SubjuGator 2016: Design and Implementation of a Modular, High-Performance AUV

R. Leyva[1], D. Dugger, D. Santiago Soto, K. Tran, J. Panikulam, J. Nezvadovitz, M. Griessler, F. Voight, E. M. Schwartz

rleyva@ufl.edu, duggerd@ufl.edu, d.soto@ufl.edu, tran6175@ufl.edu, jnezvadovitz@ufl.edu, mgriessler@ufl.edu, forrestv@ufl.edu, ems@ufl.edu

Abstract – Current autonomous underwater vehicle (AUV) research focuses on multi-agent system integration and robust control. A high performance, robust AUV design is presented with special emphasis on modularity and fault tolerance, guided by previous platform iterations and historically successful AUV designs. Modularity and fault tolerance are obtained by loose coupling of standard AUV tasks such as navigation, image processing, and manipulation. Superior performance is achieved by combining a high power-to-weight ratio system with modern robust control techniques. Major system design features including electrical infrastructure, mechanical design, and software architecture are presented. Application to the 19th annual AUVSI RoboSub competition is addressed.

I. INTRODUCTION

Leveraging 20 years of autonomous underwater vehicle (AUV) development experience at the University of Florida, which has produced 7 prior individual platform designs, the SubjuGator family of AUVs has progressed to accommodate advances in sensors, computing, and mission requirements leading to the design of the current generation SubjuGator 8 vehicle.
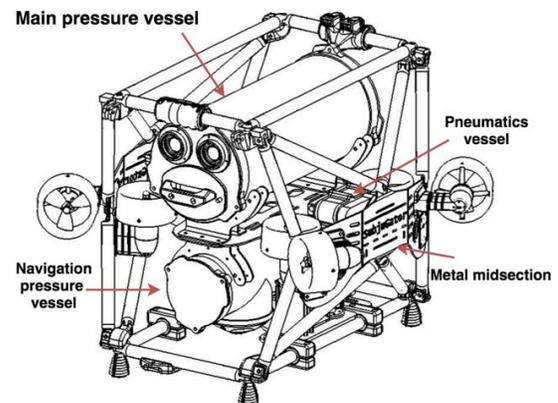

Figure 1: Assembly of SubjuGator 8 pressure vessels. The pneumatic system vessel is hidden behind a side plate.

External design influences include commercially available underwater vehicles, which are generally factored into two broad classes: long range, slender, under-actuated vehicles and short range, precision movement, and fully-actuated vehicles [1]. SubjuGator 8 falls into the latter category, as it is designed for high performance maneuvering and manipulation missions.

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsors of the 19th Annual International RoboSub Competition, to be held in San Diego, California, at the Space and Naval

Warfare Systems Command's (SPAWAR) Transducer Evaluation Center (TRANSDEC) facility, July 25th through July 31st, 2016. The eighth generation SubjuGator AUV has the capabilities to meet and exceed the challenges of the competition. With a light-weight carbon fiber framework and high-power vectored thruster configuration, SubjuGator 8 has the speed and maneuverability necessary to accomplish the competition's numerous tasks within the allotted time. It uses specialized mechanisms driven by a general purpose pneumatics system to carry out this year's manipulation tasks, and can be easily adapted to new tasks in the future. An overview of the current technologies integrated into SubjuGator 8 is presented in the following sections.

II. HARDWARE DESIGN

A major feature of SubjuGator 8 is the ability to sustain operation after a failure has occurred, where the failure can be of mechanical, electrical, or software origin. To achieve this goal, the vehicle is designed so that during a subsystem failure, the vehicle as a whole is still capable of completing a task, or at the very least, safely returning to a recovery point to be removed from the environment. As an example, the redundant eight thruster design allows for the vehicle to maintain full six degrees of freedom control in the event that on-board software detects a thruster failure. The submarine can continue to function with full motion capacities even if both a vertical and non-vertical thruster fails.

