MONTANA STATE UNIVERSITY

Department of Mechanical and Industrial Engineering

ETME 489 Capstone: Mechanical Engineering Technology Design I,

EELE 488R Capstone: Electrical Engineering Design I

and

EMEC 489R Capstone: Mechanical Engineering Design I

AUVSI: RoboSub

by

William Beckmann

Javion Blake

Catherine Bothwell

Thomas Wietecki

Ethan Block

Cooper Rictor

For: Dr. Robb Larson, Dr. David Miller, and Mike Kapus (NAVSEA-Keyport)

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Department of Mechanical Engineering Montana State University Bozeman, MT 59717

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Montana State University
2011 – 2012 Capstone:
Autonomous Underwater Vehicle

William Beckmann, Javion Blake, Ethan Block, Catherine Bothwell, Cooper Rictor, Thomas Wietecki

Advisor: Dr. David Mill

Abstract – **The AUV Bob is an underwater vehicle developed by a team of senior capstone Mechanical and Electrical Engineering students at Montana State University. MSU's AUVSI club is developing the programming that will allow Bob to run autonomously. An 8 month period serves as the design cycle, with the first half focused on the main design and the second half on the building of the vehicle. Solidworks was used to model the entire AUV and it is planned to manufacture the entire structure in house. This year's design has completely changed from the last capstone team. Notable features include the 8020 anodized aluminum frame that allows for easy movement of enclosures, the cylindrical hull, and the use of SeaBotix thrusters**

INTRODUCTION

MSU's Autonomous Underwater Vehicle capstone team's objective is to design and produce an AUV that can compete in the annual AUVSI & ONR Robosub Competition that is held in July at the San Diego, CA TRANSDEC facility. The goal of the competition is to challenge student teams designed AUVs with a series of tasks that range from the detection of different elements such as buoys, object interaction/manipulation, and navigation. These are simulations of missions that an employed AUV could perform. Within the tasks are elements such as shape/color recognition and marker dropping. Each mission the employed by the vehicle must be completed free from human control of the AUV.

The 2011-2012 MSU AUV design and build was achieved by a team of Mechanical and Electrical Engineers and Computer Scientists.

DESIGN OVERVIEW

The design of the AUV, Bob, is a modular set-up with a main central hull. This allows the system to be easily modified without having to disrupt the main housing.

Key focuses of the design were reduced weight and easy accessibility to internal parts. These were achieved through the use of an aluminum frame and removable end caps for the main hull and battery compartments.

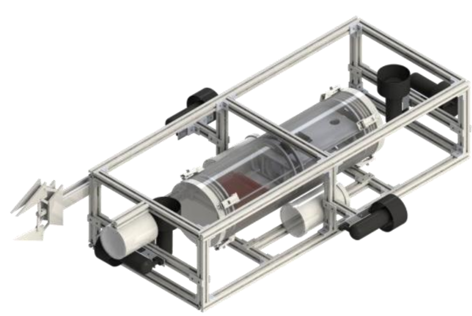

Fig. 1: A Solidworks rendering of Bob

Bob's total weight is approximately 55 pounds. It also measures 40 inches long, 16 inches wide and 10 inches tall. The main frame of aluminum is rigid and completely surrounds the main hull. There are 6 thrusters mounted to the vehicle, which allows for 5 degrees movement freedom control. Each thruster is rated to produce roughly 4.5 lb_f of force. Batteries power the entirety of the vehicles systems from the sensors to the motherboards. Through the use of an internal motherboard set up, all software processes take place onboard the vehicle.

MECHANICAL SYSTEMS

Mechanical systems are comprised of the external frame, the main hull, and external enclosures. The frame is responsible for providing a mounting structure for all the components, while the main hull and enclosures are responsible for housing all the electronics and sensors while maintaining a watertight seal to keep the components dry and functional.

