SubjuGator 2021: Design and Implementation of a Modular, High-Performance AUV

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***Abstract* – Here we present SubjuGator 2021, the ninth generation of SubjuGator. SubjuGator was made by talented and diverse individuals that consisted mostly of undergraduate students in UF's Machine Intelligence Laboratory (MIL) The current version of our autonomous underwater vehicle (AUV) focuses on adaptive control, hardware improvements, and software innovations. This model includes a controller area network (CAN) bus, onboard general-purpose graphics processing unit (GPGPU), deep learning and point cloud processing, and other challenge-specific designs. Additionally, the design changes, testing, competition, and teamwork strategies discussed were adapted based on previous experience, changes to competition rules, and structure of our team.**

I. Competition Strategy

Leveraging 24 years of autonomous underwater vehicle (AUV) development experience at the University of Florida, which has produced eight 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 new generation SubjuGator 9 vehicle (shown in Figure 1).

Moreover, for the past few AUVSI RoboSub competitions, SubjuGator 8 served as the primary development and competing platform that aided the development of the new generation submarine. For the 24th annual competition, SubjuGator 9 will join the previous iterations of autonomous underwater vehicles to mark the first year in which two submarines will be deployed together. The primary design goal for SubjuGator 9 was to allow for a division of tasks between the it and SubjuGator 8 in order to maximize the number of potential points the team could achieve in the least amount of time.

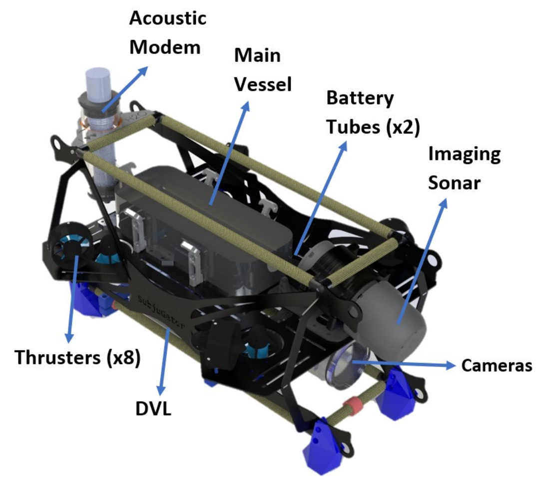


Figure 1: SubjuGator 9.

A. Mechanical

The main goals for this year with the new submarine were to improve the structure and actuation, two of the weaker points with SubjuGator 8, determined during the 2019 competition. Rather than using pneumatics, SubjuGator 9 uses water-proofed servo motors for the task manipulation. Additionally, weight and dimensions were kept at minimum to reduce the negative points and to try to make all other subsystems needed to complete tasks as compact as possible, thus allowing for potentially faster speeds. Additionally, a major feature of SubjuGator 9 (also implemented in SubjuGator 8) is the ability to sustain operation after a failure has occurred, whether the failure is of mechanical, electrical, or software origin. To achieve this goal, the vehicle is designed so that during a subsystem failure, the vehicle 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 if 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.

B. Software

Object detection and pose estimation (relative to an object), to later perform some action around said object, is a performance criterion that we have been improving (as necessitated by competition tasks) every year. Diverse sensors are used on both submarines to perform all the tasks. Each submarine searches for regions of interest to satisfy certain constraints; for example, the start gate is first found by using an active imaging sonar and then uses monocular vision and/or stereo vision depth estimation. The submarines also employ the use of a passive sonar (a hydrophone array) and cameras to locate regions of interest that contain a pinger. Upon correct discovery, the vehicle performs defined maneuvers to solve the task in which a pneumatic manipulator (for SubjuGator 8) or a water-proofed servo (for SubjuGator 9) is needed. The maneuvers include object manipulation, ball dropping, or torpedo shooting. To minimize error, software design employs several filtering, and error correction techniques.

