SubjuGator 2009

Thomas P. Feeney, Patrick Walters, Nic Fischer, Subrat Nayak, Jose Morales, Cedric Adam, Owen Allen, Gautam Dash, Brian Long, Dana Massaro, Eric M. Schwartz, A. Antonio Arroyo

Machine Intelligence Lab (MIL)
www.subjugator.org
(352) 392-6605

ABSTRACT

For the past twelve years, students from the University of Florida's Machine Intelligence Laboratory (MIL) have brought their minds together to design and create autonomous robots with a focus on solving real-world problems for industry and military applications. Most of the team is currently enrolled in the Electrical and Computer Engineering or Mechanical and Aerospace Engineering departments. These graduate and undergraduate students are continuing the development of the sixth generation of their autonomous underwater vehicle, SubjuGator, for competition in the AUVSI and ONR's 12th International Autonomous Underwater Vehicle Competition. SubjuGator is designed to operate underwater at depths up to 260 feet. Two 3.5" x 5.75" Intel Core 2 Duo computers running Microsoft Windows Server 2003 provide processing power for monitoring and controlling all systems. The mission behavior of SubjuGator is controlled with the Microsoft Robotics Developer Studio (MSRDS) framework that communicates with a network of intelligent sensors. The sensor network includes two cameras, hydrophone array, Doppler velocity log (DVL), inertial measurement unit (IMU), compass, depth sensor, imaging sonar, and altimeter. The submarine also makes use of custom-designed motor controllers with current sensing, four external actuators, and other peripherals necessary for completing the mission.

Keywords

Submarine, Autonomous, SubjuGator, AUVSI, Robot

1. INTRODUCTION

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) sponsored the twelfth annual International Autonomous Underwater Vehicle Competition, held in San Diego, California at the SPAWAR facility July 28th through August 2nd, 2009. A student team at the University of Florida's Machine Intelligence Lab developed an autonomous underwater vehicle (AUV) for the 2009 contest. This sixth generation SubjuGator (Figure) has evolved to not only meet the new challenges of the competition, but to engage in groundbreaking research projects.

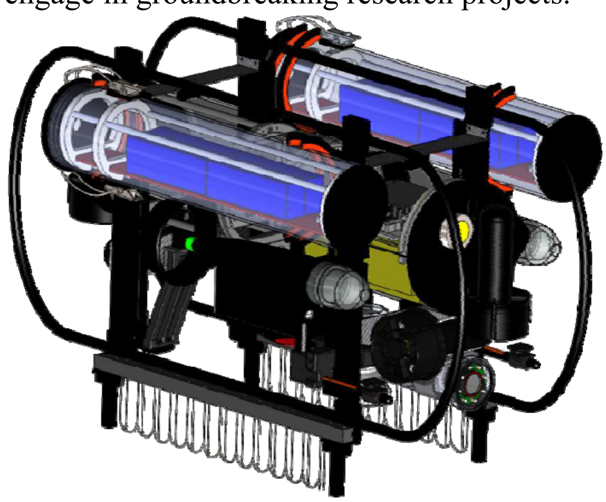

Figure 1 – CAD Rendered Model

To successfully complete the competition objectives, entrants are asked to complete seven tasks. First, the robot will demonstrate autonomous control and orientation by passing through a validation gate. Each of the tasks can be located in the TRANSDEC pool by following path segments on the pool floor. The first segment will point to a moored buoy which the vehicle must strike. The AUV must then find and traverse underneath "barbed wire," represented by two horizontally suspended pipes. Path segments will lead the submarine to a bombing run where it must drop "bombs" (weighted markers) on a specified two of four silhouette targets. A "machine gun nest," an 18" square PVC frame, must be "destroyed" by two horizontally launched torpedoes. Lastly, the submarine must locate an acoustic source, recover the PVC frame "briefcase," and surface inside a recovery zone. The remaining sections of this paper will focus on how the SubjuGator was created to satisfy these tasks, as well as an in-depth look at how each individual subsystem works in tandem with our software to accomplish each specific goal. A system diagram is shown in Figure 2.

