Technical Overview of the Development of Autonomous Submarines GY4R4D0S and M4G1K4RP

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ABSTRACT

The CSULA Autonomous Underwater Vehicle team is competing in the RoboSub competition for our 3rd time thus far. Our main strategy this year is to establish a sustainable structure for the team to advance technology while reducing the vehicle cost. This year, our team developed two submarine robots, GY4R4D0S, which is a refurbishment of the 2018 competition vehicle, and M4G1K4RP, which is a low-budget vehicle built by students new to the project to develop low cost solutions, study underwater communication, and encourage collaboration. The overall capabilities of both vehicles include manual control and autonomous stabilization and navigation, while computer vision has been bench tested and will soon be functional on both robots. During pool testing, GY4R4D0S has seen improvements from last year, including increased modality and efficiency due to this year's additions.

COMPETITION STRATEGY

This year's competition strategy will be largely influenced by our performance in past years. We ran into two main problems at the competition last year, those problems being inadequate hardware for computer vision and lack of team organization. This year, our main focus was on correcting the issues we ran into with our computer vision, and less on the hardware side of the sub. We also implemented a training program for new members to help get them the knowledge necessary to fix the problems encountered at this year's competition. Our sub is being tested to be able to enter the gate (with random start orientation), touch buoys, pick up an object, and later drop the object we picked up as well as drop preloaded objects. Our hydrophones testing has not proven successful, so our team does not expect to be able to navigate to the objects requiring sound detection. The overview of our expectations during the competition run are indicated in Appendix A.

VEHICLE DESIGNS

I. GY4R4D0S

Since GY4R4D0S is an upgraded version of the submarine used during the 2018 competition, only the new upgrades to its hardware and design will be discussed in this paper.

a. MECHANICAL

GY4R4D0S features an aluminum anodized frame, optimized for easy additions and modifications (such as a mechanical arm or torpedoes). The hull is a standard 8” diameter acrylic watertight enclosure, chosen due to the size of the motherboard used on the sub. The bulkhead is an aluminum enclosure, machined to accommodate the Micro WET-CON connectors necessary for routing electrical connections to components outside the hull, such as the motors and LED lights. The torpedoes, along with several other important components on the sub, are 3D printed with PLA plastic to keep the weight of the sub at a minimum. The following sections highlight this year's additions to GY4R4D0S.

Internal Shelving: The internal shelves needed to be redesigned to be able to implement new hardware for this year's competition. The previous shelves featured a horizontal design but lacked modularity, provided difficult accessibility, and had no space for additional components. The previous shelves are shown in Figure 1 below.

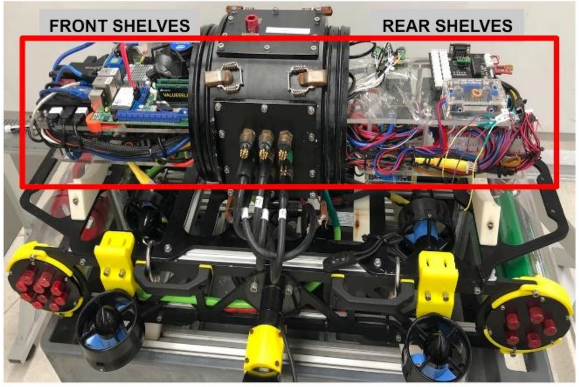

Figure 1: Previous internal shelving system on GY4R4D0S.

The main justification for this new shelving unit is the need for a GPU (graphics processing unit) on the sub. Additionally, the previous design made it difficult to service specific areas which required the entire system to be taken apart. To solve this problem, a new connector plate was designed to support the new system. The aluminum T-Slots supporting the connector plate also allow modularity in the system. Solidworks was used for stress analysis and for re-orienting circuit boards during the design of the shelving unit. Through this analysis, it was discovered that orienting the circuit boards vertically would maximize space inside the sub. Figure 2 shows the exploded and assembled views of the new implemented shelving unit.

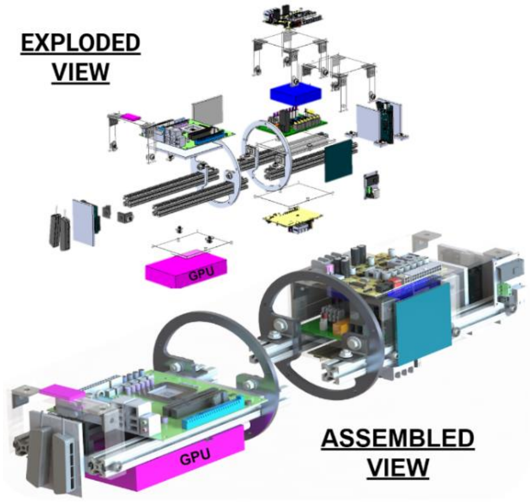

Figure 2: Solidworks CAD model of the new shelving unit implemented on GY4R4D0S.

