SubjuGator 2010

Patrick Walters, Devin Hughes, Subrat Nayak, Nic Fischer, Gautam Dash, John Phillips, Dana Massaro, Jheanell Tabana, Eric M. Schwartz, A. Antonio Arroyo

Machine Intelligence Lab (MIL), University of Florida
325 MAE Building B, PO BOX 116300, Gainesville FL 32611
www.subjugator.org

ABSTRACT
For the past fourteen 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 Mechanical and Aerospace Engineering department or Electrical and Computer Engineering department. 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 13th International Autonomous Underwater Vehicle Competition. SubjuGator is designed to operate underwater at depths up to 100ft. Two 3.5" x 5.75" Intel Core 2 Quad computers running Microsoft Windows Server 2008 provide processing power for monitoring and controlling all systems. The mission behavior of SubjuGator is being developed with the Joint Architecture for Unmanned Systems (JAUS) framework that creates a network of smart sensors and processing components. This smart sensor and component network provides vehicle and environmental state information by processing and integrating information provided by two cameras, a hydrophone array, a Doppler velocity log (DVL), an inertial measurement unit (IMU), a compass, a depth sensor, and an altimeter. The vehicle also makes use of custom-designed motor controllers with current sensing, four external actuators, and other peripherals necessary for completing a mission.

Keywords
Submarine, JAUS, Autonomous, SubjuGator, AUVSI, Robot

1. INTRODUCTION

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsors of the 13th Annual International Autonomous Underwater Vehicle Competition, to be held in San Diego, California at the Space and Naval Warfare Systems Command's (SPAWAR) Transducer Evaluation Center (TRANSDEC) facility July 13th through July 18th, 2010. A student team at the University of Florida's Machine Intelligence Lab developed an autonomous underwater vehicle (AUV) to compete in the 2010 contest. The sixth generation (revision C) SubjuGator (Fig. 1) 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 2010 competition objectives, entrants are asked to complete seven tasks. First, the robot must demonstrate a validation gate. Each subsequent task in the