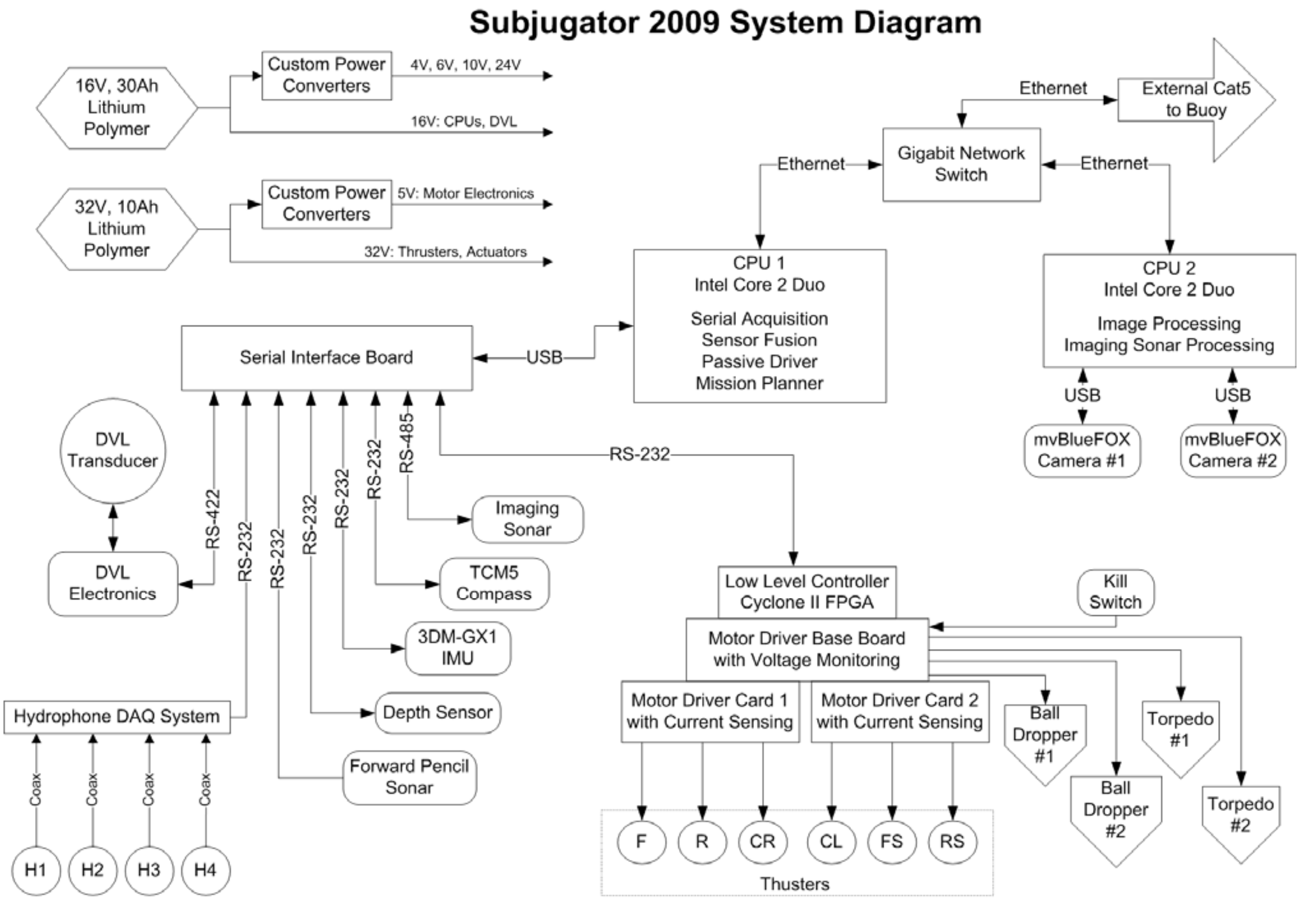

Figure 2 – SubjuGator System Diagram

2. MECHANICAL PLATFORM

As a sixth-generation vehicle, SubjuGator 6b (Figure 1) embodies the lessons learned in the previous eleven years of AUV development at the University of Florida. We considered several key design criteria, including survivability in a chlorinated or salt-water environment, inherent stability of the platform while submerged, and future sensor additions.

2.1 COMPUTER AIDED DESIGN

To assist in the mechanical design we developed a detailed computer model of our submarine (Figure 1). Nearly every component of the design was modeled to optimize placement and create an organized layout.

In a project that requires a great deal of planning before implementation, SolidWorks enables our mechanical development team to visualize potential problems and allows for open discussion of possible solutions. SolidWorks was also invaluable in helping us estimate weight, volume, and balance.

2.2 HULL

SubjuGator's central pressure vessel is built upon a 24" long x 7" OD aluminum tube with 1/8" wall thickness. Our team desired to increase the maximum operating depth of our vehicle, so aluminum was chosen as the primary construction material. Aluminum has better machining characteristics [1] when compared to the polycarbonate of previous years, and permits more efficient heat transfer from the electronics into the water.