Design for fault tolerance also motivates a modular system structure, with each module performing specific tasks while communicating with other modules via TIA-485 (formerly known as RS-485) systems. Modules are each encapsulated in their own pressure vessel. Each pressure vessel is designed to meet the desired shallow water depth rating of 150 ft (~46 m). To achieve this constraint, the pressure vessels are manufactured from $1/8^{th}$ *in* thick 6061-T6 aluminum alloy that is hard-anodized for electrical insulation and corrosion resistance. Additionally, every vessel is reliably sealed with precision-machined endcaps, each using two-barrel o-ring seals. Figure 1 shows the layout of the various modules. Interconnections between modules are made using wet-mateable connectors, allowing for easy addition or removal in the work environment. The current configuration of SubjuGator 8 has the following design parameters:

- Dry Weight: 85 *lbf* (trimmed with foam to be 1% positively buoyant in water)
- Dimensions: 15 *in* x 22 *in* x 22 *in*
- Maximum Static Surge Thrust: 62 *lbf*
- Maximum Static Heave Thrust: 36 *lbf*
- Maximum Static Sway Thrust: 72 *lbf*

To unify the different modules into a durable but light weight platform, a space-frame type chassis was constructed from carbon fiber tubes and three aluminum sheet sections. This structure provides a number of key features:

- Protection of the pressure vessels and external sensors from collision
- Thruster mounts farther away from the center of mass for improved orientation control
- Versatile mounting space for new auxiliary devices, additional vessels, sensors, etc.
- A sturdy support structure for handling and seating the platform on land

Nearly all of the hardware components were manufactured in-house by students on the SubjuGator team. A few highlights in the AUV's manufacturing are welding of all pressure vessels, CNC machining, CNC bending of the aluminum sheet sections, and FDM 3D-printing of the corner brackets. Other manufacturing techniques used in the

project include laser and waterjet cutting. Figure 2 shows the two largest pressure vessels, and Figure 3 shows the framework with thrusters. A high level overview of the hardware for each module is presented in the following subsections.

**Figure 2**: Navigation vessel before anodization (left) and main vessel with front endcap (right)
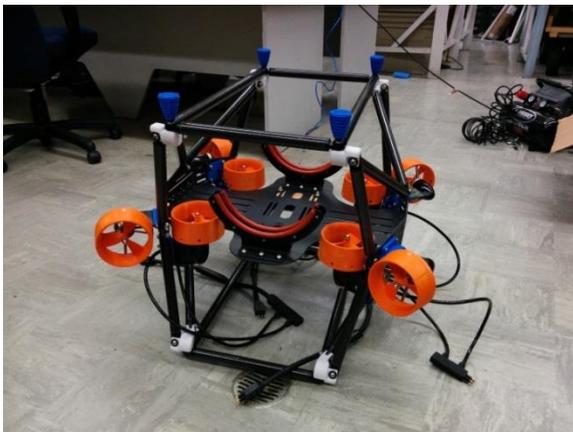
Figure 3: Hybrid carbon fiber and sheet metal framework with thrusters attached. Note the vectored thruster layout

A. Main Vessel

The main vessel contains a majority of Subjugator 8's electrical components. The major components are:

- COTS SuperMicro Intel Xeon D-1540 mini-ITX motherboard
- Custom TIA-485 networking circuitry
- Custom power management, monitoring, and regulation circuitry

For ease of installation and management, all components in the main vessel are mounted on one tray as shown in Figure 4. This was an upgrade from Subjugator 7 where two trays that had a number of interconnects proved unwieldly and awkward. Another improvement over Subjugator 7 was moving the batteries and forward cameras from individual vessels into the main vessel. Since these devices are always used together, merging their housing significantly reduces complexity, failure points, and weight.

Figure 4: Internal electronics carriage for the main vessel. Above the tray there is easy access to PCBs and wiring, while batteries are stored below the tray

Water intrusion is a constant concern for AUVs. For increased seal reliability, a 90% vacuum is pulled on the vessel. The vacuum increases the effectiveness of the endcap seals and is monitored by a pressure sensor that will alert the software of a leak.

