S.O.N.I.A. AUV Technical Design Report

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***Abstract*—S.O.N.I.A. (Système d'Opération Nautique Intelligent et Autonome) is a robotics club from the École de Technologie Supérieure in Montréal dedicated to constructing underwater vehicles since 1999. Comprised of 21 undergraduate members with expertise in mechanical, electrical, automated production, and software engineering, the club aims to customize the latest platforms, AUV8 and AUV7, for the upcoming competition while training the new generation of team members. This year's objectives consisted of improving the torpedoes and vision-related tasks with the collaboration of the three departments. These objectives were based on our competition, design, and testing strategies which we will present in this paper.**

***Index Terms* – Autonomous Underwater Vehicle, Technical Design Report, RoboSub, RoboNation**

I. Competition Strategy

Since 1999, our main values have been based on durability, reliability, and constant learning. These values help us address our main concern for this year: training new members. While many of the previous team members graduated, we were able to understand all aspects of both of our underwater vehicles, AUV7 and AUV8, with the documentation and tools they passed on to us.

This allowed us to leverage the knowledge and experience of previous years and build upon their achievements. Drawing on what we have learned, our goal for this year's competition is to score at least 3000 points.

After reviewing our options to reach this goal and considering the size and experience of our current team, we decided to limit the scope of our improvements to the most promising areas. Considering the previous efforts put into the development of the torpedo system and the inter-sub communication, we concluded that these would be the best elements to concentrate most of our resources on.

With our inter-submarine communication, both of our vehicles will work together to identify the following obstacles: the gate, the path, the buoy, the bins, and the torpedoes. The task involving the chevrons in the centre of the octagon will not be included in this year's objectives since we do not have any means to interact with the task.

It will be possible to use the two onboard cameras to detect and navigate obstacles while utilizing AI and conventional vision to accomplish all visual tasks. Despite the penalty points incurred due to the weight of AUV7, the benefits of having interchangeable parts and having two submarines working together outweigh the drawbacks.

To effectively navigate the TRANSDEC environment, our submarines rely on a model predictive controller paired with an IMU, DVL, depth sensor, and eight motors which provide them with six degrees of freedom. This control system, working in conjunction with the image detection system, enables precise alignments of the submarines with competition obstacles namely the gate, paths, and bins. Additionally, the control system allows our submarines to pass through the gate "with style," involving changing their orientation while traversing the gate.

To accomplish the torpedo task, the submarine utilizes a new launch system that can independently launch one of the two torpedoes after the alignment of the submarine with the targets. This system is activated by a solenoid mechanism, ensuring consistent torpedo deployment.

A similar actuation mechanism is employed to deploy the marker into the bins following submarine alignment. This mechanism allows for precise and controlled marker placement. Moreover, both submarines are equipped with acoustic modems, which are used to coordinate their movements and thereby avoiding collisions during mission execution.

By incorporating these control and actuation systems, we aim to enhance the performance and capabilities of our submarines with the skills and dedication of our new team members. This iterative improvement approach allows us to adapt and grow, maintaining our commitment to durability, reliability, and continuous innovation.

II. Design Strategy

A. *Software Team Strategy*

The software team has devised a strategic plan to utilize and enhance our existing system design for the competition. Our submarines will be equipped with advanced software capabilities that utilize new learning methods, building upon the previous year's work with vision algorithms, simulation environments, and state machines. This strategic approach aims to enhance the navigation and task execution of our submarines.

1) *Vision algorithms*

Leveraging our artificial intelligence and conventional vision techniques, our submarines will navigate most of the missions in this year's competition. Powered by a Convolutional Neural Network (CNN), a deep learning algorithm, this AI is effective in tasks like image recognition and object detection. Additionally, our artificial intelligence will incorporate automated data augmentation as a novel learning approach [1]. Our dataset comprises data collected from both simulations and real environments, including pools and lakes. Our simulated images are generated within the Unity environment, which enables us to determine the positions of the regions of interest relative to the reference frame of our cameras. This information is then used to generate bounding boxes. In the next few weeks, we aim to utilize this technique to automate the labelling process for all our data, thereby saving valuable time for our team members. To simplify the task for the AI, our images will be pre-processed using filters before they are used for inference.

