The Yellowfin Autonomous Underwater Vehicle Acoustic Communication Design and Testing

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1.0 INTRODUCTION

Over the past two years, the Georgia Tech Research Institute (GTRI) has developed a new Unmanned Underwater Vehicle (UUV) called the Yellowfin. The purpose of the vehicle is to provide a platform for research and development of autonomous, multi-vehicle underwater technology. This paper documents the design of the vehicle with an emphasis on the acoustic communication system, including the hardware and software. The testing of the ACOMMS hardware and software system is also discussed.

2.0 YELLOWFIN DESIGN

2.1 Design Approach

The intended design of Yellowfin is to supply a high baseline of integrated functionality while still being adaptable to a wide range of mission-specific requirements. This purpose has lead to a focus on designing Yellowfin to be modular and has also dictated some of the high-level design specifications. In order to keep cost and development time as low as possible while maintaining the quantity and quality of vehicle features along with system interoperability, the design of Yellowfin adopted the use of COTS (Commercial, off-the-shelf) components, open-source software, and industry standards whenever feasible. The vehicle itself was designed through an iterative process where one prototype was designed, built, and tested followed by several additional vehicles designed using the lessons learned from the first. The software design has also progressed in stages with the results of the implementation motivating additional cycles of design work.

Figure 1 below details the design approach for the Yellowfin. Starting with mission, performance, and design requirements, the design involves a drill down approach where many competing parameters are iteratively defined.

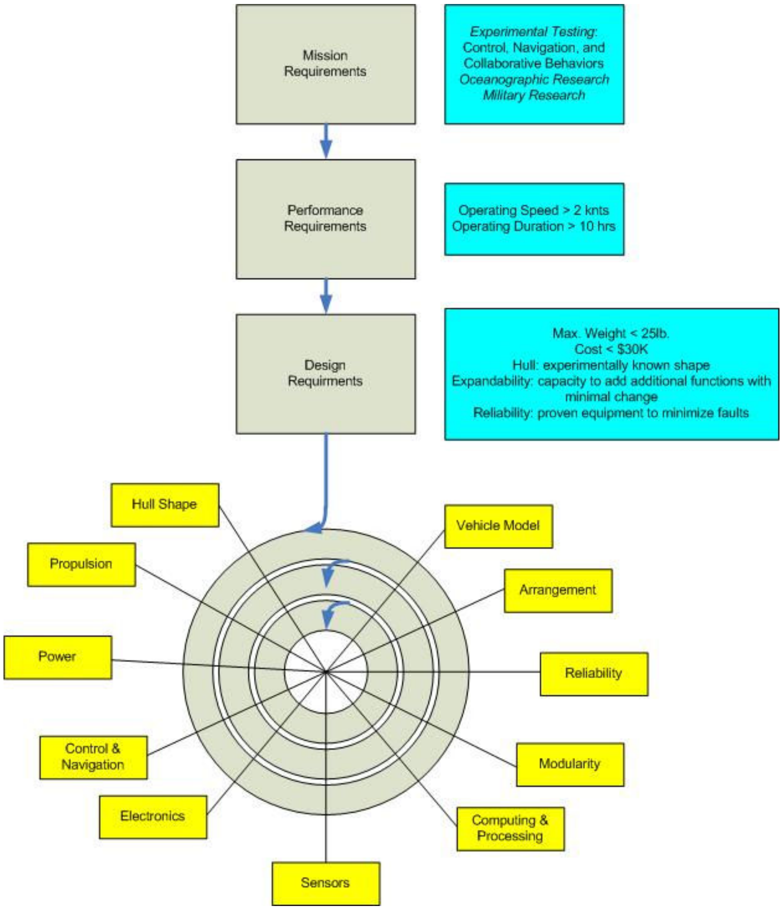


Figure 1: Yellowfin Design Approach

2.2 Mission Requirements

While the Yellowfin has been designed to perform a variety of missions, there is a set of core features necessary to perform UUV missions.

- Control, navigation, and collaborative behaviors
- Validation through real and simulated testing
- Suitability and flexibility to perform both scientific and military missions

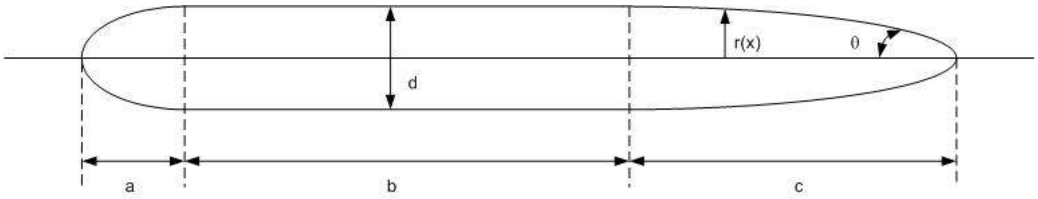
2.3 Performance Requirements

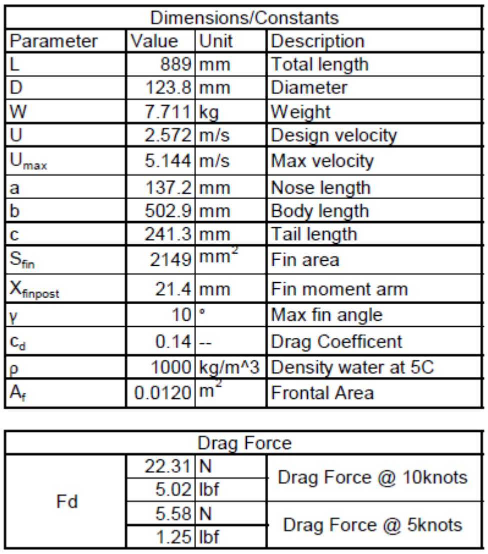
A few fundamental performance requirements are defined to insure that the vehicle can meet the mission requirements stated above. Yellowfin is required to be able to maintain a vehicle speed of at least 2 knots and to have mission duration of at least 10 hours. These two performance requirements have a significant effect on the design of the propulsion system and the power system.

