SubjuGator 2023: Design and Implementation of a Modular, High-Performance AUV

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Abstract— **Here we present SubjuGator 2023, the eighth and in-development ninth generations of SubjuGator. SubjuGator was made by talented and diverse individuals who consist mostly of undergraduate students in UF's Machine Intelligence Laboratory (MIL). The current version of our autonomous underwater vehicle (AUV) focuses on adaptive control, electro-mechanical actuation, and software innovations. This model includes a controller area network (CAN) bus, onboard general-purpose graphics processing unit (GPGPU), deep learning for computer vision, and other challenge-specific designs. Additionally, the design changes, testing, competition, and teamwork strategies discussed were adapted based on previous experience, changes to the competition rules, and the structure of our team.**

I. Competition Strategy

Leveraging 26 years of autonomous underwater vehicle (AUV) development experience at the University of Florida (UF), which has produced seven 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 8 vehicle (1) and SubjuGator 9, presently under sensor integration.

SubjuGator 8 has served as the flagship autonomous submarine for MIL for the past five years. For the 26th annual Competition: SubjuGator 8 will once again join the previous iterations of autonomous underwater vehicles to solve novel tasks in a competitive environment. Reusing SubjuGator 8 provides our team with the benefit of reliable mechanical and electrical systems. Nevertheless, we continued to innovate on these systems, to provide the vehicle with the ability to perform all tasks in the competition, which includes identifying and classifying images using computer vision and deep learning, detecting, and localizing acoustic pingers, shoot torpedoes, drop markers, and manipulate PVC structures.

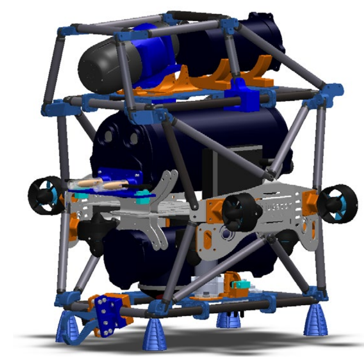

Fig. 1. SolidWorks model of SubjuGator 8. See Appendix A for higher resolution images.

SubjuGator 9 is still in development and therefore will not be used in the RoboSub 2023 competition. Major progress has been made, which will be explored in section III.

Finally, since the team this year consists of predominantly new members or members who will attend their first in-person competition, we prioritized mastering a select number of feasible tasks while maximizing test time. Thus, many of the design strategies considered team capabilities and experience, while working on top of the infrastructure left behind from previous teams.

A. Mechanical

The servo actuator system will be leveraged to perform all actuation tasks in a reliable manner. This replaced the pneumatics system used in previous competitions, as effectiveness and simpler configuration of waterproof servos compared to pneumatics justified renovation.

Advancements in 3D printing and computer-numerically controlled (CNC) machining have elevated the team's manufacturing capabilities, which facilitated structural renovations. Many previously 3D printed parts (carbon fiber brackets, thruster mounts, sensor plates) were replaced with CNC milled or abrasive water-jetted (AWJ) aluminum, which was anodized to delay the onset of corrosion. Parts deemed too time-intensive to machine were 3D printed with PETG and treated using a novel sealing technique to increase water resistance. These renovations have mass-optimized the vehicle, increased strength, impact resistance, and have increased functional longevity.

SubjuGator 8 can also sustain operation after a failure has occurred, whether the failure is of mechanical, electrical, or software origin. The redundant eight thruster design allows for the vehicle to maintain a 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. Electrical

The goals for the electrical team during the 2023 season were to improve and refine the overall electrical architecture of the sub and to improve the documentation of sub-systems and wiring. Some student-designed PCB boards on the sub were redesigned to provide better reliability and provide more data back to the main computer. The student-written firmware on other boards was modified or rewritten to improve performance and stability.

One significant hardware improvement was the introduction of two battery monitoring boards. These boards provide the rest of the sub with voltage and current outputs from the batteries. That information is then sent via the CAN bus to the main CPU, which can use the data to develop a more sophisticated power plan and protect the lifespan of the batteries. The boards are also designed to send a shut-off signal to a thruster/kill board on the sub when the batteries go below a programmed threshold.

A major firmware change was a rewrite of the queue used in the USB to CAN firmware to process serial messages. This modification resulted in large improvements to message structures, processing time, and successful packets. In most cases, we found more than an order of magnitude speedup between sending a thruster message and the message executing on the thruster/kill board.

