SubjuGator 2012

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Abstract—**Modern autonomous underwater vehicle (AUV) research is moving towards multi-agent system integration and control. Many university research projects, however, are restricted by cost to obtain even a single AUV platform. An affordable, robust AUV design is presented with special emphasis on modularity and fault tolerance, guided by previous platform iterations and historically successful AUV designs. Modularity is obtained by the loose coupling of typical AUV tasks such as navigation, image processing, and interaction with platform specific hardware. Fault tolerance is integrated from the lowest hardware levels to the vehicle's mission planning framework. Major system design features including electrical infrastructure, mechanical design, and software architecture are presented. Application to the 15th annual AUVSI RoboSub competition is addressed.**

I. Introduction

Leveraging 16 years of autonomous underwater vehicle (AUV) development experience at the University of Florida, which has produced 6 independent platform designs, the SubjuGator family of AUVs has progressed to accommodate advances in sensors, computing, and mission requirements culminating in the design of the current generation SubjuGator 7 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, fully-actuated vehicles. This large difference in capabilities forces the use of multiple vehicles with multiple payload configurations, increasing necessary overhead. SubjuGator 7 is a novel attempt to bridge the gap between the separate design classes, and unify the capabilities of both into a single low cost platform.

The Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR) are sponsors of the 15th 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 17th through July 22nd, 2012. The seventh generation SubjuGator AUV has evolved to not only meet the new challenges of the annual competition, but to engage in groundbreaking research initiatives. An overview of the current technologies integrated into SubjuGator 7 are presented in the following sections.

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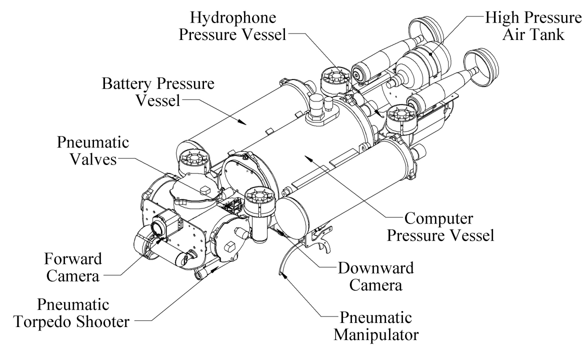

Figure 1: Assembly of SubjuGator 7 pressure vessels.

II. Hardware Design

A primary feature of SubjuGator 7 is the ability to sustain operation after a failure has occurred, where the failure can be of mechanical, electrical, or software origins. To facilitate this goal, the vehicle is designed so that during a failure event, the faulted system 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. A fault tolerant design motivates a modular system structure, with each module performing specific tasks while communicating with other modules via an ethernet medium. Modules are typically encapsulated in their own pressure vessel, but there is no requirement for all modules to be isolated. Each pressure vessel is designed to meet the desired shallow water depth rating of 150 feet (approx. 45 meters). To achieve this constraint, all pressure vessels in the current configuration are manufactured from 6061-T6 aluminum alloy that is hard-anodized for electrical insulation and corrosion resistance. Interconnections between modules

Figure 2: Demonstration of folding weldments which allow access to bulkheads and internal computer pressure vessel components through endcap removal.

are made using wet-matable connectors, allowing for easy addition or removal in the work environment. The current configuration of SubjuGator 7 has the following design parameters:

- Dry Weight: *115lb (Trimmed to be 1% positively buoyant in water)*
- Overall Dimensions: *50"x18"x18" (LxWxH)*
- Maximum Surge Thrust: *12 lbf (Bollard Pull)*
- Maximum Heave Thrust: *16 lbf (Bollard Pull)*
- Maximum Sway Thrust: *8 lbf (Bollard Pull)*

To unify the different modules into a suitable AUV platform, a 6061-T6 aluminum bottom hull was designed and manufactured. It is split into three folding weldments for easy access to the main pressure vessel and acts to both streamline the underside of the AUV, as well as protect it from collision. Figure 2 demonstrates the use of the folding hull. The overall assembly configuration of SubjuGator 7 and each of its pressure vessels is shown in Figure 1. However, the top lid and cowlings that complete the hybrid shape are not shown.

All of the hardware components were manufactured by students on the SubjuGator team and volunteers. A few of the highlights in the the AUV's manufacturing are CNC machining, welding of all pressure vessels, and marriage of the DVL box to the main frame, Figure 3. Other manufacturing techniques used in the project include laser and waterjet cutting. Custom endcaps and cabling using a urethane potting material were made to interface with the commercial thrusters, Figure 4.

