The High Performance Plunger Georgia Tech RoboSub 2018

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***Abstract*—This paper describes the design of Plunger, Georgia Tech's vehicle for the 2018 Robosub competition. By focusing on consistently being able to complete a few of the initial tasks, we expect to build upon our 5th place finish at the 2017 competition. This strategy led to the decision to incrementally improve the platform that was used in the 2017 competition. The main frame and pressure vessel were re-used, with improvements to the internal electronics tray, isolation of sensitive electronic components, and the implementation of a modular pneumatic system. On the software side of the process, more significant changes were undertaken. Primarily, ROS was used in place of the custom operating application used in previous competitions. This decision was made for exploratory reasons, as well as the hope of easier maintenance and integration for future teams. Additional software changes include a focus on navigation capabilities in state estimation, and attempts to use modern neural network based approaches to object recognition and classification.**

I. Competition Strategy

The major strategy we have taken in working towards this year's competition is consistency, consistency, consistency. This is born from observations made by members of the team at past AUVSI marine robotics competitions. Namely, the most successful teams are not those that do everything halfway, but those who do a few things very well. This has borne itself out in our approach to both hardware and software development, which will be discussed further in the following subsections.

A. Hardware Development Strategy

A major aspect of our strategy to target consistency is to develop a platform that is stable with regard to design changes. As such, there were no major external modifications made to the previous year's platform. This vehicle achieved the goals of static stability through elongation in the vertical dimension. This allowed the center of mass of the vehicle to be significantly below the center of buoyancy, yielding high stability in both pitch and roll of the vehicle. This was a highly desirable feature that in essence removes two degrees of freedom from the dynamics of the vehicle, and reduces the number of necessary motors to four to maintain effectively holonomic control.

By maintaining the same frame and main pressure vessel as the previous year, additional effort could be spent on improvements to the ease of use of the vehicle and expanded actuation capabilities. The ease of use improvements were given the highest priority, as they more closely match our strategy to push closer to the consistency side of the tradeoff with complexity. These ease of use improvements include a newly designed modular electronics tray in the main pressure vessel, improved wire routing, and an improved rear plate design.

While these improvements were the primary focus of hardware development, some focus was given to development of new actuation capabilities of the vehicle. While these additions added some complexity to the system, the decision to develop them was justified with the following logic. Software capabilities are possible, if not necessary, to be improved while on site at the competition. However, hardware development and integration of new subsystems is nearly impossible. Therefore, it is worthwhile to spend some hardware development time afforded by avoiding major changes to the vehicle frame on novel development. These efforts were focused on the development of a modular pneumatic subsystem, as this allows for easier future expanded actuation capabilities.

B. Software Development Strategy

The approach to software took a more aggressive approach to improve the consistency of the system. The most significant strategic shift was the change to using ROS as the backbone of the software stack instead of the previously used custom software stack, ARCS. This shift was taken for a few reasons. Among these were integration with a more mature software community. This is advantageous as it eases the learning curve for bringing newer team members onto the project. This was especially important, as the team is entering a phase of significant turnover as much of the initial team behind the custom software has moved on. This choice also brings our software stack more closely in line with much of the rest of the robotics community at large.

A major focus of software development was the navigation capabilities of the submarine. This was a strategic focus, as this is a necessary ability to complete any of the tasks with any consistency. Additionally, there are a significant number of tasks that can be completed with navigation alone. These tasks include the only required task, the entrance gate. Other tasks that can be scored on purely through navigation also include the Shoot Craps, Follow Paths, Buy a Gold Chip, and Cash In. While full points can't be achieved on Buy a Gold Chip, activation of the plate alone can yield a useful number of points. This is similar to Cash In. Full points requires significant actuation capabilities and a significant increase to the complexity of the vehicle, but recognition of the area and the ability to navigate to the enclosed area still yields many points. Additionally, a focus on navigation capabilities should increase the repeatability of our performance at all other tasks.

A focus on navigation capabilities requires significant sensory capabilities. These can come in many forms. However, due to cost limitations, our main sensor are our cameras. As such, the final main focus of software development was improving the vision capabilities of the system. Achieving consistency with vision systems is difficult though, as conditions can change day by day at the competition. This exact problem played significantly into the results of last year's competition. On the final day, clear weather and a freshly chlorinated pool presented significantly different conditions from the previous days in the week. This resulted in greatly reduced capabilities for most of the teams. To alleviate a difficulty like this, we plan to focus on the adaptability of our vision systems. This adaptability will inevitably add some complexity to the system, but it is worthwhile when considering the potential benefits. Additionally, this adaptability also plays into our overarching goal of achieving a consistently performing system. By ensuring the basic navigational capabilities of the vehicle are sound, the implementation of reach missions, such as the Play Slots mission, will be easier at the competition.

