Concept and Design of the 2012 SONIA AUV Platform

http://sonia.etsmtl.ca
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Team SONIA, from École de technologie supérieure, is an undergraduate student association that builds an AUV (Autonomous Underwater Vehicle) to perform at the 7th annual SAUC-E (Student Autonomous Underwater Vehicle Challenge – Europe). It consists of an obstacle course composed of real life tasks such as pipeline and wall inspection. The week after, the team will compete at the 15th annual RoboSub competition held in San Diego, CA. More oriented on computer vision, this competition includes grabbing and releasing of an object and dropping markers into bins to name a few. Both of these challenges simulate real world tasks requiring accurate navigation and swift execution. In order to be ready for both competitions, the team had to build two vehicles to facilitate the logistics. To effectively complete mission tasks, the submarine is equipped with a Doppler Velocity Log, an Inertial Measurement Unit, a Mechanically Scanned Imaging Sonar and two cameras. With the addition of the sonar, the software team added many features to the control system allowing the measuring of encountered object distances. Also, the team members improved last year's design with several modifications to reduce mission execution time and enhance overall modularity.

Quick Facts

Dry weight:	40 [kg]	***Thrusters:***	6x SeaBotix Brushless HPDC1507
Dimensions (LWH):	1.24 x 0.53 x 0.38 [m]	***Cameras:***	2x Unibrain Fire-i board Pro
Max speed:	0.5 [m/s]	***Sonars:***	1x Teledyne Explorer DVL
Max depth:	30 [m]		4x Brüel & Kjær Hydrophone
Degrees of freedom:	Surge Heave Sway Yaw Pitch		1x Tritech Micron DST Sonar
Autonomy:	4 to 5 [h]	***IMU:***	1x SBG Systems IG-500e

Team SONIA (Système d'opération nautique intelligent et autonome) was founded in 1999. The project was created to take part in the annual International Autonomous Underwater Vehicle Competition held by AUVSI (Association for Unmanned Vehicle Systems International). The team has never missed a competition and fought tooth and nail every year to obtain the first prize and the serious bragging rights that come with it. This year, in addition to the continued participation in the RoboSub competition, the team is bringing its competitive skills and sportsmanship to Italy to take part in the 7th annual SAUC-E (Student Autonomous Underwater Vehicle Competition - Europe) competition. The team is composed of 27 undergraduates from electrical, software, mechanical and mechatronics engineering. The project is split in three sub-teams (electrical, software and mechanical) working together towards the goal of developing a stable and extensible platform capable of performing many tasks. This year, at RoboSub, every competitor will have to perform the following tasks:

- Navigate through an underwater gate
- Find and hit two buoys
- Navigate over a "U" shaped lane
- Drop two markers in bins
- Locate an acoustic beacon
- Pick up and release PVC structures

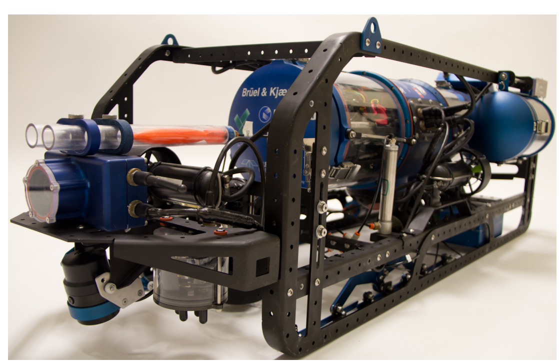

Figure 1 – Submarine's front port view

The SONIA AUV (Autonomous Underwater Vehicle) is equipped to perform the entire obstacle course:

- One Kontron 2.5GHz Core 2 Duo Mini-ITX computer with 4GB of RAM
- One inertial system IG-500e from SBG Systems
- One Explorer DVL (Doppler Velocity Log) from Teledyne RD Instruments
- One MSIS (Mechanically Scanned Imaging Sonar) from Tritech
- Two Unibrain Fire-i Board Pro cameras
- Four Brüel & Kjær hydrophones with a passive sonar signal processing board
- One depth sensor
- One object positioning system
- Six Seabotix HPDC1507 brushless thrusters
- One marker dropping unit
- One soft projectile launching unit
- One active grabbing device

Team Objectives

To improve the AUV, the team had three primary objectives:

- Correct flaws of the 2011 platform
- Reduce mission execution time
- Establish a regular test schedule

Team Organization

In each of the subgroups, a leader is democratically elected at the beginning of the year. They coordinate their team members and ensure that the team's yearly goals are reached. Moreover, a team leader and a treasurer are also elected. The team leader does management, competition logistics and global team coordination. Finally, the treasurer manages the team budget and invoices.