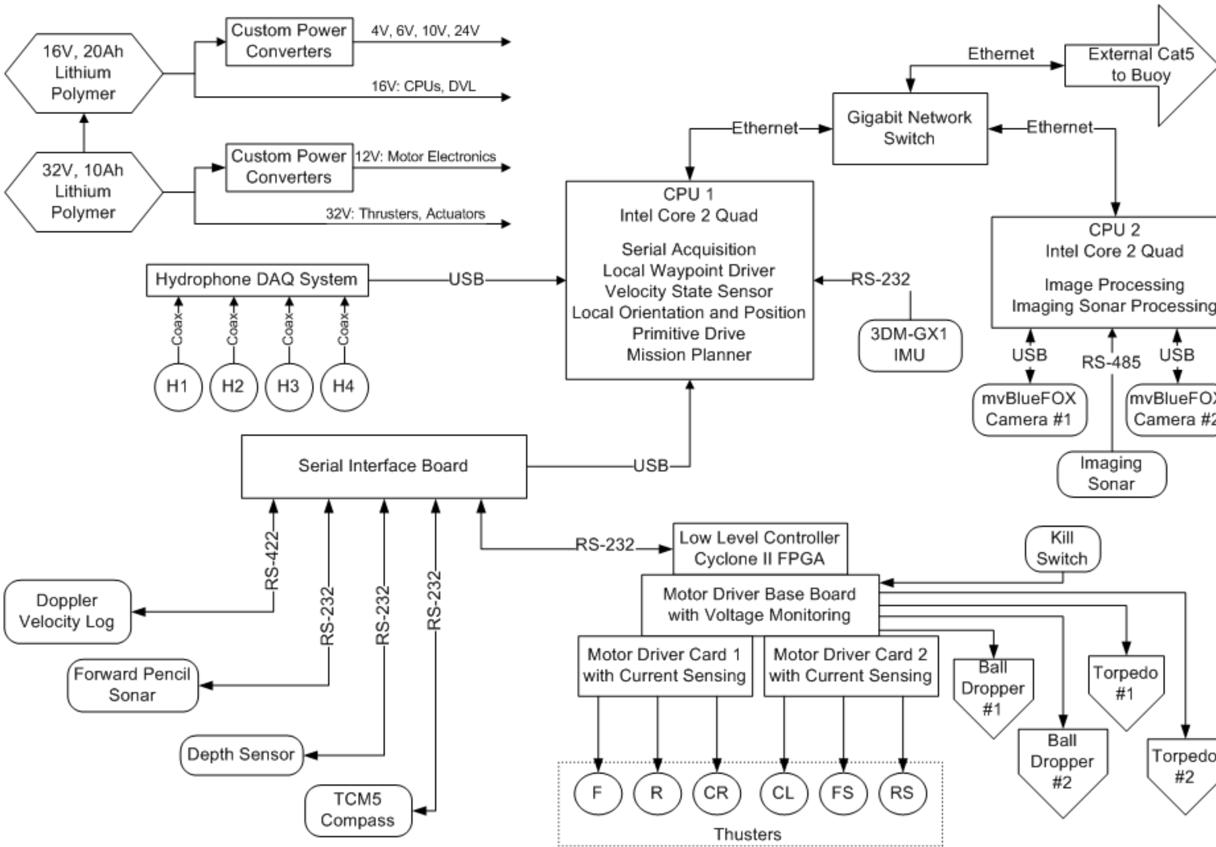

Figure 2. SubjuGator System Diagram

TRANSDEC pool can be located by following path segments on the pool floor. The first segment leads to three moored buoys, which the vehicle must differentiate and strike. The AUV will then traverse over a “hedge,” represented by a U-shaped pipe structure. Following the hedge, the vehicle can choose to complete either the “window” task or pick up “weapons.” The window task is completed by identifying two of four specified colored panes and launching a projectile though the panes. In order to pick up a weapon, the vehicle will drop a weighted marker into the bin containing the silhouette of a desired weapon. Finally, the vehicle locates an acoustic source, were it will recover a “camp counselor” (PVC pipe frame) and surface within a surfacing zone. The remainder of the paper will outline how SubjuGator will complete each of these tasks by taking a detailed look at the vehicles subsystems. A system diagram of the vehicle is shown in Fig. 2.

2. MECHANICAL PLATFORM

As a sixth-generation vehicle, SubjuGator 6c (Fig. 1), embodies the lessons learned in the previous thirteen 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, expansion for future sensors and actuators, and ease of maintenance.

2.1 COMPUTER AIDED DESIGN

To assist in the mechanical design we have developed a detailed computer model of the vehicle (Fig. 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, a computer aided design software program, enables our mechanical development team to visualize potential problems and estimate dynamic characteristics.

2.2 HULL

SubjuGator's central pressure vessel is built with a 24" long x 7" outer diameter (OD) aluminum tube with 1/8" wall thickness. Aluminum provides 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 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 main hull is protected by a cage that is constructed from a hybrid carbon fiber and aluminum superstructure. This makes the 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

Following the design intent of the hull, two battery pods are constructed of 20" long x 4.5" OD aluminum tubes that mount to either side of the vehicle. 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 inherent roll stability.

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 past success. The submarine is divided in half length-wise, with the Doppler velocity log (DVL) positioned directly in the center. The rear tray (Fig. 3) holds the motor control system and 32V auxiliary actuator control, while the rear computer is located underneath. The front tray (Fig. 7) houses a sensor interface hub, DVL electronics, hydrophone processing board, and the front computer. The two trays are guided by a pair of rails that reliably blind mate the trays to a backplane. The DVL transducer, compass and inertial measurement unit (IMU) sensor stack, and through-hull connectors are located between the two backplanes of the vehicle. This central hub allows efficient cabling between both sides of the platform, easy removal of electronics, and acts as the pass-through to the external sensors and electronics via the vehicles fourteen through-hull connectors.

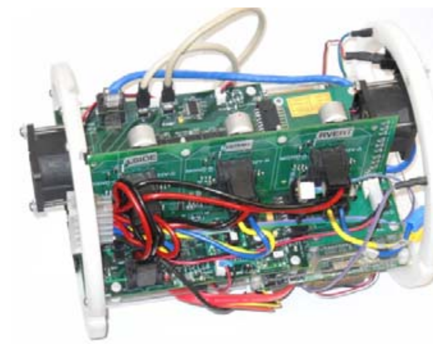

Fig. 3. Rear Tray

2.5 THRUSTERS

SubjuGator is a fully actuated platform with six thrusters. Four of the six thrusters are Seabotix BTD150 thrusters, oriented to provide control for heave, sway, pitch, and yaw. Roll control is also available; however, it is highly coupled with yaw actuation. The remaining two thrusters are VideoRay GTO thrusters which provide control for surge and yaw.