A) *Frame*

The main goal of the frame design was to facilitate easy adjustment of any mounted components. This allows Bob's weight distribution to be modified on the fly during testing or at the competition. Anodized Aluminum 8020, or T-slot bar stock, encompasses the entire outer frame. Flat and 90 degree angled brackets join the frame sections together while zinc plated connectors are used to hold the different enclosure on.

The thrusters are mounted along the neutral axis of the AUV to minimize any exerted moments. Battery canisters are attached so they are resting on the bottom of the frame, adjacent to the main hull, which is being attached to the frame using ratchet straps. As the majority of the weight is focused on the lower half of the vehicle, the roll of the vehicle will be geometrically controlled.

ANSYS FEA was run on the frame with the applied loads from the thrusters as well as the pressure that the system could encounter at the bottom of the operating environment (see Fig. 2).

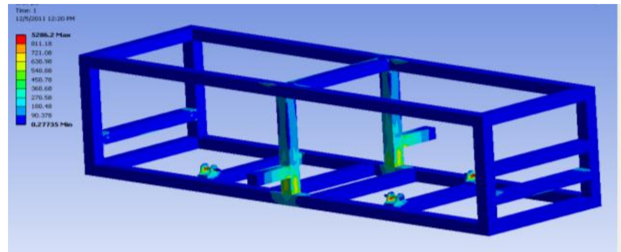

Fig 2: FEA on Bob's Fram

B) *Main Hull*

An acrylic tube makes up the main hull of the AUV which houses the electronics that run Bob. The optical clarity of the acrylic allows the downward facing camera, which is internally mounted, minimal distortion. Also, the transparent tubing allows the team to monitor the internal electronics through a series of LEDs that displays component status.

The electronics rack in the interior of the hull features three plates that hold all the electronics from the motherboard to the motor controllers (see Fig. 3). Four rings hold the plates and allow them to smoothly slide into the hull. CNC machining and hand processes were used to machine the pieces out of polystyrene.

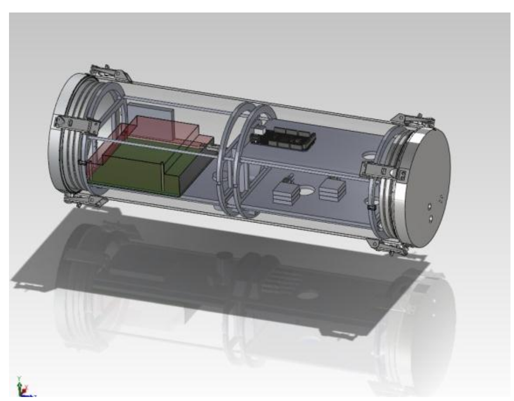

Fig. 3: Model of main hull with electronics rack.

End caps made of 6061 Aluminum were turned on a lathe and finished with a mill for the main hull. They feature an o-ring and gasket system to provide a watertight seal. The rear end cap also contains a series of wet connectors allowing for a quick disconnect of external sensors and batteries (see Fig. 4).

Fig. 4: End cap showing o-rings and wet connect cut outs.

C) Enclosures

The external enclosures on the vehicle house the batteries and the visual sensors. These are individual pressure vessels separate from the main hull and are connected to the main hull via their respective wet connectors.

i) Battery Housings

Bob's batteries are held in two separate enclosures that rest on the frame below the main hull, attached by toe-straps from snowboard bindings to the 8020. Each canister is made completely of aluminum which will help with heat dissipation while power is being drawn. One end of the enclosure will be permanent while the other end will have a layer of gasket between the cylinder and the end plate which will be held on with screws (see Fig. 5).

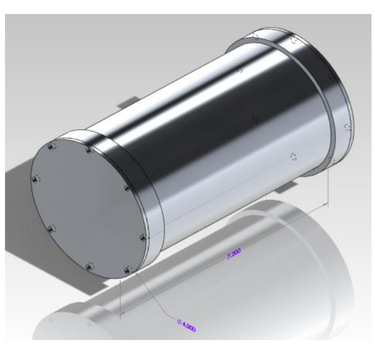

Fig 5: Aluminum battery housing

ii) Camera Housing

The camera housing is very similar to the battery enclosures. It will be built out of the same aluminum tubing but rather than being made of aluminum, the front end plate will be made of acrylic sheet. This will provide a clear viewport for the web cameras. Wet connects will be attached to the back end cap to run cables back to the main housing.