A high level overview of the hardware for each module is presented in the following subsections.

Figure 3: Top Left: CNC machining of an endcap, Top Right: DVL box in the main frame, Bottom Left: Welding of a battery pod, Bottom Right: Waterjet cutting.

Figure 4: Custom cable potting for thrusters.

A. *Main Pressure Vessel*

The main pressure vessel of SubjuGator 7 contains vehicle specific electrical hardware, and ample connections to environment sensors (e.g., cameras, hydrophone arrays, water temperature sensors, etc). It contains the following major components:

- COTS Intel Xeon Mainboard in Mini-ITX form factor
- COTS Dual 8 port Ethernet Switches
- 8 Motor Control/Power Stage Modules
- Power management and monitoring circuitry

The components inside the main pressure vessel are separated into two groups and are mounted on two independent trays, the computer tray and the rear tray. Each tray is attached to one of the endcaps and can be removed from the pressure vessel by removing the end cap. The computer tray houses the primary computer and its associated power supply. The rear tray houses the power distribution components, the networking hub and the motor control / power stage modules. Figure 5 shows each of the assembled main pressure vessel trays.

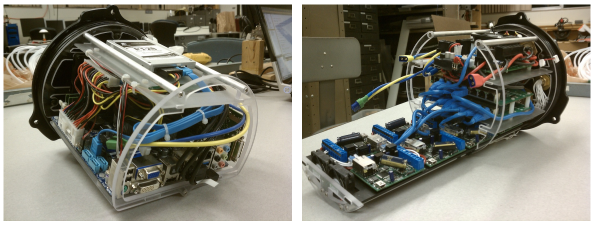

Figure 5: Left: Main pressure vessel computer tray, Right: Main pressure vessel rear tray.

The primary computer performs environment sensing and mission level tasks. It also allows for the connectivity of USB peripherals, such as cameras and specialized data acquisition devices.

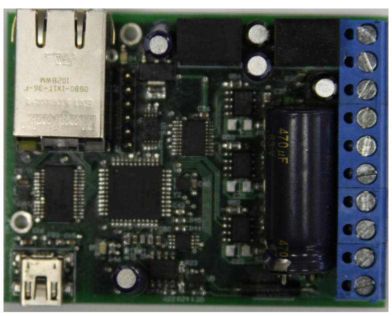

Figure 6: Motor control / power stage hardware.

The motor control / power stage modules, Figure 6, incorporate algorithms and necessary sensor interfaces to safely control brushed or sensored brushless motors at 50V with a maximum load of 10A. Default communication is facilitated through the ethernet bus; however, each motor control/power stage can be configured to emulate a standard serial port over USB. Peak current, maximum current slew, maximum motor voltage, and many other programmable features are accessible via a web browser or a programmatic serial communication protocol. Each motor in the AUV design has a dedicated motor controller. The independence of each controller is used to encapsulate catastrophic failures to a single source instead of inducing multiple failure points, an advantage over previous design iterations.

Power management circuitry, shown in Figure 7, inside the main pressure vessel allows for multiple hot swappable external power supplies to be joined into two primary 16V and 32V rails, transparent to any devices that are powered. The design also preserves the complete isolation of these two rails, segmenting any inductive or heavily switching loads to a confined power space away from sensitive sensors and microelectronics. Furthermore, each power input's present voltage and current are monitored independently, enabling the power controller to shut down in the case of dangerous over current or under voltage situations. Audible commands help to inform the operator of system status when sealed and magnetic hall effect sensors allow for power control of the system without potential leaks through mechanical switches.

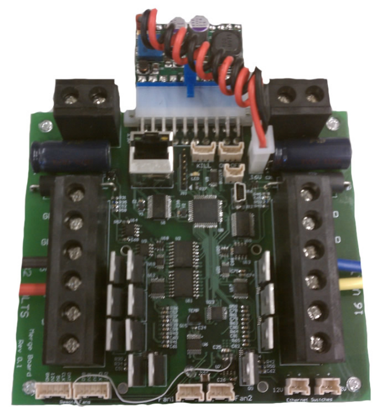

Figure 7: Power management / merge hardware.

Since nearly all of the individual modules in SubjuGator 7 were designed to communicate via ethernet, the main pressure vessel also houses the networking hub. The hub consists of two 8 port ethernet switches which allow each module to communicate to local network addresses internally as well as external addresses when SubjuGator 7 is actively tethered.

