# Concept and Design of the 2011 SONIA AUV Platform

http://sonia.etsmtl.ca
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*SONIA is an autonomous underwater vehicle (AUV) built by undergraduate students from the École de technologie supérieure (ETS) to compete at the AUVSI & ONR's 14th International Autonomous Underwater Vehicle Competition. It consists of an obstacle course which requires precise navigation and shape recognition. These obstacles resemble real life AUV challenges such as underwater navigation, pipeline inspection, black box recovery and many more. To stay competitive, team SONIA built a brand new platform. To facilitate navigation, the vehicle is equipped with an array of sensors including a Doppler Velocity Log, inertial measurement units and FireWire cameras to name a few. With its new cylindrical shape, the submarine can dive to depths of up to 30 meters. The new Li-Ion polymer batteries offer 4 to 5 hours of autonomy. To take advantage of this new platform, the team developed a state of the art software stack. At the core of this stack resides the control system which enables the vehicle to navigate the obstacle course with ease. The tight integration of the mechanical, electrical and software aspect of the project gave us the most stable platform ETS has ever built.*

## *Quick Facts*

| | | | |
|---|---|---|---|
| ***Dry weight:*** | 40 [kg] | ***Thrusters:*** | 6x SeaBotix Brushless HPDC1507 |
| ***Dimensions (LWH):*** | 1.2 x 0.50 x 0.39 [m] | ***Cameras:*** | 2x Unibrain Fire-i board Pro |
| ***Max speed:*** | 1 [m/s] | ***Sonars:*** | 1x Teledyne Explorer DVL |
| ***Max depth:*** | 30 [m] | | 4x Brüel & Kjær Hydrophone |
| ***Autonomy:*** | 4 to 5 [h] | ***IMUs:*** | 2x Microstrain 3DM-GX1 |

The SONIA AUV (Système d'opération nautique intelligent et autonome) project was incepted in 1999. The project is managed by a multidisciplinary team composed of volunteer students from École de technologie supérieure (ETS) studying mechanical, electrical, mechatronics and software engineering. The goal of this group is to design and build a highly reliable and efficient autonomous underwater vehicle (AUV) which will participate in the Autonomous Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research's (ONR) International RoboSub Competition. The team's mission is also to promote ETS as a leading engineering school and to help its members become better engineers for the demanding industry that exists today.

This year is the 14th edition of the competition. The SONIA team will be attending this competition alongside several other engineering schools from all over the world. The challenges proposed during the competition emulate real life tasks that civilian and military AUVs have to perform.

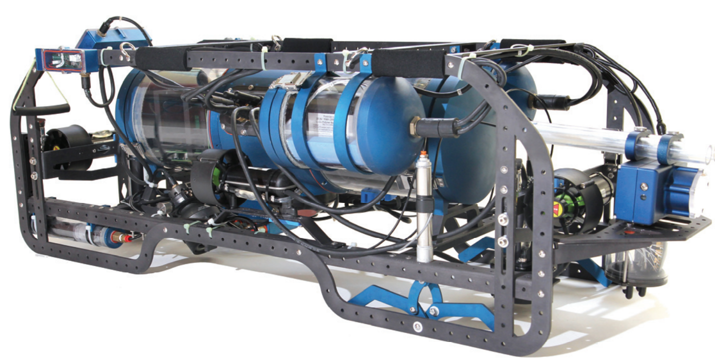

**Figure 1 - SONIA 2011 AUV**

For this edition, every vehicle will have to demonstrate its abilities by performing the following tasks:

- Navigate through an underwater gate
- Inspect and follow pipelines
- Find and hit two buoys of a specific color

- Navigate over an "L" shaped lane
- Drop two markers in bins with a specific shape
- Send a soft projectile in a heart shape cut-out
- Locate an acoustic beacon and navigate towards it
- Pick up a PVC pipe
- Navigate to a recovery zone with the object
- Surface in a recovery zone with the object
- Release the object

The 2011 SONIA vehicle is equipped with all the sensors needed to accomplish every task of the competition:

- Two Microstrain 3DM-GX1 Inertial Measurement Units (IMU)
- One Explorer Doppler Velocity Log (DVL) from Teledyne RD Instruments
- Two Unibrain Fire-i Board Pro cameras
- Six Seabotix HPDC1507 brushless thrusters
- One marker dropping unit
- One soft projectile firing unit
- Four Brüel & Kjær hydrophones with a custom passive sonar signal processing board
- One Kontron 2.5GHz Core 2 Duo Mini-ITX embedded computer with 4GB of RAM
- One depth meter
- One active grabbing device

The vehicle underwent a massive overhaul since last year. The mechanical and the electrical aspects of the project were completely redesigned from scratch. The software of the control system and its dependencies was also completely redesigned.