The computer performs all high level decision making and computationally expensive computations. All sensors and actuators connect to the computer through TIA-485 or USB.

The main vessel electronics communicate to the other vessels over six

separate TIA-485 networks or USB (Figure 5). The thrusters have built-in motor controllers commanded via TIA-485. They are connected in four pairs of two, a limit imposed by the power capacity of the thruster wiring harness. The fifth TIA-485 network is dedicated to data streaming from the navigation vessel. The sixth TIA-485 network interfaces with the power monitoring circuitry, thruster kill, external actuator, and external I/O box together. All six TIA-485 networks converge on a student designed printed circuit board that communicates with the computer via USB.

Subjugator 8 has three tiers of power management (Figure 6). The battery tray contains three sets of batteries in parallel. A battery set consists of two 6 cell 5,450 *mAh* lithium polymer batteries in series. The battery tray provides 44.4 *V* and 16,350 *mAh*. The first tier of power management combines the three sets of batteries into one rail with ideal OR-ing diodes to ensure that batteries drain evenly. Inrush current and under voltage protection are integrated into the first tier. The second
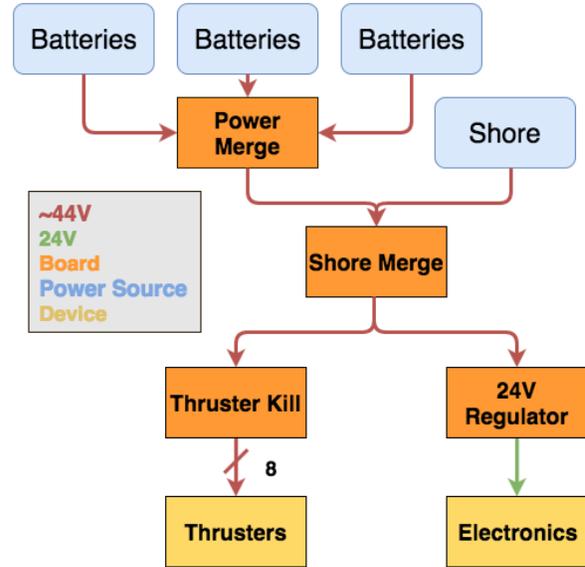

Figure 6: Power flow diagram

tier of power management switches the submarine to external power if it is present and splits the rail into the 44.4 *V* rail for the thrusters and a 24 *V* rail for all other electronics. The third tier of power management contains the hard kill and 44.4 *V* rail and 24 *V* rail monitoring circuit.
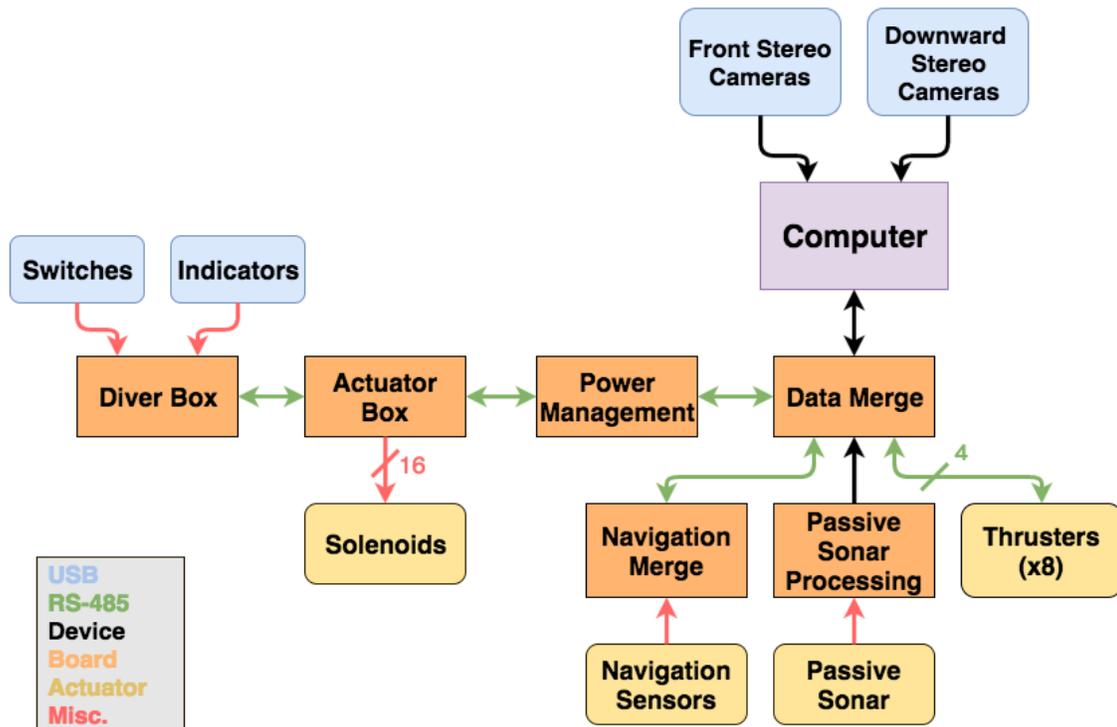

