SubjuGator 2017: Design and Implementation of a Modular, High-Performance AUV

D. Dugger[1], D. Santiago Soto, K. Tran, J. Nezvadovitz, E. M. Schwartz
duggerd@ufl.edu, d.soto@ufl.edu, tran6175@ufl.edu, jnezvadovitz@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.

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 20th 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 24th through July 30st, 2017. 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.

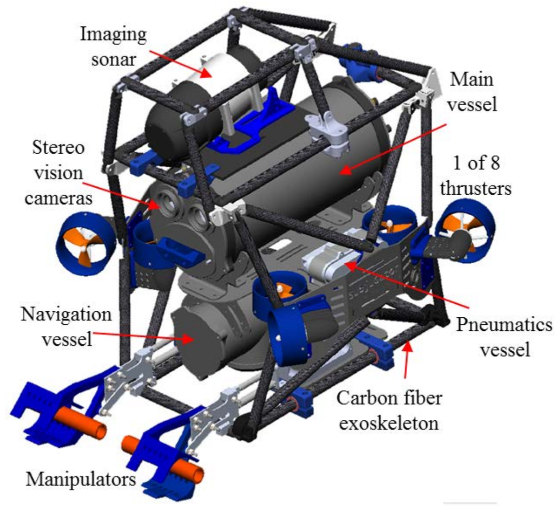

Fig 1. SubjuGator 8.

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

[1]All authors are part of the Machine Intelligence Laboratory (MIL, www.mil.ufl.edu) at the University of Florida, Gainesville, FL 32611, USA.

- Ken Tran and Jason Nezvadovitz are in the Mechanical and Aerospace Engineering (MAE) Department.
- Daniel Dugger is in the Electrical and Computer Engineering (ECE) Department.
- David Soto Santiago is in the Computer and Information Science and Engineering (CISE) Department.
- Eric M. Schwartz is the Director of MIL, an affiliate faculty member of the Center for Intelligent Machines and Robotics (CIMAR), and an ECE faculty member.

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 1/8th *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: 100 *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

Fig 2. Navigation vessel before anodization (left) and main vessel with front endcap (right).

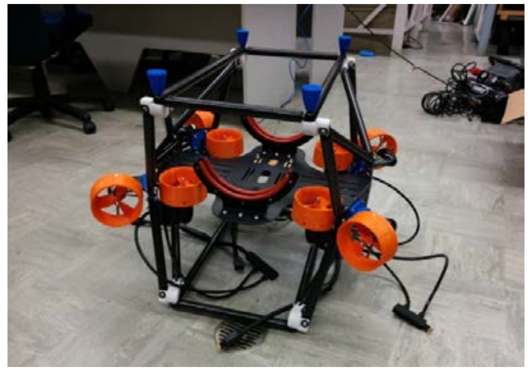

Fig 3. Hybrid carbon fiber and sheet metal framework with thrusters attached. Note the vectored thruster layout.

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.

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

Fig 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.

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.

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 consists of two 6 cell 5,450 *mAh* lithium polymer batteries in

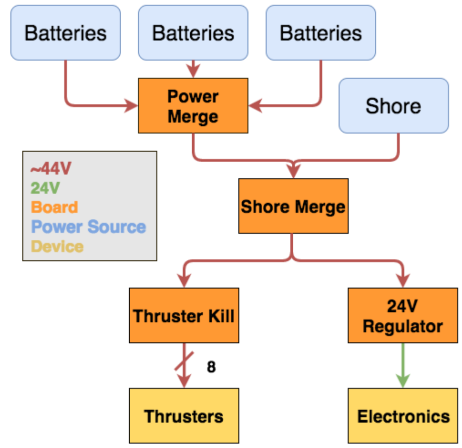

Fig 6. Power flow diagram.

series, providing 44.4 V. 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 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.