## Team Objectives

This year, the team had two objectives:

- Develop an entirely new vehicle
- Keep a high rate of deployment time

The last iteration of SONIA's submarine had been in use for two years after the 13th edition of the RoboSub competition. To correct the flaws observed during the life of the submarine, an overhaul was done on every aspect of the vehicle. Throughout this document, the upgrades that are described are driven by the team's extensive experience with the older platforms.

A key element to achieve reliability with any given system is to test it extensively. This is now a recurring goal for the team because it proved successful in the pass.

## Team Organization

The team employs a three level hierarchical structure. The captain is responsible for the coordination of the entire project, including technical and human resources management. To help him do so, three sub-team leaders are elected to guide respectively the mechanical, electrical and software teams. Each member is encouraged to bring up new ideas and most of the decisions are taken through consensus.

## Work Methodology

The same approach was retained as the one employed in the last several years. The version control system Subversion (SVN) was used to keep track of the evolution of the project.

As always, in-house training was provided to new team members. ETS staff and seasoned veterans helped new members gain more experience in various fields, ranging from part machining to software design. Over the years, the explicit inclusion of freshman training in the work strategy has undoubtedly resulted in an increased overall productivity.

### Collaboration

The team participated in the creation of a collaboration environment, based on the open source community, called Open Collaboration Tool ETS (OctETS). The main goal of this initiative is to share code with other student engineering teams from ETS in order to minimize development time and duplicated code. Moreover, the shared components underwent more test runs to find and fix bugs.

# Mechanical Design

The mechanical design underwent a major overhaul. For the first time in five years, the team changed its main hull design. This change was motivated by three objectives:

- Have a main hull tightly integrated with the electronic
- Have a platform easy to modify
- Increase the maximum depth capability of the vehicle

## Design and Fabrication

In order to achieve those objectives, the team spent several months on the design. The entire vehicle was drawn in 3D using a computer-aided design (CAD) software. Since space was very limited inside the main hull, all the electronic components, including the main computer, were included in the drawing. This allowed the team to make sure all the mechanical and electrical components would fit together perfectly.

After the design phase, the team started to work on fabrication. The majority of the vehicle was fabricated by team members using three axes and five axes computer numerical control (CNC) machines at ETS. Those machines were programmed using a computer-aided manufacturing (CAM) software. Overall, more than 200 hours of work was required to fabricate most of the vehicle. The rest of the parts were manufactured using a water jet cutting machine by one of SONIA's sponsors.

## Frame

The frame was designed in order to have an easy to modify platform. To make this possible, a drilling pattern was applied to every piece of the frame to facilitate the integration of additional sensors or enclosures. The frame is composed of 15 pieces of aluminum that received a hard anodizing treatment to maximize their resistance to oxidation and scratches. Moreover, all bolts and nuts required for the frame assembly are made of stainless steel.

## Main Hull

The main hull contains the majority of the electronics including the main computer. It is fabricated out of aluminum, polycarbonate tubing and polyoxymethylene (also known as Delrin). All the aluminum pieces received an anodizing treatment. An extensive series of tests were done on all joints to make sure they would withstand a pressure equivalent to a depth of over 30 meters of water.

One of the major design constraints for the main hull was the positioning of the DVL's transducer. The sonar array has to be half in the water and half inside the hull. The transducer also needs to see the sea floor without any obstruction. Another requirement was to superpose the DVL's head with the point of rotation of the vehicle. This positioning reduces the amount of calculation the sensor has to do. The sensor also has to be electrically isolated from the rest of the platform. Because of those constraints, the entire hull was designed around that sensor to maximise its performance.