C. Electrical

The main goal of the electrical team this past year has been to finalize and refine the electrical system that provide power to SubjuGator 9. With SubjuGator 9, we are adding additional sensors, actuators, and safety systems like the acoustic modems, servos, and a power management system to fully take advantage of the new mechanical and software features that are being implemented. The goal is to deploy two submarines simultaneously, tasking each sub with accomplishing certain tasks, mostly independently of the other sub. To fully optimize multiple subs in the water at the same time, the two subs will communicate vital information using acoustic modems. The team has spent several months testing the modems to ensure that a proper link budget can be maintained through a variety of distances, bearings, depths, and water quality. One of the main shortcomings in SubjuGator 8's electrical system was her inability to monitor the power delivery system. SubjuGator 9 address this by adding student-designed boards that can measure the current output and the voltage level of its 24 V LIPO batteries. This system can provide the monitoring systems with real-time battery status, allowing for better management of the sub. The software has additional safety features that will automatically turn off the sub if the battery's voltage drops low enough that it can become damaged.

II. Design Creativity

The ninth generation SubjuGator AUV has the capabilities to meet and exceed the challenges of the competition utilizing past experience with previous generation submarines and extensive research done throughout the pandemic, during which we were without direct access of either of our submarines for more than 12 months.

A. Mechanical

A major feature of SubjuGator 9 is the increased thrust to weight ratio and her ability to complete the actuation tasks using servo motors instead of the pneumatic, i.e., compressed air, systems. We expect greater reliability and consistency with electronic systems that what we could achieve with the pneumatic systems.

1. Electric Gripper

During the design of the new generation submarine, a new concept was developed for our gripper design. The last generation submarine's claw had minor stress points that were significantly reduced in the new gripper design. The new design (see Figure 2) uses more surface area to grab an item and using a finite element analysis (FEA) package by SOLIDWORKS®, was determined to be capable of lifting up to 3 lb outside of the

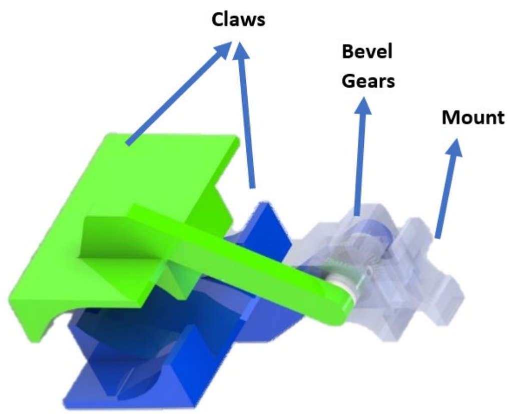


Figure 2: New gripper design.

water, with a factor of safety (FOS) of two. The gripper uses bevel gears for the servo motors to create increased torque on the claws to allow it to pick up and hold more massive items. The entirety of this mechanism is 3D printable with ABS.

The claw mechanism utilizes an electric servo motor and a set of gears to rotate the arms and capture the desired object. The servo motor is located.at the top of the housing, below the bottom half of the mounting piece.

The servo is connected to a set of bevel gears to rotate both claws. Both claws are mobile to create a large opening with the limited range of motion of the servo motor. Bevel gears are used to minimize the size of the housing and limit how much it blocks the vision of the downward facing camera. The claws are designed to best lift thin cylinders.

2. Electric Ball Dropper

The ball dropper was redesigned for SubjuGator 9 so it would work with an electrical system instead of a pneumatic system, as utilized in SubjuGator 8. After testing several prototypes, the final design for the device (see Figure 3) consists of a Hitec waterproof servo and two 3D printed components, a mount and an attachment for the servo, allowing it to store up to three metal balls with a diameter of approximately 17 mm. The mechanism for the ball dropper was

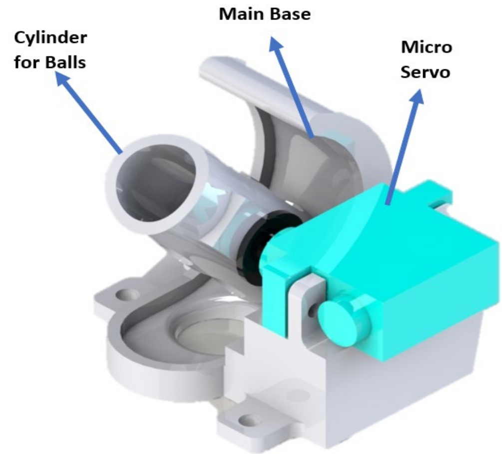


Figure 3: New ball dropper design.

inspired by the design of a "Ferris Wheel", which lets the device deposit each ball individually rather than releasing all of them at once with a rotational cylinder design. Moreover, the new design of the ball dropper was developed to minimize the space, points of failure, and to make it completely swappable within minutes.