Once the design was validated, the shelves were manufactured, as shown in Figure 3. The shelves weigh 4.38lbs, saving 43% in weight from the previous shelving system.

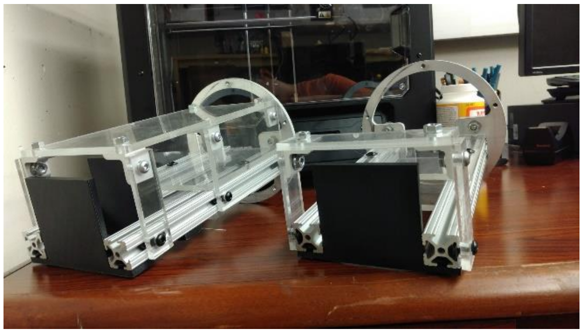

Figure 3: Assembled shelving units to be installed on GY4R4D0S.

Mechanical Arm: The previous mechanical arm design was bulky, required many non-waterproof servos, and was difficult to manufacture. The new mechanical arm design is sleeker, requires 1 linear actuator, and utilizes O-rings and enclosures for waterproofing. The 3D printed mounting plate gives the rigidity that is needed for the mechanical arm to be mounted and is lightweight. The arm is made of 3 sections of Aluminum 6061 and anodized to further improve corrosion resistance. It allows the control and manipulation of objects underwater, which is vital for gaining points at competition. Modularity is also improved, which allows for the next team to take the design and add improvements. The new arm design, after being machined, is shown in Figure 4.

Figure 4: Assembled mechanical arm for installation on GY4R4D0S.

b. ELECTRICAL

This year’s electrical system is very similar to the electrical system used in the 2018 version of our sub, with some modifications. Below, we highlight the main electrical development on the 2019 vehicle, the power regulation board.

Power Regulation Board: On the 2018 vehicle, several buck converters were used to step down the battery voltage value to the desired values for different electronic components. This year, the sub features a custom made power regulation board. The main advantage with this new implementation is an increase in space available for other electronics on the sub. The buck converters took up space on the shelving unit that was needed for other components. The power regulation board will supply voltages to the navigation equipment at 12V, to a Fathom X tether communication board, servo board, and hull LEDs at 7V, and provide additional outputs for future add-ons, including a 5V rail which was previously non-existent. Figure 5 is the initial design layout and manufactured power regulation board. The final product successfully takes a larger input nominal voltage of 14.8 V and regulates power to all required subsystems. The improved design is ¼ of the weight and space used by the previous off the shelf voltage regulators. It also added 20 more outputs for future system add-ons.

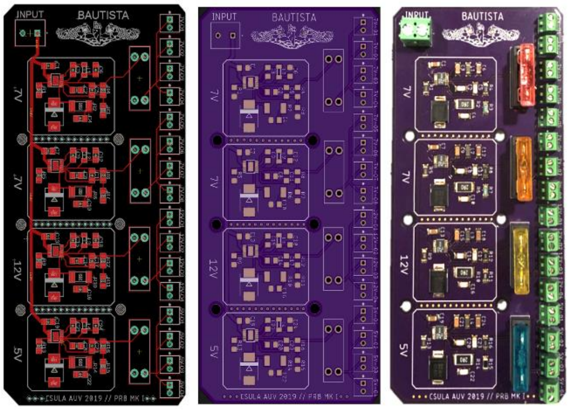

Figure 5: Initial PCB design and fully manufactured power regulation board.

c. COMPUTER SCIENCE

This year’s project is built on the ROS platform, which uses the publisher/subscriber design pattern. The middleware was programmed using Python which helps the computer vision modules communicate with functions of the AUV. The computer vision module relied on OpenCV to gather an image stream which was then sent to be processed by YOLO. YOLO is trained with labelled image data that is then processed with a CUDA enabled GPU, and then is output to a weight file which can then be used by OpenCV. The GPU is the main addition to the computer vision aspect of the project since last year, as our team’s goal for this year is to eliminate inaccuracy in our object detection image processing. The hardware used for raw data streams to be processed by different ROS modules were the Cameras, the Doppler Velocity Log (DVL) and an Inertial Measurement Unit (IMU).

This year, the team implemented a finite state machine to control the flow of events carried out by the sub. The diagram of our state machine is shown in Figure 6.