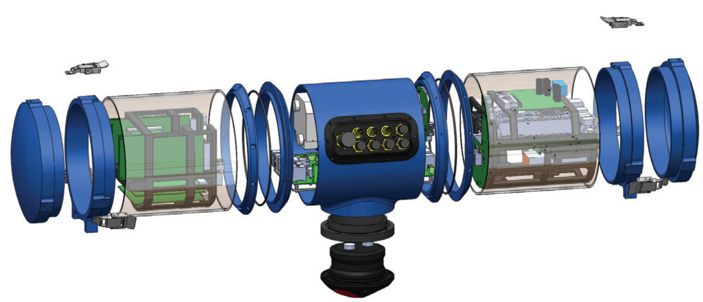

**Figure 2 - SONIA 2011 Main Hull**

The hull can be separated in three sections. The center piece is responsible for holding the DVL's transducer and receiving all the connections from the external enclosures. The custom electronic side and the computer side both have their respective custom rapid prototyping rack supporting all the components on each side.

The main hull is closed at each end by caps that can easily be removed to access the interior. The custom racks can easily be removed from each side when necessary.

## Custom External Enclosures

Every component outside the main hull requires a custom external enclosure that is attached to the frame. Most 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. In its current state, the vehicle has eight external enclosures:

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

The kill and mission switch use a magnet with a Hall effect sensor to detect a magnetic field. A small magnet is inserted at the end of a pin. This pin has two grooves coupled with a ball detent forcing it in two possible positions. One of them brings the magnet close to the Hall effect sensor and the other far from the sensor. Those positions result in a on or off signal to the electronic.

The battery compartment provides a quick and easy access to the batteries. A rack, fabricated with rapid prototyping plastic, makes sure the batteries are well supported and do not move freely inside the compartment.

## Pneumatic System

The pneumatic system of the vehicle is responsible for actuating the torpedo launcher and the active grabber. It is composed of the pneumatic enclosure and the $CO_2$ cartridge holder.

The pneumatic enclosure holds an electronic control board and six valves that can be independently activated.

The torpedo launcher is composed of two cannons, each controlled by an independent valve. The cannon launches a torpedo fabricated using rapid prototyping plastic.

The active grabbing device is composed of two grabbers. Each grabber requires two valves in order to close or open its claw. The claws are controlled by a pneumatic cylinder. A reed switch is installed on the cylinder in order to detect when the grabber is fully closed. If an object is inside the claws, they will not fully close, the reed switch will not trigger and the system can know something was grabbed.

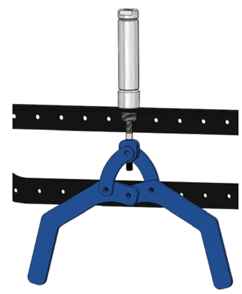

**Figure 3 – Active grabber**

## Dropping Mechanism

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

# Electrical Design

The improvements this year were all driven by the last design. After extensive use of this platform, it became clear that it was lacking two key points: reliability and ease of maintenance. Based on this, the objectives for the electrical design were to centralize the electronics, reduce air wires and ease maintenance and upgrades.

Reliability could be improved by reducing the complexity of the vehicle. To achieve this, the electronic was centralized and the number of air wires was reduced. These modifications also made maintenance easier by optimizing space. Finally, a good planning and communication between the mechanical and software teams ensured that the vehicle would be easily upgradable.

## System Overview

The first issue that was addressed is the air wires. A total of 73 distinct signals have to be routed throughout the vehicle. 40 of these signals also have to be routed outside the main hull. These signals come from sensors, actuators and power channels.

In the past, two solutions were utilized. The first one simply consists of cables running from point A to B. The second solution is backplanes. Both solutions consist of copper wires going from point to point, but the latter brings two advantages. It is more reliable because the wires are routed inside a printed circuit board and it allows the use of much smaller wires, thus making it a more compact solution.

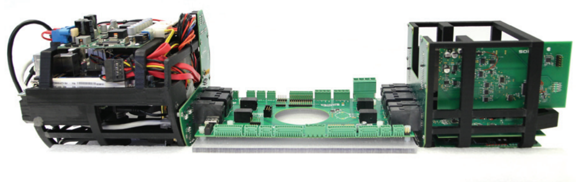

**Figure 4 - SONIA 2011 backplanes**

For these reasons, the backplane solution was chosen for the new vehicle. However, there is one major disadvantage with this solution. A modification or an addition to the signals requires the backplanes to be redesigned and reprinted. To dampen this flaw, multiple spare signals were added to the design, making the backplane solution more flexible and adaptable.

To attain modularity, the backplane solution was separated in three sections. One section is situated inside the center piece and one backplane is attached to each custom rack.