2.4 Design Requirements

Several design requirements were established to insure that the Yellowfin could meet its mission objectives. Limiting the weight to be 25 lbs or less insures that the vehicle will be man-portable and that launching and retrieving the vehicle can be handled by a single person. Limiting the cost of the vehicle to $30k increases its value as a component of a multi-vehicle system in that more vehicles can be implemented for a given budget. The hull design was based on the Myring design in order to reduce hydrodynamic drag and to improve the efficiency of the propulsion system. The design of the vehicle was also required to be modular so that different payloads can be easily accommodated to meet various sensor types and mission requirements.

Figure 2 below tabulates the final design of the Yellowfin and Figure 3 displays a CAD drawing of the modular design.





Dimensions/Constants			
Parameter	Value	Unit	Description
L	889	mm	Total length
D	123.8	mm	Diameter
W	7.711	kg	Weight
U	2.572	m/s	Design velocity
U_{max}	5.144	m/s	Max velocity
a	137.2	mm	Nose length
b	502.9	mm	Body length
c	241.3	mm	Tail length
S_{fin}	2149	mm^2	Fin area
$X_{finpost}$	21.4	mm	Fin moment arm
γ	10	°	Max fin angle
c_d	0.14	--	Drag Coefficent
ρ	1000	kg/m^3	Density water at 5C
A_f	0.0120	m^2	Frontal Area

Drag Force			
Fd	22.31	N	Drag Force @ 10knots
	5.02	lbf	
	5.58	N	Drag Force @ 5knots
	1.25	lbf	

Figure 2: Yellowfin Design

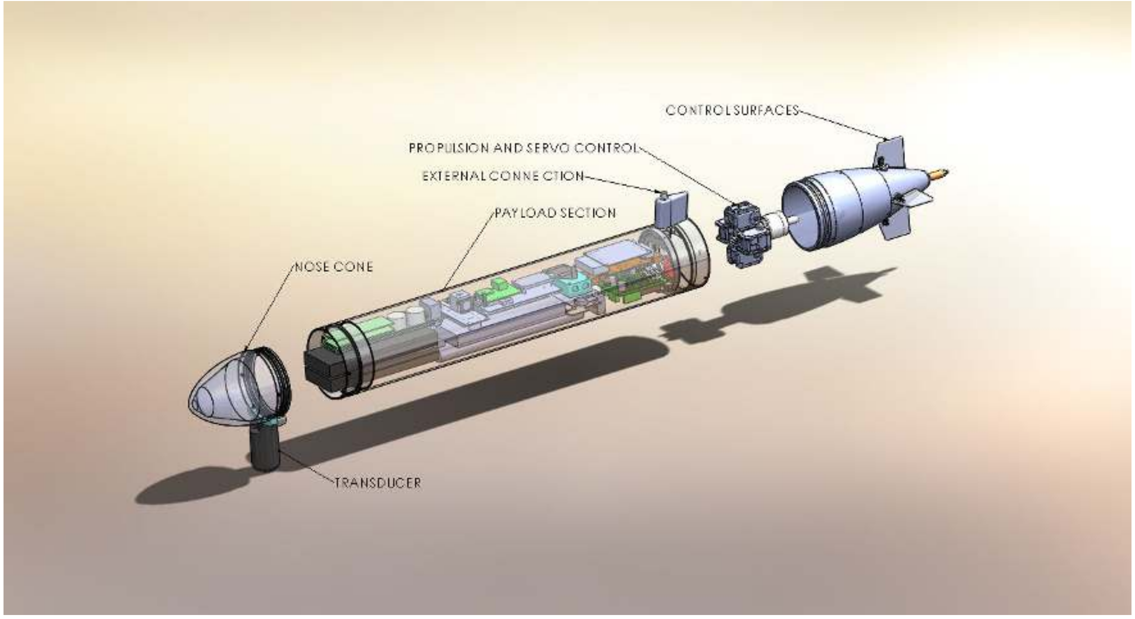


Figure 3: Yellowfin CAD Drawing

Figure 4 is a picture of the prototype Yellowfin vehicle, fully assembled.

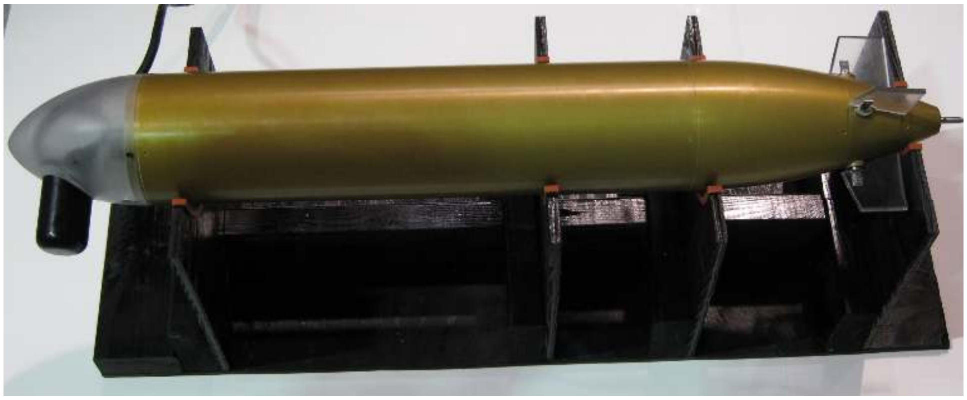


Figure 4: Fully Assembled Yellowfin

3.0 ACOUSTIC COMMUNICATION SYSTEM

Acoustic communication will be the primary method used by the Yellowfin vehicles to communicate with each other and with a base-station. While sound waves can travel great distances in underwater environments, there are several challenges that can limit successful communication.

3.1 Underwater Acoustics

Acoustic communications has been used for many years as the most efficient and reliable method of communicating over significant distances in the ocean. Acoustic modems have been developed to convert digital messages into analog signals that can be transmitted through the water using transducers. There are a variety of issues that make acoustic communication in the ocean a challenging problem.

The first issue is the speed of sound in the ocean is about 1500 m/s as compared to the speed of RF communications in the air at $3x10^8$ m/s. This relatively low speed limits the bandwidth of communications and often encourages engineers to minimize the amount of data to communicate. The slow speed of sound also increases the impact of Doppler frequency shift caused by the relative motion of the source and receiver. The received frequency $f_d = f_0\ v\ /\ c$ where f_0 is the transmission frequency, v is the relative velocity, and c is the speed of sound. It is clear that given the relatively slow speed of sound c, even small relative velocities can cause significant frequency shifts.