Methodology

Over the years, team SONIA brought together several good work practices in order to obtain a high-end platform. The team regularly does peer reviews to validate designs. This eliminates important integration problems and reduces errors. Also, multiple training sessions are given throughout the year to teach the inner workings of the platform to new members, making them more productive. These sessions ranged from vision system, electrical systems and software applications. Meetings are often organized to track team progress and to respond quickly to problems. Also, a rigorous test schedule is established early in the year enabling the team to deploy new submarine versions often. Pool tests are scheduled every three weeks during fall, biweekly during winter and weekly during summer. Also, during summer, tests can be performed in outdoor pools when the weather allows it.

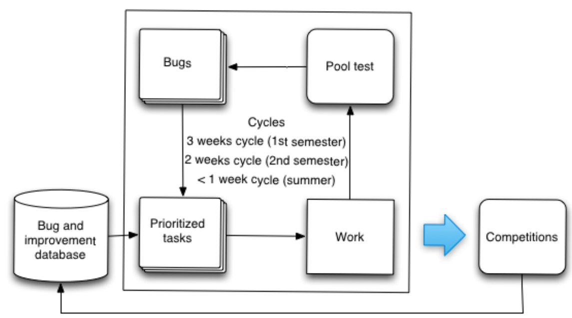

Figure 2 - SONIA Test Process

Community Outreach

In order to promote higher education and robotics, team SONIA is involved in various community events. This year, team members presented the project to high school students at Quebec FIRST Robotics. Also, as robotic enthusiasts, team SONIA judged a primary school robotic contest.

Collaboration

SONIA is actively involved in the OctETS project. OctETS, for Open Collaboration Tools École de technologie supérieure, is a sharing platform for robotic teams at ÉTS.

Mechanical Design

The role of the mechanical team is to provide a robust, yet agile platform to the electrical and software teams. After last year's major leap, the team continued to work hard and delivered two distinct submarines for each competition. The objectives on the mechanical aspect were the following:

- Eliminate glue joints on the main hull
- Solidify the frame
- Improve the grabber
- Integrate the new MSIS

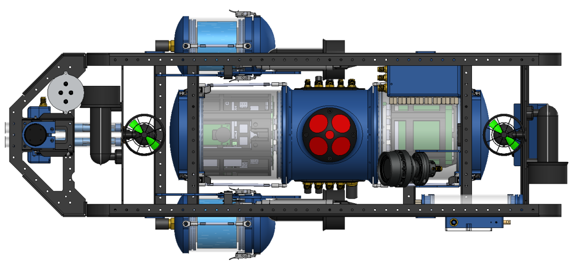

Figure 3 - Submarine's CAD bottom view

Design and Fabrication

In order to deliver a competitive platform for the competitions, the entire vehicle was drawn in 3D using a CAD software application.

Once the design phase is complete, fabrication begins. Team members fabricate the majority of the vehicle using three and five axes CNC machine. The rest of the parts were manufactured by one of SONIA's sponsors using a water jet cutting machine.

Frame

The frame of the vehicle is made out of aluminum that received a hard anodize treatment to reduce oxidation. In addition, all nuts and bolts required for the assembly of the frame are made out of stainless steel. In order to keep the platform flexible, a drill pattern was applied to every piece of the frame, making it easy to add new enclosures or sensors. One of the objectives, this year, was to solidify the frame. To do so, all parts that were flat were modified to accommodate a 90 degree fold. The same overall shape was kept and only some parts were modified.

Main Hull

The main hull contains most of the electronic of the vehicle and was designed with the objective of having an easy access to the electronic. It is fabricated using aluminum, acrylic tubing and polyoxymethylene (also known as Delrin). All aluminum parts received a blue anodizing treatment to minimize oxidation.

The hull is separated in three sections all connected to each other. The central section holds the DVL transducer and receives all external connections from sensors, actuators and external enclosures. All connections are then routed on either side of the hull using the central backplane. One side of the hull contains the main computer, the bottom camera and the marker dropping mechanism. The other side contains all custom electronic boards required to have a functional vehicle. Each side has its own custom rapid prototyping rack that can be easily disconnected and removed from the hull. The main compartment is closed at each end by a cap, which is easy to remove or install.