2.6 SHOOTERS

The shooter trigger mechanism was based on the design of a spear gun. The shooter (Fig. 4) is designed to safely carry and launch a projectile through a target window.

Figure 4. Shooter

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. The torpedo is painted a bright orange for high visibility. Since the solenoid is normally closed, the spear will not fire unless the firing solenoid is actuated. Additional safeties include: arming the shooter by engaging the latex band before firing and a safety pin that 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.

2.7 BALL DROPPERS

The dropping mechanism (Fig. 5) was designed to safely carry and deliver two markers to a target and release them when the appropriate target is detected.

Figure 5. Ball Dropper

Constrained by size and weight, our choice of marker was a 5/8-inch diameter chrome bearings, both for their mechanical and hydrodynamic properties. The markers were painted orange with automobile enamel for easy recognition and were imprinted with an emblem for identification. The design for the dropper mechanism was chosen to be as light and as simple as possible. A plastic block was machined to allow the simultaneous and safe transportation of the markers. To allow each marker to be dropped independently using two solenoids. By independently activating the solenoid, each individual marker can be delivered when desired.

2.8 GRABBER

The grabber consists of a square bar of PVC bearing stainless steel hooks on the downward facing side (Fig. 6).

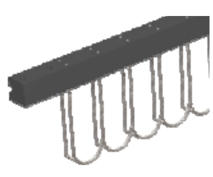

Figure 6. Grabber

The stainless steel hooks are secured with stainless steel set screws, and bent into a semi-circular profile at the free end. To maximize the possibility of engaging the counselor, SubjuGator features a grabber on both sides.

2.9 THROUGH-HULL CONNECTIONS

All of SubjuGator's through-hull connections use Fischer Connectors' hermetic locking plugs and receptacles. The fourteen connectors can be used underwater to a depth of 260 feet. The connectors support four (of six) thrusters, power from two battery pods, four hydrophones, four external actuators, an imaging sonar, a external status display, Ethernet, and two cameras.

3. ELECTRONICS

3.1 BATTERIES

SubjuGator uses two separate, isolated battery systems. The electronics battery Pod consists of four 16V, 5Ah lithium polymer battery packs in parallel, providing approximately 300Wh at 16V. The Actuator battery Pod consists of four 16V, 5Ah lithium polymer battery packs connected to provide 32V and approximate capacity of 300Wh. In typical applications, the SubjuGator is capable of running continuously for more than four hours.

Lithium polymer batteries are susceptible to permanent damage due to excessive discharging. Hence, a custom battery voltage monitor and protection system managed by an Atmel ATtiny microcontroller was implemented inside the battery pods. Latching relays require a momentary pulse to turn the output power on or off. Each battery pod is signaled from outside the pod by a magnet waved over a latching Hall effect sensor to turn the power on or off. If the voltage on any pack drops below 13.6V the monitor system sounds an audible alarm; if it drops below 12.4V the system shuts down all system power. The 32V battery pod is clearly marked and can be switched off to cut power to the six thrusters and four actuators to “kill” the submarine.

3.2 COMPUTING

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

3.2.1 EMBEDDED X64 COMPUTER

Major emphasis was placed on selecting an embedded computing solution that offers the highest performance available while being power efficient. Both computers run Microsoft Windows Server 2008 with the same hardware configuration: Intel Q9000 Core 2 Quad 2GHz CPU, 4GB of 1066MHz SODDR3 RAM, and a 64GB SSD hard disk.

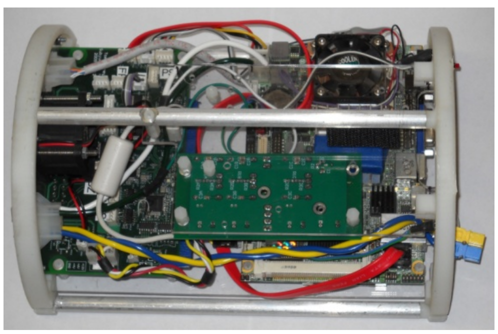

Figure 7. Front Tray

These computers are also the central point of our vehicle’s sensor information and control system.