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

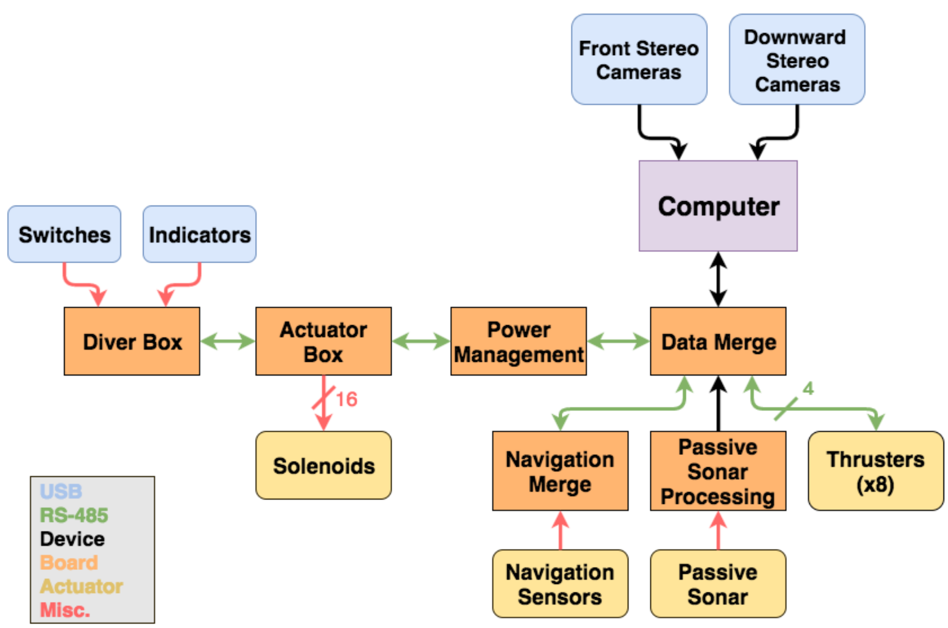

Fig 5. Communication flow diagram.

navigation vessel is vehicle-independent and can be dropped into any underwater vehicle. The sensor load-out of the vessel is:

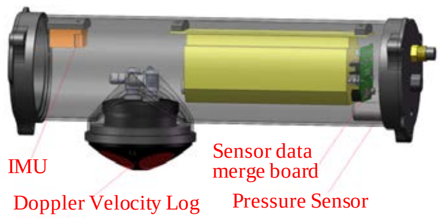

Fig 7. Model of the navigation vessel (transparent for viewing).

- 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

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). This PoE (power over Ethernet) camera offered a wide field of view and rich API. A separate camera pressure vessel enables versatile placement for expanding the range of vision.

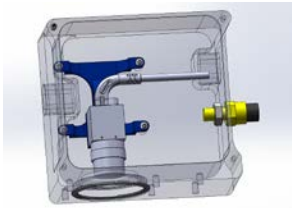

Fig 8. External camera pressure vessel with PoE camera.

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.

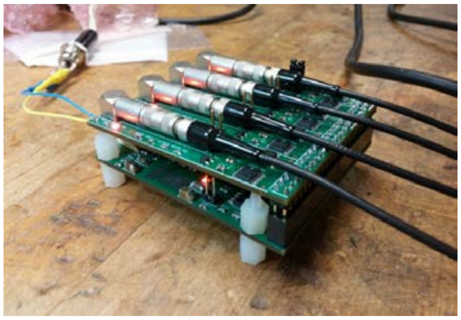

Fig 9. Passive sonar amplification and processing hardware.

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*.

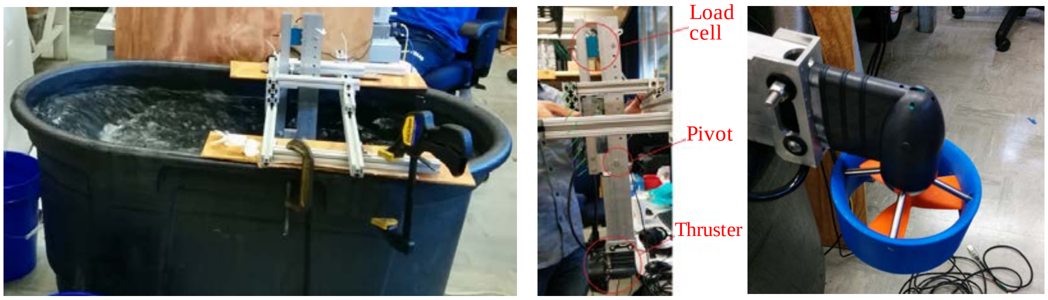

Fig 10. Thrust test (left), apparatus (middle), and current propeller/nozzle design (right).

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 twelve 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.

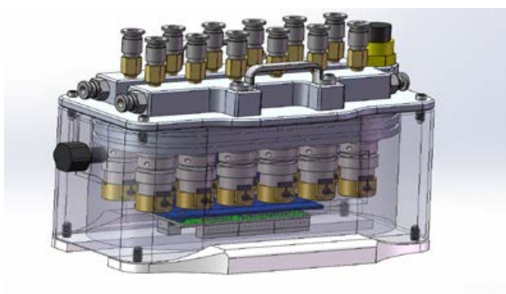

Fig 11. Pneumatic solenoid housing and control board.

G. Imaging Sonar

The Teledyne Blueview P900 imaging sonar is traditionally used for detecting underwater objects in oil rigs and various types of inspections. The SubjuGator team has chosen to use it for obstacle avoidance and to generate an occupancy grid. To protect this valuable piece of equipment, another carbon fiber spaceframe has been integrated into the original design.

III. SOFTWARE DESIGN

SubjuGator 8's software stack (Figure 12) is built on the Robot Operating System (ROS) Kinetic. 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.

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 unscented Kalman filter (Figure 13). The INS integrates inertial measurements from the IMU, producing an orientation, velocity, and position prediction. Due to noise and unmodeled errors in the inertial sensors, the INS prediction rapidly accumulates error. The Kalman filter estimates the state by comparing the output of the INS prediction 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.