Custom External Enclosures

Many components outside the main hull require a custom external enclosure. All enclosures are fabricated out of aluminum, have a vacuum testing bolt, are closed with stainless steel bolts and are sealed using a silicon O-Ring. These reduce greatly the risk of water or CO_2 leakage in the main hull, protecting sensitive and costly electronic. In its current state, the vehicle has nine external enclosures:

- Kill switch
- Mission switch
- Diver interface
- 2x battery compartment
- Front camera
- Pneumatic enclosures
- CO_2 cartridge holder
- Hydrophone array

Pneumatic System

The pneumatic system of the vehicle is responsible for actuating the torpedo launcher, the active grabbing device and the sonar rotation mechanism. It is composed of a pneumatic enclosure and a CO_2 cartridge holder. The pneumatic enclosure holds an electronic control board and six valves that can be independently activated.

The active grabbing device is composed of two grabbers. The grabbers are activated together and require two valves in order to close or open. Pneumatic cylinders control the claws. A reed switch is installed on each cylinder in order to detect when the grabbing devices are fully closed. If an object is inside the claws, they will not fully close, the reed switch will not trigger and the system will know something was grabbed.

The sonar rotating mechanism gives the ability to rotate the MSIS by 90 degrees toward the sea floor. This enables the vehicle to scan for structures such as walls or pipelines.

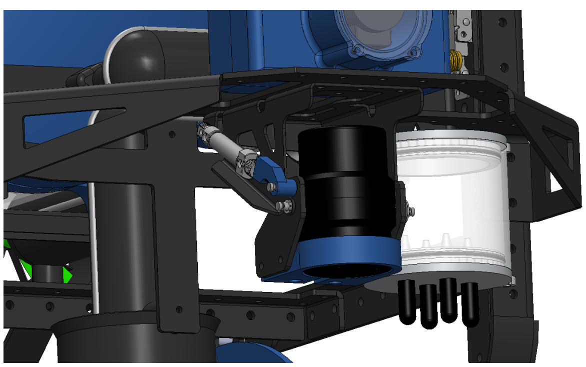

Figure 4 - Submarine's frontal sensor array

Dropping Mechanism

In order to drop markers, two tubular solenoids are installed inside the main hull against the bottom. They pull up studs outfitted with a magnet at their lower end. The markers, steel ball bearings, placed on the exterior side of the bottom wall, are held in place by the magnetic force. When the stud is pulled up, the marker drops.

Object Position Sensor

The OPSs are situated at the bottom of the vehicle and tasked with sensing objects under the vehicle. Every OPS is composed of a spring-loaded bar with one reed switch. When an object is present, the bar will be pushed up, positioning the reed switch in front of a magnet, signalling the presence of an object. Three OPSs are fixed on each side of the frame. One OPS is at the front of the vehicle, the second one is directly aligned with the grabbing device and the third one is behind the grabbing device. This topology allows the control system to know if the vehicle needs to move forward or backward to do the final alignment on objects.

Electrical Design

The role of the electrical system is to interface the control system of the vehicle with multiple sensors and actuators so it can interact with its environment. Moreover, this system must be easy to maintain, agile and robust. This year, multiple sensors were added and some were improved in order to better accuracy and speed to accomplish tasks.

System Overview

The vehicle is equipped with two cameras and an MSIS to see and sense objects around itself. In order to move accurately under water, the submarine uses a DVL coupled to an IMU and a depth sensor based on pressure. This combination enables movements measured in meters and degrees.

Multiple actuators are also installed on the submarine that allows it to accomplish different tasks. First and foremost, six thrusters are attached to the vehicle. This allows precise movements with incremental steps of rotations per minutes. To manipulate objects, the vehicle has two pneumatic grabbing devices. Combined with OPSs, the vehicle can grab and release objects. Also, a pneumatic launching system delivers torpedo shaped markers.

On top of this, the vehicle has an advanced power management system to easily control all systems and shutdown harmful components at a moment's notice.

Finally, a powerful mobile computer is housed inside the vehicle for the control system, the machine vision system and other essential components.

Onboard Computer

The vehicle's computer is composed of a Kontron KTGM45/mITX motherboard, 4 GB of RAM and an Intel Core 2 Duo mobile processor clocked at 2.5GHz. For reliability and speed, two solid-state drives are used for SONIA's software suite and logging.