D) Pneumatics

The pneumatic system for Bob has been fully designed but not yet integrated into the frame or electrical system. A claw is the most prominent feature that will allow for the manipulation of different objects within the course. Also included in the system are a marker dropper and a torpedo launcher.

ELECTRICAL SYSTEMS

The electrical systems of the AUV are comprised of power, computing and control systems. The first focus is in providing an adequate and safe power supply for all electrical systems to ensure functionality. Secondly, interconnections between all components are organized to maximize the airflow within the hull and to provide organization to assist in future troubleshooting. Finally, a stability control system is implemented by translating position data from sensors into feedback voltages, using the motherboard and Arduino, that are then fed into the motor controllers which will control thruster firing groups and thrust levels.

Prior experiences with similar complex systems are at a minimum so the complexity was reduced to a manageable area. This included the use of a USB connection for as many components as possible and by using pre-made components such as the motor controllers, Arduino, IMU sensor and PC. The hope is to create a stable platform for the future design of specialized components and systems.

A) Power supply, regulators, and protection circuits

2 packs of 7 Ni-mH batteries are regulated by the use of step-down voltage regulators to supply a direct 16.8V to the thrusters, 5V to the USB hubs and pressure transducer and finally 12V to power the Mini-ITX motherboard (see Fig 6).To regulate voltage, a power PCB has been designed using Eagle CAD. Connections from the battery and output connections made to the 5V and 12V systems come from the PCB as well as all line fusing. To satisfy the kill-switch requirement, a relay with an activation voltage controlled by the Arduino is installed on the PCB breaking the line from the battery to the motor controllers. This Arduino controlled signal is also used to power a red LED used for visual identification from the shore.

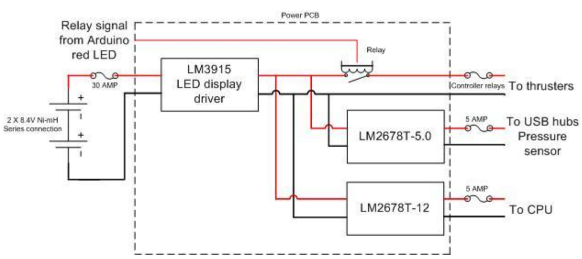

Fig. 6: A schematic of Bob’s power system

System status confirmation from shore side is made by a green-yellow-red LED system. These three indicator LEDs are connected to the system via digital pins on the Arduino and controlled by software. The green and yellow LEDs indicate normal or recoverable fault operation with the red LED signifying a non-recoverable system/software fault or the activation of the external mechanical kill switch. The activation of the red LED will always disconnect battery power from the thrusters.

B) Computing system

The computing system allows Bob to translate input sensor data into usable output signal data for control and also for autonomous operation. The main processor, used to take in sensor data and run all operation codes, is a 1.8GHz Atom D525 processor mounted in a Mini-ITX form factor. This processor supports hyper-threading so multiple operations can be performed simultaneously. Communication is then routed to an Arduino Mega 2560 board that provides all D/A and A/D conversions for signals used in the control system.

The Mini-ITX board is powered by 12V from the power PCB and connections to the rest of the system are all USB. Considerations were made to the bandwidth limitations of the USB 2.0 system, 480Mbps, so a motherboard was chosen with two Ethernet connections. This allows a serial connection from PC to Arduino while also maintaining a serial connection to shore so that communication between the PC and Arduino will never be compromised by the bandwidth limitations of USB 2.0.

The functionality of the ITX motherboard will be to communicate will Arduino while still having the capability to read and write to the static Solid State Drive (SSD) memory. The ITX will execute the navigation and artificial intelligence software.

