SubjuGator 2006

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ABSTRACT

Graduate and undergraduate students at the University of Florida are in the process of enhancing the capabilities of the fifth generation of their autonomous submarine, SubjuGator, to compete in the *AUVSI and ONR's 9th International Autonomous Underwater Vehicle* competition. SubjuGator is designed to operate underwater at depths up to 20 feet. The mission behavior of SubjuGator is controlled by a network of I^2C modules. This system includes sensors, motor controllers, and other necessary peripherals. A single-board Pentium M based computer running the Windows XP Embedded operating system provides processing power for the vision system and advanced signal processing. In this paper, we first describe the construction of the SubjuGator body and other mechanical systems. Next, we discuss the electronic and processing hardware as well as the motivation for our electronic design. Finally, we comment on vehicle control strategies and how we expect a typical competition run to proceed using the vehicle's subsystems.

1. Introduction

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsoring the ninth annual international autonomous underwater vehicle competition to be held in San Diego, California at the SPAWAR facility from August 2nd- 6th, 2006. A student team at the University of Florida is once again developing an autonomous underwater vehicle (AUV) for this year's contest. A majority of SubjuGator's electronics and mechanical systems have been completely redesigned to meet the challenges of the competition.

To successfully complete the competition objectives, submarines must be able to complete three tasks: pass under a gate to meet with a docking station, inspect a pipeline to find a target bin in which to drop markers into, and locate the surface zone.

In this paper, we first describe the mechanical construction of SubjuGator, including the mechanism used to deliver markers to the target. Next, we describe the electronic and processing hardware as well as the motivation for our electronic design. We then discuss the various on-board sensors and mechanisms, both mission-dependent as well as mission-independent. Finally, we comment on vehicle control strategies and how we expect a typical competition run to proceed using the subsystems on board SubjuGator.

2. Mechanical System

As a fifth-generation vehicle, SubjuGator embodies the lessons learned in nine years of AUV development. We considered several key design criteria, including survivability in a chlorinated or salt-water environment and its adaptability for different missions through a versatile thruster reconfiguration and future sensor additions. To assist in the mechanical design, we developed a computer model of our submarine, as shown in Figure 1.

Figure 1: SubjuGator design

The submarine was designed to be easy to work on and also easy for a diver to manage during the competition rounds. For the divers convenience the kill switch is located above and behind the submarine at a 45 degree angle. The electronics tray is easily removable from the SubjuGator body. Using a slot interface, we are able to simplify our wiring scheme and easily disconnect the electronics. The end caps are held in place by three clips placed 120° apart and two Velcro straps keep the clips from slipping. This clipping mechanism holds the end caps securely while allowing easy access to the internal electronics.

Blending composite materials with a pressure case design, SubjuGator is a compact submarine that fits in a 24" x 18" x 18" box and weighs less than 40 pounds.

2.1 Body

The central core of the body is a 6" by 17", polycarbonate tube. This gave us an inexpensive, waterproof, and lightweight housing that provides a clear front and bottom for downward and forward looking cameras. To complete the pressure case, a rear end cap is made from PVC and a front end cap is made of acrylic. Hard points and carbon fiber mounting plates support the thrusters and external peripherals. Figure 2 shows the platform body.

Two thrusters positioned in line with the body provide the submarine with forward and reverse thrust. These two thrusters will also provide yaw control. The three downward thrusters provide the thrust needed to submerse the submarine and also provide pitch and roll control. The five thruster configuration (see Figures 1 and 2) was chosen to provide control in all directions, as well as simplify the programming of the PID (Proportional Integral Derivative) controller. Each thruster can be individually controlled to thrust in either direction with a range of output power.