A second challenge to acoustic communications in the ocean is the loss incurred as the sound waves propagate through the water. There are three types of loss: spreading, absorption, and scattering. Spreading loss is a geometric loss where signal strength decreases as $1/R^2$ as the waves spread spherically as they propagate away from the transmitting transducer. In shallow water, this loss eventually becomes cylindrical in shape due to the boundaries of the surface and the seafloor so that the loss becomes proportional to 1/R.

The second type of loss is absorption loss which is highly frequency dependent, increasing with increasing frequency. Absorption loss is typically represented as an exponential function $e^{-\alpha(f)R}$ where $\alpha(f)$ is a function of frequency [2]. Figure 5 below plots the spreading loss and the absorption loss as a function of range for a few frequencies. It is clear from the figure that the geometric spreading loss dominates the absorption loss at close range. It is also clear that the range defines the transmission frequencies available to the system.

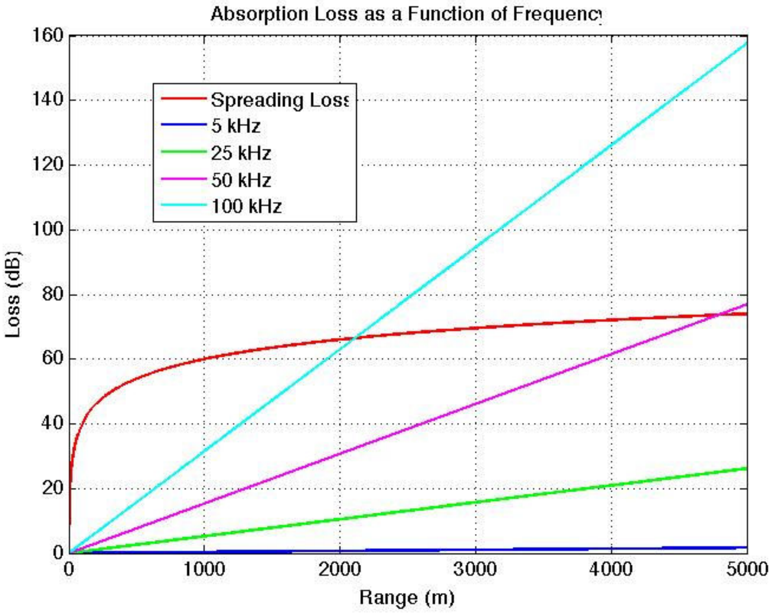


Figure 5: Transmission Loss

The third type of loss, scattering loss, can be caused by a number of sources, including bubbles. Bubble clouds can be formed by breaking waves near the surface and are more of an issue in shallow water than in deeper waters. Scattering can also occur due to large schools of fish or other biologics.

Another significant challenge to acoustic communication is the spatial and temporal variation of the speed of sound within the ocean. The sound speed in the ocean is a function of temperature, pressure, and salinity. Figure 6 below is a typical sound speed profile that shows how the sound speed changes with depth due to temperature and pressure changes.

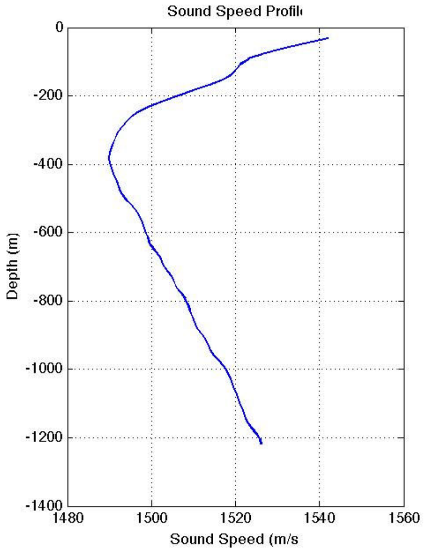


Figure 6: Sound Speed Profile

This variation of sound speed causes sound waves to diffract as they travel through the ocean. One implication of sound wave diffraction is that there will be areas within the sound channel where the sound pressure level is high and areas where it is low, called shadow zones. A method for predicting sound propagation called ray tracing was used to generate the plot in Figure 7 below. The model assumes that the surface is a perfect reflector and that the seafloor is a perfect absorber. In reality, waves on the surface reduce the reflection coefficient to something less than one and introduce delays into the reflected waves. The reflection coefficient of the seafloor is strongly dependent on the shape and material composition and is usually much less than one.

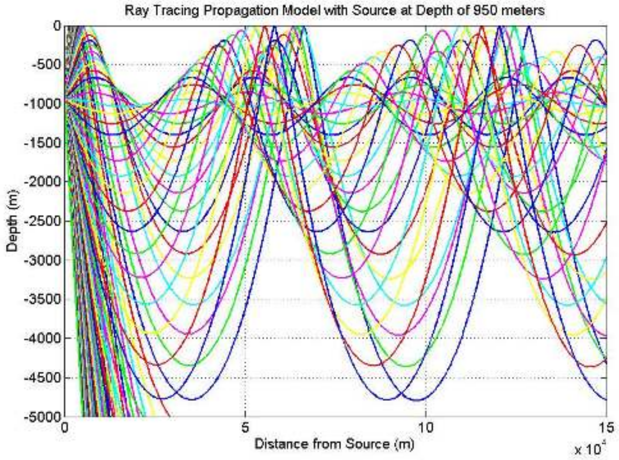


Figure 7: Effects of Sound Speed Variation on Sound Propagation

The shadow zones in this plot are obvious and indicate that communication between vehicles can be greatly impacted by the location of the source and the receiver. The plot also demonstrates the duct nature of the ocean at certain depths where sound will travel great distances. The deep sound channel is an ocean depth where the sound speed profile is a minimum. Sound generated near the deep sound channel will not refract up to the surface or to the seafloor and will propagate long distances in this duct. The deep sound channel is used by submarines to carry low frequency communications over very long ranges.