Figure 5: Communication flow diagram

B. Navigation Vessel

The sensors and components necessary to pilot an underwater vehicle are abstracted into their own vessel (Figure 7 shows a model of the navigation vessel). The navigation vessel is vehicle-independent and can be dropped into any underwater vehicle. The sensor load-out of the vessel is:

- Sensonar STIM300 9-axis inertial measurement unit (IMU)
- PNI TCM MB compass
- Teledyne Explorer Doppler velocity log
- SSI Technologies Inc. P51 series absolute pressure sensor
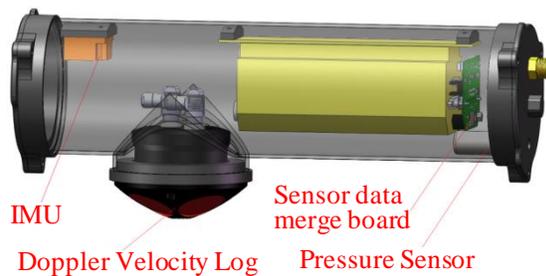
Figure 7: Model of the navigation vessel (transparent for viewing)

The raw data from all of the sensors is combined on a STM32F4 Cortex-M4 ARM processor on a student designed circuit board. There is one external connection that provides power (24 *V*) and TIA-485 communication to the main vessel.

C. External Camera Vessel

In addition to the integrated forward facing cameras, an external downward facing camera was included on the vehicle for spotting objects below the AUV. A compact Point Grey BlackFly machine vision camera is housed in an independent pressure vessel (Figure 8). These cameras offer a USB interface, wide field of view, and rich API. Separate camera pressure vessels enable versatile placement for expanding the range of vision.

Figure 8: External camera pressure vessel with front endcap prior to anodization

D. Passive Sonar

The ability to track a point source of sound in the water is encapsulated into the passive sonar pressure vessel. It contains a student-designed passive sonar amplification and filtering board (Figure 9), necessary power regulation, and USB communication. The hardware is capable of tracking multiple acoustic sources simultaneously, provided they are at different frequencies. A Texas Instruments digital signal processor (DSP) is used to collect the acoustic data, which is then transmitted to the main computer for further processing.
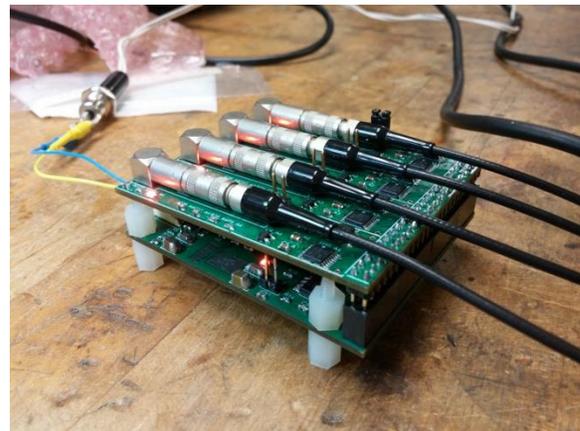

Figure 9: Passive sonar amplification and processing hardware

E. Thrusters

SubjuGator 8 uses eight VideoRay M5 thrusters. Each thruster contains a 48 *V*, 600 *W* brushless DC motor, and motor controller. These thrusters boast a very high power output, given their small size.

