BEARacuda Design Document

Autonomous Underwater Vehicle – University of Arizona (AUVUA)
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http://www.auvua.org

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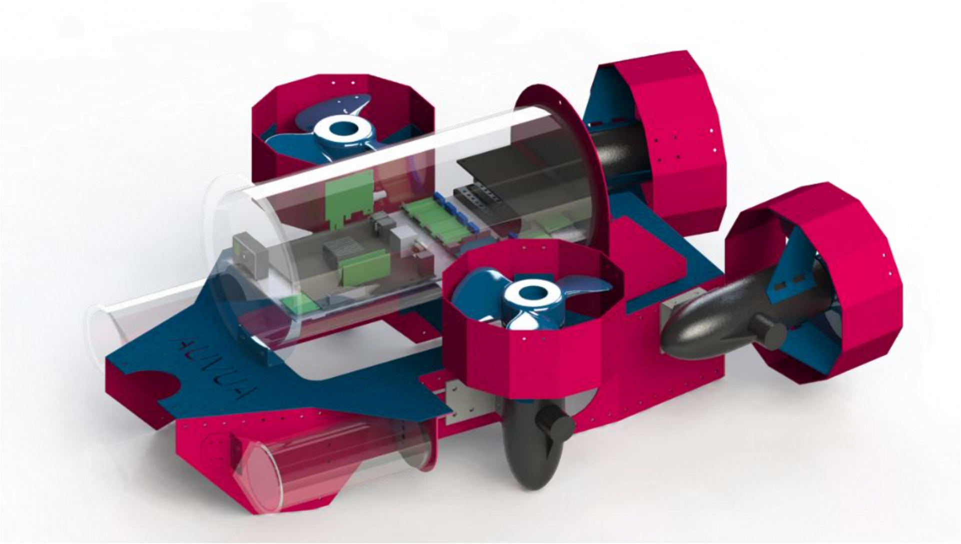
Abstract:

In its second year, the AUVUA club at the University of Arizona has made significant progress in developing a competitive autonomous system. With a budget of $5000, AUVUA presents BEARacuda, the successor to CATfish. This updated design features improved mobility, better visual processing capability, and more robust construction. The main design objective for this machine is accuracy in navigation - the design is tailored for all moving tasks including localization using the ultrasonic pinger. The team believes that successful execution of these tasks are pre-requisites for the more advanced objectives. As such, BEARacuda should prove to be a solid and expandable platform for many years to come.



Overview	
Size:	38″L x 28″W x 18″H
Weight:	Approx. 55lbs
Sensors:	1x Logitech C615 1x GoPro Hero 3 White
	PNI TRAX Digital Compass
	250 kPa pressure sensor
	Passive sonar array
Runtime:	Approx. 1.5 hours