C. *Mission Strategy*

Our approach for winning the competition was simple, we believed our best strategy would be to focus on completing a few tasks rather then attempting to complete all the challenges. Our hope was that if we focused our attention on a few tasks, we would be able to reach a point where our vehicle would have consistent success in completing these tasks. Therefore, we felt that our time would be best spent by working to improve the existing capabilities of our vehicle. The tasks we plan to attempt include entering the gate on the declared side, following path markers, and touching the buoys. A very basic system design could be used to complete these tasks, whereas a vehicle attempting to play the slots or roulette would require a much more complex system. Additionally, we figure that if our vehicle could not complete the simple tasks, it would be utterly pointless to attempt the more difficult tasks. As a result, we spent the majority of our time working on improving the navigation and sensory subsystems. By working to improve these tasks, we could ensure the vehicle's ability to complete the previously mentioned tasks.

II. Design Creativity

Among the most creative aspects of the system is the unorthodox tall frame design, with the main pressure vessel at the top of a rectangular aluminum frame and all ballast placed at the bottom. As previously discussed, this places the center of mass significantly below the center of buoyancy for the vehicle. This leads to vehicle dynamics that have significant static stability in both pitch and roll. This decision was made to reduce the degrees of freedom that would need to be controlled by the submarine. This simplification of the dynamics of the vehicle was helpful in a matching simplification of the control software. Additionally, with 2 degrees of freedom essentially removed from the system, 2 motors could be removed.

Another major feature of the vehicle is the slotted aluminum frame. This frame is what allows for the tall design, and makes modifications to sensor and actuator packages much easier. The slotted rails in use are commonly used in many varying applications, so adapters and connectors of varying forms are readily available. This makes the integration of new systems significantly easier than if a custom manufactured frame were to be used.

One such system that has been newly made for this year is a modular pneumatic subsystem. The pneumatic subsystem utilizes a compressed air tank most often used for paint ball as a main storage tank that can then be routed to various components. These components must meet some basic requirements to be compatible with our system:

- Waterproof (or fit within 4" cylindrical housing)
- Mounted with 1/4"-20 bolts
- Have an operating pressure between 50-300 psi

Within these relatively simple requirements, any number of actuators could be designed. In the final stages of development and integration are a torpedo launching system and a dropper mechanism. Both of these systems are meant to be stretch goals, as the autonomous behaviors required to utilize them will likely need to be developed at the competition.

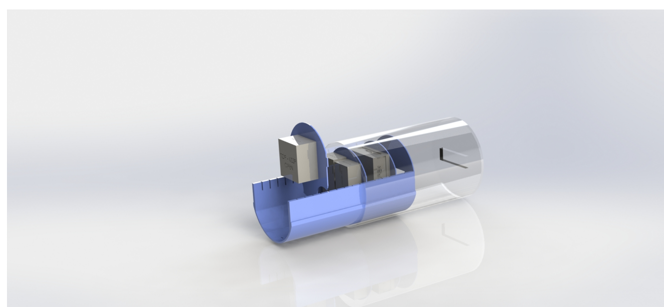

Figure 1: Rendering of the internal electronics bay. The shell of the bay is 3D printed PLA, with slots at 0.5 cm intervals. These slots allow laser-cut acrylic component trays to be mounted as needed in a modular fashion. This allows for rapid changes in components, and easy replacement of faulty components. The trays are designed to create two wiring "highways" to ease in cable management.

Another creative feature of this year's vehicle is a custom designed modular electronics tray. This can be seen in Figure 1. Previous years' vehicles had used assemblies of laser cut wood for electronics. However, these did not make for an efficient use of the space. To maximize the space, a 3D printed rack was designed that could accept trays with components attached. These trays were designed specifically for the components they would hold, and allowed for improved cable management, and therefore heat distribution. Additionally, if certain components malfunction in testing either in water or on land it is much easier to identify which components or wiring may be causing the problem and address them directly. Likewise, during setup having a much cleaner and

(a) Raw image of path marker (b) Mask filtered image of path marker image (c) Identified path marker

Figure 2: Processing steps while identifying a path marker

less-cluttered components tray made connections easier and reduced the likelihood of plugging wires into wrong places or missing a connection.

Due to budget constraints, many sensor that would aid in navigation are not included on board the vehicle. As such, some creative approaches must be taken to ensure accurate state estimation. The main navigation sensors are a Microstrain 3DM-GX3-25 IMU and two monocular cameras, one forward facing and one downward facing. While the IMU is highly accurate in providing pose information, dead reckoning of accelerometers causes significant errors to compound with time. To alleviate this, the use of visual odometry is being explored. By understanding the shift in location and angle to key points of reference in a cameras frame, a change in position and orientation can be estimated. This can be done for both the forward facing and downward facing cameras. Combining this information from the cameras with information from the IMU and an estimated vehicle dynamic model, a relatively accurate estimate of location relative to the starting location can be found. This is useful in mapping the area and allowing the vehicle to return to a task if it believes it can get more points in a second attempt. This can also be useful in bounding classification of objects within the course and the triggering of their associated behaviors.