The electrical team has also been experimenting with different solutions for hardware and firmware documentation to find one that fits the team's workflow. Currently, we are experimenting with using Wireviz to document our cables and wiring harnesses. This open-source software allows us to document board-to-board connections and break them down to a bill of materials level, which is useful during sub re-wirings.

We are also testing Sphinx with Doxygen and Breathe to produce small manuals for our boards. These documents would allow other MIL members to operate, troubleshoot, and fix subsystems inside the sub which improves the team's organizational memory and bus factor.

C. Software

The submarine employs a heavy use of computer vision techniques to identify distinct objects and provides our vehicle with an understanding of its environment through depth estimation. The passive sonar system (hydrophone array) and cameras are used to locate regions of interest that contain a pinger. Upon correct discovery, the vehicle performs defined maneuvers to utilize each of the electrical actuators, depending on the specific task. Our modularized mission system allows developers to quickly construct and change mission plans in accordance with the sub's performance and goal.

II. Vehicle Design

A. Mechanical

The mechanical design of SubjuGator 8 incorporates four independently operated electronic servo mechanisms: a gripper, two torpedo launchers, and a marker dropper. These mechanisms are used to complete mission specific tasks, and they are controlled through the servo controller board, which is housed in a separate, compact pressure vessel.

The gripper (2) makes use of two serrated aluminum jaws mounted to a 3D printed frame. The lower jaw is rotated by a high-torque waterproof servo, and threads cut into the jaws allow for simultaneous opening and closing.

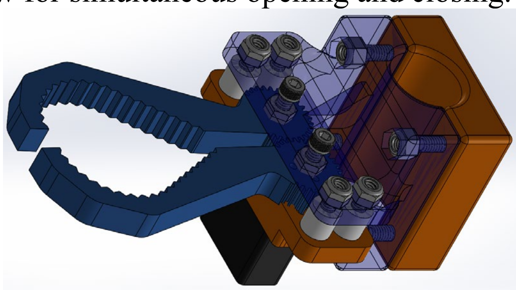

Fig. 2. Servo-actuated gripper. Main bracket is transparent to showcase machined gear teeth. The jaws were cut from 6061-T6 on the AWJ, and the frame was 3D printed from PETG and waterproofed.

The dual torpedo launchers (3) make use of two servo-actuated rack and pinion actuators to hold 3D printed torpedoes (4) in front of compressed springs. Each servo operates independently, so torpedoes can be loaded and fired independently.

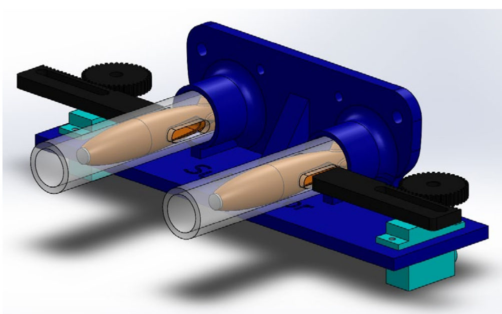

Fig. 3. Servo-actuated torpedo launchers. The frame is 3D printed from PETG and waterproof, the rack and pinion assembly are HDPE for low friction, and the tubes are polycarbonate for visibility.

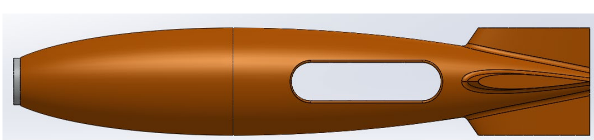

Fig. 4. 3D printed torpedo. The hull is 3D printed PETG and waterproof. A weight is placed at the bow to achieve neutral buoyancy, a slot is used to hold the torpedo in place, and a 40-60 teardrop hull with NACA 0015 fins optimizes hydrodynamic drag and stability.

The marker dropper (5) uses a servo controlled rotating design to drop a ball after a 180-degree servo rotation. The 3D printed marble chamber is mounted to a 3D printed frame and waterproof servo.

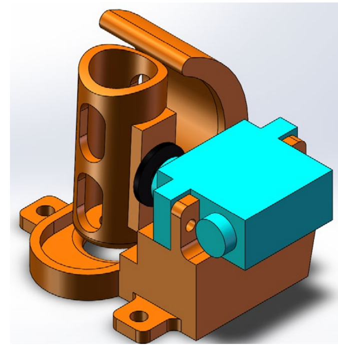

Fig. 5. Servo-actuated marker dropper. The frame and chamber are 3D printed from PETG and waterproof. A ball is dropped by rotating the servo 180 degrees.