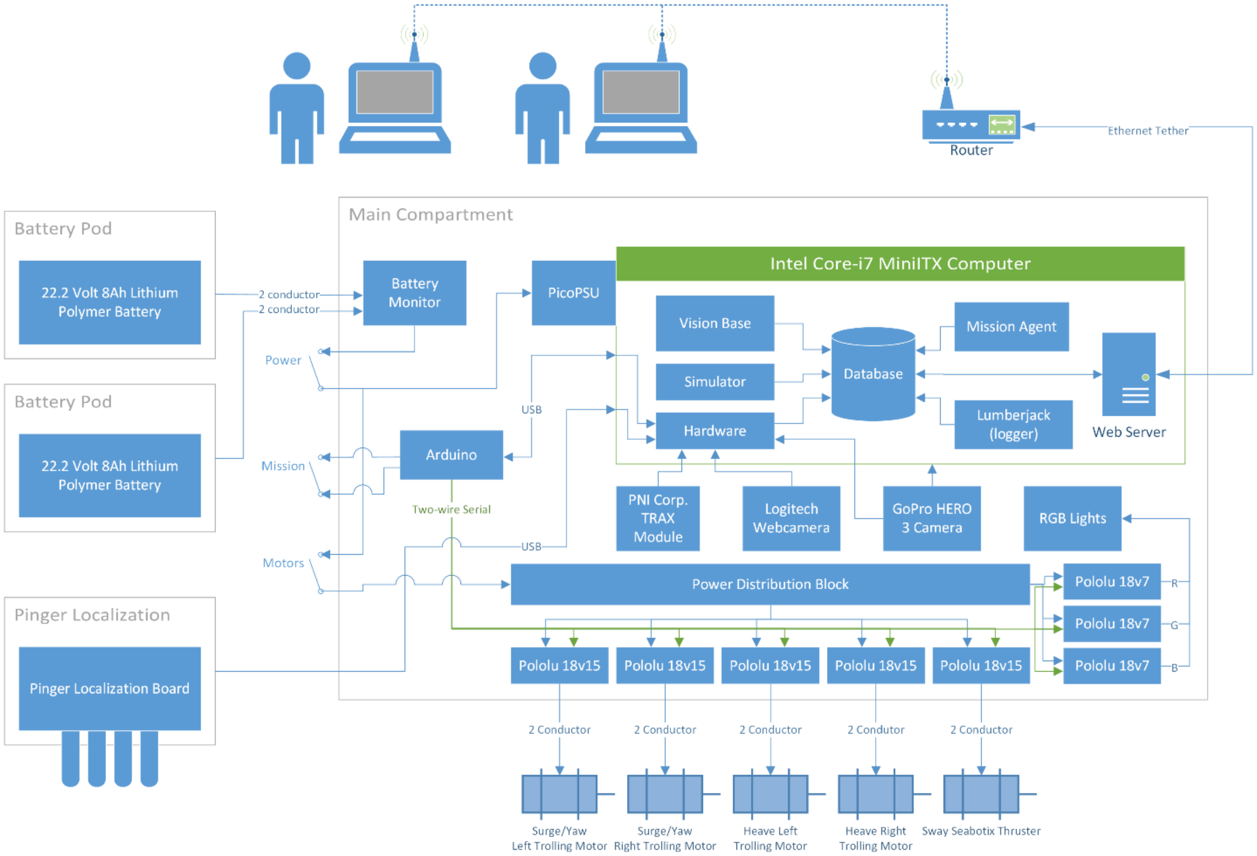


Figure 1: Block diagram of electrical, software, and user systems.

System Overview

BEARacuda is the second iteration of an undertaking that started as a senior engineering capstone project in the fall of 2012. This year, the team consists primarily of seven members from mechanical, electrical, and software engineering backgrounds. Logically, it follows that the system is decomposed into its corresponding components.

Mechanical Design

The mechanical subsystem is comprised of the sheet metal frame, watertight electronics housings, and custom thrusters. This system is able to withstand standard underwater operating conditions up to a depth of 20 feet. The main design goal is to maintain system flexibility and robustness while staying under a strict $5000 budget. In the current implementation, all mechanical design goals have been achieved, successfully supporting and interfacing with the electrical and software subsystems.

Frame

The frame is the main support structure for the rest of the housings and external components of the vehicle. It consists of several sheets of 6061 Aluminum sheet (.080 inch thickness) riveted together to form a rigid and lightweight structure. Borrowing from last year's design, one main plate serves as the backbone of the vehicle, supporting two vertical plates which are oriented along the length of the vehicle. These side plates are bent in three segments for motor orientation and aesthetics. A hull support plate rests atop the main plate, offering a rigid support for the main electronics hull. Two horizontal braces connect the side plates together, greatly increasing the rigidity of the frame when compared to last year's design.