B. Navigation Pressure Vessel

One of the major contributions of the SubjuGator 7 design is the modularization of the sensors and components necessary to pilot an underwater vehicle. This modularization is evident both electrically and mechanically. The platform specific components (e.g., motor power stages, platform specific processing, etc.) have been removed, leaving only the core essentials to navigate and control a generic vehicle. Specifically, navigation sensors that are vehicle independent such as an inertial measurement unit (IMU), Doppler velocity log (DVL), depth sensor, temperature sensor, and GPS receiver, and the processing capability to unify the data in the form of a navigation and control computer are integrated into the navigation pressure vessel. Since the majority of the sensors incorporated are common to most modern

AUV platforms [1], only the custom designed navigation computer is described in more detail.

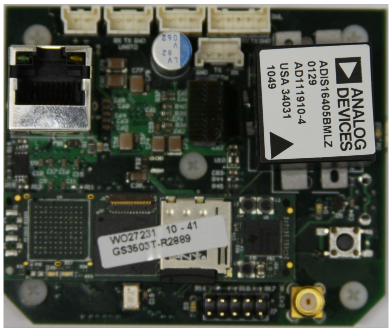

Figure 8: Navigation computer.

The navigation computer, Figure 8, consists of the following major components:

- Gumstix Overo Computer-On-Module (COM) containing a Texas Instruments OMAP3530 application processor at 720MHz
- Altera Cyclone II FPGA with level shifting and processing capabilities
- Analog Devices ADIS16405 9 degree of freedom IMU
- GPS receiver capable of 14 channel tracking and 10Hz update rate
- RS-232 connections to interface sensors
- 10/100BASE-TX Ethernet Communication

The components are combined on a custom printed circuit board (PCB) with a small form factor of 3”x2.5” and weighing less than 2 ounces excluding the GPS antenna which is typically platform specific. Despite its compact size, the board exposes enough processing power and sensor inputs to allow for accurate navigation of the AUV.

Mechanically, all of the sensors and the navigation computer are isolated into a separate pressure vessel shown in Figure 9 with only two external connections required: 16V power in and ethernet for communication.

C. Battery Pressure Vessel

The mobile power for the AUV is stored inside two independent battery pressure vessels. Each pod contains a combination of 5Ah and 10Ah, 4 cell lithium polymer battery packs and connects to to the main computer pressure vessel via waterproof cabling. Power regulating and battery monitor circuitry is included inside each battery pressure vessel to protect against low voltage and over current situations. Audible commands help to inform the operator of battery status when sealed and magnetic hall effect sensors allow for power control

Figure 9: Navigation pressure vessel.

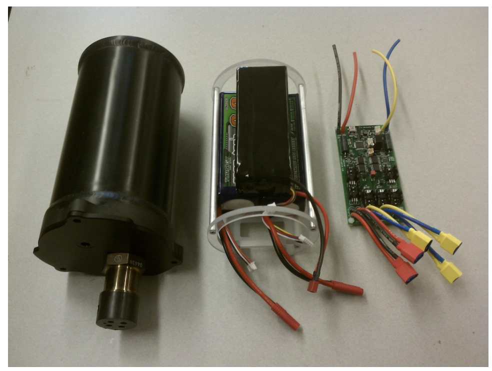

Figure 10: Battery pod pressure vessel and internal configuration.

of the pod without potential leaks through mechanical switches.

D. Camera Pressure Vessel

Machine vision is incorporated into the AUV through the use of independently housed Point Grey machine vision cameras. The cameras are affordable and offer an easy to use USB interface to the video stream. As of 2012, the machine vision cameras now facilitate color corrective lenses to compensate for color loss at depth. The decision to design a separate pressure vessel for each camera is beneficial since both the number and location of cameras is freely adaptable up to the limit of the number of USB connections exposed by the main hull, presently 5. This can be increased, however, through the use of an external hub, discussed in a later section. Figure 11 shows a single camera assembled camera housing. The configuration in Figure 1 demonstrates the positioning of two cameras, one forward facing and one downward facing.

Figure 11: Camera pressure vessel assembled with Point Grey camera.

E. Hydrophone Pressure Vessel

The ability to track a point source of sound in the water is encapsulated into the hydrophone pressure vessel. It contains a custom designed (in-house) hydrophone amplification and filtering board, Figure 12, necessary power regulation, and USB communication. The hardware is capable of tracking multiple acoustic sources simultaneously provided they are at different frequencies. An FPGA is used to collect the acoustic data, which is then transmitted to the main computer for processing.