The end cap design of the SubjuGator was driven by the desire to implement a reliable, repeatable, and quickly deployable system. Both caps implement a double o-ring sealing system that is fault-resistant to the repeated opening and closing of the vehicle during development. The caps are locked to the submarine using threaded stainless steel rods fed through flanges. Wing nuts are used to tighten the cap along these rods, while evenly distributing the forces required for cap installation.

The entire SubjuGator is protected by a cage that is constructed from a hybrid carbon fiber and aluminum superstructure. This makes our AUV rigid, lightweight, and easy to handle. In addition, this exoskeleton protects the submarine from unintended collisions, eliminates the need for a stand, and provides a frame for the attachment of temporary or experimental sensors.

2.3 BATTERY PODS

Vehicle runtime has been extended with the addition of two external battery pods. Following the design intent of the hull, the pods are constructed of 20" x 4.5" OD aluminum tubes. The tubes are symmetric so that the both sides and a spare can be freely interchanged. Stainless steel band clamps are utilized to allow for modular mounting with the existing aluminum superstructure. The positively buoyant pods are mounted near the top of the exoskeleton, adding roll stability. By removing the batteries and battery monitoring circuitry from the central hull, more electronics can be added to the central hull while increasing battery capacity.

2.4 INTERNAL LAYOUT

SubjuGator implements a symmetric two-sided design to facilitate the easy assembly and removal of the internal electronics. This aspect of our AUV has proved very pertinent to our recent success. The submarine is divided in half length-wise, with the DVL positioned directly in the center. The rear tray (Figure 3) is divided by a sheet of polycarbonate. The top holds the motor control system and 32V actuator control; the rear computer is underneath. The front tray houses the sensor interface hub, DVL electronics, hydrophone processing board, and front computer. The two trays are guided by a pair of rails that reliably blind mate connect the trays to the backplane.

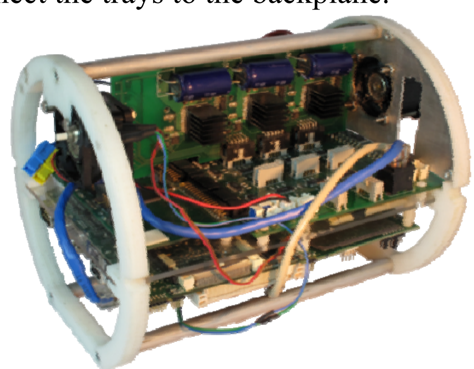

Figure 3 – Rear Tray

The DVL transducer head, compass/IMU sensor stack, and through-hull connectors are in the center of the submarine. Each Fischer connector is routed cleanly to the backplane system allowing all electronics to be removed easily. This central mechanical hub allows extremely efficient cabling between both sides of the platform and the pass-through to the external sensors and electronics.

2.5 THRUSTERS

Four of the six thrusters are Seabotix BTD150 models, orientated to provide control for heave, sway, pitch, and yaw. Two forward-mounted VideoRay GTO thrusters provide control for surge and yaw. Internally, both the GTO and the BTD150 thrusters employ the same 9200 series Pittman motor, albeit with different voltage windings. The GTO employs a 3:1 gearhead transmission, hydrodynamic casing, and a unidirectional propeller. Thus, spinning forward, the GTOs provide about the same amount of force, but use 3.5 times less power. Unfortunately, the GTO unidirectional prop provides 40% less force in reverse.

2.6 THROUGH-HULL CONNECTIONS

All of SubjuGator's through-hull connections use Fischer Connectors hermetic locking plugs and receptacles. All fourteen connectors can be used underwater to a depth of 260 feet. The most unique connector passes four RG-178 coaxial cables for the hydrophones through the hull. The connectors support four (of six) thrusters, power from two battery pods, six hydrophones, two torpedo launchers, two bomb droppers, an imaging sonar, a kill switch, Ethernet, and two cameras.

2.7 EXTERNAL CAMERAS

SubjuGator's external cameras utilize custom designed aluminum housings with Matrix Vision mvBlueFox-120a color USB camera, Pentax 4mm f/1.2 CS-mount lenses, and LED arrays for illumination. See [2] for more details on the external cameras and the housing.

2.8 LAUNCHER

The torpedo trigger mechanism was based from the design of a spear gun. The shooter (Figure 4) is designed to safely carry and launch a projectile through its target.