A custom propeller and nozzle were designed by the SubjuGator team [2] to match the performance characteristics of these thrusters. Various propeller and nozzle designs were tested empirically using a custom made static load measurement system (Figure 10). The propeller and nozzle combination was designed to meet goals of thrust symmetry, hydrodynamic efficiency, limited cavitation, and full-range loading of the motor. The current design yields a maximum static thrust of 20 *lbf* in the forward direction and 18 *lbf* in the reverse direction at around 2800 *rpm*.

F. Pneumatics System and Actuators

SubjuGator 8 integrates three types of independently operated pneumatic mechanisms (a gripper, torpedo launcher, and marker dropper) into its design. The mechanisms can be used to complete mission specific tasks and are controlled using four of six pneumatic solenoid valves which are housed in a separate, compact pressure vessel (Figure 11). This design allows for quick-disconnect fittings to facilitate easy addition or removal of pneumatic subsystems.

The entire system is powered by a 68 in^3 carbon fiber air tank, which is regulated down to a working pressure of 100 *psi* via two in-line regulators. The actuator pressure vessel also includes a student-designed actuator board, which drives the solenoids while communicating with the main computer.

Figure 11: Pneumatic solenoid housing and control board

III. SOFTWARE DESIGN

SubjuGator 8's software stack (Figure 12) is built on the Robot Operating System (ROS) Indigo. ROS is an open source framework that combines many libraries, simulators, and algorithms useful for robots and defines a simple publish/subscribe communication framework to allow for easy interoperation. By porting our existing algorithms to ROS, we gained access to its vehicle-agnostic logging, visualization, and debugging tools. Similarly, we strove to keep our in-house algorithms as general as possible, and through ROS, were able to use several SubjuGator algorithms on PropaGator, our university's entry into the RoboBoat competition and NaviGator, UF's entry for Maritime RobotX 2016. After RoboSub 2013, we made (and have continued to make) our repositories public to the greater ROS community in hopes that other projects would make use of them and are now in the process of documenting them to encourage external use.
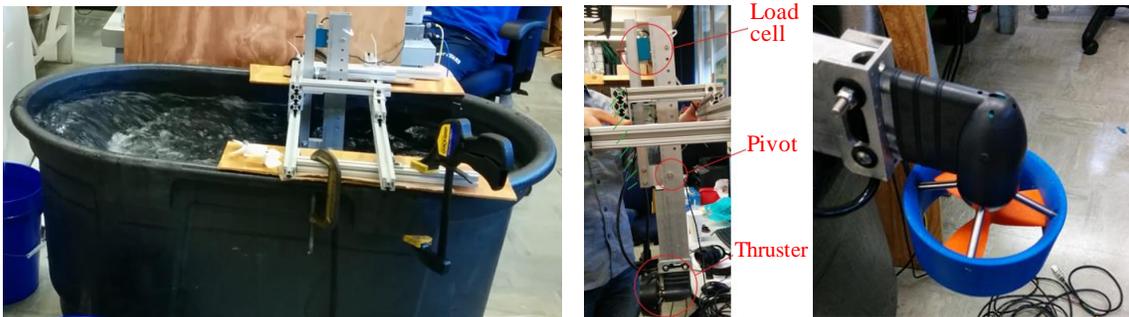
Figure 10: Thrust test (left), apparatus (middle), and current propeller/nozzle design (right)

A. Thruster Mapper

The thruster mapper is a ROS node responsible for translating a wrench (force and moment) onto an arbitrary set of thrusters using a box-constrained least squares solver. The solver uses knowledge of the thrusters' performance characteristics to minimize the error between the requested wrench and the actual wrench generated by the vehicle. The mapper also monitors the health of the thrusters and can adjust the mapping to handle thruster failures. In the case of SubjuGator 8, any one of the eight thrusters or some combinations of two can be lost while retaining full controllability.