2) *Simulation environment*

Recognizing the value of our 3D simulation environment [2], we have decided to further enhance its capabilities. Specifically, we have introduced new images exclusively for this year's competition and made modifications to various objects and environmental details within our Unity project. These enhancements enable us to collect data for our AI and practice missions within the simulation environment. Additionally, we are collaborating with a course in ÉTS to improve the speed and efficiency of changing and building the simulation, providing valuable insights for our telemetry module.

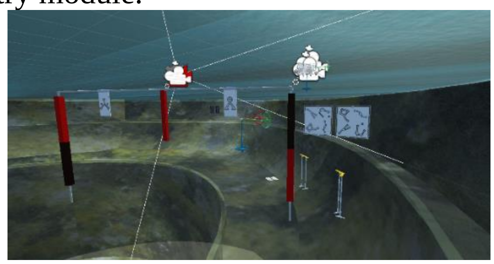

Fig. 1. 3D simulation in unity

3) *States Machine*

Our behaviour engine, FlexBe, empowers us to create advanced states and behaviours for our missions. Additionally, by structuring our missions into layers based on complexity, we are easily able to reuse various sections. With this structure, our missions (or sub-missions) will be useful for years to come, facilitating the work for future generations. Moreover, these missions can be conveniently tested within our 3D simulation environment, enhancing our development and validation processes.

With these tools, our software team aims to maximize the capabilities and performance of our submarines in the competition. The integration of AI, automated data augmentation, and the use of the ROS engine allows us to tackle complex tasks efficiently and adapt to evolving challenges.

B. *Electrical Team Strategy*

The electrical team plays a crucial role in providing the necessary infrastructure within the submarine. This includes the power distribution system, communication system, actuators, and motor control system.

1) Power distribution

The power distribution system needs to provide a stable supply of power to all the components of the submarine. A particular challenge is the current required by the eight motors (which can all draw up to 12 amps). The stability of the voltage is also very important as the onboard computer is very sensitive to variation in its supply. In the past, we observed that an unstable power supply caused the system to shut down, which could be catastrophic during a competition run. Consequently, bulk capacitors are included on the power distribution board to stabilize the output voltage during transient events.

To meet the requirement of the competition, the power distribution board can also shut down all eight motors. This is accomplished by controlling the power supply of the electronic speed controller (ESC) based on the status of the kill switch. In software, individual motors can be activated or deactivated by manipulating the power of individual channels through MOSFETs. Furthermore, when the kill switch is activated, high-current relays interrupt power to all channels, ensuring a complete shutdown. It's important to note that this mechanism is purely electrical and does not rely on any software dependencies.

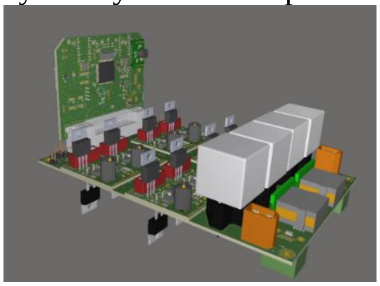

Fig. 2. Power distribution system on AUV8

2) Communication

Communication within the submarine is crucial as all the interactions within the submarine are done through the communication system. Many factors were taken into consideration when deciding the communication protocols to use. In the end, three communication buses (Ethernet, USB, and RS-485) were selected depending on the needs of each system.

The Ethernet bus is responsible for communication with the onboard computer, the Doppler Velocity Log (DVL), and the outside world via tethers. It utilizes a network switch to interconnect these elements and has been chosen for its reliability, high throughput, and user-friendliness.

The USB is utilized for connecting the cameras to the computer, as well as serial devices such as the Inertial Measurement Unit (IMU), depth sensor, and acoustic modem. USB has been selected for its high throughput (in the case of the cameras) and universal compatibility (in the case of the serial devices).