3.2.2 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 Category 5e (CAT5e) Ethernet cable that connects to a gigabit switch inside the vehicle. The tether allows for easy viewing of real time system information, as well as access to the tunable parameters. When the tether is removed, the AUV becomes a completely isolated, independent and autonomous entity.

3.3 NAVIGATIONAL AND ENVIRONMENTAL SENSORS

For even the most basic operation, an AUV must be able to maintain depth and attitude. Regardless of mission specific operations these sensors provide position and orientation information for basic AUV control.

3.3.1 EXPLORER DVL

Figure 8. DVL Transducer

Teledyne’s Explorer Doppler Velocity Log (DVL transducer head in Fig. 8) is a sensor that directly measures 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 transducer. By performing an autocorrelation of the four signals, the information results in a precise velocity vector, with accuracy on the order of ±0.02 m/s. Additionally, on each ping, the sensor outputs an estimation of the error, and height over the average bottom. This information is sent as packet to the front computer over RS-422 at variable rates from 5 to 8 Hz.

3.3.2 TCM5 COMPASS

The primary orientation reference is the Precision Navigation TCM5 compass. This compass is rigidly mounted near the geometric center of our vehicle. The compass contains a 3-axis accelerometer, a 3-axis magnetometer, and a microcontroller to perform hard-iron calibration. But the SubjuGator only uses raw magnetometer and accelerometer data. The raw magnetometer data gets corrupted by three sources of errors namely – hard iron, soft iron and fields due to current carrying coils like thrusters and power lines. The hard and soft iron calibration is done by first finding the parameters offline and then using them to cancel out the errors in real time. Dynamic field compensation running in real time is used to cancel out the variable error due to currents flowing through the thrusters.

3.3.3 3DM-GX1 IMU

The Microstrain 3DM-GX1 contains a magnetometer, gyroscope, and accelerometer triad, which output gyro compensated and filtered data at approximately 80 Hz and unfiltered raw data at 333 Hz. SubjuGator utilizes the IMU's unfiltered raw gyroscope and accelerometer data to estimate position and orientation between updates from the DVL and compass or during the period of time when the DVL no longer gives valid data.

3.3.4 DEPTH SENSOR

SubjuGator utilizes a Measurement Specialties Model 85 Ultrastable 30 psia pressure transducer. The piezoresistive elements of the transducer form an internal Wheatstone bridge. Fig. 9 shows how the transducer is utilized in our custom depth sensor system.

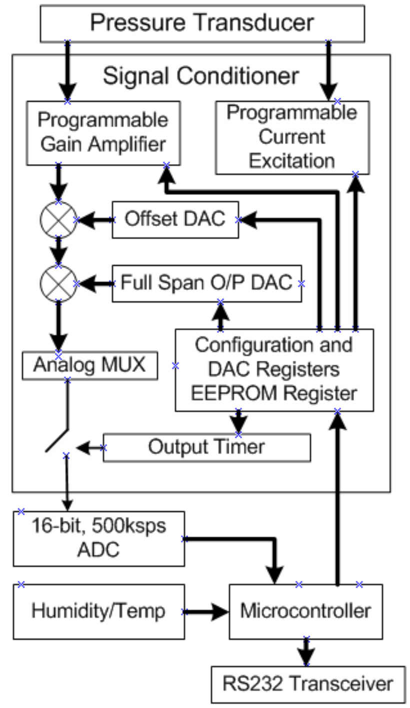

Figure 9. Custom Depth Sensor

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 Devices AD7686 ADC, at 500ksps and transmitted over Serial Peripheral Interface (SPI). A PIC 16 microcontroller 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 sound waves in the water, and is specifically tuned to listen to an acoustic source. The system has four stages:

1. Hydrophone Receiver/ Transducer
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 (Fig. 10) to create the geometry needed to identify the direction from which the received signals originate [3].