Multi-path scattering is a phenomenon in ocean acoustics where sound from a single source can arrive at a receiver through many different paths. Sound waves generated by a source will travel in a direct path from source to receiver but will also reflect off the sea surface and seafloor and arrive at the receiver as well, with some magnitude and phase change. Figure 8 below shows an example of multi-path scattering.

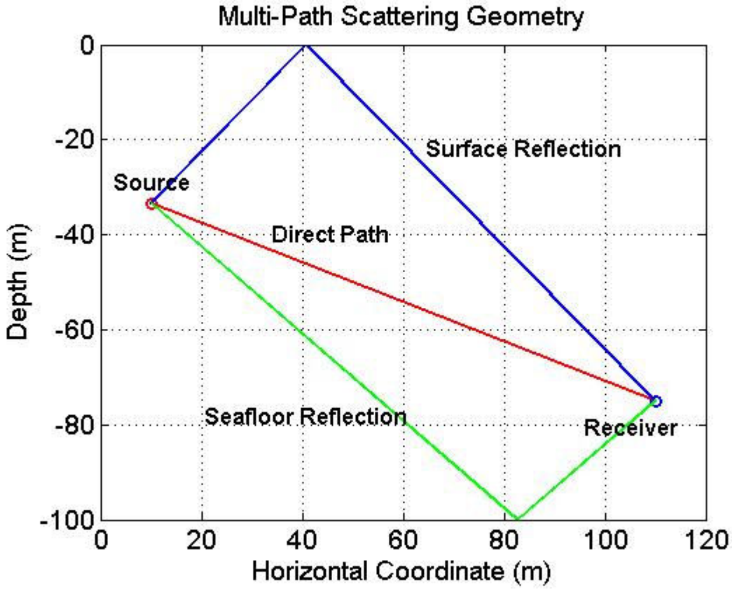


Figure 8: Multi-Path Scattering

Given the relatively slow speed of sound, these signals potentially can all arrive before the direct signal has finished arriving, and thus must somehow be distinguished from the direct signal. Figure 9 below is a pseudo-color plot of the time difference between the direct path and the first arriving multi-path signal as a function of depth and range. This delay is the maximum message length in time before the multi-path signals arrive and potentially corrupt the direct signal. The data was generated assuming the source and receiver were at the same depth which was chosen to be half the ocean depth. The dashed lines are lines of constant delay and indicate the boundary at which the multi-path signals will become a problem. The top line is a delay of 24 ms which corresponds to a message length of 16 bytes (JAUS message header size) and the second line is a delay of 96 ms which corresponds to a message length of 64 bytes (JAUS *ReportGlobalPose* message size).

The area above the dashed lines potentially will have corrupted signals due to multi-path scattering. The plot shows that multi-path scattering becomes less of a problem as range decreases and as depth increases. It also shows that virtually any shallow water communication will have to deal with the effects of multi-path scattering. There is also clear benefit to reducing the message size.

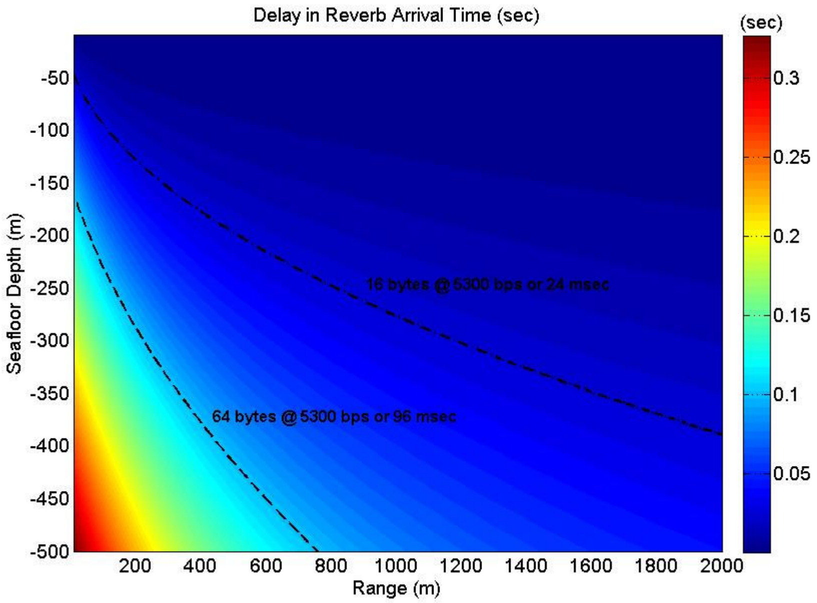


Figure 9: Delay Times Between Direct Path and Surface Reflection as a Function of Ocean Depth and Range

Ambient noise also poses a significant problem to underwater communications. There are numerous sources for noise in the ocean, both man-made and natural. Man-made noise is most prevalent in shallow water environments and includes boat, watercraft noise, and oil rigs. Natural noise sources include biologics such as fish and whales as well as the noise introduced from wave action on the surface. Waves also inhibit shallow water communication by creating bubble clods that can scatter sound waves and from Doppler effects due to the motion of the water column.

3.2 WHOI Micro-Modem

Numerous commercial companies have developed acoustic modems for use in ocean communication applications. The Woods Hole Oceanographic Institution (WHOI) has been a leader in research in ocean communications and has developed the WHOI micro-modem. The modem has several modulation schemes including low rate frequency hopping, frequency-shift-keying (FH-FSK) and variable rate phase-coherent keying (PSK).

The WHOI micro-modem is composed of 3 boards: a main board, a power-amplifier, and a floating-point coprocessor board. The WHOI micro-modem was designed to consume low power to support its implementation in underwater vehicles operating on a limited battery supply. Onboard computers communicate with the micro-modem using serial communications over a standard RS-232 port. The power amplifier is designed to drive the ceramic transducer, to act as a single channel receiver, and to provide power conditioning to the system. The coprocessor board was designed to perform the computationally complex PSK equalization algorithms [3]. The WHOI micro-modem is shown in Figure 10 below.

The user interface for the WHOI micro-modem is based on the NMEA 0183 standard developed for marine electronics. Each message is a sentence that begins with "$" followed by a 5 character talker or message identifier. Following the talker, there are some number of comma separated fields, a "*" symbol, followed by an 8-bit checksum. Georgia Tech has written a C++ library that allows an application to configure the micro-modem and to send and receive messages via the NMEA standard.