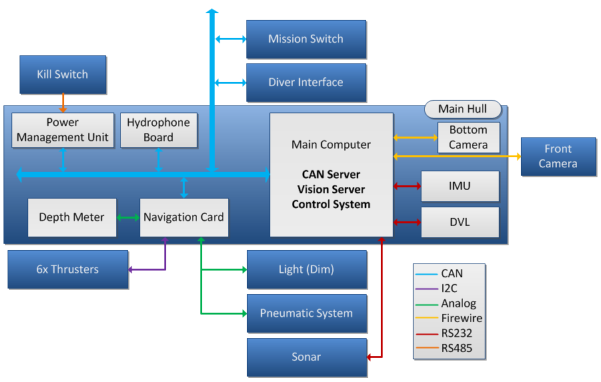

Figure 5 - Communication diagram

Doppler Velocity Log

To communicate with the sensor, several serial interfaces are required. One serial port is used to send commands and receive data. The other one is used to feed parsed data containing the attitude of the vehicle. Finally, the DVL requires a power channel with a capacity of four watts to operate properly.

Inertial Measurement Unit

To communicate with this sensor, a serial interface is used. This allows the vehicle to start, stop and calibrate the sensor. To operate properly, the latter needs 0.6 watt.

Imaging Sonar

Similarly to other sensors, this sonar communicates through a serial port. This allows the vehicle to start, stop and calibrate the sensor. To be powered properly, a four watt power channel is required.

Passive Sonar System

The tip of the spear is the array of hydrophones positioned at the front of the vehicle. Four of these pressure transducers are positioned in a diamond shape on the same geometric plane. The side of this rhombus is short enough so it does not exceed the half wavelength associated to the highest frequency the passive sonar has to detect.

Next, each analog signal needs to be properly conditioned before information can be extrapolated. Although the pressure wave from the beacon is a dominant signal underwater, it translates to a very weak electrical signal. The sonar system has two stages of amplification. The first one is a precision pre-amplification stage. At this point, the signal can be boosted up to 190 times its original amplitude. The other stage is an adjustable amplification stage and is capable of applying an additional 100 times magnification.

Another important part of the analog front end is its filters. Much noise is introduced in the signal by the fact that the thrusters of the submarine create pressure waves. Noise is also added while the electrical signal is routed to the processing board. This system removes all high frequency noise with a low pass 10^{th} order filter.

The next step is to digitalize the signal so it can be processed with a DSP (Digital Signal Processor). The signal is then filtered again with a discrete band pass filter. Since the pressure wave generated by the beacon is periodic, the system must wait for the proper moment before trying to determine the phase difference between each channel. To do so, an FFT (Fast Fourier Transform) is used to trigger on the amplitude of a single spectral component of the signal. With this technique, false triggers are greatly reduced while the submarine is in motion.

Once the system has triggered, it will further filter the samples to be processed. Each signal, which all went through the same process in order to affect the phase in the exact same way, are compared with each other to find phase differences. These phase differences are then compared to a look up table. The entry with the smallest error is used to take the correct heading and determine if the vehicle is above the beacon.

Actuators

To move underwater, the submarine is equipped with six Seabotix thrusters. These thrusters are controlled with a numeric bus interface, the I^2C (Inter-Integrated Circuit) bus. The power consumption of a single thruster can reach up to 240 watts if used at full power.

To drop markers, solenoids must be activated. A binary signal, zero to 12 volts, is used to trigger a MOSFET transistor which in turn activates the solenoid. A pneumatic system is used for the torpedo launcher, grabbing system and sonar rotation mechanism.

Navigation Board

All actuators and some sensors are not compatible with standard interfaces of the onboard computer. The navigation board has the task of interfacing these devices. This is done with the help of a CAN (Controller Area Network) bus. The board receives commands and sends information through the bus.

This system converts high level commands to the correct voltage level or numeric command. Furthermore, it interprets the analog signal of pressure sensors, for depth and pneumatic system, and sends it back to the main computer in millimeters and pascal respectively.

Power Management

The vehicle is powered by two 25.9 volt lithium-ion polymer batteries connected in parallel. Each has a capacity of 10 amp-hours. This power has to be adapted and distributed throughout the vehicle. The power management board breaks down the raw input given by the batteries into multiple adapted, protected and manageable channels.