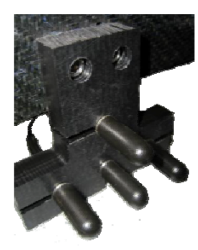

Figure 10. Hydrophone Array

Reson's TC4013 hydrophone transforms the sound waves to an analog voltage signal. A 2nd order analog bandpass filter/amplifier is used to attenuate frequencies outside the desired band and selectively amplify the signals within the desired band (Fig. 11). Each of the 4 analog signals is then digitized by its own Analog to Digital converter at a sampling speed of 250 kHz. An Altera Cyclone II FPGA collects the digital signals into a buffer and transfers them serially as a complete packet to the front computer. For high speed data logging, the board has a USB 2.0 interface formed by the FTDI FT2232H IC. The digital packets of data are processed on the front computer by an algorithm written in MATLAB to determine the three time-of-arrival differences between the center and the surrounding three hydrophones. Knowing the speed of sound in water, the three distance differences are then converted to azimuth and polar angles of the source relative to the hydrophone array.

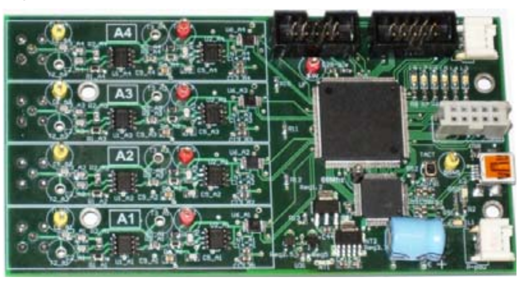

Figure 11. Hydrophone Signal Processor

3.3.6 CAMERAS

SubjuGator's external cameras utilize custom designed aluminum housings with Matrix Vision mvBlueFox-120a color USB cameras. The rear onboard computer captures real-time video feeds from two cameras at rates ranging from 5 to 90 Hz at a resolution of 640x480. One camera faces forward to detect objects ahead of SubjuGator while a second camera faces downwards to detect objects lying below the vehicle.

3.4 SUPER SERIAL BOARD

SubjuGator's custom designed Super Serial board merges all of the serial devices/sensors into one USB connection to the front computer. It is comprised of a 4-port USB hub, made using a USB2514 IC, and four quad serial-to-USB translators, made using the FTDI FT4232H IC. The serial signals are then translated to RS232 using a MAXIM MAX213E transceiver and to RS422/485 using MAXIM MAX3079E transceiver. The board can provide power and connections for up to ten RS-232 and four RS-422/485 serial devices.

3.5 ACTUATOR DRIVERS

The six thrusters are made up of permanent magnet DC motors. Each motor is driven by a custom built H-bridge type motor driver made of four n-channel MOSFETS driven by Intersil HIP4082 MOSFET drivers. The current through each motor is sensed using bidirectional Hall effect sensors. The solenoids used to actuate the ball droppers and shooters are driven by p-channel MOSFETS. The actuator drivers are powered from a 32V supply that is completely isolated from the computer side power and signals using Analog Devices digital isolators. An Altera Cyclone II FPGA acts as the interface between the computer and the actuator drivers. It uses a RS232 communication line to receive commands and send status updates, including the measured current through the motors, to the computer. The FPGA also handles the various state machines and generates all the necessary signals to run the actuator drivers and current sensors.

4. SOFTWARE DESIGN

The Team has developed a Joint Architecture for Unmanned Systems (JAUS) compliant software framework for SubjuGator.

4.1 ARCHITECTURE

JAUS is an unmanned systems framework that provides an open and common communication protocol [4]. SubjuGator's implementation is designed to separate the vehicle's software into components (Fig. 12). Inside of the JAUS topology, the vehicle is defined as a subsystem. Within that subsystem are nodes with defined processing capabilities. In the case of SubjuGator, the front, rear, and external computer (which house the vehicle's real-time graphical user interface) are defined as nodes.