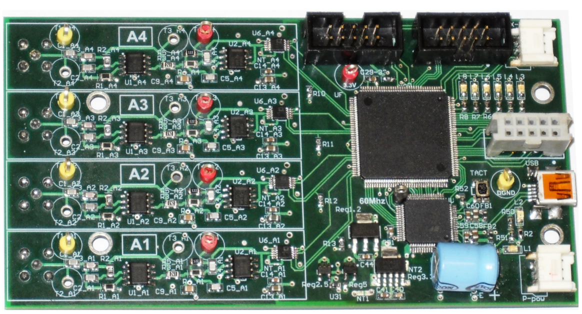

Figure 12: Hydrophone amplification / processing hardware.

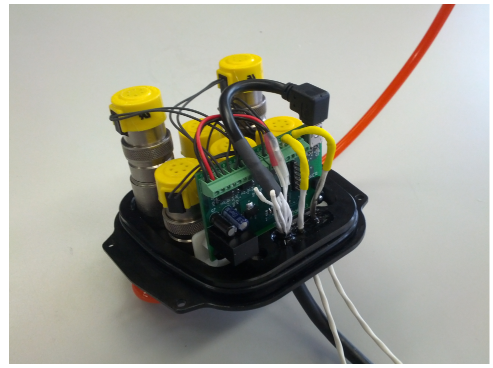

Figure 13: Pneumatic solenoid valve housing and control board.

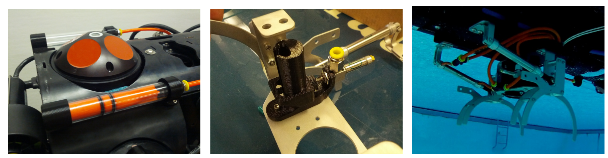

Figure 14: Left: Torpedo shooter, Middle: Ball dropper, Right: Manipulator assembly.

F. External Expansion Hub

An external expansion hub may be incorporated to allow for reasonable expansion. It is responsible for exposing necessary serial, USB, or ethernet ports to additional sensors, devices or vehicles, and multiplexing the data streams onto a single ethernet connection for communication with other system modules.

G. External Actuators

SubjuGator 7 integrates three types of independently operated pneumatic actuator mechanisms into its design. The mechanisms can be used to complete mission specific tasks in its environment and are controlled using pneumatic solenoid valves which are housed in a separate, compact pressure vessel, Figure 13. The system is powered by a 68 cu in. carbon fiber air tank, which is regulated down to a working pressure of 100 psi via two separate regulators. The actuator pressure vessel also includes a custom design actuator board which drives the solenoids while communicating with the main computer. Currently, the vehicle's capabilities include a single, multi-fire ball dropper, two single-fire torpedos, and two infinite-use manipulator claws. SubjuGator 7's configuration supports up to 6 independent actuators. Each of the currently integrated mechanisms are shown in Figure 14.

III. Software Design

In modern robotic development, many design options exist for software implementation. Major pushes toward multi-agent interoperability have spawned the necessity for seamless communication over varying mediums including shared memory, LAN, or even WAN. Two major communication standards used at the University of Florida are the Joint Architecture for Unmanned Systems (JAUS), and Data Distribution Services (DDS). These schemes are not directly compatible; however, the AUV must still be able to interoperate with other vehicles or control stations that may be utilizing either standard with minimal extra development time. To overcome this challenge, the standalone functionality of SubjuGator 7 has been designed independently of any communication scheme. By utilizing standard object oriented coding

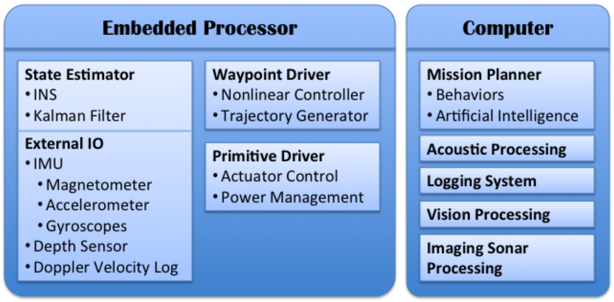

Figure 15: Software high level block diagram.