3. Electric Torpedo Launcher

This year's torpedo launcher (see Figure 4) is 3D printable and uses a high compression spring. A servo motor is used to release the spring's stored energy.

Accelerating the torpedo from rest with only electrical power would require high power motors, which would negate the weight savings from forgoing a pneumatic system. Instead, energy is stored using a strong compression spring. The spring is compressed when the torpedo is manually loaded. A hook holds the torpedo down and prevents the spring pressure from releasing until the hook is

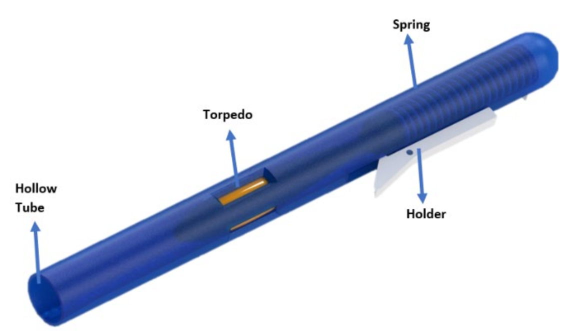


Figure 4: New torpedo launcher design.

moved by a servo. A second torpedo tube can be independently launched by the same servo, rotating further. More calculations and revisions need to be analyzed to perfect the system. Unfortunately, due to the pandemic and the resulting restrictions on utilizing our laboratory, the final design and testing needed to manufacture the final designs for the torpedo launchers was necessarily postponed.

4. Chassis

This new generation submarine's chassis would similar to previous generation submarine, since it provided little propensity for failure and was designed to be easy to manufacture. To this end, the new sub's chassis will be manufactured from 1/8th inch thick 6061-T6 aluminum alloy. After the necessary spot welding, the chassis will be hard-anodized for electrical insulation and corrosion resistance.

The current configuration of SubjuGator 9 has the following approximate design parameters:

- Dry weight: 60 lb
- Dimensions: 36 in × 24 in × 20 in

Moreover, 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 several 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.

B. Electrical

SubjuGator 9 consists of a robust set of industry standard as well as student designed electronic components. The heart of the electronic system features the main processing unit which incorporates a Jetson NVIDIA and NUC CPU. With the combined efforts of these devices, SubjuGator 9 is capable of processing at high bandwidths, while having the flexibility to interface with many devices.

Peripheral to the main processing unit is a suite of devices to aid in navigation, cooling, safety, and communication. The cooling system includes fans and appropriate heat sinks to keep SubjuGator 9 running at optimal thermal efficiency. (Unlike SubjuGator 8, due to the more power efficient computing resources and a better thermal design, a water pump will not be necessary in SubjuGator 9.) The navigation system includes a Doppler Velocity Log (DVL) and inertial measurement unit (IMU). The communication system has both inter and intra communication mechanisms. The tether allows an Ethernet interface that is leveraged when a hard-wired connection with SubjuGator 9 is necessary during testing. The acoustic modem allows the robot to wirelessly communicate with other aquatic devices. This is a crucial aspect in the system because it will facilitate inter-robot communication in the future.

The safety system incorporates both battery monitoring and emergency shut-off components. The battery monitoring module is one of the student-designed circuit boards that allows SubjuGator 9 to monitor power consumption. This is important when deciding when to safely change batteries on the robot. Furthermore, the thrust/kill board is another student designed board that allows the robot to control thrusters as well as cut power to them, creating a safe shut-down feature. If all else fails, there is also a manual shut-off feature that can be triggered by placing a magnet on the appropriate location of the vehicle; thereby cutting power to the thrusters. This action is facilitated by hall-effect sensors and relays.