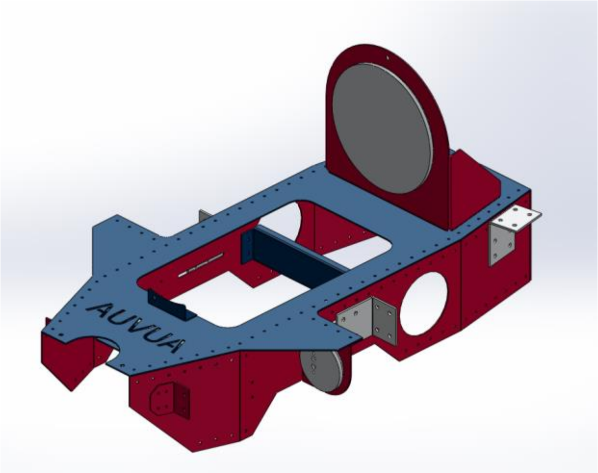


Figure 2: Aluminum sheet metal frame.

Main Hull

The main hull is the largest watertight compartment on the vehicle. It houses most of the electronic components (excluding batteries) and is designed for rapid disassembly if required. An 8 inch outer diameter, 1/8 inch wall polycarbonate tube is used to allow visibility of electronic components as well as vision for internal cameras. One end of the tube is terminated by a polycarbonate cap which is chemically bonded to the tube. This provides a transparent surface for the forward facing camera to view through. At the aft end, an aluminum end cap (re-used from last year's vehicle) is fitted inside the tube, using an o-ring bore seal to maintain a watertight interface up to the maximum depth of the acoustic trap of the TRANSDEC (16 feet). The front plate and rear hull support plate are tied together with two steel threaded rods, while the front end of the hull is supported by a small bracket attached to the main frame.

The end cap at the rear of the hull is considered a permanent fixture of the vehicle. It allows wires in and out of the main housing for transporting power to and from external components. The electronic components are also tied to this end cap via a cantilevered electronics rack. This rack is built from aluminum sheet and is mounted using threaded holes in the fixed end cap. The hull/window assembly is easily removed by undoing four nuts. This allows access to internal components without major disassembly of the vehicle.

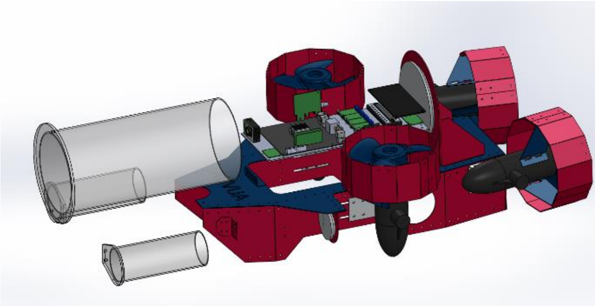


Figure 3: Compartment access.

Secondary Hulls

In addition to the main hull, three other enclosures are included in BEARacuda. Two 3.5 inch diameter polycarbonate battery tubes exist on either side of the forward end of the vehicle. These hulls are constructed similar to the main hull, with a forward polycarbonate window and a rear aluminum plug fitted with an o-ring. One lithium polymer battery is placed inside each tube so that they may be isolated from the main hull in case of failure. In each battery housing, two power wires join with the main hull end cap.

The third waterproof enclosure is recycled from last year's vehicle. This hull houses the hydrophones and localization board, and is easily removed from the vehicle. This compartment is to be shared with the Carl Hayden High School Robotics Team during competition, so it was designed to be modular and easily mounted. Two aluminum end caps seal a 5 inch length of polycarbonate tube. These end caps are pulled together using two 1/4 inch stainless steel rods.

Waterproofing

There are several locations where waterproof seals are necessary. The bore seals on the compartment end caps use single EPDM O-rings which press against the inner surface of the hull tubes. Sufficient compression allows for tight fits which do not fail or leak during normal operation. Some end caps are designed with holes for wires to pass through. These holes are sealed in a similar way, with O-rings slipped around each wire and fitted into a counter-bored hole. The O-rings around these wires were sized to fit snugly inside the wire holes to facilitate wire removal if necessary.