The micro-modem implements a robust communications scheme known as frequency-shift keying with frequency hopping that has been shown by WHOI to function very well in shallow water environments. The scheme allows for low-rate communications where multi-path scattering is a problem. The modem can be configured to operate in one of 3 frequency bands: 7.6 to 12 kHz, 12.5 to 17 kHz, and 23 to 30 kHz, each having a 4 kHz bandwidth. The data rate including the error correction is 80 bps [4].

The micro-modem also implements several high-rate phase-shift keying (PSK) algorithms from with data rates of 300 to 5000 bps. The micro-modem can transmit these PSK signals but the co-processor is required to receive and process them.

The micro-modem can send data in one of two packet configurations. The first is known as a mini-packet and contains only 21 bits. This packet type is used for cycle initialization messages which alert the receiver modem that the sender modem is about to send a message to it. Mini-packets can also be used to send very short messages and are useful in navigation and localization schemes. The other packet configuration has variable frame sizes, ranging from 32 to 248 bytes. The modem also has a ping command which can be used to estimate the distance between two nodes. The sender modem sends out a ping message to the receiver modem which responds after a fixed turn-around time. After receiving the response from the receiver modem, the sender modem then computes the one-way travel time from the receiver modem by subtracting the turn-around time.

4.0 YELLOWFIN ACOMMS TESTING

4.1 ACOMMS Hardware

Georgia Tech conducted a series of Yellowfin ACOMMS tests in the acoustic tank located in the Love building in the school of Mechanical Engineering. The tank is 48 feet by 35 feet and 22 feet deep. The tank is equipped with 32 channel data acquisition system with a 3D motion control system. Georgia Tech has developed a library of Matlab and Labview software for data acquisition and motion control of targets within the tank. The Yellowfin acoustic communication system was tested in this tank.

The acoustic communications system is comprised of an on-board computer, the WHOI micro-modem, and a transducer. The on-board computer communicates with the modem via the serial port using standard RS232 communication. The WHOI micro-modem is stack of three boards: a modem board, a power-amplifier board, and a co-processor board. Messages from the on-board computer are converted from digital signals to analog signals and sent out through the power amplifier to the transducer. Incoming signals received by the transducer are processed by the modem and communicated back to the on-board computer. High data rate PSK messages are processed by the co-processor.

The WHOI micro-modem stack and the BTech BT-2RCL transducer used by Yellowfin are shown in Figure 10. The micro-modem stack as shown has a LFF format power-amplifier with a modem board mounted on top. The co-processor board is then mounted on top of the modem board. The BTech transducer is designed for the 20-40 kHz range with a resonance frequency at 28 kHz.

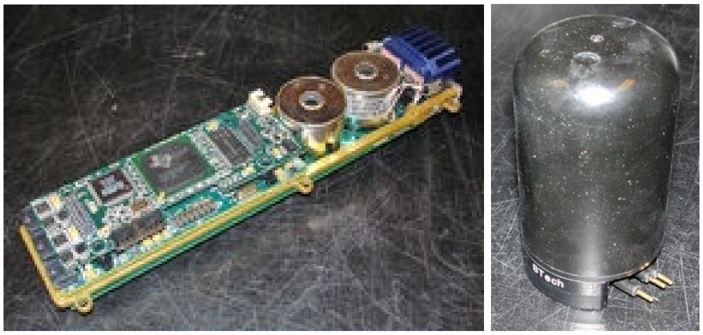


Figure 10: WHOI Micro-Modem and BTech transducer

Georgia Tech also purchased a multi-channel micro-modem deckbox and a towfish transducer for use as a base-station. The deckbox and towfish are shown in Figure 11. The deckbox contains a WHOI micro-modem, batteries, and a charger system. The deckbox can take input from a single transducer or an array of hydrophones. The towfish is designed to maintain the proper orientation of the transducer as it is hung over the side of a boat or dock.

Figure 11: WHOI Deckbox and Towfish

4.2 Initial Testing

Initial testing of the software and hardware focused on demonstrating the ability to create JAUS messages and to send and receive them through the water column. The test setup was intended to demonstrate the underwater communication between the base-station and a Yellowfin vehicle. Initial tests used a pair of computers, one to represent the base-station and one to represent the vehicle. The base-station computer was connected to the deckbox via a RS232 serial cable. The deckbox was then connected to the towfish transducer via the transducer cable. The vehicle computer was connected to the WHOI micro-modem stack which was then connected to the BTech transducer hanging in the water. Figure 12 shows the test setup.

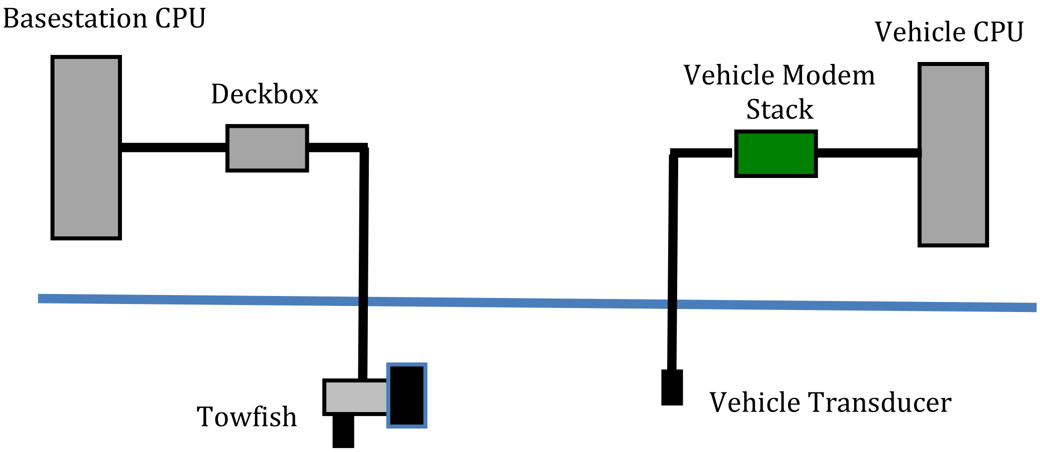


Figure 12: Yellowfin Acoustic Testing Diagram

The goal of the testing was to implement a message from the vehicle to the basestation through the water column. The message of interest was chosen to be the *ReportGlobalPose* JAUS message in which the vehicle reports its location to another node. The six floating point numbers reported in the message are the location values of longitude, latitude, and altitude as well as the rotation values of yaw, pitch, and roll.