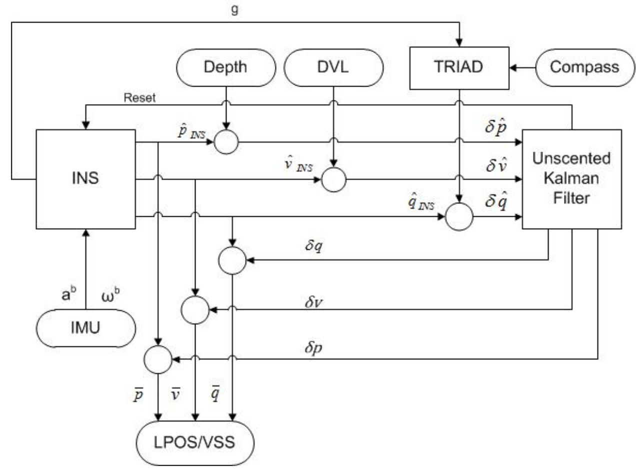

Figure 16: Indirect Unscented Kalman filter.

practices, a loosely coupled behavior-communication relationship is established.

Overall component functionalities (including component specific algorithms, behavior logic, etc.) are abstracted above the hardware allowing for expedient platform changes - even to a different AUV (e.g., SubjuGator 6). The remainder of this section presents the major software components implemented in the AUV, illustrated in Figure 15.

A. Primitive Driver

The primitive driver component (utilizing nomenclature from the JAUS specification [2]) is responsible for translating a generic output request onto the AUV. For instance, a desired force and moment about the center of mass of the vehicle are decoupled into the 8 desired normalized forces that are sent to the motor control modules, or a request to move a manipulator is packaged and sent to the hardware actuator board. Setting files describe thruster count and orientation, as well as actuator payloads. The primitive driver also monitors the health of the vehicles thrusters. In the event of a thruster failure, the primitive drive can adapt the thruster mapping to continue to provide the requested force and moment.

B. State Estimator

The state estimation component is responsible for acquiring navigation specific sensory data, and encapsulating it into a generic vehicle pose (position and orientation) data object referenced in the locally fixed North-East-Down (NED) frame.

To achieve this, an Indirect Unscented Kalman filter (Figure 16) estimates the error in position, velocity, and orientation quaternion generated by the inertial navigation system (INS). The INS high speed sensory inputs ($\sim$205Hz) include three-axis magnetometer, accelerometer, and gyroscopic inputs. Low speed reference sensors are used to generate the input error signals for the Kalman filter: DVL 3-axis velocity, GPS, depth, and a filtered tilt/magnetometer/gravity based estimation of attitude. In the event of a sensor failure, the state estimation module attempts to continue providing a best estimate of vehicle pose, however, it notifies the system of the reduced capacity.

C. Waypoint Driver

The waypoint driver component contains two primary workers. The first worker is a trajectory generator 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, and permits asymmetric constraints. We make use of asymmetric trajectories on Subjugation 7 to take advantage of, for example, our ability to generate greater thrust in the forward direction, while still maintaining an obtainable, lower speed when traveling in reverse. 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 second worker 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, and the output is a generic desired force and moment applied to the AUV.

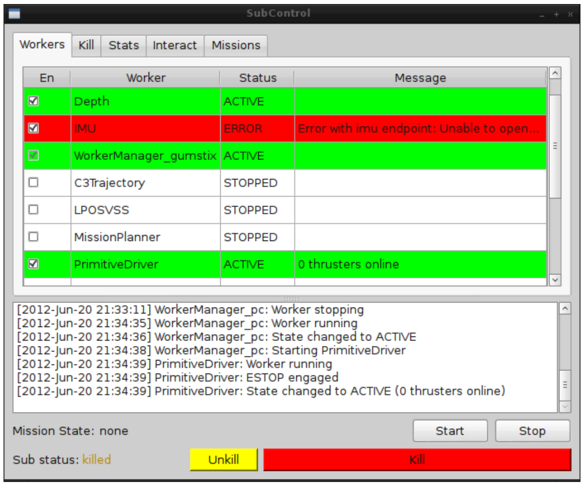

Figure 17: Arbiter GUI interface.

D. *Vehicle Scripting and Mission Planner*

Almost all aspects of the vehicle can be controlled through a set of Python libraries built on a Python DDS binding. This allows for rapid prototyping and experimentation with vehicle functionality. The scripting framework is also used to automate many vehicle calibration procedures, including invoking MATLAB scripts and saving the results in appropriate configuration files for immediate usage.

The Mission Planner is also written in Python, and can execute a user specified sequence of missions. The missions are ordinary scripts which communicate their state and any failure conditions to the Mission Planner. If a mission does report a failure, the planner can execute a fallback mission sequence. The planner also supports interactive execution of Python snippets over DDS, which allows for quick execution of real time scripts, as well as serving as an lightweight interface for general vehicle control.