Based on the mechanical design and the solution chosen, the next figure shows the electrical architecture of the new vehicle.

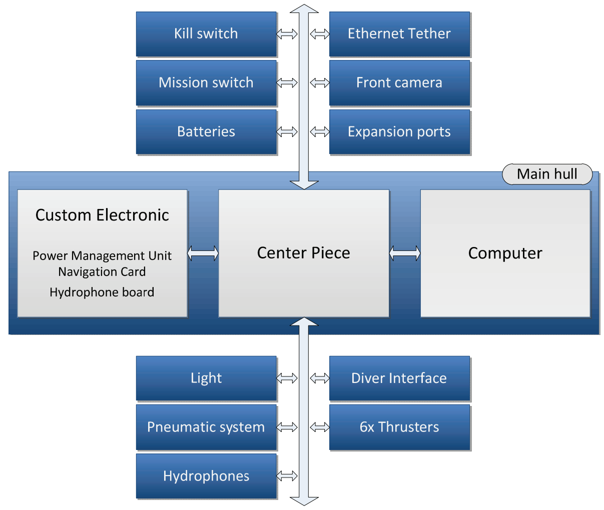


**Figure 5 - SONIA 2011 electrical architecture**

The second issue to be taken care of was the ease of maintenance and upgrades. Part of the upgrade problem was already solved by the spare signals added in the design. To make this architecture more scalable, two control cards were added in the design. Moreover, each control card has access to every control and sensor signals of the submarine. This ensures that upgrades can be done with minimal modifications to the existing hardware.

The present design uses Controller Area Network (CAN) to allow the electronics to communicate. This protocol has been proven reliable and useful in the previous design. However, Ethernet communication lines have been added to the design for future upgrades.

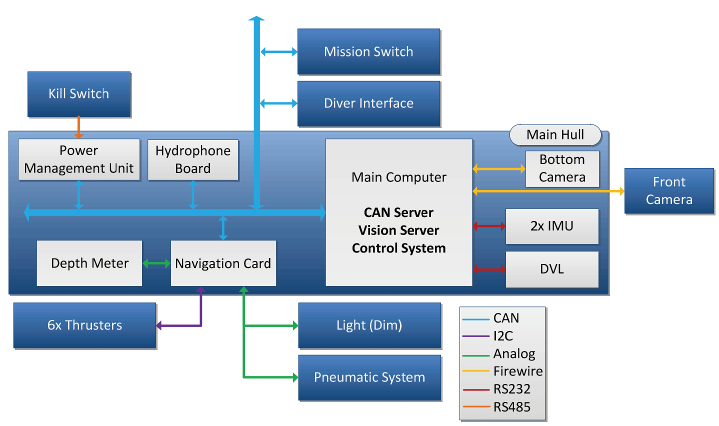


**Figure 6 - SONIA 2011 communication diagram**

Finally, all required sensors and controllers were implemented in one control card to centralize the electronic, thus reducing complexity.

## Power Management

The vehicle runs on two 25.9 volts lithium-ion polymer batteries connected in parallel. Each has a capacity of 10 amp-hours, giving the submarine a power source of 518 watts.

The submarine has an average autonomy of five hours. Of course, this depends on how much it uses systems that are power consuming such as the thrusters or the bottom light.

The power management unit is a printed circuit board with the following tasks:

- Redistribute power to 18 different components
- Adapt the input voltage for every component
- Limit the current drawn
- Kill every harmful system on command

To suit every device a total of nine different power channels were implemented, each with a unique current limit and surge protection.

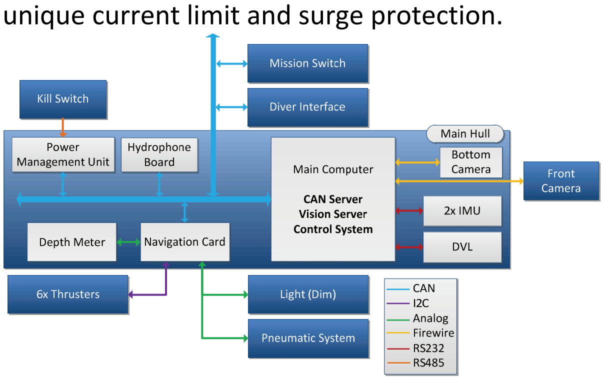


**Figure 7 - SONIA 2011 power diagram**

Since not all devices can handle the voltage generated by the batteries, it had to be converted into different voltages. The computer's power supply, the pneumatic system, the bottom light and the thrusters all function using the voltage of the batteries. The Doppler Velocity Log functions to a level of 18 volts. The remaining of the electronics and sensors use 12 volts. Each channel has a current limit. This feature protects the electronics from damaging itself, but it also protects the batteries from a deep discharge.