The space-frame type chassis, made from carbon fiber tubes and aluminum sheet sections provides protection for delicate components of the sub, while providing modularity for component addition and renovation. As modularity was a priority in our design, there was much room for creativity in designing attachments and brackets. SubjuGator 8 was first constructed when 3D printing became available to the public, and now ultra-precise CNC machines are mimicking that growth. A mass-optimized, abrasive water-cut design of the first ever plate bracket is used in 2023 (6).

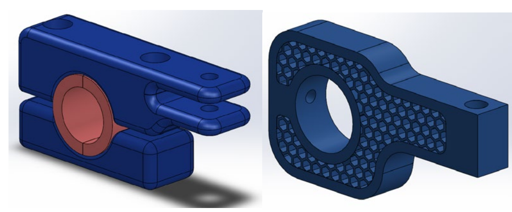

Fig. 6. Old 3D printed bracket (L) and new water cut bracket (R). The old design, printed from PLA, featured adhesive rubber strips. The new design is anodized 6061-T6 aluminum and features a hexagonal lattice.

B. Electrical

SubjuGator 8 consists of a robust set of embedded industry standards and student-designed electronic devices. Peripheral to the main computer is a suite of devices to aid in navigation, safety, power delivery and communication.

The navigation system includes a Doppler Velocity Log (DVL) and an inertial measurement unit (IMU). 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 safety system incorporates both battery monitoring and emergency shut-off components. The battery monitoring module allows SubjuGator 8 to monitor power consumption which helps reduce the number of batteries that die from overuse. SubjuGator 8 also has a student-designed thrust/kill board that allows the robot to control thrusters and cut power to thrusters with its safe shut-down feature. As an immediate option to cut power to the thrusters, there is a hall-effect-based manual shut-off feature that can be triggered by removing a magnet on the appropriate location of the vehicle. The design of this hall-effect shut-off uses two opposite polarity unipolar hall-effect switches to alter the behavior of the kill system. This choice allows for quicker recovery from shut offs during testing and complete shutoffs during competition runs.

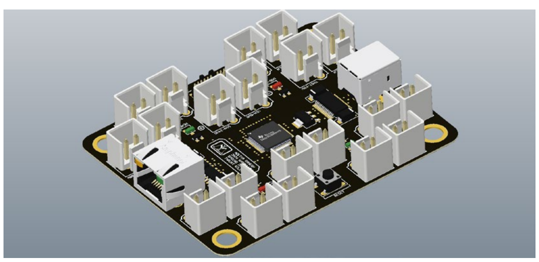

Fig. 7. The student-designed thruster/kill board. It has an RJ45 connector for CAN communications, a USB-B connector for UART communications, 8 independent relay connectors, 8 independent thruster PWM connectors, and two independent kill system connectors.

The power delivery system focuses on safe, consistent power delivery to crucial components in the sub. A student-designed power merge board safely combines the power of two 24-volt batteries to create one 24-volt power source that is routed throughout the rest of the system. The servo controller board contains three low-current buck regulators and one high-current buck regulator to supply power to the electronic actuators on the submarine. These outputs are voltage controlled and current monitored to prevent damaging the servos from overvoltage and unnecessary stress.

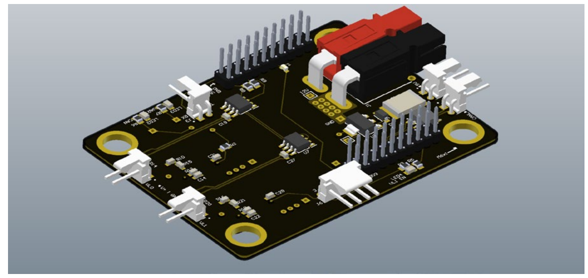

Fig. 8. The student-designed servo controller board. It has connectors which supply 2 different voltage levels, connectors for CAN and UART communications, and a connector for PWM outputs. A TM4C123GXL launchpad is connected to the 2-row header pins.

Our communications system includes a tether which connects to an Ethernet interface. This system is leveraged when a hard-wired connection to SubjuGator 8 is necessary during testing. Internal communications are handled through a student-designed USB to CAN board which takes serial communications from the main computer and converts them to CAN messages that are sent to other boards in the sub.