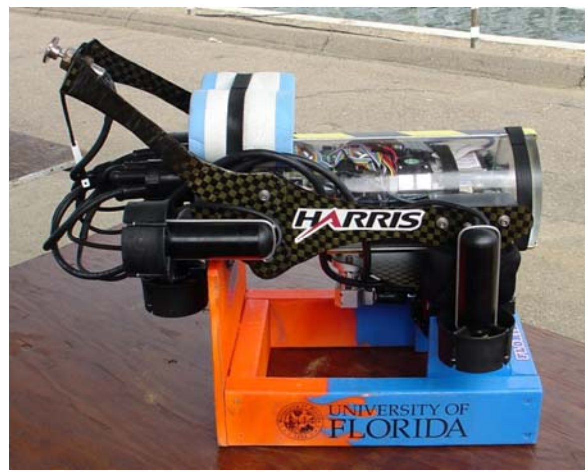

Figure 2: Platform body and thrusters

2.2 Motors

All five motors are Seabotix SBT150 sealed thrusters with 3" diameter propellers. At 24V these thrusters provide 6.4 lbs of thrust and require up to 80 watts. Each thruster weighs 1.5 lbs, adding 7.5 lbs to the total weight of the submarine. The thrusters are rated for a depth of 500 feet, and feature integrated leak detectors and current limiters. For safety, each thruster is shrouded to prevent accidental blade contact.

2.3 Through-hull connections

All of SubjuGator's through-hull connections use SEACON ALL-WET split series wet mate-able connectors. A kill switch is implemented with a Gianni hermetically sealed push-pull switch that disconnects power from the thrusters and initiates a software motor kill routine. A serial line and connections for the hydrophones are also accessible.

To keep the analog signal lines short, the hydrophone amplifier and acquisition board is mounted externally.

2.4 Interior Layout

A carbon fiber shelf fitted against the polycarbonate body provides support for all the internal electronics and power. The heavy batteries and are stowed under the shelf to provide a self-righting center of gravity for the submarine, making SubjuGator inherently stable. Electrical connections terminate at connectors on the back end cap of the submarine (see Figure 3) for efficient removal of the electronics shelf.

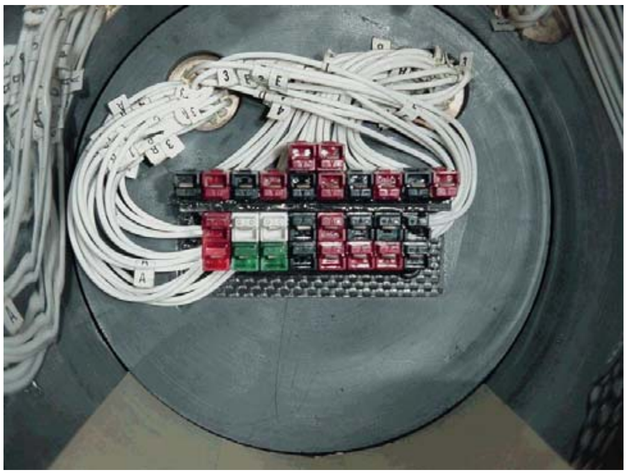

Figure 3: Through-hull electrical connections

2.5 Marker dropping mechanism

The dropping mechanism was designed to safely carry and deliver two markers to the active target and release them when the target is detected. The markers selected for use on SubjuGator are steel bearings with a diameter of 15/16 ± 0.002 in. A spherical shape was chosen to simplify the dropper mechanism design and the loading procedure.

The dropping mechanism is mounted externally on the bottom of the submarine. The mechanism is actuated by a solenoid that frees the steel bearings. Throughout the mission, the mechanism carries the markers within a machined aluminum holding tube (see Figure 4). When the target is detected, the solenoid is activated, pulling a pin that allows the markers to fall onto the target.

Figure 4: Ball dropper mechanism

3. Electrical System

The electrical system of our submarine consists of batteries, computing resources (x86 microprocessor and microcontrollers), and various sensors that provide environmental feedback to the vehicle. In this section, we describe each of the robot's subsystems in further detail.