A crucial task of the power management unit is to kill harmful systems when needed. A switch outside the main hull generates a square wave at a specific frequency. This wave is received by the power management unit. Once the correct frequency is detected, all the systems on the vehicle are powered. If someone would pull the kill switch or, for some reason, the square wave signal would be compromised, all hazardous systems will cease to function in the submarine.

## Navigation Board

The navigation board is the interface between the control system and the actual hardware. It receives sensor information from pressure sensors for the pneumatic system and the depth of the submarine.

It is also able to activate the thrusters, torpedo launcher, active grabbing device, dropping device and light.

The navigation board controls the thrusters using the Inter-Integrated Circuit ($I^2C$) protocol. The thrusters have a built-in security which consists of stopping the thrusters after 10 seconds when no update has been received. Thus, the navigation board only updates the speed of the thrusters when it receives a new value from the control system. Hence, if a problem occurs with the communication, the submarine will stop moving.

## Brushless Thrusters

A long time goal of the team has been to install thrusters with a closed-loop control on their rotational speed. This would allow the vehicle to move much more smoothly. Also, a thruster can be replaced with the certainty that it would perform the same way as its predecessor.
The team acquired new brushless thrusters from Seabotix. The drive inside those thrusters

insures that the thruster will reach and hold its target speed.

## Onboard Computer

The onboard computer hosts the software suite that controls the vehicle. This year's vehicle necessitated a new form factor so the team updated the computer to a Kontron KTGM45/mITX with 4 GB of Random Access Memory (RAM) and an Intel Core 2 Duo processor clocked at 2.5 GHz.

Due to the constant vibrations and shocks, the team updated to solid-state drive (SSD) hard drives to ensure data integrity in the vehicle.

## Passive Sonar System

In order to complete the task of locating an acoustic beacon, the vehicle is equipped with a custom passive sonar system.

The first element of this system is an array of pressure transducers called hydrophones. Four of them are positioned in a diamond shape at the front of the vehicle.

The signal of each hydrophone is then routed to an acquisition card. This card will condition the four signals by amplifying and filtering them. A digital signal processor (DSP) on the card simultaneously samples the four channels of sound.

The state machine running on the DSP functions as follow:

1. Wait for a minimum amplitude
2. Accumulate samples
3. Apply a pass band filter on the samples
4. Calculate the phase difference between the reference channel and the remaining three
5. Send the phase difference over CAN

Once the control system receives the phase difference, it compares them with a pre-calculated table of possible values. It then chooses the heading and elevation of the acoustic beacon associated to the value in the table with the smallest difference.

## Sensors

The submarine depends on two Inertial Measurement Units (IMUs), a Doppler Velocity Log (DVL) and two cameras to navigate

The IMU is actually an array of sensors that allows the vehicle to know its pitch, yaw and roll. Two IMUs are positioned at the center of the vehicle. They are offset from one another and their outputted values are averaged for a lesser error.

The DVL is a powerful instrument. Using four transducers, it tracks the movement of the sea floor underneath the vehicle. The sensor can return data under multiple formats and level of pre-processing. The vehicle uses the distance traveled from the initial point which is calculated by the sensor's electronics.

Finally, two FireWire cameras with a resolution of 1024 by 768 pixels are installed on the submarine.

## Actuators

The vehicle is equipped with a dropping device, an active grabbing device, a torpedo launcher and a light.

All the actuators have an isolation circuit which simplifies their control. Any of these devices can be activated with a binary signal with low being 0 volt and high being 12 volts.

# Software Design

The software architecture consists of a CAN/TCP server, a machine vision server and the control system (AUV6).

The following diagram explains the relation between the various components and tools.

