connected to the 5V, GND and A0 pins respectively on the Arduino Uno board (see **Figure 3** below for the complete wiring schematic).

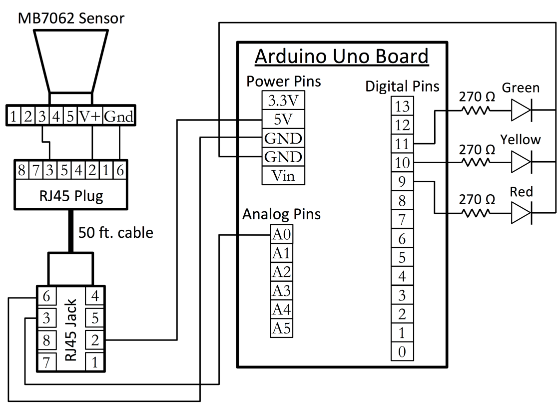

Figure 3 – Wiring schematic to connect the MaxBotix MB7062 ultrasonic sensor to the Arduino Uno microcontroller (with 3 LED indicators).

Sonar systems can be made with a single transducer that acts as both the transmitter and the receiver, or they can be made of multiple transducers working together. When using a single transducer, as is the case with the MB7062, the minimum detectable distance is increased, because it takes a noticeable amount of time for the transducer to transition from transmitter to receiver. If an object is close enough to the transducer, the emitted sound waves can reflect off of the object and return to the transducer before it is ready to detect the echo. This problem is amplified underwater, because the sound waves from the transducer travel a much larger distance in the same amount of time. (This is because sound travels more than 4 times faster in water than in air.)

Testing

In order to test the sonar device, a submersible measuring system was designed and constructed out of ¾" PVC pipe to be used in a swimming pool. The system consists of a base pipe with marked distances, and a holder for the sensor. The base was made with three five-foot lengths of PVC pipe that were connected by slip-slip couplers. Strips of black electrical tape were carefully wrapped around the PVC in one-foot increments, starting at five feet from the end of the pipe, all the way up to 13 feet from the end of the pipe. A 6" piece of PVC was attached perpendicularly to the end of the base pipe so that when the base was pressed against the edge of the pool, the sensor was pointed directly at the edge of the pool, and not off at an angle.

A piece of ¾" PVC pipe was attached to the built-in threading on the back of the sensor. This pipe was connected perpendicularly to another piece of PVC that snapped onto the 15-foot PVC base described above. Using the bands of electrical tape as reference points, the sensor-holder was snapped onto the PVC base, and 50 measurements were recorded at each of the marked increments on the base.

The Arduino code that was used to collect the data included threshold distances that determined which color of LED to turn on for any reported distance. For this test, a reported distance greater than 10 feet was programmed to turn on the green LED, a reported distance between 6 and 10 feet was programmed to turn on the yellow LED, and a reported distance less than 6 feet was programmed to turn on the red LED.

The distances measured by the sonar sensor were output on the Arduino serial port and captured using the built-in serial monitor in the Arduino IDE. The data for each distance measurement was stored in a text file, and then loaded, analyzed and plotted in Matlab.

Calibration

The measurements from the MB7062 sensor require an initial calibration to account for several variables in the system, including: the speed of sound in water, and the actual timing of the built-in circuitry. Because the speed of sound in water is influenced by so many variables, it is difficult to determine its exact value without special equipment. Also, due to some potential error in the circuitry of the MB7062, it is likely that the distances reported by the sensor need some adjustment.

In order to calibrate the device, several data points were collected at varying distances. As expected, the reported distances were offset from the actual values. The offsets from all of the data points were averaged to determine a scaling factor that would shift the average reported distances as close to the actual distances as possible. Once this factor was determined (≈ 0.886 for this particular sensor), it was incorporated into the Arduino code, and applied to all of the measurements reported by the sensor.

Results

The statistical data for each measured position is shown in **Figure 4** below.

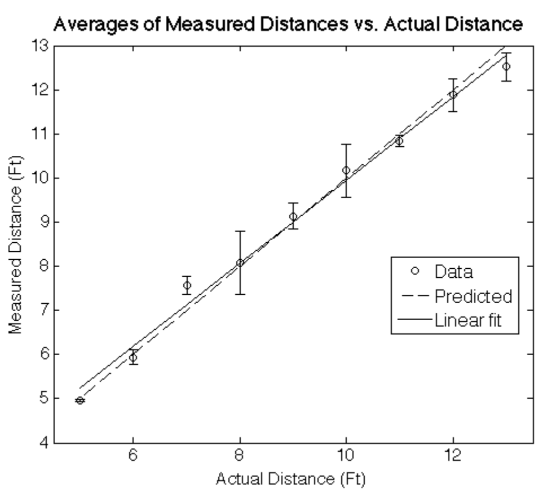

Figure 4 – Distances reported by the MB7062 sonar sensor plotted against the predicted distances. Each data point shown is an average of 50 measurements taken at a depth of 3.5 ft. in a swimming pool at BYU (Richards Building).