3.1 Power supply

SubjuGator uses four PolyQuest polymer battery packs to power the thrusters. Each pack is made from four 4Ah lithium polymer cells connected in series. Lithium polymer chemistry batteries are preferable over other battery chemistries because of their higher energy density and lower cell count. Each pack is rated to continuously source 48A; since the submarine will draw a maximum of only 20A, the batteries will produce a very linear voltage until the packs run out. This will allow the submarine to provide the same performance throughout the life of the battery.

For the drive system, SubjuGator uses two of the 14.8V, 4Ah lithium polymer batteries connected in parallel. This provides the submarine with a 14.8V, 8Ah power source for the thrusters. The worst case run time of the submarine is estimated to be 24 minutes; each of the five thrusters will draw 4 amps maximum, producing a 20A maximum current draw.

The submarine uses a single 14.8V, 4Ah lithium polymer battery to power the electronics system. Finally, a single 12.1V 4.4Ah battery is used to drive a 120W pico-psu embedded switching power supply. The pico-psu delivers reliable power while only occupying a space slightly larger than a standard ATX connector alone.

3.2 Computing

The various tasks of the computing system on SubjuGator demand different approaches, requiring various hardware and software solutions. The vision system requires a powerful processor to perform real-time scene analysis. Thus, an Advantech PCM-9380 Pentium M 3.5" embedded single-board computer is utilized for on board processing. The 1.8Ghz Pentium M processor coupled with 1GB of DDR RAM provide a powerful platform for vision processing, debugging, and in-water programming. The Windows XP Embedded operating system along with Matlab 7 were utilized in order to create an easy and quick development environment. This computer uses a 6GB microdrive for program and data storage.

The subsystems and sensors of the AUV are integrated using Atmel AVR microcontrollers. The microcontrollers make higher level decisions and control analog and timing related interfaces.

3.2.1 Microcontrollers

The core of the SubjuGator computing system is a network of 5 ATmega8 modules and 2 ATmega128 modules linked together using an I^2C bus. The ATmega8 and ATmega128 eight-bit microcontrollers have a multitude of peripheral capabilities that lend themselves to straightforward implementation of sensor and control units. Each microcontroller has a specific task such as controlling a motor, reading a compass, or as an interface to the PC. (The architecture for our system can be seen in Figure 9, at the end of this document). This distributed system allows for circuit/software problems to be quickly isolated and thus debugging is much easier than in a conventional centralized system.

The 2006 microcontroller network has had some significant changes in comparison to our 2005 networks. One main change is the arbiter microcontroller is now an ATmega 128 instead of an ATmega 8. The ATmega128's larger memory allows us to implement a much more robust search and controls algorithm.

The only sensors not integrated directly to the microcontrollers are the cameras and the hydrophones (which require preprocessing to obtain the desired information).

Please see Figure 9 at the end of this paper for a diagram of the high level system architecture.

3.2.2 Altera FPGA

An Altera Cyclone EP1C3T144 FPGA serves as the hydrophone data acquisition device. For further information on the hydrophones, please refer to Section 3.4.3.

3.2.3 Image processor

Image processing is handled by an on-board 3.5" SBC (Single Board Computer). The Pentium M based 1800MHz board has 1GB of RAM, 6GB microdrive, USB 2.0, and runs Windows XP Embedded. The 5.75" inner diameter of the submarine and the computationally intensive computer vision algorithms influenced the decision to go with the Advantech PCM-9380.

Windows XP Embedded is the operating system used for the on board computer. The XP-E OS speeds development by allowing the use of commercial drivers for peripherals such as the cameras.

3.2.4 Wireless system access

A communications interface between a base station and the vehicle utilizes a water proof Category 5 Ethernet cable that connects the submarine to a wireless Ethernet router (802.11b/g) with up to a 54Mb/s data path. We are using a floating wireless buoy that is dragged behind the sub to provide engineers with real time data even while the robot is submerged. This allows remote access to SubjuGator's computer, FTP, and simultaneous programmer access for parallel code development and debugging.

Testing of the submarine is performed by remote operation through software running across the wireless link. By viewing the real-time sensor data, we can tune most aspects of the submarine's intelligence and control, including PID coefficients and arbiter modes.