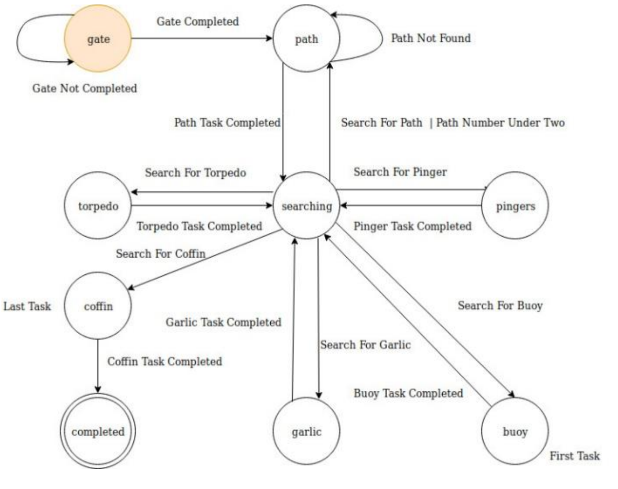

Figure 6: Finite state machine architecture for GY4R4D0S navigation system.

This state machine is based on the objectives that we will perform during the competition, and all states besides the exit state will return back to the searching state. We decided to use a state machine to avoid a dead state in the AUV, which will increase our success by never being stuck somewhere. This is a major development from last year, as the state machine implemented on the 2018 vehicle kept pausing at times that it should have been carrying out a task.

II. M4G1K4RP

M4G1K4RP is the sub built by the students that will comprise next year's team, intended for practicing intervehicle communication while maximizing modality and cost efficiency. This vehicle was built on a very low budget and has less advanced electronics and materials than those of GY4R4D0S.

a. MECHANICAL

The mechanical design of Cal State LA's M4G1K4RP AUV was geared towards low cost and modularity. Moreover, the entirety of the manufacturing for the AUV was done in-house at the Cal State LA machine shop and AUV lab. The frame was manufactured with polycarbonate sheets and off-the-shelf T-slotted aluminum extrusions, modified for assembly and mounting other subassemblies. The AUV frame design is shown in Figure 7. The polycarbonate sheets had to be water jetted, since polycarbonate can't be laser cut safely. However, the polycarbonate was chosen, despite this inconvenience, for its flexibility and so the added complexity in manufacturing was worth the beneficial material properties. The frame is designed with mounting areas at the top and bottom of the vehicle for actuators and buoyancy control. Two forms of passive buoyancy control are utilized on M4G1K4RP, weights mounted to the bottom of the sub, and buoyancy foam installed at the top.

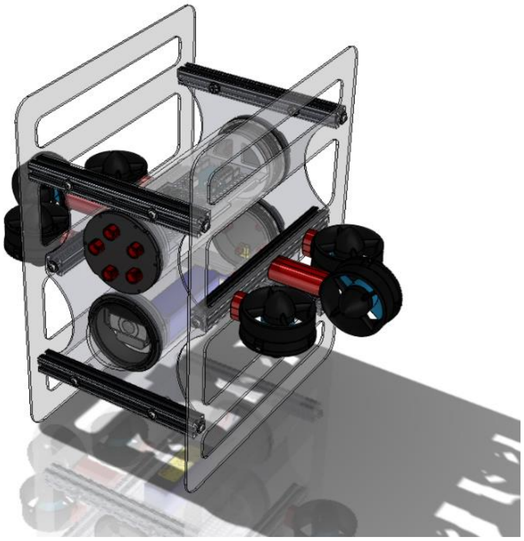

Figure 7: Solidworks CAD model of M4G1K4RP frame with thruster configuration.

M4G1K4RP's thruster configuration allows for pitch, roll, and depth to be controlled simultaneously via adjacent corners of the AUV. Side thrusters are mounted at a farther distance from the AUV's center of gravity to maximize torque and for mounting clearance. The side thrusters are utilized to control yaw and forward/backward motion. The AUV's electronics are mounted to a shelving unit with breadboard style modular mounting holes made from laser-cut acrylic sheets. The electronics shelving unit maximizes special efficiency for the electronics and helps with clean wire management. The upper hull houses the AUV's primary electronics, including the motherboard and thruster control board. The bottom hull houses the battery and cameras. The top view of the sub is shown in Figure 8, highlighting the thruster configuration and shelving unit in the top hull.