The main reason to have multiple power channels is the incompatibility between sensors for the operating voltages. The next valuable point for this kind of topology is the ability to limit the current going through each channel. Finally, for safety and versatility, power channels can be individually shut down or activated.

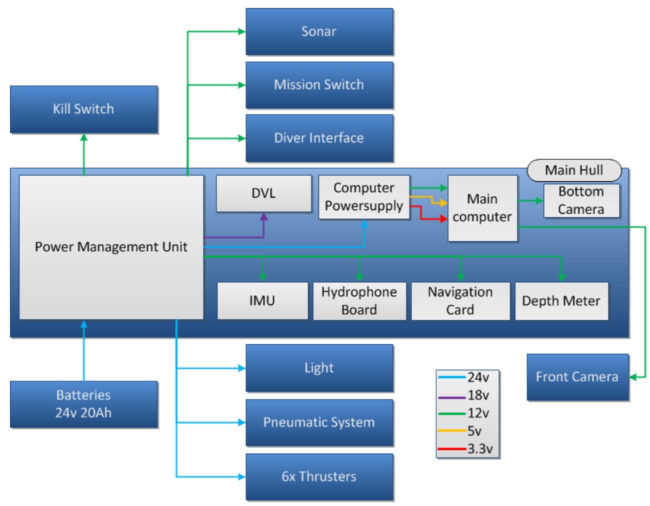

Figure 6 - Power distribution diagram

Backplanes

A total of 73 distinct signals have to be routed throughout the vehicle and 40 of these signals also have to be routed outside the main hull. Moreover, many key components have to be changed, removed and tested often. Hence, the system must be modular for easy maintenance and modification.

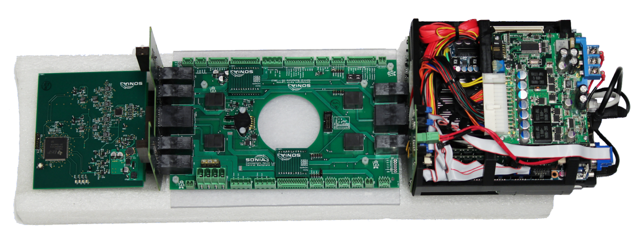

Figure 7 - Backplanes

To fit all those requirements, a backplane solution is used in the vehicle. This means that all wires are routed through printed circuit boards. The submarine has three main backplanes. The core is the central backplane. It receives the connections for the watertight connectors, IMU and DVL. It also links together the onboard computer with all the custom electronics components.

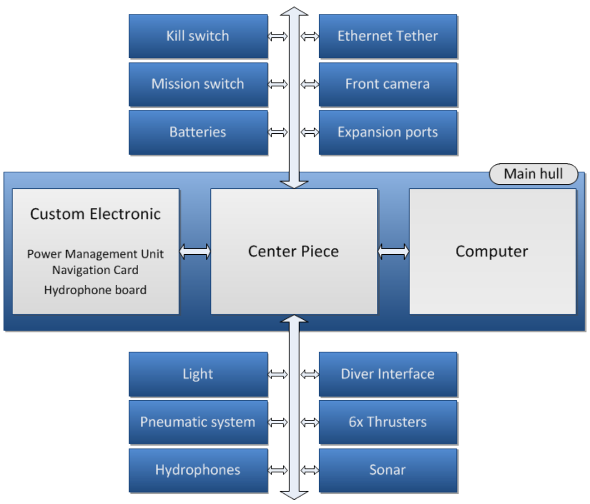

Figure 8 - Connection diagram

Software

The SONIA software team is responsible of mission planning, computer vision and development of several software tools to ease the operation of the vehicle and debugging. This year, the team had three main objectives to improve last year's platform:

- Reduce mission task execution time
- Reduce mission errors
- Improve software tools

Software design

The submarine's software architecture is composed of three main systems designed in accordance to the client/server model using TCP protocol:

- Vision Server
- Control System (AUV6)
- TCP/CAN Server

Moreover, the SONIA software suite includes other applications such as:

- Simulation System
- Vision Development Tools
- Log Replay
- Mission Editor
- Pool Editor
- Hydrophone Calibration Tool
- Telemetry software