Other student designed boards include a power merge board, servo controller, and system status board. The power merge board safely combines the power of two 24 V batteries to create one 24 V power source that is routed

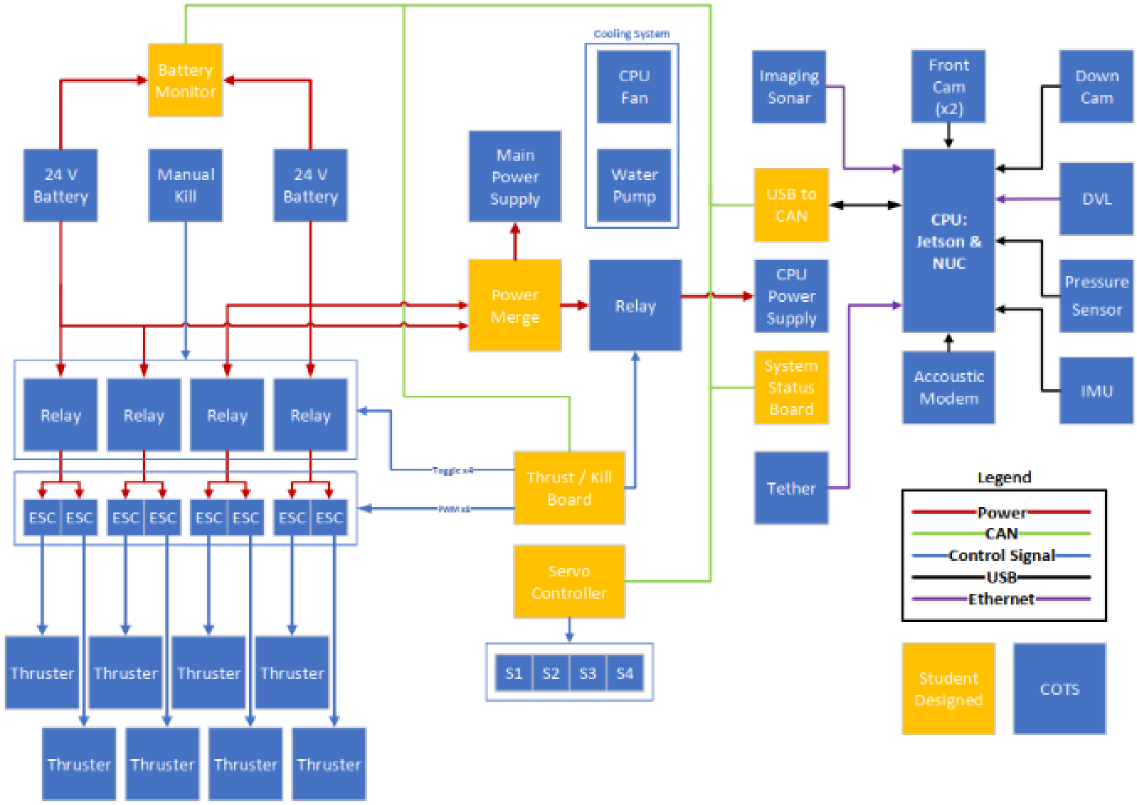


Figure 5: Electrical architecture.

throughout the rest of the system. The servo controller allows the robot to take on a myriad of servos, of varying power, and command them with utmost controllability. The system status board provides real-time diagnostics of SubjuGator 9 through CAN and wireless interfaces.

The remaining components of the Electrical system include other commercial off the shelf products. The power system consists of two 24 V LiPo batteries with safety several relays connecting to eight Blue Robotics T200 thrusters and the power merge board mentioned above. The system also includes a passive sonar (hydrophone array) device that gives the vehicle the capacity to accurately track a point source of sound in an aquatic environment. (The founder of Sylphase, a company that was formed by former team members, designed the passive sonar system while a student, but manufactured and donated the system after forming the company. Sylphase now sells a GPS/INS system that was originally designed for one of MIL's RoboBoat vehicles. The latest GPS/INS design was utilized on MIL's two Maritime RobotX Challenge systems in 2016 and 2018.)

There are several other components throughout the electrical system which include, three cameras, electronic speed controls, imaging sonar, moisture sensors, and pressure (depth) sensors. A comprehensive visual of the SubjuGator 9 electrical system is shown in Figure 2.

C. Software

SubjuGator 9's software stack is built on the Robot Operating System (ROS) Melodic. After RoboSub 2013, MIL made (and continued to make) our repositories public in hopes that other projects would make use of them. We provide tutorials and documentation

[1]All code is located at https://github.com/uf-mil/mil. The mil_common repository contains code common across all of MIL projects. The SubjuGator repository contains code specific to SubjuGator.

for all parts of the code, to aid future members and further encourage external use. Our ROS Teledyne Blueview Driver, along with the rest the software is open-sourced, and available on GitHub[1].