B. State Estimator

The state estimator uses an inertial navigation system (INS) and an indirect (error-state) extended Kalman filter (Figure 13). The INS integrates inertial measurements from the IMU, producing an orientation, velocity, and position. Due to noise and unmodeled errors in the inertial sensors, the INS rapidly accumulates error. The Kalman filter estimates this error by comparing the output of the INS against the reference sensors, which are a magnetometer, depth sensor, and Doppler Velocity Log (DVL). By correcting the INS using the errors estimated by the filter, the vehicle maintains an accurate estimate of its state.

This architecture allows us to slow the computationally expensive EKF to 50 Hz while still processing our inertial data in the INS at high speed. Additionally, by periodically correcting the INS and resetting the filter's error estimates to zero, many small error approximations apply to the EKF, allowing for a better linearization than in a direct filter implementation.

The filter is designed to use unprocessed DVL data consisting of up to four radial velocities from the DVL's beams. This makes the filter more robust to DVL beam errors, as the filter incorporates knowledge of which beam failed and can also operate on two or even one beam solutions, though the error state is not completely observable during these conditions.
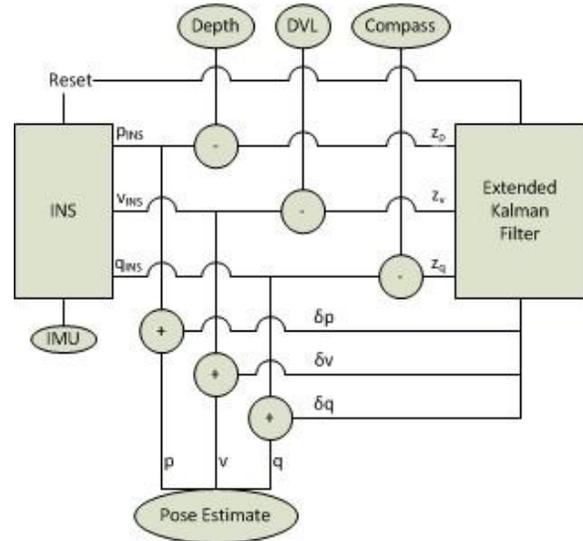

Figure 13: Indirect Unscented Kalman filter

C. Trajectory Generator and Controller

The trajectory generator and controller work together to move the vehicle to its desired waypoint. The trajectory generator is based on a nonlinear filter that produces 3rd-order continuous trajectories given vehicle constraints on velocity, acceleration, and jerk [3]. The constraints can be adjusted on each vehicle DOF, potentially being asymmetric. The generator can be issued any series of position and/or velocity waypoints, allowing greater flexibility of commanded inputs, while guaranteeing a continuous output and remaining within vehicle constraints. The trajectories can be tuned to meet the dynamic specifications of the vehicle, ensuring high-performance trajectory tracking is always obtainable by the controller.

The controller is responsible for keeping the vehicle on the trajectory and correcting for disturbances such as drag and thruster

variation. It is a trajectory tracking controller which implements a nonlinear robust integral of the sign of the error (RISE) feedback control structure [4]. This controller was developed by a member of our team and outperforms most tracking control designs available in literature. All feedback is provided via the state estimator component, finishing with a wrench being output to the thruster mapper.

D. Mission Planner

The vehicle's mission planner is responsible for high level autonomy and completing the competition tasks. It is implemented using a Python coroutine library and custom ROS client library (txROS) to enable writing simple procedural code that can asynchronously run tasks with timeouts, wait for messages, send goals, etc., enabling a hierarchical mission structure that can concisely describe high level behaviors, such as commanding waypoints and performing visual feedback.