The Arduino is what will communicate with the motor drivers and read in any external voltages from sensors or transducers. The five volt I/O pin capability makes it ideal for controlling signals to the drivers with maximum precision.

C) Motor controllers and thrusters

Pololu 21v3 digital PID motor controllers are used for feedback gain correction, and current regulators to the thrusters. The controllers can be programmed by the ITX to define the P, I, and D gains. A range of 0-5[v] can be set by the feedback pin in order to lose the loop around the control system.

6 BTD150 SeaBotix thrusters are used for propulsion. The motors will have an operation range of 0-3[A] due to the 3A restriction of the motor controllers.

D) Sensors

An Inertial Measurement Unit (IMU), which consists of a 3-axis accelerometer, 3-axis gyro, and 3-axis magnetometer, is used to measure the vehicles yaw, pitch, and roll angles (see Fig. 7). The data from the IMU is stored in the hard drive using the ITX motherboard then sent to the Adriano Mega for use by the motor controllers.

Fig. 7 : The IMU that will provide information to the ITX

A pressure transducer will allow the depth of the vehicle to be measured. The sensor outputs 0-5[v] which connects straight to the Arduino, that sends data back to the ITX and out to the motor controllers.

2 Microsoft HD cameras are used for vision (see Fig. 8). Both cameras run to the ITX board and are used in the ITX for navigation by the artificial intelligence software.

Fig. 8: Microsoft webcams will be the vision sensors

E) Control systems

Closed loop controls are implemented in the system to maintain stabilization. The IMU data is parsed through the ITX motherboard to the Arduino processor, where it is fed back into the motor controller. Pressure sensor data is used in the same way to control the vehicle's depth.

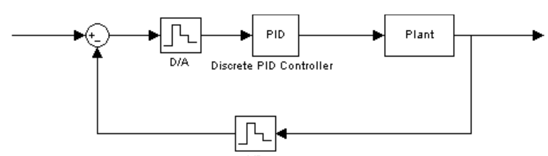

Fig. 9: A schematic of Bob's control loop

The closed loop system response is determined by the gains of the PID controller. The controller gains C(S) will place a pole and a zero in the system, which in turn alters the response of the plant to a given input value. The equation:

$$\frac{\emptyset(s)}{I(S)} = \frac{G(S)C(S)}{1+G(S)C(S)} \quad \text{(Closed Loop)}$$

is used to analyze the behavior of the closed loop system. Where G(s) is the plant, $\emptyset(s)$ is the output angle, and I(S) is the input current.

In order to characterize the plant, the system is assumed to act as a simple harmonic oscillator. This assumption led to the model of the plant being:

$$\frac{x(s)}{I(s)} = \frac{k}{ms^2 + Ds}$$

Once the model of the system was obtained, the pole placement method was used via root locus to find the position of the optimal poles for the design. This procedure was done in all three linear directions as well as roll, pitch, and yaw angles. After the optimal poles were located, the dominate poles were solved for in the closed loop transfer function of the individual systems, giving the equivalent PID gains for the feedback loop.

Using Simulink the response of each system was simulated to show the actual response of the estimated plant (see Fig. 10).

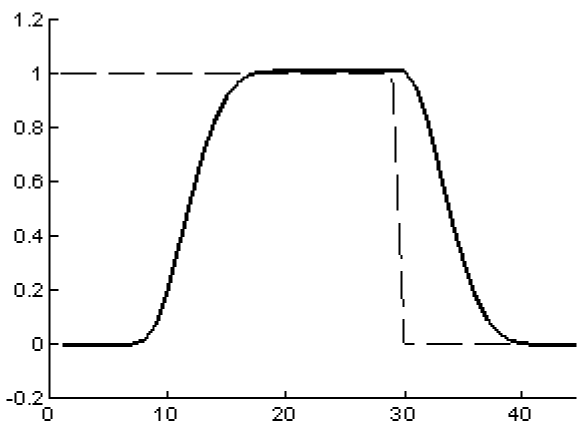

Fig. 10: The response to pitch control feedback loop

By evaluating the response it is apparent that the pole placement provided approximately the desired response of the system.