GT developed a command line program called *ModemConfig* to configure and test the WHOI micro-modem. WHOI supplies a program with the modem that they developed which provides much of the same functionality but the code is only available in Windows format and the source code is not available. GT is working primarily with the Linux operating system so *ModemConfig* was developed to allow users to configure the modems and to test their functionality from a Linux-based computer. The WHOI micro-modems have about 65 NVRAM parameters that it stores on the board. A few examples of these parameters include the modem address (SRC), the analog gain (AGN), and the serial port baud rate (BR1). The command line driven code allows the user to query the modem for a given parameter, to set a parameter to a new value, and to reset all to the factory defaults. This code is very valuable in testing in that the modem setup can be quickly validated if there are difficulties in communications. The code also implements the ping command provided by the WHOI modem. Users can ping other modems and see the one-way travel times computed by the modem. This capability allows the user to validate that the modems are properly connected both to their power and data sources.

GT wrote several software libraries to handle JAUS messages and to be able to code and decode them into the NMEA 0183 protocol used by the WHOI modems. For the purpose of these initial tests, a command line program was written that could be used for both transmitting JAUS messages and also for listening to the serial port for incoming messages. These initial tests were successful in validating that the software was able to form JAUS messages including the global pose data, to pack that message into a NMEA hex binary message, to send it out the modem to the transducer, to receive that message on another modem, to extract the JAUS message, and to parse the global pose data out of the JAUS message. Figure 13 below shows the steps required to send a JAUS message from one node to another using the WHOI micro-modems.

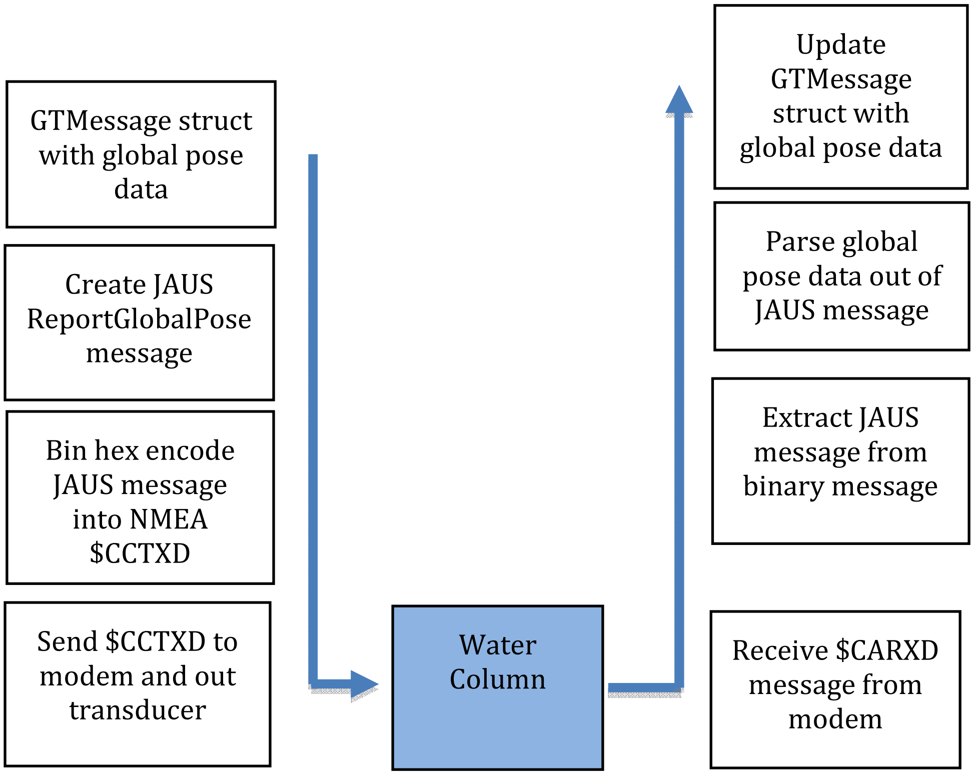


Figure 13: Data Flow from Node to Node

Figure 14 contains a couple of pictures from the testing. The picture on the left shows L-R the vehicle computer, the vehicle modem stack, a power amp, the deckbox, and the basestation laptop. The picture on the right shows the vehicle transducer and the towfish in the tank.

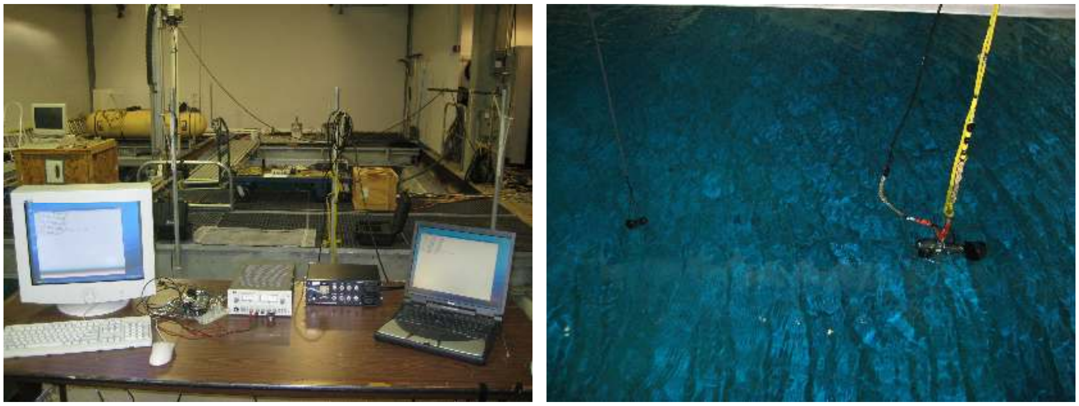


Figure 14: Tank Testing

The initial testing of sending JAUS messages through the water column was successful. Tests showed that the JAUS *ReportGlobalPose* message could be formed and sent to another node through the water. Other JAUS messages were also tested and shown to work as well.