E. Vision Processing

SubjuGator 8 uses a novel approach for robustly finding objects in varying lighting and water conditions using a particle filter. Each particle in the filter represents a guess of where the object might be in three-dimensional space, as well as what orientation the object might have. The filter then produces a template image of that guess by taking a model of the object and rendering it as it would be seen by the camera. The template is compared to the actual image received by the camera and given a score. Then, high scoring particles are reproduced while low scoring particles are removed, and when all the particles become close together, the filter has an accurate estimate of where the object is located.

This approach is used because it is blind to environmental influences on color,

requires no thresholding, and gives a three-dimensional pose of the object. The filter can converge even if a diver or cable is obscuring part of the object, because although the obstruction reduces the score of the template, as long as the object is still partially visible, the actual object is still the highest scoring pose, causing particles to accumulate there. It is also useful for competition elements that change colors unpredictably, because again while the score changes, the actual object remains the maximum and continues to accumulate particles.

Along with the particle filter, more traditional techniques, namely image segmentation via adaptive thresholding followed by contour analysis, are used to find many of the competition elements. When using these techniques, the three-dimensional pose of the object is estimated by using a priori knowledge of either the distance to or the size of the object.

In addition to being able to predict the pose of objects of interests in three-dimensional, Subjugator 8 employs the use of a stereo camera system to further check these estimates. Using two Point Grey Chameleon cameras we are able to generate more robust 3D information of our world when operating in favorable conditions. This includes generating a point cloud of the
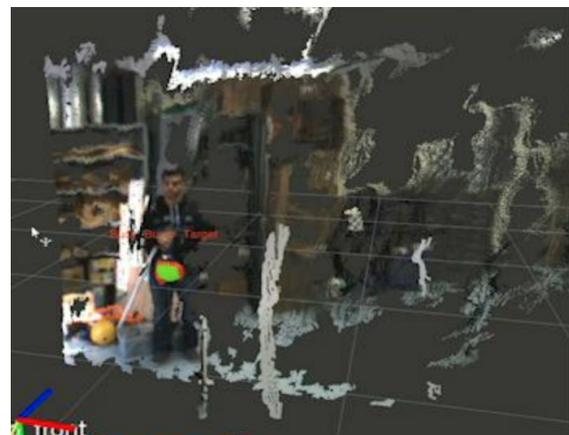
Figure 14: Stereo point cloud generation

environment (Figure 14), and triangulating the exact location of corresponding points in the environment.

In addition to persistently tracking targets of interest, two-dimensional visual servoing techniques allow for vehicle navigation with respect to the target (e.g., docking, object avoidance, surveying maneuvers). The Euclidean position and orientation information obtained by the vision system (most notably, normal distance to the target) can be used as additional feedback in visual servoing (Figure 15). Internal camera calibration and distortion parameters are obtained using [5].
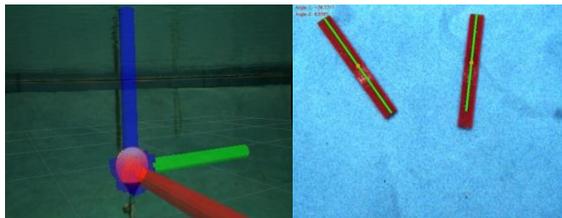
Figure 15: Sample of vision processing capabilities

F. Simulation

A large effort was made to improve the tools that are used to simulate SubjuGator 8. This entailed moving the entire simulation stack to Gazebo. Gazebo allowed the team to tie into an already existing OpenGL graphics system to visualize the simulations (Figure 16), while also providing physics simulations via the ODE and Bullet physics engines. Gazebo tied in seamlessly with the already existing SubjuGator software. This allowed the team to not only emulate the protocols of the various hardware devices found on the AUV, but to also define vehicle dynamics, change physics properties, modify lighting on the fly, and also simulate sensor noise. In addition to providing these features, adding course elements and testing missions in a faster-than-real-time manner allowed the team to quickly prototype different strategies for solving missions and quickly receive constructive feedback.