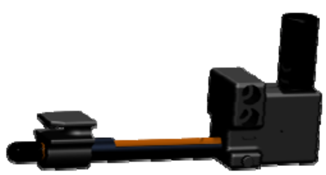

Figure 4 –Launcher

The torpedo is propelled by a latex band and actuated by an electronic solenoid fixed to the firing lever. The torpedo is a 3/8” aluminum rod that has been weighted and balanced to enhance flight characteristics. Also the torpedo is painted a bright orange for high visibility. Since solenoid is normally closed, the spear will not fire unless the firing solenoid is actuated. Additional safeties include: a blunt, soft rubber cap on the torpedo, the launcher must be armed by engaging the latex band before firing, and a safety pin locks the firing lever in a safe position. Testing has confirmed that if accidentally fired toward a support diver, the torpedoes will not inflict a bruise.

Figure 5 – Ball Dropper

2.9 BOMB DROPPER

See [2] for details on the bomb dropper (Figure 5).

2.10 BRIEFCASE GRABBER

The briefcase grabber consists of a square bar of PVC, bearing stainless steel hooks on the downward facing side (Figure 6). The stainless steel hooks are secured with stainless steel set screws, and bent into a semi-circular profile at the free end. The hooks are bent into semi-circular profile, and ensure there are no dead zones where the briefcase could get stuck on the outside of the grabber. The mechanism also features a second row of wires to resist the briefcase rotating and releasing. The free end of each wire is slightly bent to aid in directing the briefcase onto a hook. To maximize the possibility of engaging the briefcase, SubjuGator features a grabber on both sides.

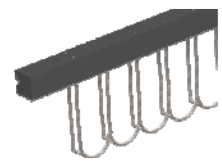

Figure 6 – Briefcase Grabber

3. ELECTRONICS

3.1 BATTERIES

SubjuGator uses two separate, isolated battery systems. The electronics battery system consists of six 16V, 5Ah lithium polymer battery packs in parallel, providing approximately 450Wh at 16V. The motor battery system consists of four 16V, 5Ah lithium polymer battery packs, 2 in series, then in parallel. This arrangement provides approximately 300Wh at 32V. In typical applications the SubjuGator is capable of running over five hours uninterrupted.

Lithium polymer batteries in particular are susceptible to permanent damage from heat and discharging to too low of a voltage. We developed a Battery Protection and Control

System powered by an ATtiny microcontroller that provides protection functionality, independent of all computers. Latching relays only require a momentary pulse to turn the output power on or off. This is controlled by the microcontroller, and signaled from outside the pod by a magnet waved over a Hall Effect switch. An undervoltage monitoring network will cause an audible alarm if the voltage on any pack drops below 13.6V, and will interrupt all system power at 12.4V. Thermisters monitor temperature at three different points and will interrupt system power if the temperature exceeds 140°F.

3.2 COMPUTING

The wide variety of computing challenges posed by autonomous underwater robotics requires the SubjuGator to use a diverse mix of processing systems to accomplish its goals.

3.2.1 EMBEDDED X86 COMPUTER

Major emphasis was placed on selecting an embedded computing solution that offers the highest performance available while being very power efficient. Both computers (front computer on Figure 7) run the Microsoft Windows Server 2003 with the same hardware configuration: Intel T7600 Core 2 Duo 2.33GHz CPU, 2GB of 533MHz DDR2 RAM, and a 16GB SSD hard disk.

Figure 7 – Front Tray

These computers are also the central point of our vehicle's sensor information and control system. Microsoft Robotics Developer Studio (MSRDS) is installed on the two nodes and coordinates transactions between the sensors and intelligence.

3.2.2 SUPER SERIAL BOARD

SubjuGator's custom designed Super Serial board merges all of the serial devices into a single USB connection to the front computer. Containing a 4-port USB hub and four quad serial-to-USB translators, the board and backplane connector provides power and connections for 10 RS-232 and 4 RS-422/485 serial devices.

3.2.3 ALTERA FPGA

Two Altera Cyclone II EP2C8 FPGAs are utilized: one in the hydrophone data acquisition system and one in the motor control system. FPGAs are extremely versatile and allow a tremendous amount of customization to these systems.

The motor control system uses the FPGA to generate all of the PWM signals for motors and all the actuation control signals. This FPGA is the interface between the PC and the drive system's electronics.

The FPGA in the hydrophone data acquisition system is used for parallel data acquisition of all four passive sonar channels. After acquisition, the data is thresholded and uploaded to the PC for signal processing.