The RS-485 bus is employed to establish a connection between the onboard computer and the custom PCBs within the submarine. These PCBs include the power distribution system, the kill switch, the ESC interface, and the actuator control board. The decision to use the RS-485 bus was driven by its robustness and ease of implementation on PCBs. During the design phase of the RS-485 software stack, attention had been given to reduce timing jitters when going through the RS-485 bus as this can adversely affect the stability of the control loop of the submarine [3]. This is achieved, in the case of the ESC interface, by prioritizing the receiver task over other tasks and making sure that data received is treated right away.

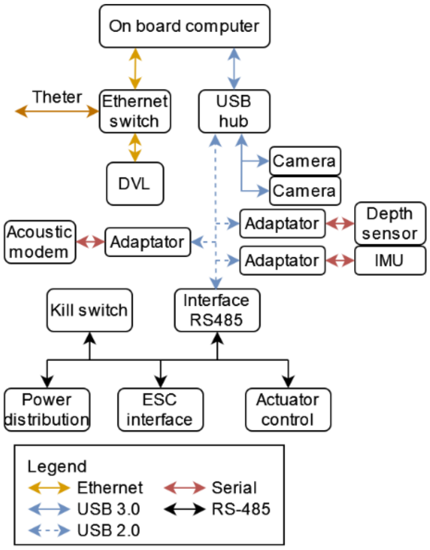

Fig. 3. Communication systems on the submarine

By ensuring stable and reliable communication, we make sure that the submarine is able to complete the competition tasks accurately and efficiently.

3) Motor and actuator control

The AUVs are equipped with eight brushless motors that are controlled by electronic speed controllers (ESCs). To provide the ESCs with the necessary PWM (Pulse Width Modulation) signals, a custom PCB generates these signals based on commands received from the onboard computer. In the case of AUV8, the integration of this PCB within the power management system has been done to optimize the space within the submarine. The ESC boards used to control the motors are rated for a much higher current (up to 30 A) than the expected current required by the motor. This ensures that the motors will always receive the required power needed to move the submarine. Thanks to the robust control system of the motors, the submarine can move reliably within the competition area.

The actuator system is used to control the torpedo and dropper systems which are used to complete the “Goa’uld Attack” and “Location” tasks respectively. Both systems are actuated by solenoid controlled by MOSFET located on the IO board. This board receives commands from the onboard computer to activate or deactivate the solenoids. Additionally, the IO board receives the signal from the kill switch, which when enabled, will disable the ability to trigger the actuators. With this system, the submarine can complete the torpedo and bin tasks with consistency.

C. *Mechanical Team Strategy*

The Mechanical Team’s strategy primarily focuses on the design of the torpedoes and their launch system for the AUV8. Additionally, some other changes were implemented in conjunction with the new torpedo system.

1) Floaters

Due to its smaller form factor than AUV7, AUV8 does not displace enough water to float without additional floaters. With the old modular floaters, we were able to adjust continually the balance of the submarine, to compensate for weight changes when changing components on the inside and outside.

Once AUV8's competition configuration was finalized, the submarine's balance in the water was fine-tuned using the floaters. Archimedes' principle was employed to measure the final volume of the floaters, and their shape was transferred into a 3D CAD model. This information enabled final tweaks to the floater shape before sending them off for production. The team chose expanded polypropylene (EPP) as the floater material for its excellent compressive strength and low water absorption characteristics, ensuring improved durability without compromising functionality [4].

2) Torpedo system

For this competition, a new torpedo system was developed with the primary goal of improving reliability and range while introducing individual torpedo launching capability for increased flexibility and control during missions.

a) Torpedo launcher

Extensive research was conducted to find an appropriate release mechanism for the new torpedo launcher. After reviewing several existing mechanisms, a crossbow-like release mechanism was chosen for its compact form factor and integration of a solenoid as the blocking component. To enhance torpedo guidance and reduce friction, grooves were added to the launcher tube. Additionally, the positioning of the torpedo propulsion spring between two components ensured a non-hyperstatic state, allowing the spring and torpedo to travel in a straight path. Those improvements helped us achieve more consistent trajectories with the torpedoes.