IV. COMMUNITY OUTREACH

The SubjuGator team and the Machine Intelligence Laboratory are proud to partner with several organizations in Northwest and Central Florida to provide insightful outreach programs to our community. The SubjuGator team presents the SubjuGator family of vehicles to grade school students and community members at local museums,
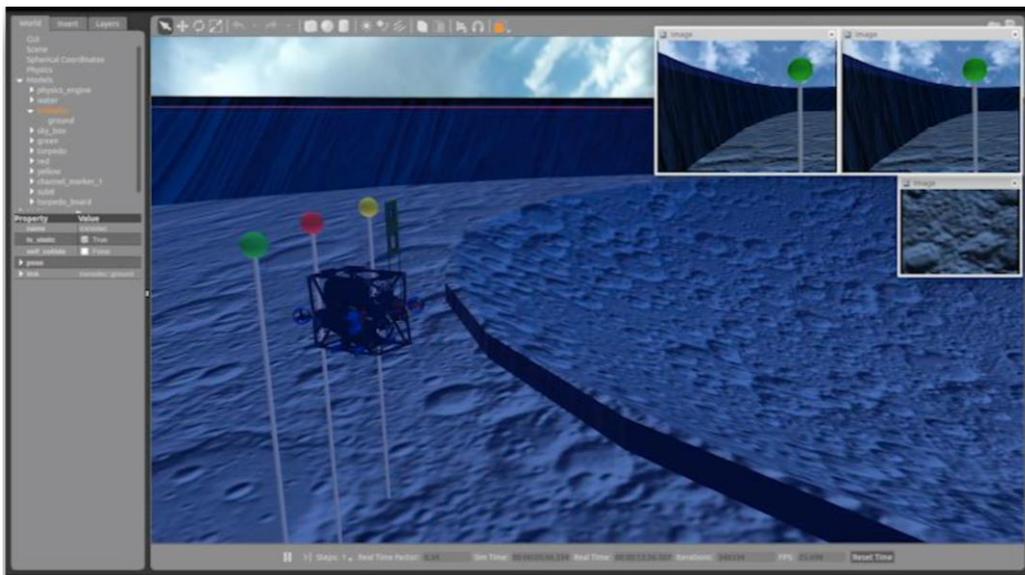

Figure 16: Sample simulation showing output from onboard cameras

UF's Engineering and Science Fair, and UF's Robotics Fair. Notably, for the past four years, SubjuGator members have taken several weeks out of their summer to instruct robotics summer camps for elementary and middle school students (ages 5-12) (Figure 17). Students at this camp are taught principals of robotics, controls, and autonomy using Lego Mindstorms. The team's hope is to generate excitement for science and engineering in all ages.

Figure 17: Everitt Middle School (left), Robotics summer camp (right)

V. CONCLUSION

SubjuGator 8 is a modular, high-performance AUV design suitable for many research tasks at the University of Florida. This AUV is easily maintained and deployed by two people. Future work includes further development of the software and control architecture, deployment of the software to multiple vehicles, and underwater multi-agent cooperation.

VI. ACKNOWLEDGMENTS

The latest SubjuGator developments can be found on our web page www.subjugator.org or by following us on twitter @SubjuGatorUF.

VII. REFERENCES

[1] P. Miller, J. Farrell, Y. Zhao, and V. Djapic, "Autonomous underwater vehicle navigation," IEEE Journal of Oceanic Engineering, vol. 35, no. 3, pp. 663–678, July 2010.

[2] J. Nezvadovitz, "Symmetric Propeller and Nozzle Design for a Marine Robot," University of Florida Journal of Undergraduate Research, Volume 17, Issue 2, Spring 2016.

[3] L. Biagiotti and C. Melchiorri, Trajectory Planning for Automatic Machines and Robots. Springer, 2008.

[4] N. Fischer, S. Bhasin, and W. Dixon, "Nonlinear control of an autonomous yunderwater vehicle: A RISE-based approach," in IEEE Proc. American Control Conference, 2011, to appear.

[5] Z. Zhang, "Flexible camera calibration by viewing a plane from unknown orientations," in IEEE Proc. International Conference on Computer Vision, vol. 1, 1999, pp. 666–673.