3.2.4 WIRELESS SYSTEM ACCESS

A communications interface between a base station and a floating buoy utilizes a wireless Ethernet (802.11n) connection with up to a 300Mbps data path. The buoy is tethered to SubjuGator with CAT5e Ethernet cable that connects to a gigabit switch inside the sub. By viewing the real-time sensor data, we can tune the PID coefficients and the mission parameters. This communication link is only available when the floating buoy is tethered to the submarine.

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 DVL

Figure 8 – DVL Transducer

The Doppler velocity log (DVL transducer head in Figure 8) is a sensor that directly measures it's velocity in three dimensions with respect to a stationary plane (the seabed). To measure this, the piston head emits a 600 kHz acoustic pulse called a ping from four ceramic transducers. The seabed reflects this energy and the returning signals are measured by each ceramic. By performing autocorrelation of the four signals, the information result is a precise velocity vector, with accuracy on the order of ±0.5" per second. Additionally, on each ping, the sensor outputs an estimation of the error, and height over the average bottom. This completed packet is sent to the front computer over RS-422 at variable rates from 5 to 8 Hz.

3.3.2 COMPASS

The primary heading reference is the Precision Navigation TCM5 compass. This compass is rigidly mounted near the geometric center of our vehicle. While the compass contains accelerometers and a microcontroller to perform hard-iron calibration and filtering, we only use the raw magnetometer data since we perform dynamic magnetic field compensation and the hard iron calibration in real-time on the front computer. Although the compass only has an update rate of 20 Hz and the magnetometers of the IMU update at 50 Hz, the magneto-inductive sensors of the compass have ten-fold better repeatability.

3.3.3 INERTIAL MEASUREMENT UNIT

The Microstrain 3DM-GX1 contains triaxial magnetometers, gyroscopes, and accelerometers, which output at approximately 80 Hz. We utilize the gyroscopes to stabilize our rotational position, and the gyro-stabilized accelerometers to stabilize our translational position in between updates from the DVL. In the case the DVL beams are occluded, causing it to no longer output velocity information, the accelerometers are able to continue stabilizing the position for a short time.

3.3.4 DEPTH SENSOR

Until last year we used the Desert Star SSP-1 sensor with full scale range 100 psig which corresponds to a maximum depth of 239 feet. The wide range reduced the resolution and hence reduced the accuracy of the reported depth when in the shallow range of the TRANSDEC pool. A smaller range SSP-1 was not available, so we designed our own (described in Figure 9).

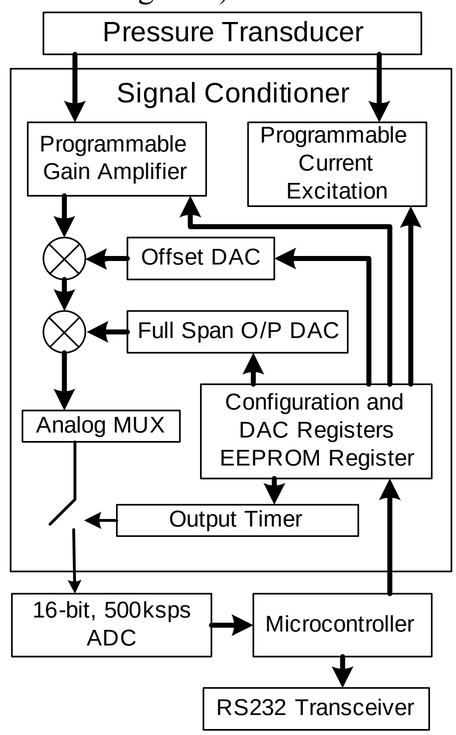

Figure 9 – Custom Depth Sensor

The Measurement Specialties Model 85 Ultrastable pressure transducer with 30psig full scale was chosen. It is a small profile, piezoresistive silicon pressure sensor in a stainless steel housing. A ceramic substrate is attached to the package that contains laser-trimmed resistors for temperature compensation and offset correction. This Transducer ensures non-linearity of ±0.1%, pressure hysteresis of ±0.02%, and repeatability of ±0.02%. The piezoresistive element forms an internal Wheatstone bridge and ensures a substantially higher change in resistance and hence higher sensitivity and stability than a standard strain gauge.