1. State Estimator

The state estimator uses an inertial navigation system (INS) and an unscented Kalman filter. 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.

2. 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 controller is responsible for keeping the vehicle on the trajectory and correcting for disturbances such as drag and thruster variation. Our trajectory tracking controller implements a proportional-integral-derivative (PID) controller with feed-forward velocity and acceleration terms to anticipate drag and buoyancy.

3. 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., thus enabling a hierarchical mission structure that can concisely describe high level behaviors, such as commanding waypoints and performing visual feedback.

4. Vision Processing

Traditional techniques, namely image segmentation via adaptive thresholding, followed by contour analysis, are used to find many of the competition elements.

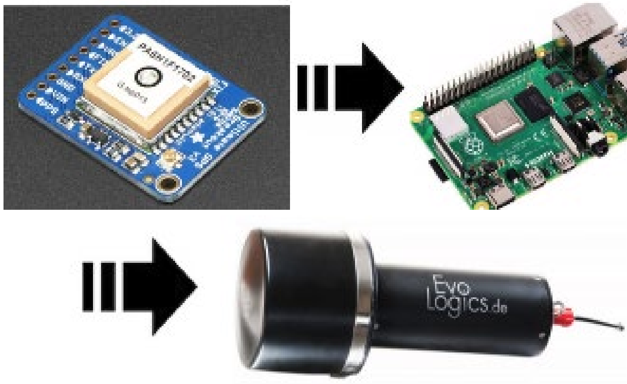
Deep neural networks are also used to assist traditional computer vision techniques. In particular, the architecture known as *Faster Regions with Convolutional Neural Networks* (Faster RCNN) [4] is used, which is trained by using transfer learning and with the inception v2 model [5]. After the feedforward step, Faster RCNN returns regions of interests (ROI), which are then passed through traditional computer vision techniques for further verification and segmentation. The training data is labelled by the team using a collaborative labeling tool for machine learning called *LabelBox* [6].

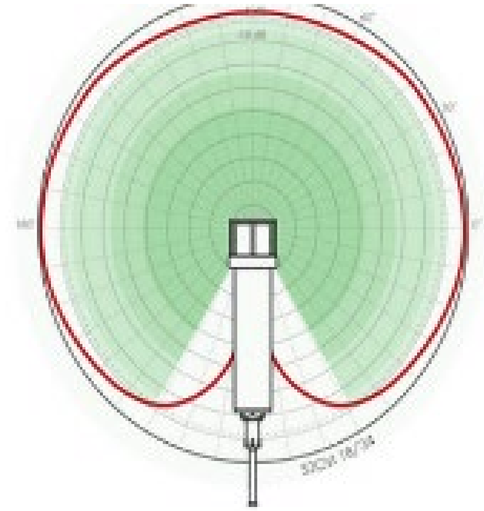
After segmentation, the 3-D pose of the object is estimated by using a priori knowledge of either the distance or the size of the object; by using multiple observation points and a least squares cost function; or by processing a 3-D point cloud, either from a stereo camera system or imaging sonar. Additionally, this year, by modeling object motion, a dynamic scene can be reconstructed by an unsupervised learning technique [7] which enables monocular depth predication and serves as an initial guess for object pose prediction. Using one Point Grey Chameleon camera and one e-con See3CAM CU20, we generate robust 3-D information of our world when operating in favorable conditions. Internal camera calibration and distortion parameters are obtained using [8].

5. Imaging Sonar Processing

A ROS Driver was developed to abstract the closed-source Blueview Software Development Kit (SDK), enabling ROS to

Technical Specifications:
- Operating Depth: 200 m
- Beam Pattern: Horizontally omnidirectional
- Connect: up to 13.9 kbits/s
- Lowest transmit mode: 2.8 W, 1000 m range





S2C M 18/35 Directivity Pattern

Figure 6: Acoustic modem specifications.

communicate with the Teledyne Blueview P900-130. The driver produces images along with range profiles in ROS.