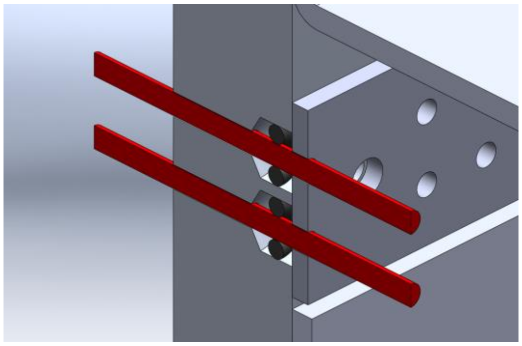


Figure 4: Wire waterproofing technique.

A retaining plate is fitted over each wire hole to constrain movement of the O-rings. This sealing technique is robust and easy to implement, allowing wires for additional actuators to be added without much design effort.

Thrusters

Five thrusters are used for propulsion for BEARacuda. Last year's solution used cheap bilge pump motors with cut-down RC airplane propellers and custom adapters. Although a cost-effective solution, the team experienced a failure during a test-run in which a shaft seal wore down, causing a leak. Additionally, the four horizontal vectored motors provided only 8-9 pounds of thrust, crippling the top speed.

This year, although speed was a determining factor, the team approached the issue with a similar cost-efficient mindset. Minn-Kota 30 pound trolling motors were adapted to use bidirectional 3D-printed propellers, and a potting resin provides a water-tight wire seal. One Seabotix thruster allows for lateral motion. Each of the Minn-Kota motors is fitted with a custom propeller with superior bi-directional capabilities, allowing for equal thrust characteristics in forward and backward movement.

Figure 5: 3D printed bi-directional propeller.

Material Selection

The system makes use of several different materials. The main frame consists primarily of 5052 aluminum sheet due to its availability, low cost, and ease of bending. Aluminum is more corrosion resistant than other materials such as steel, which is beneficial in an underwater environment. Structural strength is not a large concern, but sheet aluminum is sufficient for the low-impact nature of submersible vehicles. The end caps are made from 6061 aluminum block for its machinability characteristics.

The waterproof enclosures are constructed using polycarbonate tube. This material was chosen for its light weight and transparency. It is also shatter resistant, making it a good choice over other low strength plastic tubing. The team's experience making waterproof hulls using polycarbonate tubing made it an obvious design choice for use in the AUV's compartments.

This year's vehicle also takes advantage of 3D printing technologies. The standard trolling motor propellers exhibited poor bi-directional performance, so custom propellers were manufactured from PLA for its superior printing qualities. Rapid prototyping allowed for an optimal choice of propeller geometry at a very low cost.

Buoyancy and Stability

The system is neutrally buoyant in order to prevent unwanted vertical movement when no thrusters are powered. The mass of the system must equal the mass of the water displaced in order for buoyancy and gravitational forces to cancel out. The system is constrained to four degrees of freedom of motion: Translational movement in all three directions, as well as rotation about the vertical axis (yaw). In order to prevent pitch and roll rotation, the system uses a mass distribution which is gravitationally stable. This is done by placing positively buoyant components (such as the hollow main housing) above negatively buoyant components (such as counterweights or batteries). Any deviation from the default vertical orientation will create a torque which will force the system to return to an upright orientation. For further stability, each pair of thrusters has up to three inches of adjustability perpendicular to the plane of action; the thrusters may be repositioned to pass through the center of mass of the vehicle. Therefore, when a thruster is powered, the vehicle is constrained strictly to movement in the thruster's plane of action. This allows for more predictable movement as well as increased stability for performing high precision tasks.

In its current configuration, BEARacuda has a displacement of approximately 55 pounds. The main hull displaces 35 pounds, while the remaining thrusters, enclosures, and frame occupy the remainder. Preliminary mass analysis indicated a total mass of 50.1 lbs. To maintain neutral buoyancy, 5 pounds of adjustable counterweights are included in the design. Combined with the adjustability of the main drive thrusters, system stability can be maintained in a variety of machine configurations.