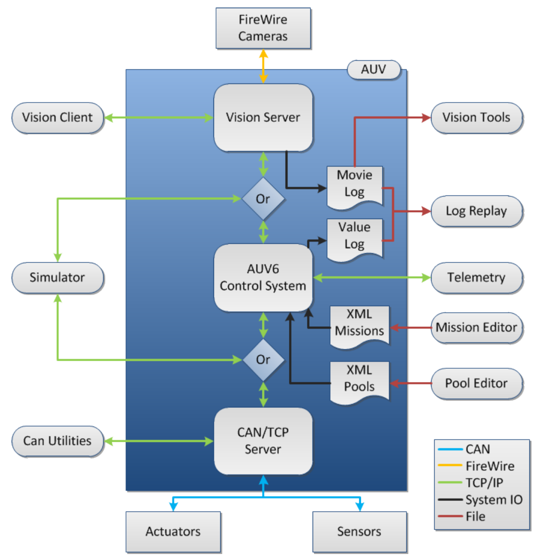

Figure 9 - Software architecture

Control System

The vehicle's control system is composed of four components:

- Providers
- Mission state machine
- Controllers
- Loggers

A control loop running at 14 Hz activates these components allowing the submarine to perform various tasks. Providers offer current pose estimation of the vehicle and map of the current environment around the vehicle. The mission state machine is loaded from an XML. Each state is then processed using the current state of the vehicle and known environment. It also interacts with the different controllers, setting targets such as moving the vehicle to waypoints or activating any actuators. At the end of each loop the system records log to the disk enabling operators to replay any mission run and debug any issues encountered.

Mapping

A map of the environment is built to classify objects surrounding the submarine. Updates of the map are performed every time the sonar filters or Vision Server detected objects in the vicinity of the AUV. Depending on object type, various algorithms are used to merge data from various sources.

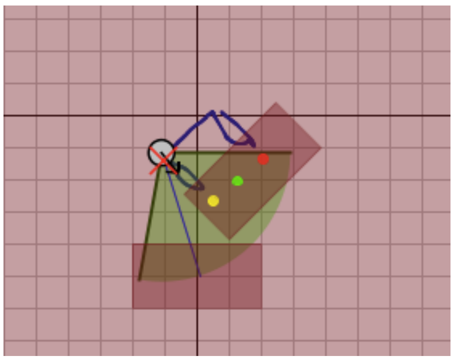

Figure 10 - Navigation map

Sonar

The vehicle is equipped with an MSIS that scans a 100 degree sector in front of the AUV. Data returned by the sonar is processed every time an entire sector is scanned. Firstly, the raw data is pre-filtered to detect local maxima, discarding low echoes or image distortion. Once the pre-filter is applied, a line detection algorithm extracts lines from the received image using a Hough Transform algorithm.

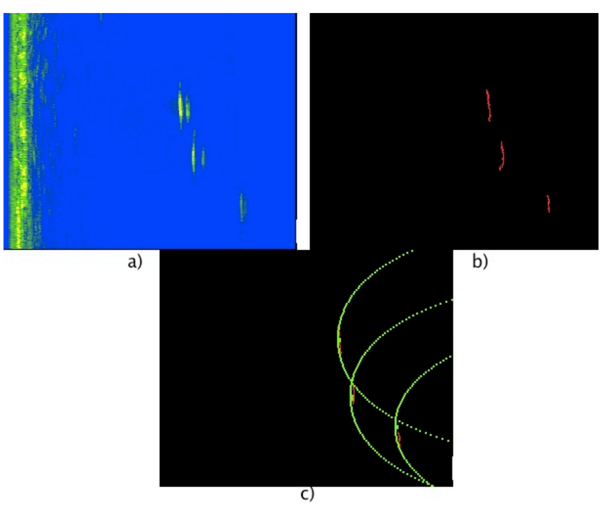

Figure 11 - a) Raw sonar data b) Local maxima extraction c) Lines extracted from the data

Object Mapper

Using information gathered by the sonar filters, the different mappers discriminate information based on position of the object and size of the detected object. Operators inform the different mappers where in the pool should the different objects be located using an a priori map of the competition pool. Once basic checks are done, a merging algorithm is used to merge objects. A very simple minimum distance approach was used to merge objects and works perfectly due to the relatively big distance between object versus the precision of the various sensors and filters.

Localization

The vehicle's pose is calculated using data from the DVL and the IMU. The DVL returns velocities, which are then integrated to obtain a position in meters. This approach enables a position update every time needed. This greatly reduces error in mapping.