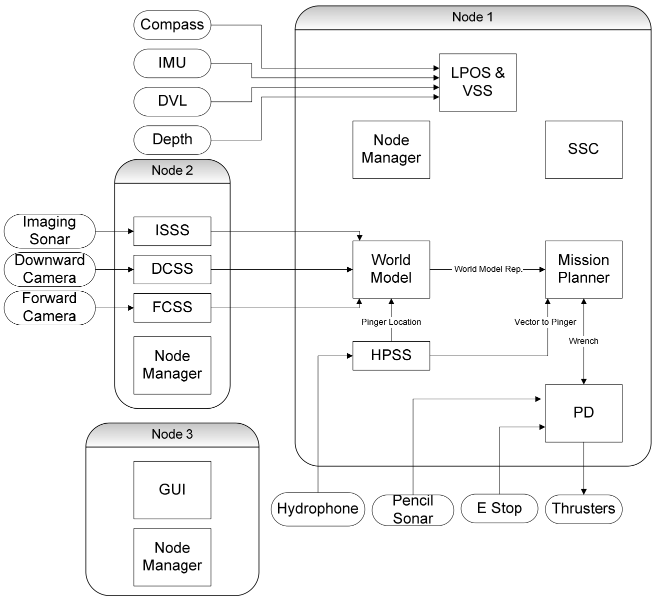

Figure 12. Software Architecture

The JAUS standard includes many predefined components that are common to most unmanned platforms. SubjuGator utilizes four predefined platform components which include the Local Waypoint Driver, Local Orientation and Position Sensor (LPOS), Velocity State Sensor (VSS), and Primitive Driver (PD). SubjuGator developed an array of custom smart sensors that capture, process, and package relevant information from three environmental sensors which include two cameras and hydrophone array.

All communication between components is directed though the node's Node Manager and is made available to all the connecting nodes and their components. At any time components can be seamlessly moved to different nodes. This allows for flawless integration of the software into an evolving hardware platform

The Mission Planner component acts as the software's central processing unit. It uses information from environmental smart sensor, LPOS, VSS, and a priori mission plan to determine the next course of action which is taken by setting waypoints or activating the ball dropper or shooter.

4.2 STATE ESTIMATION

SubjuGator's data acquisition system gathers data from four multirate sensors: the TCM5 Digital Compass, the 3DM-GX1 IMU, the Teledyne Explorer DVL and our custom depth sensor. These sensor measurements are used to update and estimate the position, velocity, and orientation states of the system in the LPOS and VSS components.

The Compass, IMU and DVL give out data in their own instrument coordinate systems. This data needs to be aligned with the body coordinate system. This was accomplished by means of a linear rail experiment where the direction vectors found from the DVL and the IMU were used to find the misalignment using the TRIAD algorithm [8]. The misalignment between the compass and IMU was also found using the TRIAD Algorithm.

The IMU generates translational accelerations and angular velocities in the body coordinate system at 200 Hz. The accelerations and angular velocities are integrated and transformed to a fixed coordinate system along the local North, East, Down (NED) directions to give an estimated position, velocity, and orientation in the Inertial Navigation System (INS) [6]. These estimates are corrected using an Indirect Unscented Kalman Filter (UKF) [7]. The indirect filter uses state error measurements to converge on a best estimate of error, which is subtracted from the INS estimated state (Fig. 13). The error measurements are generated by subtracting low order sensor measurements from the INS estimated state.

The DVL provides readings at approximately 6Hz for translational velocities in the vehicle's frame. The velocities are transformed to the fixed NED coordinate system and used as the low order sensor to generate velocity error.

The magnetometer and gravity vectors found from the compass are used to estimate the quaternion relating BODY and NED coordinate systems using the TRIAD Algorithm [8] [9]. The attitude quaternion is used as the low order sensor to generate orientation error.

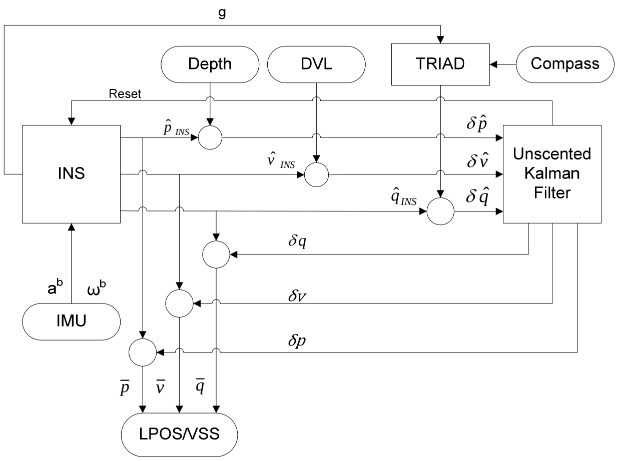

Figure 13. State Estimator Design

The depth sensor provides depth measurements in the NED coordinate system at 20 Hz, and is the low order sensor generating depth error.