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

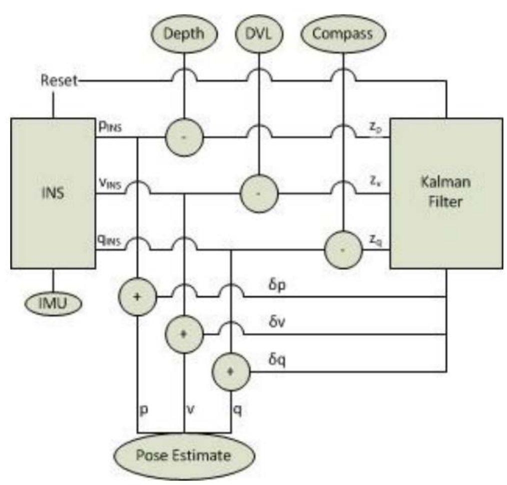

Fig 13. Unscented Kalman filter.

even one beam solutions, though the state is not completely observable during these conditions.

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

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

Fig 14. Stereo point cloud generation.

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].

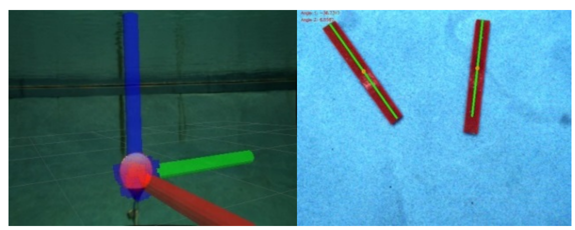

Fig 15. Sample of vision processing capabilities.

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

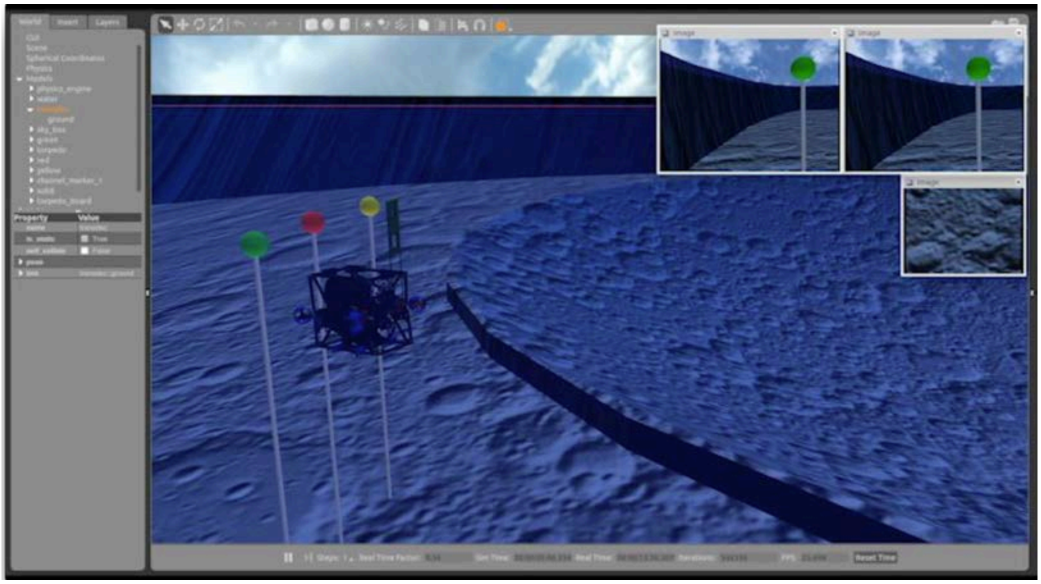

Fig 16. Sample simulation showing output from onboard cameras.

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, middle, and high school students and community members at local museums, UF's Engineering and Science Fair, and other events. Notably, for the past several 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. Figure 18 shows students soon to be entering 10th or 11th grade from the Gator Computing Program camp just a few weeks ago.

Fig 17. Everitt Middle School (left), Robotics summer camp (right).

Fig 18. Gator Computing Program (camp) students with SubjuGator team at testing pool on campus on June 7, 2017.

The SubjuGator team's hope is to generate excitement for science and engineering in all ages.

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 University of Florida SubjuGator team would like to thank everyone who has supported us throughout the year, including the University of Florida's Electrical and Computer Engineering Department and Mechanical and Aerospace Engineering Department., and the students and faculty in UF's CIMAR (Center for Intelligent Machines and Robotics). We would also like to thank several former students who have contributed to our team financially and with advice. Each of the following corporate sponsors were gracious in assist with both monetary and product donations:

- Diamond Sponsors: Harris Corporation
- Platinum Sponsors: Northrup Grumman
- Gold Sponsors: UF Dept. of Electrical and Computer Engineering, UF Dept. of Mechanical and Aerospace Engineering, JD^2
- Silver Sponsors: Texas Instruments, IEEE Gainesville Section, Altera, Advanced Circuits, DigiKey

Finally, the Machine Intelligence Laboratory is also honored to have recently been sponsored by the University of Florida's Herbert Wertheim College of Engineering, mostly in support of our Maritime RobotX Challenge 2016 champion, NaviGator AMS (autonomous maritime system).

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

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