3.3 Navigational sensors

For even the most basic operation, an AUV must be able to maintain a heading, depth and attitude.

Regardless of mission specific operations these sensors provide basic AUV control.

3.3.1 Digital compass

SubjuGator uses a TCM5 compass (see Figure 5) from Precision Navigation. With a triaxial magnetometer and a microprocessor, this compass generates heading, tilt and roll information throughout its operational range. This sensor interfaces with a serial port on an Atmel microcontroller.

Figure 5: Precision Navigation TCM5 Compass

The compass provides a set of outputs that, when combined with a subset of the desired parameters, contribute to the determination of some of the error inputs to the PID controller.

3.3.2 Depth sensor

Depth measurements are gathered with a Measurement Specialties MSP-300 series pressure sensor. This sensor is rated to 100 PSI, with a rated accuracy of +/- .25 PSI, and outputs an analog voltage between 1 and 5 volts. This translates to a depth resolution of +/- 2 inches. The depth sensor interfaces with an A/D converter on an Atmel microcontroller. This is used as an error input to the PID controller.

3.4 Mission-specific sensors

To complete the mission objectives, the submarine needs sensors specific to each of the six distinct tasks. The first task requires the submarine to hold a steady heading while passing under the validation gate. Additional points can be accumulated during the second task by viewing and decoding the information provided by a random order light box. These lights describe the mission parameters for the pipeline stage. The frequency and color of the light determines the proper bin in which the submarine should drop its markers.

After passing through the gate, the submarine must attempt the third task: to locate and engage a simulated docking station. The docking station is represented by three omni-directional light sources and can be engaged by lightly tapping the station with the submarine.

The forth task is to find and follow a pipeline in order to locate the target bin described in the second objective. To complete the fifth task, the submarine needs to drop two markers in the appropriate target bin. The pipeline is represented by orange PVC panels and the target bin by a black 1’ x 2’ rectangular box inside a white 2’ x 3’ rectangular box. Each of the four drop zones has a unique green hatching style.

The sixth and final task requirement calls for the submarine to surface in a 9’ diameter octagonal surface zone. The surface zone is marked by an acoustic pinger resonating at a pre-run specified frequency (between 20 and 40 kHz) every two seconds. The rest of this section describes the higher-level sensors and algorithms used in the SubjuGator to complete this mission.

3.4.1 Color Sensor System

The random order light box emits a signal specifying the bin in which the sub must drop the marker. This signal is classified by a color, red or green, and a frequency, 2 kHz or 5 kHz. The 2 kHz or 5 kHz is also modulated at 2Hz or 5Hz, respectively.

Detection and classification of the signal is done using a color sensor (Taos TCS230) that outputs the detected intensity of red and green light individually. This output is a frequency modulated signal, ranging from approximately 100 kHz to 600 kHz. An FPGA is used to sample this sensor by simply counting the time between rising edges on the output. These samples are fed into a microcontroller at a rate of 50 kHz. The microcontroller takes the inverse of the count value, providing a frequency that corresponds to the intensity value.

An IIR resonance filter is then applied to the intensity values to determine the frequency of the blinking light. This filter includes two tight pass bands centered at 2 kHz or 5 kHz. The average magnitude of the time-domain output is computed for green and red light, filtered at 2 kHz and 5 kHz. However, the values between red and green cannot be directly compared due to differences in intensity of the ambient light for red and green. Instead, the ratio of the maximum of the two frequencies for each light to the minimum is computed, and these ratios are compared. The ratios are also compared to a threshold to ensure that the light box is actually in view.