A Maxim MAX1452 analog-sensor signal conditioner was chosen to provide the desired current excitation, offset correction and Gain. The MAX1452 architecture includes a programmable current excitation, 16-step programmable-gain amplifier, 768 bytes internal EEPROM, four 16-bit DACs for offset, span and temperature compensation, uncommitted op-amp and on-chip temperature sensor. The fully analog signal path introduces no quantization noise in the output signal while enabling digitally controlled trimming with the integrated 16-bit DACs. It has a single serial digital I/O pin used for setting the configuration and DAC registers and reading their status. It automatically detects the baud rate of the host computer when the host transmits the initialization sequence. The analog output pin is also multiplexed to output various internal analog voltages. The Frequency response was adjusted to 150Hz bandwidth using the on-chip uncommitted op-amp.

The analog output is digitized to a 16-bit value by an Analog AD7686 ADC, at 500ksps and transmitted over Serial Peripheral Interface (SPI). The Atmega128 controls the internal registers of the MAX1452, reads SPI data from the ADC, processes the pressure data, scales it appropriately and then outputs the information over RS-232 to the front computer.

3.3.5 HYDROPHONE SYSTEM

The hydrophone system detects acoustic vibrations in the water, and is specifically tuned to the acoustic pinger located in the surface zone. The systems four stages are:

1. Hydrophone Receiver
2. Analog Filter and Amplifier
3. Data Acquisition
4. Digital Signal Processing

SubjuGator utilizes four hydrophones mounted in a planar configuration resembling the letter T (Figure 10) to create the geometry needed to identify the direction and distance from which the received signals originated [3].

Figure 10 – Hydrophone Array

The Reson TC4013 hydrophones transform the acoustic pressure wave to a voltage signal, where the amplitude represents the magnitude of the wave. A 2nd order analog passband filter is used to remove frequencies outside the 19 to 31 kHz band, followed by an instrumentation amplifier to linearly increase the voltage (Figure 11). Each signal is discretized by its own analog-to-digital converter at a throughput rate of 250 kHz. The FPGA transfers the sample to local memory, and if the signal meets a threshold, transfers a complete packet to the computer over RS-232. The digital signal processing is done with MATLAB to determine the three time-of-arrival differences between the center hydrophone and the surrounding three. Knowing the speed of sound in water, the three distance differences can be converted to attitude and azimuth angles and a distance from the array to the pinger.

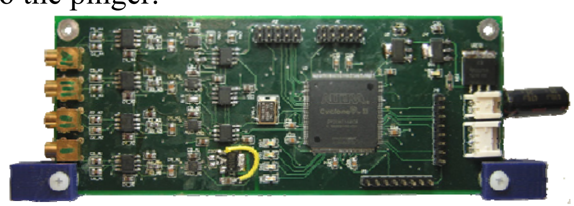

Figure 11 – Hydrophone Signal Processor

4. SOFTWARE AND CONTROLS

4.1 SOFTWARE ARCHITECTURE

Our team is using Microsoft Robotics Developer Studio (MSRDS) as the software framework for SubjuGator. MSRDS is a robotics framework that provides both the Coordination and Concurrency Runtime (CCR) and the Decentralized Software Services Protocol (DSSP). The CCR provides a thread pool, task based concurrency library. The DSSP provides a service oriented architecture, based on the Publish-Subscribe model, that is used to communicate between PC's. The DSSP uses the CCR to asynchronously handle service messages, lending itself well to handling asynchronous inputs from multiple sensors. This combination allows the seamless implementation of large scale multi-processor applications.

The SubjuGator uses a set of custom coded Robotics Studio services to encapsulate major tasks (Figure 12). For example, there is a service for every sensor that encapsulates the communication protocol; there are several services for manipulating incoming data, and a service for control. An added benefit of using a service-oriented architecture in this manner comes in the way of simulation. To simulate sensory input, a simulation service emulates each sensor service to simulate sensory input. At anytime these services can be seamlessly moved to different PC's and still communicate messages over a LAN/WAN, via TCP/IP, that would otherwise be an internal local message. This property makes the DSSP especially useful for the SubjuGator because the sub uses multiple computers. Even if hardware is moved, the code base stays the same.

The Mission Control is a service that chooses which underwater task is the intended task to complete. The missions are set up in some predetermined order. The mission control loads up a mission, runs its specific algorithm, analyzes the results of the algorithm, updates the grid, and finally chooses a waypoint for the sub. Each algorithm is given a certain timeout "weight" based on the point value of that task, so that the SubjuGator manages time allocated to each task efficiently. Updates to the grid are made to keep track of incomplete tasks that are within proximity of a relevant sensor. The grid's intent is to streamline searching so that less time is wasted on searching and more time may be allocated to executing tasks. The grid may be queried by the mission control to aid way-point decision making in transitioning between tasks.