Component	Weight
Thrusters	4 x 7.5 lbs
Frame + Endcap	9.6 lbs
Batteries	2 x 2.4 lbs
Electronics	4.5 lbs
Hydrophone Enclosure	1.2 lbs
Total	50.1 lbs

Table 1: Vehicle weight distribution

Electrical Design

The electrical subsystem is composed of power distribution, main computing, peripheral sensors, and power outputs, including high-current switches and motor controllers. Operating in an underwater environment, the system has to have a robust design to tolerate leaks, shorts, and other hazardous electrical phenomena. The final subsystem design meets all the aforementioned goals.

Figure 6: Main electronics rack with all components mounted, prior to wiring.

Power Distribution

Two 24 volt, 8 amp-hour lithium-polymer batteries tied in parallel provide up to 384Wh of energy to the sub, enough to operate continuously for over an hour. The 24 volt system ensures high compatibility with many other devices without as drastic a voltage drop of a 12 volt system using the same power. The two battery packs, located in individual auxiliary hulls, are connected to the system via a high power relay and 50 amp fuse. This isolation and protection helps prevent catastrophic failures from destroying other sensitive electronics.

To alleviate last year's issues of metastable signals driving power relays, a power management board was designed with a large low-pass filter run through Schmitt triggers. The result is clean transitions during power-on/off and kill with little to no impact on other circuits. The power management board also integrates current to provide an estimated state-of-charge and relays all information to the CPU via USB.

While all other peripherals are either run on the main 24 volts or from USB/RS232 power provided by the motherboard, the mini ITX platform itself required a PSU with minimal footprint. An 80 watt picoPSU DC-DC power supply is used to translate 24 volts into the required 3.3v, 5v, 12v, and 24v rails used by the motherboard and peripherals.

Motor Control

The success of the Pololu Simple Motor Controllers on the CATfish carried to BEARacuda. Due to a higher current load, the 18v15 model was chosen as a successor, which works with power supplies up to 30 volts and can source up to 15 amps without a heatsink. A highly desirable feature of the Pololu controllers is the configurability via USB – the Pololu software allows the user to change device IDs, adjust interface settings, set maximum duty cycles, and set acceleration and deceleration rates to limit current spikes. In addition, the controllers can receive commands through a serial interface.

Peripherals

An Arduino Leonardo hosts a custom shield that powers LED strips for indication, interfaces with the depth sensor, and measures humidity to prevent catastrophe in the event of a leak. The Arduino is also responsible for communicating motor commands to the Pololu Simple Motor Controllers on a serial bus.

Tethered Operation

CATfish sported a keyboard, video, mouse (KVM) extender, which was mediocre at best and abominable at worst. The team moved to a server-based setup in which static html pages are sent over a CAT5 tether to an on-short router. Users can access the router and load the dashboard, which transfers telemetry and commands through websockets. This allows more than one member to work on the vehicle, increasing throughput and decreasing the cost and number of components.

Sensors

What sets AUVs apart from their ROV relatives is the amount of data collection and manipulation. The accumulation of sensory input is what allows an AUV to measure and act upon changes in its environment. The BEARacuda employs a combination of sophisticated and low-cost sensors to achieve this goal.

A Logitech C615 HD web-camera and a GoPro Hero 3 White provide high-res visual feedback in the forward- and downward-facing directions, respectively. An MPXA4250AC6U pressure sensor provides linear depth measurement at sub-inch accuracy. The battery voltage, current, and state-of-charge are monitored by the power management board.

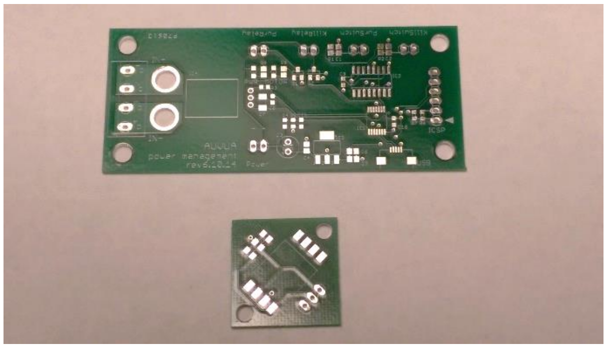


Figure 7: Power management and pressure sensor boards prior to population.