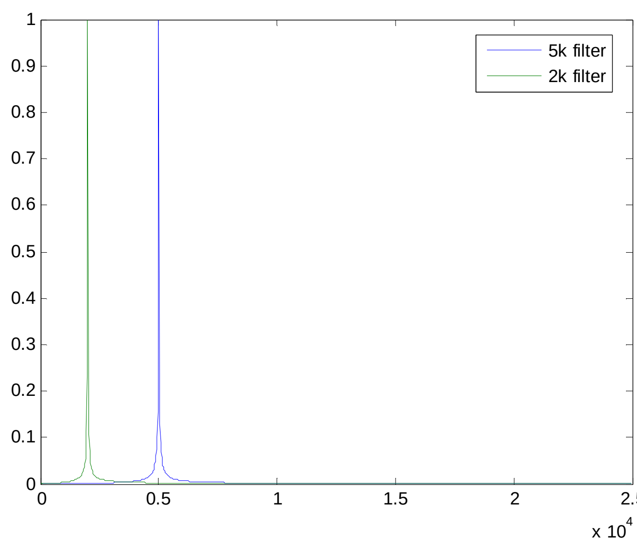

Figure 6: Resonance Filters Impulse Response

The IIR resonance filters are 2^{nd} order. The impulse responses of the filters are shown in Figure 6.

3.4.2 Computer Vision System

The onboard SBC takes in video feeds from two USB cameras. Both cameras are mounted inside the transparent pressure case. One camera is mounted behind the clear acrylic end cap in the front of the sub and the other is mounted in the back of the sub facing down.

The submarine searches for the pipeline using the downward facing camera. To find the pipeline, we characterize the image using a pre-trained Gaussian Mixture Model (GMM),

$$p(x|\theta) = \sum_{k=1}^{n} w_k N(x, \mu_k, \Sigma_k),$$

where n represents the number of Gaussians in the model, μ the mean, ∑ is the variance, and w is the weight of the k^{th} Gaussian component.

The multi-dimensional Normal function, N, is

$$N(x, \mu, \Sigma) = \frac{1}{2\pi|\Sigma|^{\frac{D}{2}}} exp(-\frac{1}{2}(x-\mu)^T \Sigma^{-1}(x-\mu)).$$

defined as,

A GMM is trained for each of the three major classes of objects to be encountered in this stage of the competition: Water/pond floor, pipeline, and the drop zones. While the training of a single Gaussian can be done using Maximum-Likelihood Estimation, multiple Gaussians have no closed-form solution and require the EM (Expectation-Maximization) algorithm to iterate to a solution. The EM algorithm guarantees the convergence of the models parameters, θ, to a local maximum.[1]

The GMMs generated in training are then continuously evaluated during the mission. Once a significant length of pipe is found, a Canny edge filter is applied to find the edges of the pipeline. The edge image is then used by a Hough Transform to find the orientation of the lines. The orientation of the pipe relative to the submarine's current orientation provides a new offset heading for the submarine to follow.

To avoid confusion in variably-lit environments where colors can appear similar and less substantial intensity changes can obscure edges, SubjuGator employs a color analysis to detect bins surrounded by a green hatched area on a white background. If the proper hatching is found, the algorithm then calculates the center of mass of the selected bin. The analysis is implemented using an algorithm of run-length coding followed by a pair wise line splicing.

The pipeline is followed until a break in the pipelined is discovered using the same Gaussian modeling procedure. The angle of the stripes relative to the angle of the pipeline determines whether the submarine ignores the bin or attempts to drop the ball in the bin. If the correct bin is detected, the sub attempts to center itself over the center of mass of the bin. Once over the bin, the two markers are released using the solenoid-activated ball dropper mechanism described in section 3.5 and shown in Figure 4.

During testing we noticed that the sun light was sometimes too intense for the cameras, causing them to saturate or "white out." We added two 2.0 Wratten filters to the cameras to help limit the amount of light coming into the lenses.

3.4.3 Hydrophone System

The hydrophone system consists of four basic stages that aid in obtaining and processing the signals transmitted by an acoustic pinger:

1. Acoustic Transducer
2. Analog Filter and Amplifier
3. Data Acquisition
4. Digital Signal Processing

The hydrophone system provides a means with which to detect acoustic vibrations in the water, such as the signals transmitted by the acoustic pinger located below the center of the surface zone. SubjuGator utilizes three hydrophones mounted in an isosceles triangle configuration to create the geometry needed to identify the direction from which the received signals originated.