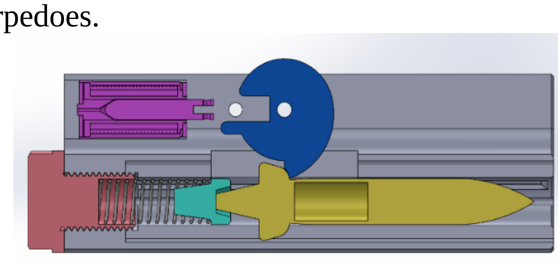

Fig. 4. Torpedo launcher mecanism

To enable independent torpedo launches, the mechanism can be duplicated on either side of the submarine. This symmetric configuration on both sides of the XZ plane reduces the complexity of balancing the submarine.

b) Torpedo

The previous torpedo design had issues with high drag coefficient and negative buoyancy. Computational fluid dynamic simulations were used to calculate the drag coefficient and facilitate a rapid prototyping loop. This approach allowed efficient optimization of the torpedo's drag. Overcoming turbulence generated by the torpedo fins was a specific challenge addressed during the design process, resulting in a reduction of the drag coefficient of 127%. Meaning that, for the same initial force, the new torpedo will go much further.

To achieve neutral buoyancy, a hermetic hole was designed inside the torpedo, with the volume of the hole determined based on the exceeding mass, the material density, and the 3D printer's filling setting.

Different positions for the hole inside the torpedo were experimented with, and empirical observations led to the determination that shifting the hole slightly towards the back of the torpedo yielded better results.

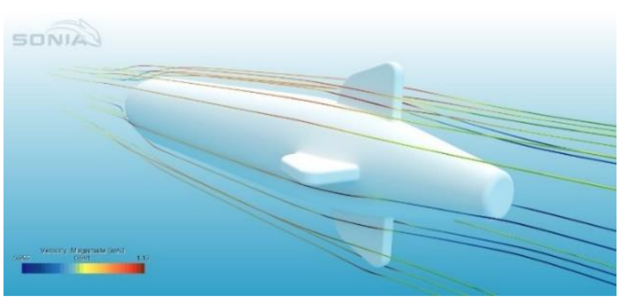

Fig. 5. Fluid simulation of the new torpedo

By addressing buoyancy concerns, and developing an enhanced torpedo system, the mechanical team has contributed significantly over the year to improving the overall performance and capabilities of the submarine for the competition.

III. Testing Strategy

A. *Software Testing Strategy*

1) Labelling in real environment

To enhance the efficiency of our data augmentation technique, we expanded the size of our training dataset. To achieve this, we captured real-world images in diverse settings, including lakes, outdoor environments, and indoor pools with rosbag command from ROS [5]. Our primary objective is to diversify our dataset by incorporating images with varying water colours, lighting conditions, and other environmental factors.

2) Simulation environment

Before conducting tests in a real environment, we utilized the Unity environment to test our missions and filters. This simulation allowed us to replicate real trajectory missions of the submarine, employing both AI and conventional vision within a virtual environment.

3) Communication inter-sub

We were able to test the communication inter-sub alongside other tests to check the durability of the communication. Ros logs were saved for post action analysis. With this approach, we were able to optimize our testing time.

B. *Electrical Testing Strategy*

1) Power distribution

To evaluate the power distribution system's capacity in managing the power draw of the motors, a bench test was created. Since the motors account for the largest power draw, we focused our testing efforts on them. A motor was mounted on a rod and submerged in water, then activated at maximum speed for extended periods. The power distribution system was kept in an enclosed space and its temperature was monitored in strategic places. The MOSFET that controls the power of the motor was identified as the hotspot. During testing, we observed an increase of about 25 °C over ambient on the external case of the MOSFET without active cooling. Since this falls within the acceptable parameters for temperature and this represents a worst-case scenario, we are confident that the temperature of the power distribution system will be acceptable during normal operation. Similar testing has been done by repeatedly turning ON and OFF the motor channel, to test the system response to transient load. The temperature and behaviour of the system aligned with our expectations.