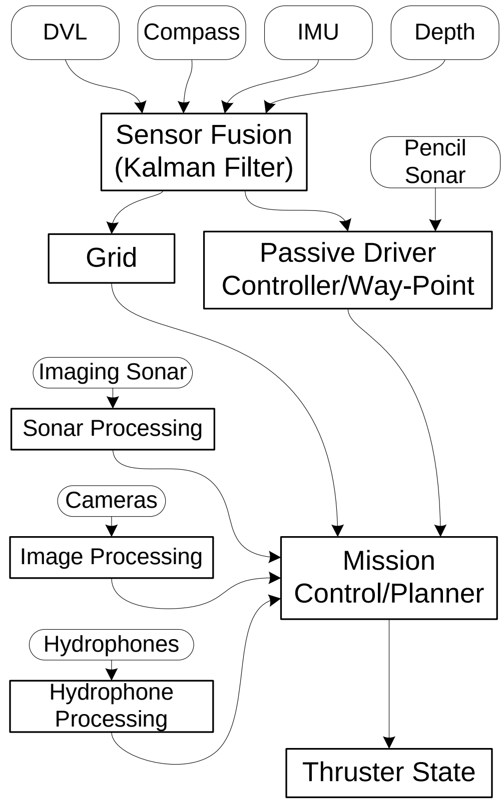

Figure 12 – Software Architecture

4.2 CONTROL SYSTEMS

Control of the submarine is implemented in the primitive driver service. This service is responsible for position based feedback control of pitch, heading, roll and depth, and velocity based feedback control of forward and strafe motion using a decoupled set of proportional, integral, derivative (PID) controllers [4] [5]. Feedback is attained through a depth sensor, DVL, IMU, motor current sensors, and compass. These sensors allow the SubjuGator to measure many of the states needed to effectively control its pose in the water. The measured states are the three translational velocities, yaw position, pitch position, roll position, approximate motor thrust, and the depth. Control of these states is simplified by decoupling pitch and depth control from roll and yaw control by assuming that the two do not interact. This assumption is valid if pitch and roll are regulated to zero. Since it is desirable to control the rate at which SubjuGator is traversing the pool, velocity controllers are used for linear forward and strafe motion. All of the control loops run at 10 Hz. Control inputs to the primitive driver service are sent from the arbiter service. Continuous PID calculations are converted to discrete-time equivalents and the errors are calculated from the difference between the current and desired state information using the standard PID equation.

The individual gains (K_p, K_i, K_d) were tuned through experimentation at various depths and operating conditions.

In order to properly control the thrusters, a thruster calibration device was designed to measure power-thrust curves. Each thruster type has its own unique power-thrust curve available in order to simplify the control algorithm. The details of the hardware setup and experiments can be found in [2].

4.2.1 ACQUISITION AND STATE ESTIMATION

The Subjugator's data acquisition system gathers data from four multirate sensors; the TCM5 Digital Compass, the 3DM-GX1 IMU, the DVL and our custom depth sensor. These sensor measurements are used to update and estimate the positional and orientational states of the system.

The compass generates yaw, pitch and roll readings at approximately 20 Hz. These readings are in the form of Euler angles in the ZYX convention. The heading from the compass is corrected for hard iron and soft iron calibrations before being used to update the system state.

The IMU generates translational accelerations and angular velocities along X, Y, and Z axes at approximately 80 Hz. These readings are in the vehicle frame of reference and are based on Euler angles. The DVL provides readings at approximately 6 Hz for translational velocities along X, Y, and Z axes, and the depth and height over bottom.

The data from the various sensors is passed through a Kalman filter to estimate or predict the position and orientation states. The system states maintained are translational velocities, angular velocities and translational accelerations along X, Y and Z axes, the depth and height over bottom, and the heading, pitch and roll. While the compass, the DVL and the depth sensor are used to estimate the new states, the IMU is used to predict the new states. The equations governing updates using the Kalman filter are the predicted state, the predicted estimate covariance, the optimal Kalman gain, the updated state estimate, and the updated estimate covariance.

The IMU data is used to calculate the predicted state X_k and the predicted estimate covariance Σ_k. Using these values, the Kalman gains K_k are calculated for the compass data and the DVL data. The depth sensor data and the DVL depth readings complement each other. Using these gains, the new states and covariance estimates are updated at approximately 20 Hz.