4.3 MOOS Database and Localization Testing

The next level of testing involved the implementation of the ACOMMS system using the MOOS database with the JAUS messaging protocol. Georgia Tech is leveraging a MOOS application developed at MIT by Toby Schneider called *pAcommsHandler* and has developed a pair MOOS applications as well. The goal of the testing was to implement a simple localization algorithm so that the vehicle could determine its location relative to a fixed hydrophone array and then to communicate that information back to a base station using JAUS messaging.

One of the goals of the Yellowfin design was to leverage as many existing technologies as possible in order to minimize development time. In the case of the software system, the Yellowfin sought to implement existing software libraries already in use in the unmanned system community. The core of the Yellowfin's software is the Mission Oriented Operating Suite (MOOS) database, a robotics framework designed to ease the development process for robotic platforms. To augment this framework for autonomous behaviors, a library called MOOS-IvP-Helm was included into Yellowfin's software package as well. MOOS-IvP-Helm is the MOOS implementation of Mike Benjamin's Interval Programming, a mathematical model designed to select the optimal decision given a competing set of objective functions.

Yellowfin implements acoustic communications through the *pAcommsHandler* application developed at MIT. *pAcommsHandler* is a MOOS module that interacts with the WHOI Micro-modem firmware to handle intelligent message queueing, prioritizing, and management. There are four main components of *pAcommsHandler*: encoding and decoding via the Dynamic Compact Control Language (DCCL), priority based message queueing of DCCL messages, a WHOI micro-modem driver, and a time division multiple access medium access control. The TDMA MAC handles the transfer of DCCL messages from the queue and intelligently decides how to send them through the water column via the transducers in the most efficient manner.

Georgia Tech developed a MOOS application to work in concert with *pAcommsHandler* called *pJAUSCodec*. *pJAUSCodec* essentially replaces the DCCL encoding with JAUS message encoding. *pJAUSCodec* takes any message posted to the MOOS database and can decode or encode messages out of or into JAUS binary format.

Another MOOS module developed at GT is called *pLocalization*. This MOOS application pings some number of hydrophones in a fixed array using the WHOI firmware ping commands. Each ping command returns the one-way travel time in seconds from the vehicle to that hydrophone. Knowing the location of each hydrophone and the speed of sound, the vehicle's location can be easily computed.

Once the simulated vehicle's pose is calculated, it is posted to the MOOS database so that *pJAUSCodec* can pack it into the JAUS *ReportGlobalPose* message and post it to the MOOS database. *pAcommsHandler* can then send it through the WHOI micro-modem through the water to the base station.

The receiving base-station node can then decode the *ReportGlobalPose* and output the UUV's location to *FalconView*, a mapping program developed at the Georgia Tech Research Institute. *FalconView* can then update a map centered on the Love building with the UUV location.

4.4 Localization Testing

Three BTech transducers were connected to WHOI micro-modems and were hung in the acoustic tank at Georgia Tech. Each hydrophone was hung at approximately half-depth or 11 feet from the surface. Each micro-modem was configured to have a unique address and powered using a power amplifier. A Yellowfin vehicle was simulated using a BTech hydrophone moving slowly through the water. Figure 15 below shows the layout of the hydrophones in the tank.

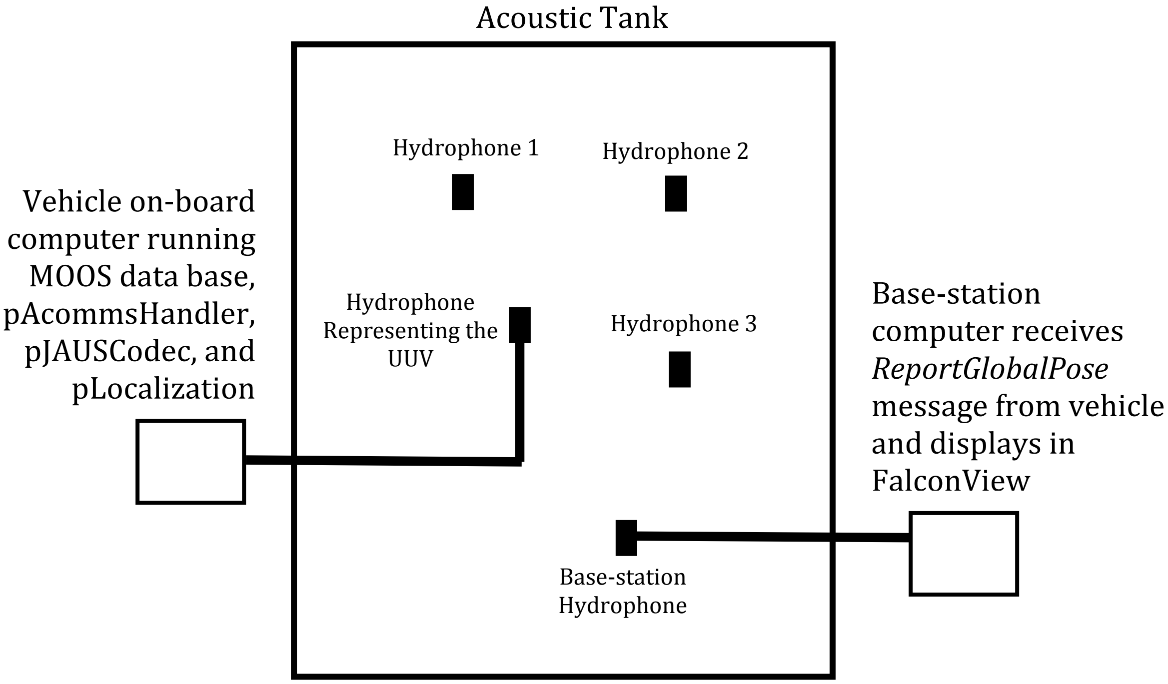


Figure 15: Top-Down View of Acoustic Tank: Localization Testing

GT found that this was a challenging test to perform in a tank the size of the acoustic tank. Careful placement of the hydrophone array and lowering the analog gain of the modems to a very low value were required to lessen the effects of reverberation. GT also noted that consistent vertical orientation of the transducers was critical to achieve successful localization results. The results indicate that the software successfully implemented the MOOS database and *pAcommsHandler* to use JAUS messaging protocols to send global pose information through the water.