The equation for the linear regression displayed in **Figure 4** is:

$$y = 0.945x + 0.5057 \quad (ft.)$$

Where x is the actual distance to the object.

During the testing process, the proper lighting of the LEDs was verified. As the sensor moved incrementally away from an object, the LED indicators lit up in the proper order and at the proper times (red for distances ≤ 6 feet, yellow for distances > 6 feet and ≤ 10 feet, and green for distances > 10 feet).

The average error of the measured distances was 0.20 feet. The standard deviations for all measured positions were averaged to give the standard deviation for any given measurement reported by the sonar sensor. For a 95% probability, the instrument uncertainty was calculated to be ±0.66 feet.

The zero-order uncertainty of the sensor was calculated using the following equation [6]:

$$u_0 = \pm\frac{1}{2} * resolution \ (95\%)$$

For the ultrasonic sensor, u_0 was determined to be ±0.85 inches or ±0.071 feet (based on the smallest increment between reported distances over all tests).

Discussion

An ideal measuring system would report distances that follow the line $y = x$, meaning that the measured distances matched the actual distances exactly. It is apparent from the data shown in **Figure 4** that the measured distances followed a linear trend, which validates the measurements reported by the sensor. The linear fit of the data has a slope of 0.945, which is reasonably close to the ideal 1.0.

The calculated instrument uncertainty of ±0.66 feet is large enough to merit some concern about the reliability of this particular sonar sensor. It is important, however, to take into consideration all of the factors that may have contributed to this calculated error. One of which is the interference caused by swimmers in the swimming pool at the time the device was tested. Swimmers in the adjacent lane of the swimming pool frequently caused disturbances in the water that shifted the measuring apparatus slightly during testing. Special care was taken to minimize these shifts, but they occurred nonetheless. Also, the value used in the Arduino program for the speed of sound in water was only an approximation, since the water temperature and salinity were unknown at the time of testing. Hence, it is possible that the instrument uncertainty is somewhat lower than ±0.66 feet, but a more controlled experiment would need to be performed to know definitively.

Conclusion

The objective for this sonar sensor was not to determine the exact distance to objects in the path of the ROV, but rather to report to the ROV operator the relative distances to objects in its path (e.g. far away, somewhat close, very close, etc.). Thus, the calculated uncertainty is considered acceptable for this application. If greater resolution or less uncertainty is desired, a multiple-transducer system may perform better.

Several small (14mm diameter) waterproof transducers were tested in the research phase of this project. These sensors worked well over short distances; however, they were not sensitive enough to reliably detect echoes over distances greater than just a few inches. Future research may find more sensitive sensors (perhaps hydrophones) that could be used in a two-transducer (sender and receiver) setup. This type of system would have a shorter minimum detection distance, higher resolution and accuracy, and could potentially be less expensive overall, but it would also require a lot more circuitry and programming to implement.

Based on the results, it can be seen that this experiment successfully developed a sonar sensor that meets the specifications outlined in the introduction of this paper. This system provides a useful tool to help ROV operators navigate through areas of limited visibility.

References

[1] Somers, M.L.; Stubbs, A.R., "Sidescan sonar." *Communications, Radar and Signal Processing, IEE Proceedings F* 131.3 (1984): 243-256. Print.

[2] Bin Yusof, M., & Kabir, S. "An Overview of Sonar and Electromagnetic Waves for Underwater Communication." *IETE Technical Review 29*.4 (2012): 307-317. Print.

[3] Bloch, Heinz P. "Ingress Protection code explained." *World Pumps* 2009.11 (2009): 26. Print.

[4] Wilson, O. Bryan. *An Introduction to the Theory and Design of Sonar Transducers*. Washington, D.C.: Naval Sea Systems Command, 1985. Print.

[5] "MB7062 XL-MaxSonar-WR Datasheet." *MaxBotix Ultrasonic Sensors, High Performance Distance & Proximity Sensors*. MaxBotix, Inc., 2005. Web. 26 Feb. 2013. <http://www.maxbotix.com/documents/MB7062-MB7072_Datasheet.pdf>

[6] Figliola, Richard S., and Donald E. Beasley. *Theory and Design for Mechanical Measurements*. 5th ed. John Wiley & Sons, Inc., 2011. Print.