The UKF is run at a continuous rate of 100Hz, assuming the change in error over the time step between reference sensor measurements is constant. This allows for handling of reference measurement delays and dropouts in a seamless manner.

4.3 CONTROL SYSTEMS

Control of the vehicle is implemented in the Local Waypoint Driver (LWD) component which receives waypoints from the mission planner. This service is responsible for feedback control of position and orientation using a nonlinear multilayer neural network feedforward and RISE feedback control structure [14]. Waypoints are transformed into a desired continuous position and velocity trajectory which maintains continuity through acceleration. Feedback is obtained through use of position and velocity information from the LPOS and VSS components. These components post state information that allows the SubjuGator to effectively control its position and orientation in the water. Control inputs to the PD service are sent from the LWD service in the form of a desired wrench which can be seen as the combination of a force and torque. The PD maps the incoming wrench to the vehicle's six thrusters through a force mapping algorithm [5]. The requested force is then transformed into PWM commands using a voltage to force relationship unique to each thruster.

4.4 COMPUTER VISION SYSTEM

Objects are identified by first thresholding the raw images captured by the cameras. Adaptive thresholding techniques are used to segment objects of interest from the rest of the image [10] [11]. 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.

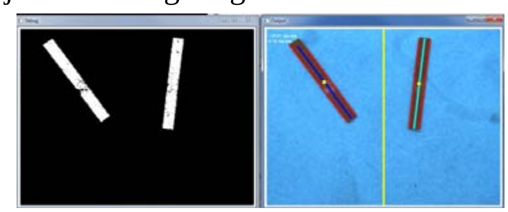

Figure 14. Pipe Identification

The major objects which must be detected using the vision system include buoys, path segments, hedge, weapon bins, window, and counselor. Due to the similarities in object shapes, 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 (Fig. 14).

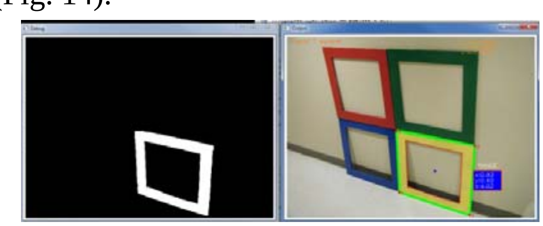

Figure 15. Geometric Pose Extraction

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 (Fig. 15). A homography based approach presented in [12] [13] allows for the determination of relative distance and orientation to objects within the field of view of the camera. Euclidean homography relationships are used to recover the pose of an object with respect to a camera frame. The Euclidean pose information obtained by the vision system can be used as additional feedback to the controller. Internal camera calibration and distortion parameters are obtained using [14].

5. 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, Texas Instruments, Fischer Connectors, JD^2, and Microsoft, and 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.

6. REFERENCES

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

[2] Feeney, Thomas P., 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] *The Joint Architecture for Unmanned Systems (JAUS): Reference Architecture*. Vol II, Version 3.3, Jun 27, 2007.

[5] Hanai, A.; Choi, H.T.; Choi, S.K.; Yun, J., "Experimental study on fime motion control of underwater robots," Advanced Robotics, vol. 18, no. 10, pp.963-978, 2004.

[6] Titterton, David H., and John L. Weston. Strapdown Inertial Navigation Technology, 2nd Edition. IET. © 2004.

[7] Foss, H.T; Meland, E.T., "Sensor Integration for Nonlinear Navigation System in Underwater Vehicles," Master of Science Thesis, Norwegian University of Science and Technology, Norway, 2007

[8] Shuster, M.D.; Oh, S.D., "Three-Axis Attitude Determination from Vector Observations," AIAA, vol.4, no. 1,pp. 70-77, 1981.

[9] Itzhack Y. Bar-Itzhack, "New Method for Extracting the Quaternion from a Rotation Matrix," Journal of Guidance, vol.23, no. 6, pp. 1085-1086, 2000.

[10] 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.

[11] 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.

[12] 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.

[13] 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.

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

[15] P. M. Patre, W. MacKunis, K. Kaiser, and W. E. Dixon, "Asymptotic Tracking for Uncertain Dynamic Systems via a Multilayer Neural Network Feedforward and RISE Feedback Control Structure," IEEE Transactions on Automatic Control, Vol. 53, No. 9, pp. 2180-2185 (2008).