SubjuGator 8 uses a student-designed water-cooling system to run at optimal thermal efficiency. Water flows in a closed loop through the ESCs, the main computer, and the GPGPU to transmit the heat to an external radiator that dissipates the heat to the pool water.

C. *Software*

SubjuGator 8's software stack is built on the Noetic version of the Robot Operating System (ROS). Our stack has grown to over 60+ ROS packages, all of which are open-source[1], allowing other teams to share the benefits from our work. Many of our packages feature extensive documentation, and we are constantly improving their documentation and features.

1) State Estimator

The state estimator uses an inertial navigation system (INS) and an unscented Kalman filter [1] operating on manifolds for more efficient handling of attitude singularities. The INS integrates inertial measurements from the IMU, producing an orientation, velocity, and position prediction. The Kalman filter estimates the state by comparing the output of the INS prediction

[1] All code is located at https://github.com/uf-mil

against the reference sensors, which are a magnetometer, depth sensor, and DVL.

2) *Trajectory Generator and Controller*

The trajectory generator is based on a nonlinear filter that produces 3rd-order continuous trajectories given vehicle constraints on velocity, acceleration, and jerk [2]. Our trajectory tracking controller implements a proportional-integral-derivative (PID) controller with feed-forward velocity and acceleration terms to estimate drag and buoyancy.

3) *Mission Planner*

The vehicle's mission planner is responsible for high level autonomy and completing the competition tasks by enabling asynchronous support in Python. This library has been developed and used for the past ten years and is continually being augmented and improved. We recently rewrote the module to use our custom *axros* Python package, an interface between asyncio and ROS 1.

4) *Vision Processing*

Traditional techniques, namely image segmentation via adaptive thresholding, followed by contour analysis, are used to find many of the competition elements, notably the orange path markers and explicit contours of objects in the underwater environment.

Deep neural networks are also used to assist traditional computer vision techniques. In particular, the architecture known as *You Only Look Once* (YOLO) [3] is used, which is trained by using transfer learning and with the darknet YOLOv7 model [4]. After the feedforward step, YOLO returns bounding boxes and object classifications. The training data is labeled by the team using a collaborative labeling tool for machine learning called *LabelBox* [5].

Additionally, by modeling object motion, a dynamic scene can be reconstructed by an unsupervised learning technique [6] 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 a standard printed calibration board viewed from multiple frames [7].

III. SubjuGator 9

Limitations caused by the pandemic significantly delayed the manufacturing of the SubjuGator 9 (10) chassis, making the ninth generation SubjuGator unavailable for RoboSub 2023.

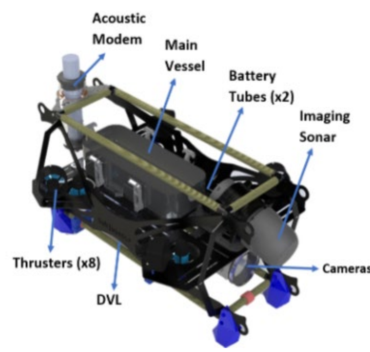

Fig. 9. An overview of SubjuGator 9 and its subsystems.

However, significant progress has been made in the manufacture of the complete aluminum chassis (10) as well as the main electronics hull (11).

Fig. 10. SubjuGator 9 chassis. Made from ¼" 6061-T6 plates.

Fig. 11. SubjuGator 9 electronics hull. CNC machined from 6061-T6 stock. Finite element analysis simulations were performed to mass-optimize the hull.

IV. Experimental Results

Our submarine was rigorously tested, both in simulated and physical environments. Since most of the active team working on the SubjuGator are new members, we prioritized having an extensive 2023 testing schedule to ensure that each team member gained an understanding of how the sub performs in a physical environment.

A. Mechanical

The main testing goals for this iteration was to have the actuators and the hardware kill system working reliably, and to make sure the submarine moves and floats in a stable manner by adjusting the weight distribution on the current configuration.

B. Electrical

Physical testing was done to refine the electrical architecture. Each board was tested using laboratory tools, such as oscilloscopes, microprocessor development boards, and computers, to ensure each board worked as functioned. Back-up PCBs were assembled as replacements, if necessary. Through this process, the team ensured the electrical systems functioned and communicated properly between the boards and the computer.