The hydrophones provide a voltage representing the strength of the acoustic signal. To clean up the signal, we filter out all frequencies outside 20 to 40 kHz using a 2nd order band pass analog filter. The filtering removes low and high frequency noise present in the signal. The resulting voltage level of the signal is typically in the range of 50 to 200 mVp-p, depending on the strength of the pinger's signal, and must be amplified to a range appropriate for the analog-to-digital converters.

Data acquisition is controlled by an onboard FPGA. The FPGA samples all three hydrophones simultaneously at a rate of 400 kHz. The data is stored in local memory and shifted out serial to the onboard SBC. The signals are then passed through a tight band pass filter to reject neighborhood frequencies in the practice area. Finally, the phase difference between the three sampled signals determines the heading of the acoustic pinger relative to the submarine.

3.5 Solenoid

A solenoid is mounted on the ball dropping mechanism outside the submarine on a platform mounted underneath the sub. The purpose of the solenoid is to retract a rectangular pin, actuating the marker dropping mechanism and releasing the markers onto the target. The dropping mechanism and markers are discussed in section 2.5.

The solenoid is triggered by a transistor circuit. When the circuit receives a logic high signal from the FPGA controller, the signal activates a transistor which grounds the solenoid and allows current to flow. The solenoid in turn actuates the dropping mechanism to drop the markers onto the target.

4. Vehicle control and strategy

4.1 PID controller

Control of the submarine is implemented using a proportional, integral, derivative (PID) based controller. This general control technique is used in four independent PID algorithms that calculate compensator values for four different degrees of freedom. These are pitch, roll, depth, and yaw for which feedback is attained through the depth sensor and compass unit. The controller calculates a value for each thruster based upon the relevance that each compensator has towards the thruster's effect upon the submarine. This relevance is determined by internal gain settings defined during testing. Each motor is independently affected by each of the four degrees of freedom giving the submarine the ability to navigate into any direction.

Each of the continuous control equations are converted to their discrete-time equivalent and the errors are calculated from the differences between the current and desired heading, pitch, and depth, using the following equation:

$$m(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$$

In the above equation, m(t) represents the motor value and e(t) represents the error at time step t. The individual gains (Kp, Ki, Kd) are tuned through repetitive testing at various depths and operating conditions. For each of our possible speed and depth range configurations, we maintain a separate set of control parameters. These parameters are determined through experimentation and simulation. (Figure 7 shows the submarine in the water during the tuning of these control parameters.) The PID controller was initially designed in MATLAB and ported to an Altera ATmega microcontroller for control in the submarine.

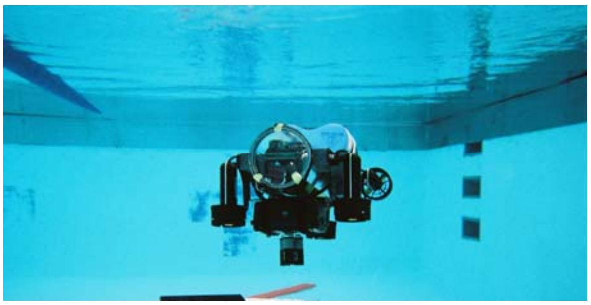

Figure 7: Testing the PID control of SubjuGator

Depending on the mission task, the error inputs for the PID control are determined by the arbiter. For example, during the docking task, the computer vision algorithm will determine the error input for the PID control, along with the depth, pitch, and roll sensors. During the surface zone mission task, the hydrophone processing error would be input to the PID control in place of the vision processing error.