5. ARBITER/BEHAVIOR SERVICES

The service-based architecture of MSRDS is used in the implementation of the high-level control for the SubjuGator. The behavior services consist of individual software components that evaluate sensor feedback and make recommendations to the arbiter. The arbiter service is a dynamic state machine that is defined at initialization by a script file containing mission specific parameters. The arbiter controls the behavior that can instantaneously exert control over the submarine. However, all behaviors constantly make recommendations, allowing the arbiter to prioritize control based upon a priori defined mission parameters.

5.1 COMPUTER VISION SYSTEM

The rear onboard computer captures real-time video feeds from two USB cameras, each contained within an aluminum housing with a transparent glass lens. One camera faces forward to detect objects such as the machine gun nest and flare; the second camera faces downward to detect objects such as the path segments, barb wire, bombing run, and briefcase.

Objects are identified by first thresholding the raw image frames received from the cameras. Adaptive thresholding techniques are used to segment objects of interest from the rest of the image [6] [7]. A Gaussian model is used to accurately segment objects with high variances. The main benefit of adaptive thresholding is the ability to segment a single object that may have different color space values at different locations on the object due to lighting variations or noise.

The major objects which must be detected using the vision system include rectangular-shaped path segments, rectangular-shaped bombing targets, square-shaped machine gun nest, circular-shaped flare, and rectangular-shaped barbed wire. Due to the similarities in shape, contour based search algorithms help to identify the thresholded objects in each frame. Each object contour allows the vision system to bound the contours with geometric shapes, which can be used to provide feedback for visual servo control.

In addition to two-dimensional visual servo control, the vision system incorporates the ability to sample real-time geometric pose information using coplanar feature points on the objects. A homography based approach presented in [8] [9] allows for the determination of relative distances to objects within the field of view of the camera frame. Euclidean homography relationships are used to recover the pose of an object with respect to a camera frame. This technique is used specifically in the bombing run and machine gun nest tasks to determine the best three dimensional position and orientation of the SubjuGator with respect to the individual objects. The internal camera calibration and distortion parameters are obtained using [10].

6. ACKNOWLEDGEMENTS

We would like to thank Harris Corporation for their continued and substantial support. Lockheed Martin Corporation, UF's ECE and MAE Departments, the Gainesville section of IEEE, Altera, Fischer Connectors, Microsoft, and Dundas Data Visualization have also provided valuable support. We are grateful to the previous SubjuGator team members who have contributed to the legacy of SubjuGator and to the many other members of the Machine Intelligence Laboratory (MIL) and the Center for Intelligent Machines and Robotics (CIMAR) who have helped over the last year with our submarine.

7. REFERENCES

[1] Evans, Ken. R. 2001. *Programming of CNC Machines*. 9th. Prentice-Hall, Inc.

[2] Burnette, D. J., et. al, "SubjuGator 2008.", AUVSI/ONR 12th International Autonomous Underwater Vehicle Competition, July 28-Aug 2, 2009

[3] Clare, C.P., "Acoustic Direction Finding Systems," U.S. Patent 4 622 657, November 11, 1986.

[4] Rogers, R. M. 2000 *Applied Mathematics in Integrated Navigation Systems*, AIAA (American Institute of Aeronautics & Ast.), 2000.

[5] Dorf, R. C. and Bishop, R. H. 2000 *Modern Control Systems*. 9th. Prentice-Hall, Inc.

[6] Dempster, A. P., Laird, N. M., and Rubin, D. B. Maximum Likelihood from Incomplete Data via the EM Algorithm. *J. Royal Statist. Soc. B-39*, 1–38, 1977.

[7] Perona, P. and Malik, J. 1990. Scale-Space and Edge Detection Using Anisotropic Diffusion. *IEEE Trans. Pattern Anal. Mach. Intell.* 12, 7 (July 1990), 629-639.

[8] Dani, A.P.; Velat, S.; Crane, C.; Gans, N.R.; Dixon, W.E., "Experimental results for image-based pose and velocity estimation," Control Applications, 2008. CCA 2008. IEEE International Conference on , vol., no., pp.1159-1164, 3-5 Sept. 2008.

[9] Gans, N. R.; Dani, A.; Dixon, W.E. "Visual Servoing to an Arbitrary Pose with Respect to an Object Given a Single Known Length," Proceedings of the American Control Conference, 2008, Seattle, WA, USA, pp. 1261-1267.

[10] Bouguet, J., "Complete camera calibration toolbox for MatLab," http://www.vision.caltech.edu/bouguetj/calib_doc/index.html.