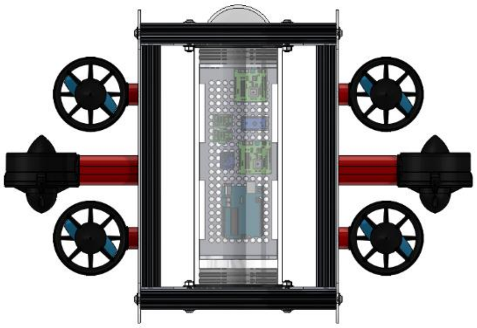

Figure 8: M4G1K4RP top view showing thruster configuration.

b. ELECTRICAL

The electrical components on M4G1K4RP were chosen with cost and simplicity as the main priorities. M4G1K4RP features a power distribution system utilizing buck converters to step down the battery's 14.8 volts for other components for simple power distribution. The components powered by this system include an Arduino board for stabilization, a custom made PWM board for thruster control, and the motherboard (which also powers the cameras). The thruster board was designed with special restrictions in mind and features a modular design with ESCs on both sides of the board and connectors and fuses along the sides of the board to save space. The board attached to the shelving unit is shown in Figure 9.

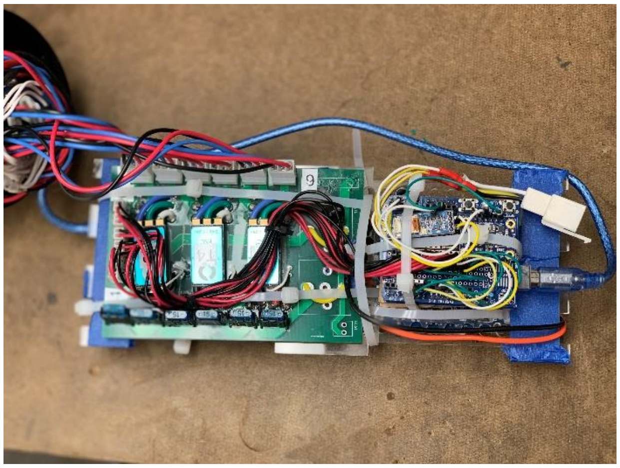

Figure 9: M4G1K4RP internal shelving unit with electronics attached showing custom thruster PWM board.

c. COMPUTER SCIENCE

A LattePanda development board was chosen for the primary control of the sub due to its low cost and sufficient capabilities for object recognition. The state machine architecture for M4G1K4RP is very similar to the architecture designed for GY4R4D0S (see Figure 6), with some simplifications due to hardware limitations. A ROS top-level architecture is implemented for navigation, and the computer vision is trained using a Haar Cascade model. The sub features LED lights that act as indicators of the task the sub is currently attempting to complete.

EXPERIMENTAL RESULTS

I. GY4R4D0S

During the year-round pool testings with GY4R4D0S, the team was able to accomplish full manual control of the sub and has done decent work on the computer vision algorithms. The pool testing dates have been mainly aimed towards waypoint navigation with the DVL, and the team has achieved many successes in understanding last year's code and changing it to suit the needs of this year's team. The machine learning algorithms have seen increased functionality with the addition of a GPU and the state machine model works well for our competition strategy this year. The power regulation board was also bench tested with several different electrical configurations.

II. M4G1K4RP

The testing time in the pool is primarily spent testing the navigation, control, and computer vision of the sub. Through our controls testing and buoyancy adjustments, we were able to achieve a very polished stabilization algorithm. Our results from testing computer vision and navigation are comparable to those of GY4R4D0S, as it supports a similar software structure. Currently, the team is testing object detection with M4G1K4RP and has seen some success thus far during tests.

ACKNOWLEDGEMENTS

We would like to thank our advisers, J. Diego Santillan, Dr. He Shen, Dr. Mark Tufenkjian, and Dr. Mark Sargent for their countless hours of dedication towards helping us succeed throughout the year on this project. Mark Tufenkjian's grant from the ONR largely funded our project, as well as the CSULA Associated Students, Inc. Additionally, we would like to thank our machinist, Blake Cortis, for his help machining our arm and bulkhead and for providing his advice. We would also like to thank Sparkfun for sponsoring us for $200 towards materials, as well as Mathworks and Dassault Systèmes for the kind contributions of software licenses for our team.