E. *Arbiter*

The software Arbiter controls all aspects of individual sub processes. Because the software architecture is broken down into core components, the Arbiter maintains the ability to start, stop, restart (automatically, via integrated fault detection capabilities) processes as well as report vital status information back to the operator during tethered operation (e.g., DVL dropouts, kill status, etc.). The Arbiter also is capable of commanding hardware kill messages to the merge board at any time. Figure 17 illustrate the GUI interface for the Arbiter.

F. *Vision Processing*

The computer vision system on SubjuGator 7 is capable of generating feedback control signals utilizing

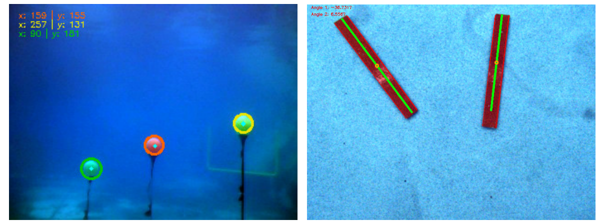

Figure 18: Example vision processing algorithm result for buoy and pipe tasks.

both two dimensional and three dimensional feature information from complicated scenes. Because underwater environments can pose many types of challenges for object identification such as varying luminosities, sunlight dissipation, particle noise, and occlusions, combinations of novel normalization, filtering techniques, and color space models are utilized to robustly extract relevant target information from the scene in real-time. Feature and contour-based descriptors allow for accurate and robust target identification between frames.

After identification, target tracking algorithms ensure that objects of interest are maintained within the field of view of the camera during servoing, displayed in Figure 18. SubjuGator 7 has developed the ability to track multiple stationary or moving objects at one time using a multi-tiered control structure which includes vehicle trajectory planning, image-based identification, tracking, and servo control. This problem is motivated by the hypothesis that multiple targets can be maintained within the field of view of an autonomous imaging system through actuation of the vehicle's position and orientation by analyzing constraints in dispersion covariance, quality of service, relative distance of targets and the system's dynamics.

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). When multi-point feature information is available for the object in the frame, nonlinear homography-based control methods [5], [6] are used to identify the Euclidean position, orientation and velocity of targets relative to the camera as they are being tracked. 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. Internal camera calibration and distortion parameters are obtained using [7].

IV. Vehicle Testing

SubjuGator 7 has seen nearly 80 hours of in-water testing since January, 2012, with additional 100 hours

Figure 19: Pool testing facility for SubjuGator 7.

Figure 20: Robotics summer camp, taught by student members of SubjuGator team.

of in-water testing in the Summer and Fall of 2011. Stringent calibration procedures have been streamlined and are now obtainable within a 30 minute time-frame should the systems need to be re-calibrated (e.g., magnetometer calibrations, alignments, buoyancy, etc). The AUV is fully capable of sustaining autonomous operation with minimal operator supervision and has a run time of approximately 4 hours on half-battery power and 8 hours on full-battery power. The main testing facility for SubjuGator 7 is a swimming pool at the University of Florida, shown in Figure 19.

V. Community Outreach

The SubjuGator team and the Machine Intelligence Laboratory are proud to partner with several organizations in Central Florida to provide insightful outreach programs to our community. The SubjuGator team has presented the SubjuGator family of vehicles to grade school students and community members at local museums, UF's Engineering and Science Fair, and UF's Robotics Fair. Also, laboratory tours are frequently given to prospective students and community members, such as the residence of Oak Hammock, a local retirement community. In addition, SubjuGator members also instruct two, week-long robotics summer camps for elementary and middle school students (ages 5-12), Figure 20. Students are taught principals of robotics, controls, and autonomy using Lego Mindstorms. The team's hope is to generate excitment for science and engineering in all ages.

VI. Conclusions

SubjuGator 7 is a hybrid, modular AUV design suitable for many research tasks at the University of Florida. This relatively low cost 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.

VII. 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 Mechanical Engineering departments. We would like to extend an appreciative thank you to our advisor, Dr. Eric Schwartz, without whom this project would not be possible, and to Dr. Anthony Arroyo and the Machine Intelligence Laboratory at UF. We would also like to thank each of our corporate sponsors for graciously assisting with both monetary and product donations:

- **Tier 1 Sponsors**: JD^2
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The latest SubjuGator developments can be found at our web page www.subjugator.org or by following us on Twitter: @SubjuGatorUF.

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