During our testing, we discovered that the depth of the container played a crucial role in power consumption. Specifically, when the motor operates in shallow water, it generates an air vortex that alters the motor's power consumption. With the presence of the air vortex, the drag on the motor props is reduced, meaning that the motor necessitates less power to run at the same speed. Running the motor at the same speed without the presence of a vortex necessitates a higher power input, exerting a greater strain on the power distribution system.

Fig. 6. Power distribution system test setup

C. *Mechanical Testing Strategy*

1) Prequalification

While preparing for the annual competition, we made the decision to push our submarines to their limits. We conducted tests to evaluate the motor capacity, enabling our submarines to reach their maximum speed over a short distance. This process allowed us to identify areas that require improvement before the competition day.

2) Pressure test

To ensure our submarines are ready for real-world environments, we conducted a pressure test. For this test, the submarine is depressurized until the outside air creates pressure equivalent to that of water at a depth of 7 m. This test helps us identify any potential leaks and allows us to address them before any potential damage could occur.

3) Torpedo testing

We created a simple manual torpedo launcher consisting of a cylinder, a plunger, and a spring to test the effect of the torpedo's centre of mass on its trajectory and stability in water. By experimenting with different torpedo designs, we concluded that slightly shifting the centre of mass towards the front yielded more stable trajectories.

By implementing thorough software, electrical, and mechanical testing strategies, we ensure the reliability, performance, and readiness of our submarines for the competition.

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Bronze: Anodisation Expert, Attaches Richard, Blue Robotics, Connect Tech, General Dynamics, Groupe Rivest, Hakko, Laser AMP, Multi Caisses, Nvidia, Omni Robotics, Simplify 3d, Water Linked

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APPENDIX A
COMPONENT SPECIFICATIONS (AUV7)

Component	Vendor	Model/Type	Specs	Custom/ Purchased	Cost	Year of purchase
Buoyancy Control	-	Added mass	Brass plates	Custom	150$	2022
Frame	-	CNC aluminium system	6061-T6 CNC machined, anodized and painted	Custom	-	2020
Waterproof Housing	Homemade	CNC aluminium system	6061-T6 CNC machined, anodized and painted	Custom	7000$	2020
Waterproof Connectors	MacArtney	Subconn connector	Wet Mate	Purchased	4000$	2020
Thrusters	Blue Robotics	T200 (x8)	0.02 kg f	Purchased	-	2016
Motor Control	HobbyKing	AFRO ESC	30A	Purchased	-	2016
High Level Control	-	LTV MPC	-	Custom	-	2022
Actuators	-	Droppers only	Solenoid Activation	Custom	-	2022
Battery	MaxAmps	4S 16000mAh	14.8V	Purchased	-	2022
Converter	Texas Instruments	LM25116MH	Synchronous Buck Controller	Purchased	-	2020
Regulator	-	Powersupplies	12V 15A Step-down	Custom	-	2020
CPU	Nvidia	Jetson AGX Xavier	16GB RAM	Purchased	-	2019
Internal Comm Network	-	RS485	2 twisted pairs Ethernet cables	Custom	-	2022
External Comm Network	ConnectTech	XDG021	1000 Mbps Switch	Purchased	-	2016
Compass	VectorNav	VN-100 Rugged AHRS	Standard calibration +25°C	Purchased	-	2022
Inertial Measurement Unit (IMU)	VectorNav	VN-100 Rugged AHRS	Standard calibration +25°C	Purchased	-	2022
Doppler Velocity Log (DVL)	Nortek	DVL500	300m	Purchased	-	2016
Vision	Flir	Chameleon 3 USB	55FPS, 3.2MP	Purchased	-	2022
Acoustics	Bruel & Kjaer	8103	0.1 to 180kHz	Purchased	-	2016
Inter-vehicule communication	Water Linked AS	MODEM M64	64 bits, omnidirectional	Purchased	2000$	2021
Algorithms: Vision	OpenCV TensorFlow2	- MobileNet	- -	Custom Custom	- -	2022 2022
Algorithms: Localization and Mapping	Matlab Octomap	Extend Kalman Filter 3D occupancy grid	TBD -	- -	- -	2021 2022
Algorithms: Autonomy	FlexBe	Finite-state-machine	-	Custom	-	2021
Open-source software	OpenCv, FlexBe, AirFlow, TensorFlow, ROS, Unity Robotics, Docker, WikiJS, Github					
Team Size	21					
Expertise ratio	3/21					
Testing time: simulation	35 hours					
Testing time: in-water	50 hours					
Programming Languages	C/C++, C#, Python, Matlab					