Appendix A: Expectations

Subjective Measures

	Maximum Points	**Expected Points**	**Points Scored**
Utility of Team Website	50	25	
Technical Merit (from journal paper)	150	110	
Written Style (from journal paper)	50	40	
Capability for Autonomous Behavior (static judging)	100	85	
Creativity in System Design (static judging)	100	70	
Team Uniform (static judging)	10	10	
Team Video	50	40	
Pre-Qualifying Video	100	100	
Discretionary points (static judging)	40	30	
Total	**650**	**510**	

Performance Measures

Weight	See Table 1 / Vehicle	-130	
Marker/Torpedo over weight or size by <10%	Minus 500 / marker	0	
Gate: pass through	100	100	
Gate: maintain fixed heading	150	150	
Gate: coin flip	300	300	
Gate: pass through 60% section	200	200	
Gate: pass through 40% section	400	0	
Gate: style	+100 (8x max)	0	
Collect pickup: crucifix, garlic	400 / object	400	
Follow the “path” (2 total)	100 / segment	200	
Slay vampires: any, called	300, 600	300	
Drop garlic: open, closed	700, 1000 / marker (2 + pickup)	700	
Drop garlic: move arm	400	400	
Stake through Heart: Open Oval, Cover Oval, Sm Heart	800, 1000, 1200 / torpedo (max 2)	800	
Stake through Heart: Move lever	400	0	
Stake through Heart: Bonus - Cover Oval, Sm Heart	500	0	
Expose to Sunlight: Surface in Area	1000	1000	
Expose to Sunlight: Surface with object	400 / object	0	
Expose to Sunlight: Open coffin	400	0	
Expose to Sunlight: Drop Pickup	200 / object (crucifix only)	0	
Random Pinger first task	500	0	
Random Pinger second task	1500	0	
Inter-vehicle Communication	1000	0	
Finish the mission with T minutes (whole + factional)	Tx100	500	

Appendix B: GY4R4D0S Component Specifications

Component	Vendor	Model/Type	Specs	Cost (if new)
Buoyancy Control	Amazon	Arduino Mega	PID controller	Re-used
Frame	Various	Aluminum	¼”, waterjet & anodized	Re-used
Waterproof Housing	Blue Robotics	Waterproof acrylic enclosures	8” series and 4” series	Re-used
Waterproof Connectors	SEACON	Wetcon	6 pin and 10 pin	Re-used
Thrusters	Blue Robotics	T200	5.1 kgf max thrust	Re-used
Motor Control	Blue Robotics	ESC	30 amp	Re-used
High Level Control		ROS, Python 2.7		
Actuators	Amazon	Aqonix linear actuator	12V, 225lbs	$39.95
Battery	HobbyKing	MultiStar	10000mAh / 14.8V	$122.44
Regulator	OshPark	Custom PCB		$65.00
CPU	Amazon	Intel i5	3.1GHz	Re-used
Motherboard	Newegg	Micro ATX	Support for i7/i5/i3/Celeron processor	Re-used
Programming Language 1		Python 3		
Programming Language 2		C++		
Inertial Measurement Unit (IMU)	Vectornav	VN-100 IMU/AHRS	32bit processor, 3-axis accel, gyro, mag	Re-used
Doppler Velocity Log (DVL)	Teledyne	Pathfinder	600kHz	Re-used
Camera(s)	Blue Robotics	Low-light HD usb camera	2MP, 1080p	$89.00
Algorithms: vision		YOLO v2		
Algorithms: localization and mapping		Custom		
Algorithms: autonomy		Custom		
Team size (number of people)		20		
HW/SW expertise ratio		50/50		
Testing time: simulation		0hr		
Testing time: in-water		50hr		

Appendix C: M4G1K4RP Component Specifications

Component	**Vendor**	**Model/Type**	**Specs**	**Cost (if new)**
Buoyancy Control	Blue Robotics	Buoyancy Foam	6” x 12”	$20
Frame	Amazon T-Slot Aluminum	Polycarbonate N/A	12” x 24”	$24
Waterproof Housing	Blue Robotics	Acrylic Tube and Aluminum Endcaps	4” series	Re-used
Waterproof Connectors	SEACON	Wetcon	6 pin	Re-used
Thrusters	Blue Robotics	T200	5.1kgf max thrust	Re-used
Motor Control	Blue Robotics Amazon	ESC Arduino board	30 amp Uno	$25 Re-used
High Level Control		ROS, Python 2.7		
Battery	HobbyKing	MultiStar	10000mAh / 14.8V	Re-used
Regulator	Amazon	Buck converter	12V / 5A	$15.18
Motherboard	Amazon	LattePanda	4GB / 64GB	Re-used
Programming Language 1		Python 2.7		
Programming Language 2		C++		
Inertial Measurement Unit (IMU)	Adafruit	Bosch BNO055	9-DOF, integrated dev board	$34.95
Camera(s)	Logitech	C615 HD webcam	8MP, 1920x1080px, 30 fps	Re-used
Algorithms: vision		Haar Cascade		
Algorithms: localization and mapping		Custom		
Algorithms: autonomy		Custom		
Team size (number of people)		20		
HW/SW expertise ratio		50/50		
Testing time: simulation		0 hr		
Testing time: in-water		20 hr		