Due to the nature of acoustics, error and noise is prevalent, leading to the development and adaptations of filtering algorithms. Using the returned ranges and the estimated SubjuGator pose, a 3-D point cloud is constructed, populating the world-frame over time. Statistical outlier removal is used to remove noise from the constructed point cloud. The resulting filtered point cloud is then examined for clusters, with parameters such as maximum and minimum size. After clustering points into objects, higher-level mission software can interpret and react to 3-D position estimates and size. Moreover, with the presence of a global filtered point cloud, tasks such as obstacle avoidance using Oct-tree representation for occupancy grids along with correcting for global state drift with simultaneous localization and mapping (SLAM) become possible.

III. Experimental Results

A. Mechanical

Due to limitations imposed by physical distancing, mechanical design and manufacturing planning for the new submarine was prioritized to start the manufacturing process (following social distancing protocols) as soon as complete access to the laboratory is granted. Moreover, many SOLIDWORKS® simulations such as computational fluid dynamics (CFD) and finite element analysis (FEA) were used to improve the structural and actuation mechanisms in the new generation submarine during the virtual time spent during this pandemic.

B. Electrical

Acoustic modems (see Figure 6) are a vital part of our competition strategy going forward. Before the modems are implemented onto the two submarines, testing needed to be done to verify that enough data can be transmitted across between them. Separate water-resistant box's that implements Raspberry Pi, a battery and the modems were designed to create an easy-to-use portable test bed. To improve testing, GPS is added to get more accurate distance data. The team has completed basic testing and is planning, in the coming months, on preforming more in-depth testing with varies distances, bearings, and depths.

C. Software

Software has been tested against recorded data from previous pool testing, while missions were simulated with the seamlessly integrated Gazebo simulator (see Figure 7).

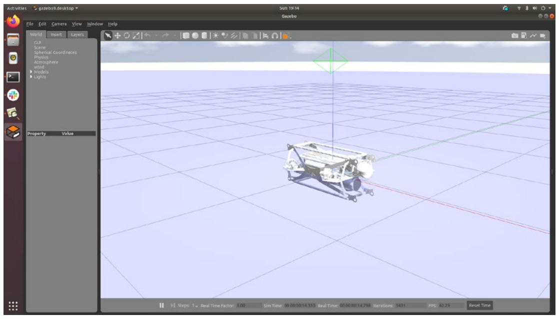


Figure 7: SubjuGator 9 simulated in Gazebo.

The tasks that utilized the passive sonar (hydrophone array) were tested by having a Gazebo model of a pinger publish a frequency and vector value to the ROS Topic to which the passive sonar code listens when using the physical board and hydrophones. In simulation, the submarine model was able to successfully listen to the pinger model and move to the desired location.

The tasks that utilized the cameras were tested by having Gazebo publish camera data from the model's simulated surroundings. The computer vision related configuration files were tested with the physical e-con See3CAM CU20 used by SubjuGator 8. This was to help in tuning them such so that it could be ensured that the physical vehicle would be able to recognize the images for the task in the future. This real camera data was also tested and fed into our computer vision related topics while the Gazebo simulation was running so that the vehicle model, after being shown an image (such as the badge or tommy gun) could recognize and move in the relative direction of the image. For example, if the image is on the right side of the camera frame, the vehicle model would yaw to the right. If the image is in the center of the camera frame, the vehicle model would move forward. Various other mechanisms were put in place to allow the vehicle model versatile movement based on the incoming camera data.

Additionally, using video conference tools, each of the sub-team (mechanical, electrical, and software) met once a week to discuss ideas, designs, and algorithms. Sub-team leaders also met separately, about once a week. Faculty advisors were able to provide recommendations and feedback of the team's progress roughly once a month. Overall, due to proactive decisions and discussions, along with prioritization, communication, and planning, the team was able to effectively balance remote design, software testing, and online coursework.

IV. ACKNOWLEDGMENTS

The University of Florida's MIL 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, 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 with especially valuable advice.

Each of the following corporate and MIL alumni sponsors were gracious to assist with either (or both) monetary and product donations:

- Diamond Sponsor: Harris Corporation
- Platinum: Texas Instruments
- Gold Sponsors: UF Dept. of Electrical and Computer Engineering, UF Dept. of Mechanical and Aerospace Engineering.
- Silver Sponsors: Kevin Phillipson (MIL Alumnus)/Apple(matching), SolidWorks, DDS Dassault Systemes, SolidCAM.
- Bronze: Sylphase, Edward Kallal (MIL Alumnus)/Qualcomm (matching), Charles Barker Jr. (MIL Alumnus)/Cisco Systems (matching), NVIDIA, DigiKey, Advanced Circuits.