Figure 16 is a picture of the hydrophones in the tank with the one in the middle moving to simulate the vehicle.

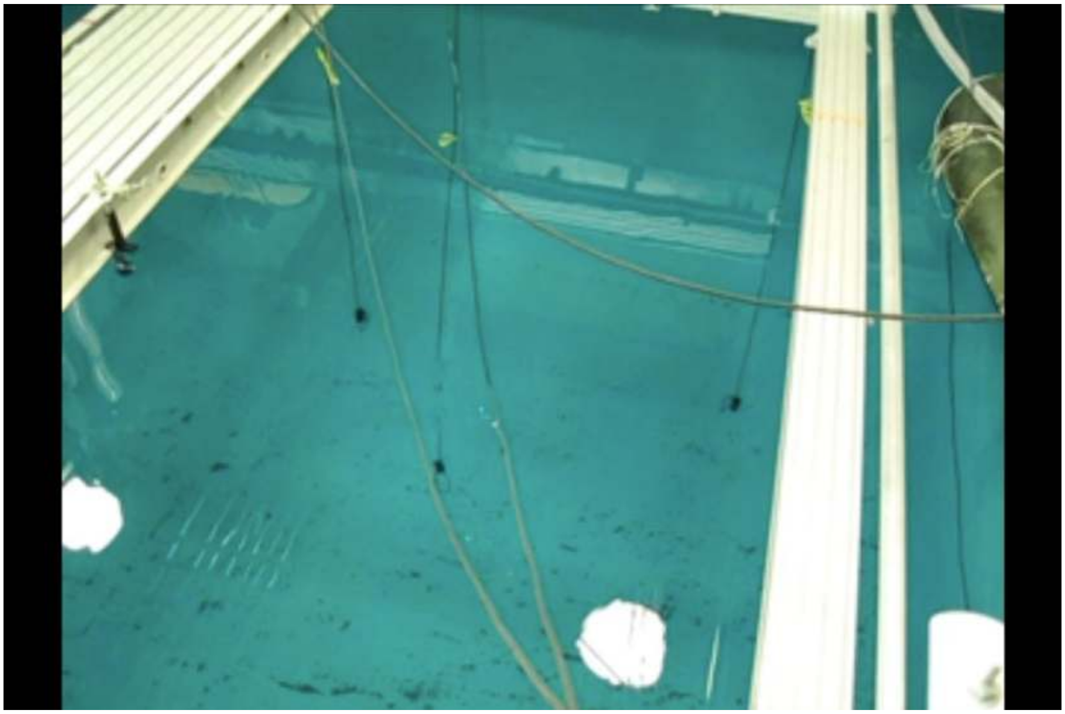


Figure 16: Localization Testing in Acoustic Tank

The image in Figure 17 is a screen shot from the *FalconView* program showing an aerial view of the Georgia Tech mechanical engineering building with the UUV designated by the orange rectangle.

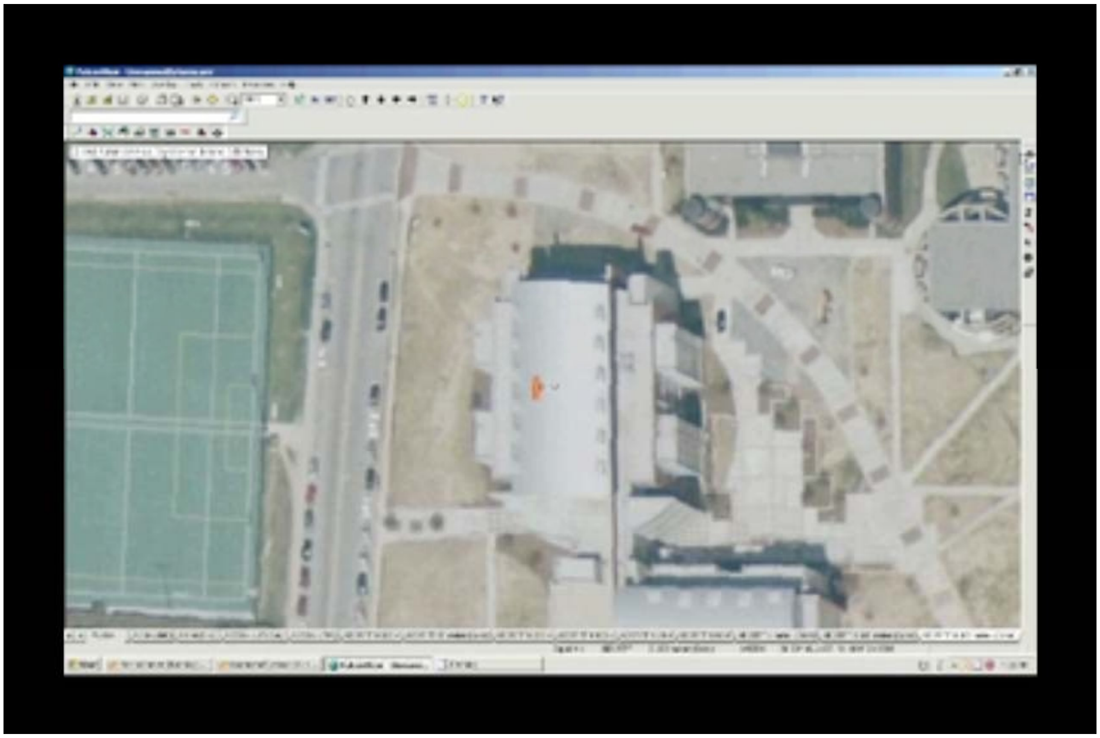


Figure 17: Screenshot from *FalconView* program of UUV in acoustic tank

5.0 Summary

The Yellowfin autonomous, underwater vehicle is presented. The design was centered on developing a small, man-portable UUV with flexible payloads as a platform for researching collaborative behaviors. The design and testing of the acoustic communication system is presented with an emphasis on the design's attempt to leverage COTS technologies, to adhere to industry standards, and to utilize open-source software whenever possible.

References

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