C. Software

Our software systems were dually tested in a physical environment (using a university pool) and a simulated environment (using the Gazebo simulation software). The simulation environment allowed for rapid development of various SubjuGator components, while testing in a real-world environment ensured that our environment allowed for rapid development of

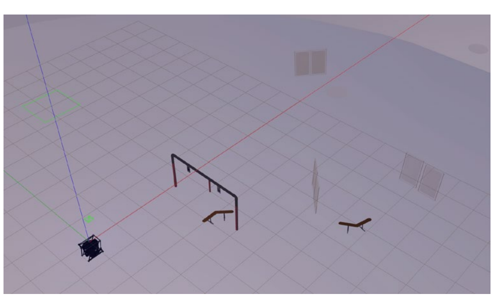

Fig. 12. The SubjuGator simulation environment, featuring SubjuGator, the task elements, and a dimensional grid in a replicated TRANSDEC aquatic environment.

environment allowed for rapid development of various SubjuGator components, while testing in a real-world environment ensured that our systems were operating as expected in a true environment. The simulation environment includes a physics engine capable of reproducing drag, gravity, and buoyancy, alongside internal plugins for replicating hydrophone data. The environment is highlighted in Fig. 12.

V. References

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VI. Appendix A

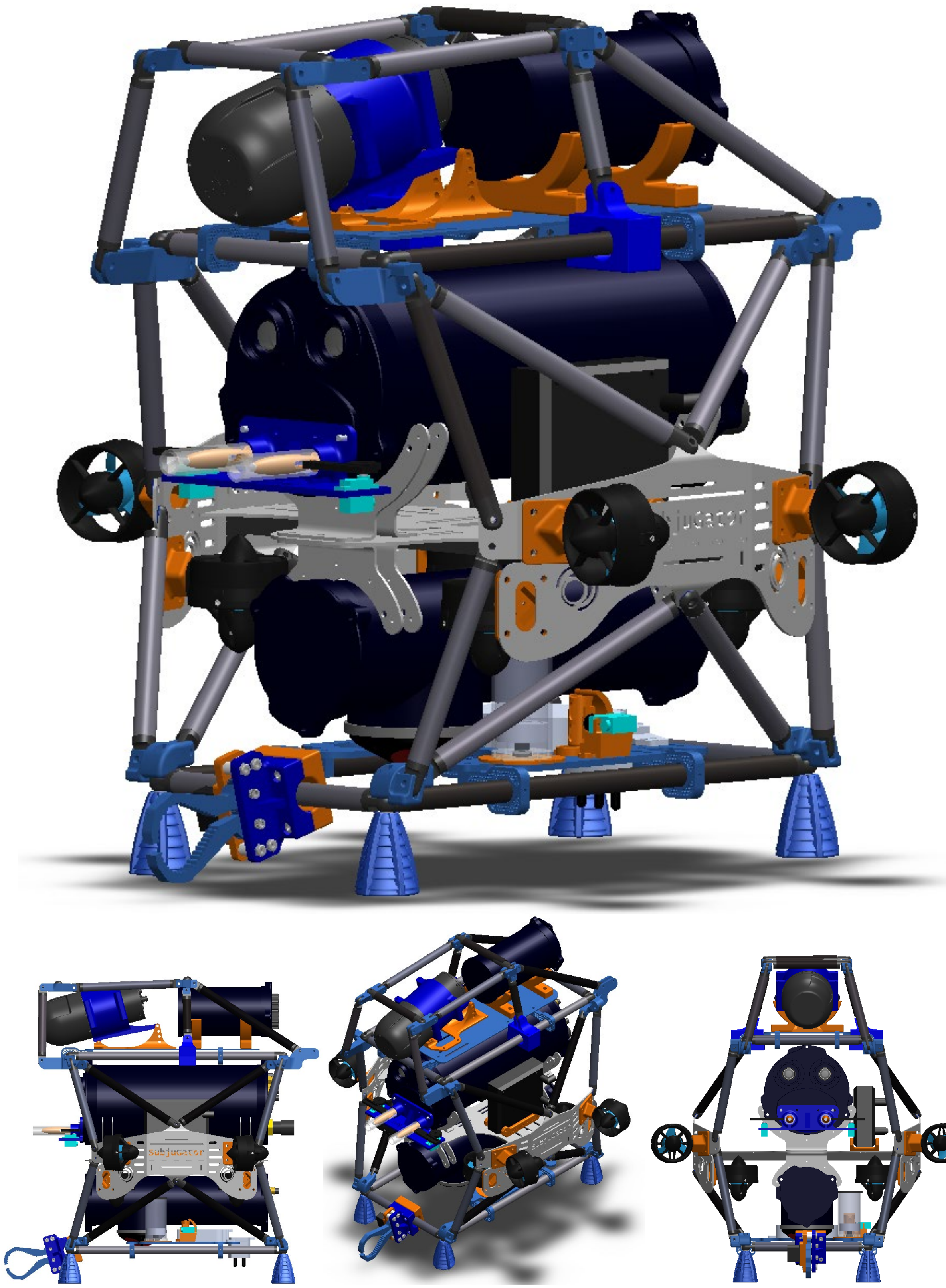

Fig. 13. High resolution images of SubjuGator 8.

VII. APPENDIX B

Component	Vendor	Model/Type	Specs	Origin	Cost	Purchase Year
Buoyancy Control	No hardware - Positively buoyant (thrusters control depth)					
Frame	DragonPlate	Carbon fiber	Space frame	Custom		
	Students	Aluminum	Frame core	Custom		N/A
Waterproof Housing	Students	Aluminum	Main vessel	Custom		N/A
	Students	Aluminum	Navigation vessel	Custom		N/A
	Students	Aluminum	Servo control vessel	Custom		N/A
	Blue Robotics	Aluminum	Downward camera vessel	Custom		
	Students	Aluminum	Power Vessel	Custom		N/A
Waterproof Connectors	SubConn	Wet-connect	External wet-mate connectors	Custom		
	SEACON	Wet-connect	External wet-mate connectors	Custom		
Thrusters	Blue Robotics	T200		Purchased	$169	2021
Motor Control	Blue Robotics	Basic ESC	7-26v, 30amp, PWM	Purchased	$25	2019
High Level Control				Custom		
Waterproof servos (3)	ServoCity	HS-5086WP Servo	4.8V-6.0V, 0.15sec/60°	Purchased	$168	2023