The most important sensor for underwater navigation is the PNI Corp. TRAX AHRS module, which provides very accurate heading, pitch, roll, angular velocity, and accelerations with hard- and soft-iron correction. Magnetometers measure magnetic disturbances and switch the heading measurement from the digital compass to the gyroscopes for temporary stability. Without a DVL or active sonar, determining the AUV's exact location becomes extremely difficult, but the high-precision digital compass provides a sufficient means of closing that gap.

Pinger Localization

The final mission task of surfacing above a pinger presents a unique challenge for which there are no COTS solutions. Although it's possible to create a cheap, home-built hydrophone, a higher quality solution was desirable. AUVUA partnered with the Carl Hayden High School Robotics team in 2013 to build a localization module for mutual use between the two teams during the competition. Falcon Robotics purchased four Reson TC4013 piezoelectric hydrophones, while the AUVUA designed and fabricated a localization board that utilizes the hydrophones and interfaces easily with both platforms. Although the board won a PCB design award, it was not successfully deployed at competition.

This year, a simplified design will be used, taking advantage of a Xilinx FPGA on a Mojo V3 board. A shield was created with programmable gain amplifiers and 16-bit, 500ksps analog-to-digital converters, both with SPI interfaces. The FPGA dynamically adjusts the gain and uses a fast, 64-point fast-Fourier transform to detect the presence of a signal. Once found, four channels store data for one millisecond at full speed. Finally, the data is sent to the main CPU for computation. Eventually this final step will be off-loaded to the FPGA, creating a user-friendly passive sonar detector.

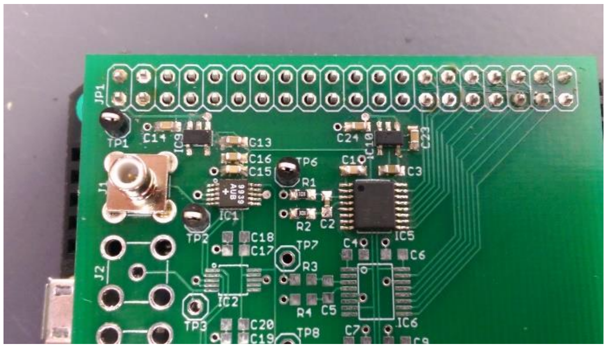


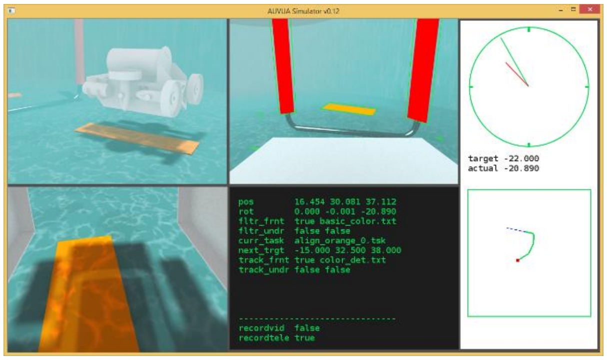
Figure 8: Single channel of localization board. The 10-pin TSSOP is a MAX9939 programmable gain amplifier, and the 16-pin SOIC is an ADS8327 16-bit ADC.

Software Design

Introduction

The software for BEARacuda was designed from the ground-up to be user-friendly and easy to adjust. Because CATfish was the inaugural vehicle, the team had a limited understanding of the competition environment and which elements were of the utmost importance. The main feature this year is the ability for members to edit mission files and view telemetry concurrently on a fluid interface built on sound technology.