4.2 Arbiter

Each of the sensor analysis processes makes heading, speed, and/or depth requests to improve the position of the submarine in relation to the targets. Due to the various strengths and weaknesses of particular sensors and the occasional sensor anomaly, these requests may sometimes conflict. Therefore, we have implemented an arbiter, a rule-based algorithm specifically tuned for the competition environment. The arbiter is tasked with deciding on the next action for the submarine, given the various, possibly erroneous, sensor inputs. The arbiter is implemented in an Atmel ATMega128 microcontroller. This microcontroller is interfaced with the PC for the vision and hydrophone sensors and the ATMega8 microcontrollers for the color sensor, compass, and motor drivers. The mission order and strategy implemented in the arbiter is described in section 3.4.

Our solution to locating the correct target and delivering our markers to the target will logically proceed as follows: The submarine will dive to a predetermined depth and travel through the validation gate. While traveling through the gate, SubjuGator will look for the random order light box to determine which of the four bins is the target bin. SubjuGator will continue on its course while using its camera system to find the docking station. When the docking station is found with the vision system, SubjuGator will attempt to run into it to complete the docking task.

The vision system's downward looking camera will then look for the pipeline. When the pipeline is found, SubjuGator will follow the course of the pipeline until it finds the amorphous blob. The vision system will then center the submarine over the proper target bin and drop the markers. After dropping the markers, the hydrophone system will then tune itself to the frequency of the pinger and the submarine will travel towards the signal until the surface zone is reached. The surfacing of the submarine will signify the end of our run.

5. Updates for 2006 and for 2007

In the 2006 SubjuGator we have redesigned most of the electronics (designing nine new printed circuit boards), rebuilt the body and hard points, added a new set of smaller and more sensitive hydrophones, and also added a new external electronics enclosure. We have also designed a new body that we plan on using for the 2007 competition.

We have already made the tube, hard points and composite material mounting structure for the 2007 SubjuGator. There are really two major differences in the 2007 body and what we are now using in 2005-2006 body, thruster configuration and weight distribution. The 2005-2006 SubjuGator thruster configuration allows us to control roll, but we found that we did not need stabilization around the roll axis. The inherent roll stability of the sub is due to the heavy batteries at the bottom of the sub. For the 2007 SubjuGator design we therefore plan to remove one of the three vertical thrusters. The plan is to add a thruster underneath the sub as shown in Figure 8. (Compare Figure 1 to Figure 8 to notice the changes.) Pitch and yaw axis will now be controlled using only 4 thrusters (instead of 5) and the 5th thruster will allow us to strafe. The locations of the thrusters in the new sub will also help with the weight distribution, allowing us to lighten the sub by about 20 percent. This weight will come from the removal of the two 2½ lbs weights wrapped around the forward thrusters. With the removal of these weights we will also be able to remove the floatation device at the back of the sub. (The blue and white floatation device can be seen in Figure 2 on the back of the sub.)