High-torque waterproof servo	Hitec	DB961WP	4.0-8.4V, 0.15 sec/60˚	Purchased	$179	2023
Propellers	Blue Robotics	Stock		Custom		2021
Battery	MaxAmps	LiPo	LiPo 5450 6S, 22.2v	Custom		2023
Converter	Students		Power over Ethernet (POE)	Custom		N/A
Regulator	Various			Custom		N/A
CPU	ASRock	ASRock Z390M-ITX	mini-ITX motherboard	Purchased	$140	
	Intel	i9-9900k		Purchased	$500	
GPGPU	Nvidia	RTX 2080		Purchased	$700	
Internal Comm Interface	Students		CAN	Custom		N/A
	Various		USB	Custom		N/A
External Comm Interface			Ethernet	Custom		N/A
Compass	PNI	TCM MB		Custom		
IMU	Sensonar	STIM300	9-axis	Custom		
DVL	Teledyne	Explorer	600kHz	Custom		
Manipulator	Students			Custom		N/A

Component	Vendor	Model/Type	Specs	Origin	Cost	Purchase Year
Algorithms	Adaptive PID controller					
Vision	OpenCV (Canny Edge Detection, Thresholding, Optical Flow), RCNN (YOLOv7)					
Acoustics	Scipy, Numpy (Time of Arrival, Least Squares, Fast Fourier Transform)					
Localization + Mapping	Unscented Kalman Filter on Manifolds implemented with Eigen					
Autonomy	Robot Operating System (ROS) Noetic					
Open-Source Software	Most SubjuGator software is published under an open-source license; most libraries used by SubjuGator are open-source (OpenCV, Scipy, ROS, Numpy, PySerial, PyYAML)					

VIII. Appendix C
Acknowledgements

The SubjuGator team, at the Machine Intelligence Laboratory (MIL) at the University of Florida (UF), would like to thank everyone who has supported us throughout the year, including the University of Florida's Electrical and Computer Engineering (ECE) Department, Mechanical and Aerospace Engineering (MAE) Department, and the students and faculty in our sister laboratory, UF's Center for Intelligent Machines and Robotics (CIMAR).

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:

A. Diamond Sponsor

L3Harris Corporation.

B. Platinum Sponsors

Erik de la Iglesia (alumnus), Reid Harrison (alumnus).

C. Gold Sponsors

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