To accomplish this feature detection and object recognition, the OpenCV library is used. This allows for low level operations, such as edge detection, bluring, etc., to be done using a trusted and tested open source library. While not completed at the time of submision, the computer vision team ultimately aspires to implement a convolution neural network [1] [2] in order to ”train” the submarine to recognize the typical features of the RoboSub obstacle course including the starting gate, path markers, buoys, push plates, and walls and provide information about the relative location of these features with respect to the submarine. Other vision architectures are also being investigated, such as recurrent neural networks [3] to take advantage of the inherent time-varying aspects of the visual data. Currently in development is a pipeline to ease the implementation of new data and test new algorithm ideas. An example of the different stages of this pipeline is shown in Figure 2. The goal of this pipeline is to simplify the testing and verification of ideas that will need to be implemented at competition, such as recognizing the new obstacles throughout.

III. Experimental Results

A general approach to testing was taken that transitions from basic proof of concept to bench test to in water testing. This approach has been incredibly valuable in catching errors in implementation before the vehicle is in the water. This also maximizes the debugging capabilities early in the process, when changes are easiest to make. Our desired amount of testing is at least once per week, which allows us to see the results of any changes made that week. If any issues come up during testing, they can be resolved before moving forward with the sub. We feel that testing once a week would be a good balance between progressing with the design and actually validating our work.

Testing of new vision algorithms has largely been at the proof of concept level to this point. This includes testing algorithms against still images captured from previous competitions, and testing low level feature detection on previously recorded video. This footage provides the benefit of simulating the in-water conditions that the submarine will encounter, without requiring the submarine to be submerged every time a change or optimization is made to the code. This also allows numerous tests to be conducted and ensures that algorithms will be reliable under similar in-water conditions. The results of the current computer vision are positive, with successful edge and color detection on photos that clearly showed course features. While these previously captured data are not entirely accurate to the current course description, they provide a useful conceptual test of new ideas. Future testing is planned on a bank of images that are less than ideal due to external conditions such as high sun glare, mottled pool floor coloring, and sharp angle of features with respect to the submarine. Some construction of new course elements has also been done to test new algorithms with actual in-water testing.

Lab bench tests have included the debugging of motor control software, intra-process communications, and basic sanity checks before putting the sub in the water. Old log files from previous competitions has also been used to simulate the competition experience and observe the response of new algorithms. The bench testing setup with the entire assembled sub can be seen in Figure 3.