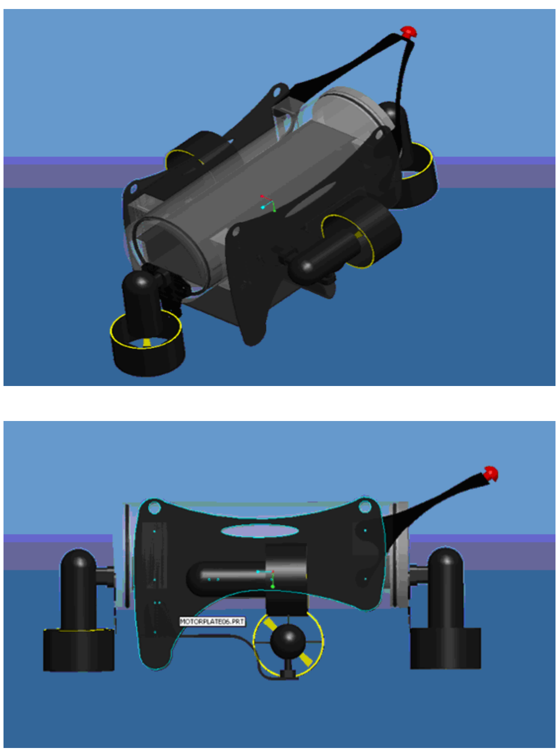

Figure 8: 2007 SubjuGator mechanical design

6. Acknowledgments

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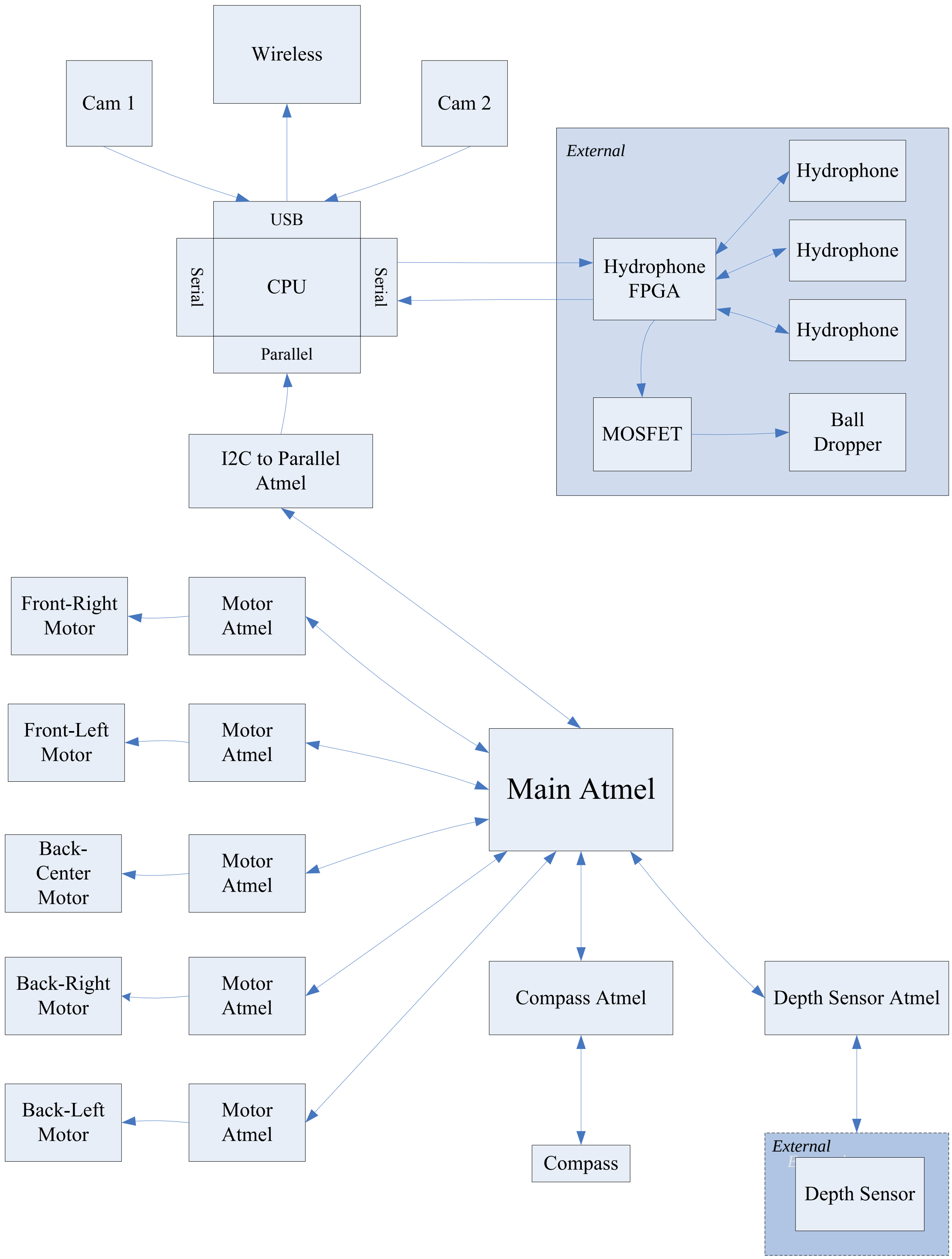

Figure 9: SubjuGator high level system architecture