SOFTWARE DEVELOPMENT

The Mini-ITX motherboard serves as the main computing unit. The processor will have a thread specifically for the feedback sampling. On the dedicated data sampling threads used for digit sampling of the sensors for control purposes, there is a method that samples data from the IMU at 10ms. The data that is collected will be saved to folder in the static SSD. After storing the data, the ITX will store another copy of the value into a temp file that will be called "data_packet."

Once 'data_packet' is filled with all the sample data from the 10ms sample period, it will be sent to the Arduino microprocessor with a command to call the "data_out" method. The "data_out" method in the microprocessor parses in the values from "data_packet" then samples the data from sensors that input directly to the microprocessor. Finally a calculation is performed to convert the data sample variables into a normalized 0 to 5 volt signal on the I/O pins to the controllers. After the data is outputted on the pins, any variables sampled from the microprocessor will be stored to a file called "data_collected." That file will then be sent back to the ITX with a command to call a data storage method that stores the sampled data it receives in the static SSD. This process will repeat every 10ms.

Because the computer stores all the sampled data from the run, the data can then be analyzed after each practice trial to observe what data the AUV was actually seeing. This will allow for better correction methods in the navigation system for the vehicle.

ONGOING ADJUSTMENTS

The final weight of the AUV will be determined using a scale in the machine shop or EE storeroom. Initial buoyancy calculations will be updated in MathCAD and weight will be added or components modified to make the AUV neutrally buoyant.

Modifications to reduce weight would include welding frame sections that experience little to no movement to eliminate fasteners, drilling holes in the frame, and removing excess material on battery and camera housings.

Once the weight of the AUV is finalized, the neutral axis will be calculated and thrusters will be adjusted to lie on the same plane. Bubble levels will be utilized to adjust the translational and yaw thrusters so that they are horizontal to frame of the AUV. The housing positions will also be adjusted by moving along the frame, with the use of bubble levels attached to the frame. Once all adjustments are complete, the AUV should sit level in the water while no thrusters are being utilized.

A) Design Changes Made

Mechanical System

During the manufacturing process, several changes to the AUV were required. The epoxy specified to attach the latches to the hull didn't provide adequate strength, which was largely due to the interface between the acrylic and steel. An intermediate piece of acrylic was riveted to the latches and then attached to the acrylic hull using an acrylic-acrylic epoxy. The seal on the front of the camera housing was changed to a silicone epoxy instead of using a rubber gasket. This prevented the acrylic face from cracking when the screws were tightened.

The aluminum frame was modified to allow the hull to be attached to the top of the frame instead of the bottom. Four members were added and are depicted in the updated part drawings. Also the wet connects for the battery compartments were changed from Seaconn connectors to Teledyne Impulse connectors. A pneumatic claw was also completed. Originally, this was a "bonus" goal for the team if time this semester permitted. The claw has been added to the AUV with extra t-slot aluminum being added to house it on the front right of the sub. Computer code is currently being developed to control the claw and should be done by the competition in July.

Electrical System

A capacitor bank was added to the input of the voltage regulator to resolve the issue of low power during momentary current spikes.

Logic circuitry was added to the power PCB to handle the detection of kill switches instead of using Arduino resources.

Trace isolation on the power PCB proved to be problematic due to unexpected short circuits due to small copper fibers from the milling process or conductive material dropped onto the board. Another board was designed to eliminate the solid ground plane and the excess copper was milled away.

In the second revision of the power PCB a trace was created so that the activation of the external kill switch could be recognized by the Arduino. The accidental connection of this line to a hot 5V connection on the Arduino caused an internal short of the 5V system causing the USB chipset on the motherboard to burn up. This detection line was removed in the third board revision to reduce the chance of a repeat occurrence.

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