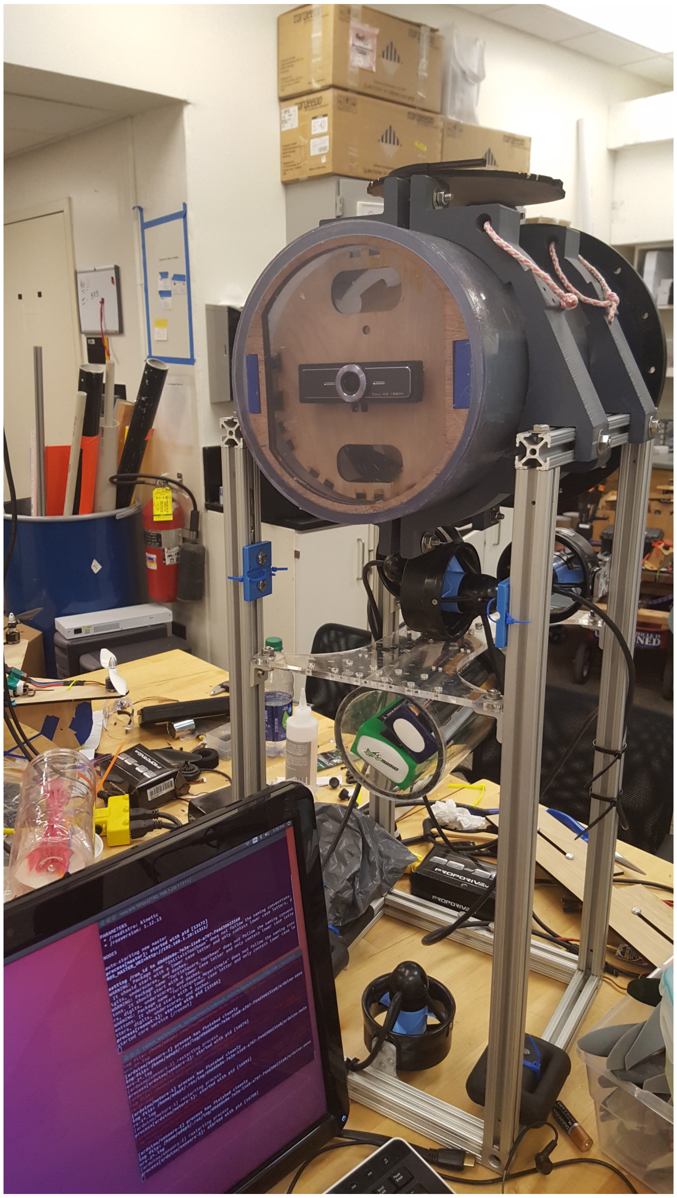

Figure 3: Bench testing setup, allowing hardware in the loop simulation of vehicle performance.

To date, the vehicle has had 3 in water tests of roughly 2 hours each. In-water testing began with testing basics such as waterproofness of the main and other pressure vessels, and the natural buoyancy of the sub. A slight positive buoyancy such that in the case of connection or power failure the sub would ultimately return to the surface was achieved through attaching small diving weights to the bottom of the sub. The second test was of basic motor capabilities and calibration of the motor controllers. This ensured that all commands given to the motors would not cause poor behavior, such as resetting the ESCs or causing a the motors to stall due to too large of an input signal. The third test tested depth and turning calibration. An input was sent for the sub to submerge to a desired depth and this was tested until the output consistently matched the input within a small error percentage. Turning/rotation in the water was tested similarly. A range of rotation inputs were sent to the sub including, 45, 90, 180 and 360 degrees. Not only was the intent that the sub would turn the desired angle, but also to cease rotation once this was achieved. This required calibration of the PID controller with the motors. After confirming the sub's turning was calibrated, we tested forward and reverse inputs, with the desired goal of the sub moving an intended distance and stopping within a small percentage error. However, motor and wiring issues caused this test to largely be unsuccessful. This test has been rescheduled and should be completed well before the competition.

Additional testing is also planned. As has been discussed, our vehicle features a design that ensures a high degree of static stability. This static stability does not guarantee dynamic stability, though the highly damped underwater environment certainly helps this. Even so, the vehicle used in the 2017 competition had some issues where under thrust in either the forward or strafing directions would cause an associated pitch or roll of the vehicle. This was due to the thrusters being placed off axis from the center of gravity. This year, the thrusters were placed so as to minimize these effects. Initial placement was determined through a rough analysis of the center of mass in Solidworks. With a rough estimate of proper thruster placement, pool testing is planned to make further refinements. Requirements on maximum allowable induced pitch and roll will be set through experiments with our vision system. With these requirements set, a basic system identification mission will be run to understand and map pitch/roll disturbances to thruster location.

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References

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APPENDIX A
COMPONENT SPECIFICATIONS

Component	Vendor	Model/Type	Specs	Cost (if bought new)
Buoyancy Control	Sea Pearls	Vinyl Coated Lace Thru Weights	Miscellaneous sizes, 1-5 lbs.	Varies, up to $30 for a 5 lb. weight
Frame Rails	McMaster-Carr	T-Slotted Framing	Single	$17.68 per 5ft. section
Waterproof Housing	Custom Made	Clear PVC Tube	7” ID	N/A
Waterproof Connectors	Amazon	Generic IP68 Waterproof Connector	2-8 pin	Roughly $3 / connector
Thrusters	Blue Robotics	T200	No ESC	$169
Motor Control	Hobby King	Afro ESC	30 Amp	$11.36
Mid Level Control	Arduino	Mega	N/A	$38.50
Battery (Motors)	Hobby King	Turnigy Multistar 10000mAh	4S, 10C	$47.64
Battery (Electronics)	Hobby King	Turnigy Multistar 5200mAh	4S, 10C	$29.04
CPU	Intel	NUC, i7 (discontinued line)	N/A	From $212.83
External Comm Interface	Microhard	VIP2400	N/A	N/A
Programming Language (Navigation)	Python	3.7	N/A	N/A
Programming Language (Vision)	C++ / Python	11 / 3.7	N/A	N/A
Inertial Measurement Unit (IMU)	Lord Microstrain	3DM-GX3-25 (discontinued)	N/A	$1615.00
Camera (forward)	Genius	Widecam F100	120 degree FoV	$49.99
Camera (downward)	ELP	Fisheye Lens 1080p Wide Angle		$45.00
Open source software	ROS	OpenCV	Scikit-learn	
Team Size	15	AE/ME/ECE/CS	Rotated throughout year	Priceless?
HW/SW expertise ratio	1:2	N/A	All team members had basic HW proficiency	N/A
Testing time: simulation	20-30 hours			
Testing time: in-water	To date, 8 hours		Planned: 12 hours	