Appendix A

Bill of Materials					
Qty.	**Description**	**Part #**	**Supplier**	**Price (Ea.)**	**Total**
1	MB7062 XL-MaxSonar-WR Ultrasonic Sensor	MB7062	Amazon.com	$ 94.95	$ 94.95
1	Arduino Uno R3 Microcontroller	N/A	Amazon.com	$ 21.95	$ 21.95
1	Pre-formed 140-piece Jumper Wire Kit	N/A	Amazon.com	$ 6.50	$ 6.50
1	Cat5e Network Ethernet Cable - Blue - 50 ft.	N/A	Amazon.com	$ 6.45	$ 6.45
1	Microtivity 5mm Assorted Clear LED w/ Resistors (6 Colors, Pack of 60)	IL184	Amazon.com	$ 6.11	$ 6.11
3	Monoprice Cat5e Punch Down Keystone Jack	105376	Amazon.com	$ 1.68	$ 5.04
1	Solderless Breadboard 170 tie points	N/A	Amazon.com	$ 4.95	$ 4.95
1	Permatex Clear RTV Silicone Adhesive Sealant, 3 oz.	80050	Amazon.com	$ 4.81	$ 4.81
1	Gardner Bender 22-18 Gauge Butt Splice Connectors, 22-Pack	N/A	Amazon.com	$ 3.79	$ 3.79
1	Shaxon, 3 Port Single Gang White Keystone Wall Plate	BM303WP3-B	Amazon.com	$ 2.98	$ 2.98
1	Cat6 Snagless Patch Cable, Blue (1 Foot/0.30 Meters)	27140	Amazon.com	$ 2.59	$ 2.59
1	270 Ohm 1/2W Flameproof Resistor 10 Pcs.	N/A	Amazon.com	$ 0.96	$ 0.96
1	Gardner Bender 4-Ounce Black Liquid Electrical Tape	LTB-400	Lowes	$ 6.54	$ 6.54
1	Charlotte Pipe 3/4-in x 10-ft 480 PSI Schedule 40 PVC Pressure Pipe	N/A	Lowes	$ 2.28	$ 2.28
1	LASCO 3/4-in dia. 90-Degree PVC Sch 40 Snap Tee	N/A	Lowes	$ 1.40	$ 1.40
1	CARLON 22 cu in 1-Gang New Work Plastic Electrical Box	N/A	Lowes	$ 0.52	$ 0.52
1	LASCO 3/4-in dia. PVC Sch 40 Female Adapter	N/A	Lowes	$ 0.46	$ 0.46
1	LASCO 3/4-in dia. 90-Degree PVC Sch 40 Slip Elbow	N/A	Lowes	$ 0.42	$ 0.42
1	LASCO 3/4-in dia. PVC Sch 40 Male Adapter	N/A	Lowes	$ 0.34	$ 0.34
				Total:	**$ 173.04**

Appendix B

Arduino Code

```
/* SONAR distance measuring program for MaxBotix MB7062 ultrasonic sensor
      Written by: Daniel McArthur
      Description: Reads distance measurement data from the analog output of the
                   MB7062 at ~ 10 Hz. Uses LEDs to indicate proximity to obstacles
*/

int distPin = 0; //Analog Reading pin
float distVolt, distance, scalingFactor; // variables for distance measurement

//Set up LED Indicator
int ledPin;
int prevLED = 9;
int redPin = 9;
int yellowPin = 10;
int greenPin = 11;

void setup()
{
  pinMode(distPin,INPUT);
  pinMode(redPin,OUTPUT);
  pinMode(yellowPin,OUTPUT);
  pinMode(greenPin,OUTPUT);
  Serial.begin(9600);
  // Default is 1, change this value after calibration
  // Testing in a pool at BYU suggests a scaling factor of about 0.886
  scalingFactor = 1;
}
```

```
void loop()
{
  // Measure the voltage on pin 3 of the MB7062 (analog out)
  // This value corresponds to the distance measured in cm
  distVolt = analogRead(distPin);

  // Since the device is calibrated to measure distances in air, a multiplier is
      needed
  // to compensate for the distance in the velocity of sound under water, this value
      is
  // 1497 / 346.13 = 4.32 (based on speed of sound at 25 degrees C)
  distance = distVolt * 4.32;
  distance = distance / 2.54; // Convert distance to inches
  distance = distance * scalingFactor; // Apply the calibration factor

  //Print value to Serial monitor if you want to monitor the distance with a computer
  Serial.print("Distance: ");
  Serial.println(distance);

  if(distance > 10*12) // Distance > 10 ft, safe distance, green light
   {
     ledPin = greenPin;
   }
   else if(distance > 6*12) // 6 ft < Distance < 10 ft, moderate distance, yellow
      light
   {
     ledPin = yellowPin;
   }
   else //Minimum distance, red light
   {
     ledPin = redPin;
   }
   //Turn of the LED that was on previously
   digitalWrite(prevLED,LOW);

   // Turn on the appropriate LED with 50% PWM (half-brightness to save battery power)
   // Set to 255 for 100% brightness
   analogWrite(ledPin, 128);
   prevLED = ledPin; // Store current LED pin # for next loop iteration

  delay(100); // Measure distance at ~ 10 Hz per MaxBotix Datasheet
}
```