The software system of the AUV is composed of several main sections: the model, agent, server, and simulator, as well as a separate hardware interface process. The model contains a current world-view of the vehicle accessible globally by other components. The agent executes the mission, altering the path and tasks dynamically based on task outcomes and parameters. The server communicates to the users' browsers through websockets, collecting commands for movement, relaying telemetry data, and receiving updates to the mission path and vision filters. The simulator and hardware interfaces are interchangeable, allowing the team to test various mission scenarios before running them on a physical machine. A simple message library, ZeroMQ, is responsible for transferring information between the simulator/hardware and the main components.



```
target -22.000
actual -20.890
```

```
pos         16.454 30.081 37.112
rot         0.000 -0.001 -20.890
fltr_frnt   true basic_color.txt
fltr_undr   false false
curr_task   align_orange_0.tsk
next_trgt   -15.000 32.500 38.000
track_frnt  true color_det.txt
track_undr  false false



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recordvid   false
recordtele  true
```

Figure 9: Early simulator GUI.

Planning Agent

The majority of the artificial intelligence takes the form of a mission planning agent. This agent is responsible for loading and parsing mission XML files into task objects that are then run sequentially. Tasks are written in native Java code and parameterized by the XML files. Tasks are hard-coded into the agent and parameterized and itemized in XML to achieve runtime adaptations for faster autonomous script testing. Tasks are threaded and capable of creating and executing additional tasks, allowing for a hierarchical, modular mission design. Each task can complete in three ways: success, failure, and time-out, giving more flexibility in the execution of the course.

Image Processing

The need for image processing is essential for underwater autonomy. Java bindings for OpenCV enable the team to include powerful, open-source vision algorithms with little effort. One unique algorithm uses RANSAC and affine transforms to create a map of the floor of the pool, which can then be referred to for measurements and location determination.

Peripheral Interface

The primary method for the host computer to interface with the physical world is through the Arduino peripheral controller. An Arduino Leonardo acts as a simple bridge, reporting digital and analog inputs and relaying commands to switch high power outputs. From a software perspective, the peripheral board maintains a constant communication line with the host processor to ensure a high level of safety. Once a safety layer has been put in place, the only remaining work is to switch digital outputs to the desired setting and collect, package, and send basic telemetry information.

Pinger Localization

The hydrophone localization board features a Xilinx Spartan-6 FPGA on a Mojo V3 development board. The FPGA is capable of performing Fast Fourier Transforms (FFT) on each of four hydrophone signals to determine the heading and altitude to the pinger source. The pinger generates a sinusoidal pressure wave at a constant frequency between 22kHz and 30kHz (in 1kHz increments, so 22kHz, 23kHz, 24kHz, etc. are all possibilities) for 1.3 milliseconds every two seconds. As such, the algorithm requires a peak detection scheme to identify the front of the wave. Once the wave front is detected, each hydrophone channel is recorded for the 1.3ms duration, then processed in the remaining two seconds until the next wave. Processing involves taking a high-point complex FFT of each channel, extracting the phase angle at the given frequency, and comparing phase shift between pairs of hydrophones. Basic trigonometry and physics are used to determine the heading and altitude to the pinger. Hydrophones are spaced apart by a maximum of the half-wavelength of the highest target frequency being measured (in this case, 30kHz).

Community Outreach

Members of AUVUA have spent numerous hours mentoring southern Arizona robotics teams: the Bit Buckets and team CRUSH of Tucson and the NERDS from Sierra Vista, who participate in the FIRST Robotics Competition and similar challenges. The team has shown the CATfish at several community events, including a National Robotics week STEM outreach event at a local library. AUVUA met with middle- and high-school students at College Knowledge for Parents to promote higher education and its tangible results. Once the AUVUA has a finished system, the team intends to increase its efforts in the community.

Acknowledgements

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> Marcos Garcia Acosta and Intel, PNI Corp, Advanced Circuits, Fredi Lajvardi, Carl Hayden Robotics team, Jim Forbes, David Forbes, Steven Forbes, and Dr. Hal Tharp.