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

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

[3] P. Walters, R. Kamalapurkar, F. Voight, E. Schwartz, W. Dixon, "Online Approximate Optimal Station Keeping of a Marine Craft in the Presence of a Current." *IEEE Transactions on Robotics*, Vol. 30, No. 2, pp 486-496, April 2018.

[4] S. Ren, K. He, R. Girshick and J. Sun, "Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 39, No 6, pp. 1137-1149, 2017.

[5] C. Szegedy, V. Vanhoucke, S. Ioffe, J. Shlens and Z. Wojna, "Rethinking the Inception Architecture for Computer Vision", *Arxiv.org*, 2015. [Online]. Available: https://arxiv.org/abs/1512.00567.

[6] Collaborative labeling tool for machine learning. Commercial software (with free academic version). https://labelbox.com/.

[7] V. Casser, S. Pirk, R. Mahjourian, and A. Angelova. "Depth Prediction Without the Sensors: Leveraging Structure for Unsupervised Learning from Monocular Videos", *Arxiv.org*, 2018. [Online]. Available: https://arxiv.org/abs/1811.06152.

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

APPENDIX

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	No hardware		Positively buoyant; thrusters control depth	
Frame	Dragon plate	Carbon fiber	Space frame	
Frame	Student Design	Aluminum	Frame core	
Waterproof Housing	Student Design	Aluminum	Main vessel	
Waterproof Housing	Student Design	Aluminum	Navigation vessel	
Waterproof Housing	Student Design	Aluminum	Pneumatic vessel	
Waterproof Housing	Blue Robotics	Aluminum	Downward camera vessel	
Waterproof Housing	Student Design	Aluminum	Power Vessel	
Waterproof Connectors	SubConn	Wet-connect	External wet-mate connectors	
Waterproof Connectors	SEACON	Wet-connect	External wet-mate connectors	
Thrusters	Blue Robotics	T200		$169
Motor Control	Blue Robotics	Basic ESC	7-26v, 30amp, PWM	$25
Propellers	Blue Robotics	Stock		
Actuators	Student Design	ABS/PLA		
Battery	MaxAmps	LiPo	LiPo 5450 6S 22.2v	
Converter	Student Design		Power over Ethernet (POE)	
Regulator	Many			
CPU	Intel	NUC 10	Intel® NUC 10 Performance Mini PC - NUC10i5FNKPA	$140
CPU	Nvidia	Jetson	Jetson Xavier NX	$500
GPGPU	Nvidia	RTX 2080		$600
Internal Comm Interface	Student-designed		CAN	
Internal Comm Interface	Various		USB	
External Comm Interface			Ethernet	
Programming Language 1	C++			
Programming Language 2	Python			
Compass	PNI	TCM MB		

Component	Vendor	Model/Type	Specs	Cost (if new)
Inertial Measurement Unit (IMU)	Sensonar	STIM300	9-axis	
Doppler Velocity Log (DVL)	Teledyne	Explorer	600kHz	$6800
Camera(s)	Point Grey	BlackFly	5.0 MP, 22fps	
Camera(s)	Point Grey	Chameleon	1.3 MP, 18fps, USB 2.0	
Camera(s)	e-con Systems	See3CAM CU20	2.0 MP HDR, HD at 45fps, USB 3.0	$89
Imaging Sonar	Teledyne	Blueview P900	130-degree FOV, 900kHz, 2-60 meters	
Hydrophones	Teledyne Reson	TC 4013	4	
Hydrophone components	Sylphase	Custom	Former Student-designed data acquisition PCB	
Hydrophone components	Analog Devices	ADAR7251	4-Channel, 16-Bit, Continuous Time Data Acquisition ADC	
Manipulator	Student Design			

Software Component	Libraries	Algorithm
Vision	OpenCV	Canny Edge Detection, Thresholding, Optical Flow
Machine Learning	TensorFlow, Keras	Faster RCNN
Acoustics	Scipy, numpy	Time of Arrival, Least Squares
Localization	Eigen	Unscented Kalman Filter
Mapping	PCL, OpenCV	Statistical Outlier Remove, Euclidean Clustering
Communication	ROS	