APPENDIX B
COMPONENT SPECIFICATIONS (AUV8)

Component	Vendor	Model/Type	Specs	Custom/ Purchased	Cost	Year of purchase
Buoyancy Control	-	Added Volume	Foam	Custom	150$	2022
Frame	-	CNC aluminium system	6061-T6 CNC machined, anodized and painted	Custom	-	2020
Waterproof Housing	Homemade	CNC aluminium system	6061-T6 CNC machined, anodized and painted	Custom	7000$	2020
Waterproof Connectors	MacArtney	Subconn connector	Wet Mate	Purchased	4000$	2020
Thrusters	Blue Robotics	T200 (x8)	0.02 kg f	Purchased	200$/each	2019
Motor Control	Emax	Bullet Series ESC (x8)	30A	Purchased	15$/each	2019
High Level Control	-	LTV MPC	-	Custom	-	2022
Actuators	-	Droppers only	Solenoid Activation	Custom	-	2022
Battery	MaxAmps	4S 16000mAh	14.8V	Purchased	2000$	2020
CPU	Nvidia	Jetson AGX Xavier	32GB RAM	Purchased	1000$	2020
Internal Comm Network	-	RS485	2 twisted pairs Ethernet cables	Custom	-	2020
External Comm Network	ConnectTech	XDG021	1000 Mbps Switch	Purchased	-	2020
Compass	VectorNav	VN-100 Rugged AHRS	Standard calibration +25°C	Purchased	-	2022
Inertial Measurement Unit (IMU)	VectorNav	VN-100 Rugged AHRS	Standard calibration +25°C	Purchased	-	2022
Doppler Velocity Log (DVL)	Teledyne	Pathfinder	600kHz,140m	Purchased	20000$	2020
Vision	Flir	Chameleon 3 USB	55FPS, 3.2MP	Purchased	1200$	2020
Acoustics	Bruel & Kjaer	8103	0.1 to 180kHz	Purchased	-	2020
Inter-vehicule communication	Water Linked AS	MODEM M64	64 bits, omnidirectional	Purchased	2000$	2021
Algorithms: Vision	OpenCV TensorFlow2	- MobileNet	- -	Custom Custom	- -	2022 2022
Algorithms: Acoustics	-	Time Differental of Arrival (TDOA)	FPGA Implementation	Custom	-	2022
Algorithms: Localization and Mapping	Matlab Octomap	Extend Kalman Filter 3D occupancy grid	TBD -	- -	- -	2021 2022
Algorithms: Autonomy	FlexBe	Finite-state-machine	-	Custom	-	2021
Open-source software	OpenCv, FlexBe, AirFlow, TensorFlow, ROS, Unity Robotics, Docker, WikiJS, Github					
Team Size	21					
Expertise ratio	3/21					
Testing time: simulation	100 hours					
Testing time: in-water	75 hours					
Programming Languages	C/C++, C#, Python, Matlab					