Mission

The mission component is based on a state machine. States range from navigating to a waypoint to surveying a pipeline at the bottom of the pool. Every state has direct access to snapshot values via the various providers. States use this information to determine the next course of action to take to accomplish their tasks. Once the next course of action is chosen, targets are set to various controllers and control is then sent back to the control loop waiting for the next iteration.

Controllers

Controllers enable the submarine to activate actuators in order to interact with its environment. The position controller is the most important one. It is in charge of sending commands to the thrusters in order to reach the various waypoints set from the states or the telemetry software. Every degree of freedom (surge, heave, sway, yaw and pitch) is controlled using a PID controller. Some PID controllers were adapted to better suit our needs. For example, the PID controlling the depth had to be modified to take into account the fact that the submarine was slightly buoyant which causes the depth waypoint reaching unstable.

TCP/CAN Server

The TCP/CAN Server acts as an interface between the electrical and software components. It receives TCP CAN messages and dispatches them to the submarine's CAN bus. On the other hand, every message received from the CAN bus is forwarded back to every TCP clients.

Tools

Vision Client

The vision system operator primarily uses this tool when the submarine is deployed. It allows him to visualize the raw camera streams. The operator can also choose to visualize the output generated by the system vision filters. This is very useful when filter chains do not correctly identify objects. With filter debugging streams, operators can adjust the filter parameters using the Vision Client. It can also be used to save videos and images of streams, which are then used to develop new filter chains.

Telemetry

Using the JAUS (Joint Architecture for Unmanned Systems) architecture, the Telemetry is a set of tools allowing operators to fully monitor and control the vehicle's control system. It contains numerous widgets each meeting a specific need. Extensibility was a key requirement when this tool was developed in order to support all future control system features. To do so, many custom JAUS messages have been added to the standard ones.

Vision Server

The vision server is a standalone application that handles the camera inputs and returns a high level description of the vehicle's environment. This high level description contains the object types that have been detected as well as their characteristics, such as color-based identifiers, distance relative to the vehicle and orientation. Using this high level description, the control system can react appropriately to objects present in the vehicle's field of view.

Bloody Caesar Detection

This filter uses a HSV color filter to search the red or the blue side of the obstacle. Thereafter, the filter uses a polygon approximation on contours returned by the function cvFindContours. The same algorithm is used to determine if two circles can be found inside the square formed by the external contour. If the filter finds two circles, it sends the center of those two circles and the color of the obstacle.

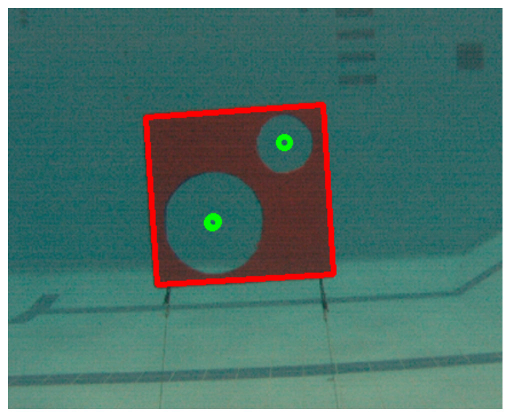

Figure 12 - Ceasar filter chain's output

Conclusion

This year allowed team SONIA to reaffirm the excellence of its platform. Overall robustness and modularity of the vehicle was greatly improved with the modifications done to the design. The rigorous test schedule allowed the team to deliver a high quality platform ready to perform at both competitions. Finally, the sonar integration improved and simplified obstacle navigation, allowing it to perform the mission tasks faster and more precisely.

By participating at two competitions, every team members pushed their boundaries to meet the annual objectives. More challenges are before us at the competitions and the team is eager to get there.

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Thanks to the AUVSI, ONR and NURC for organizing these challenging events.

We would also like to thank our sponsors who have made our participation possible:

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- **Gold:** Circuit Imprimés de la Capital, Collège Édouard-Montpetit, Fonds de développement de l'ÉTS, Labo Circuits inc., Kontron, QNX Software Systems, Vortex CM Labs
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- **Personnal Contributions:** Olivier Allaire, Michaël Bernard, François Campeau, Tennesse Carmel-Veilleux, Alexandre Gagné, Martin Morissette, Felix Pageau

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- **Treasurer:** Jacques Bertrand
- **Graphic Designer:** Isabelle Carrier
- **Technical Advisors:** Marc-André Courtois, Martin Morissette
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