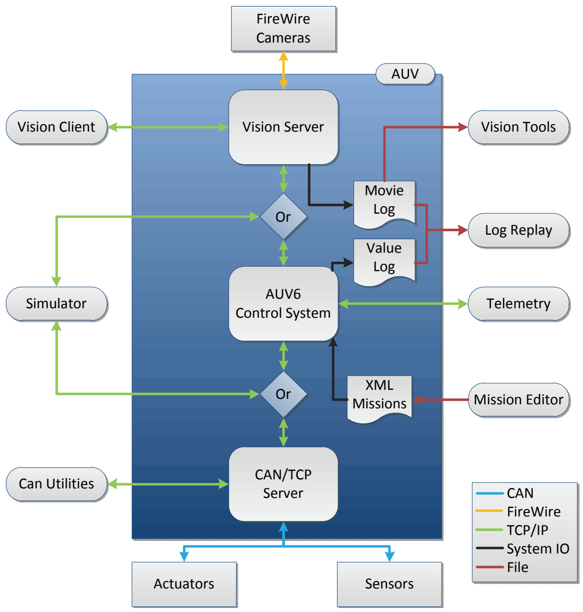


**Figure 8 - SONIA 2011 software bloc diagram**

Over the years, the team created a tool suite to help the development and debugging of the project. This suite includes the following applications:

- JAUS Telemetry
- Mission editor
- JAUS Log replay
- Vision development tools
- Simulation system
- CAN Workbench
- HydroScope

The majority of the project's software is built using the Java language. However, some applications such as the machine vision server and the CAN/TCP server are built using C++ to take advantage of existing libraries.

The primary objectives for the software team were:

- Enhance control
- Enhance maintainability and modularity
- Standardize communication
- Share software with other ETS teams

Those objectives were achieved by rewriting the decision center and by developing a new telemetry software.

## Control System

The control system, Autonomous Underwater Vehicle 6 (AUV6), is the software responsible for analysing the data from the various sensors on the vehicle and taking decisions based on this information to perform its mission objectives.

Like its predecessor, AUV6 was designed using a multi-layered architecture. Top layers use data filtered by lower layers to control the vehicle and take decisions based on its environment. The processes controlling the vehicle were designed using a linear control loop paradigm. At the beginning of every iteration, a snapshot of the vehicle's state and sensor values is taken to ensure time-determinism.

For control, the software uses simple and effective heuristic algorithms on top of classic Proportional Integral Derivative (PID) controllers. This year, control was greatly improved. The software is now able to control all five axes (x, y, z, yaw, pitch) simultaneously. Moreover, the DVL is now fully integrated in the position controller.

The mission system remains the same as in the last few years. A finite state machine defines the relationship between tasks that need to be accomplished. States and transitions are defined by an operator using the visual Mission Editor tool and then stored in XML definition files.

This year, the SONIA CAN usage standard was fully integrated in the control system. This allows AUV6 to request the identification of all connected hardware on the CAN bus. These identification responses are used to determine if it is possible to obtain information from different devices and determine which firmware version runs on the different devices, allowing for better backward compatibility.

To replace the old communication protocol between AUV5 and the telemetry software, the team chose Joint Architecture for Unmanned Systems (JAUS) as its main protocol. This choice was driven by the possibility of sharing code with three robotic teams at ETS. A JAUS library in java was developed in house to meet the multiple requirements from those projects. The following diagram demonstrates how the dependencies were organized to allow easy code sharing between the teams.

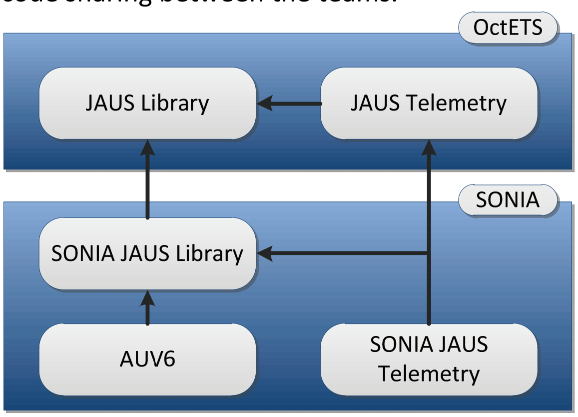


**Figure 9 – OctETS and SONIA dependencies diagram**

## JAUS Telemetry

The telemetry software was completely rewritten to integrate JAUS. SONIA had to create a subset of specific messages in JAUS to display information pertaining to AUV6 and the different sensors.

The telemetry software consists of a series of widgets that displays information and allows users to modify the submarine's behavior. These range from PID calibration, to attitude indicator, to waypoint navigation.

## JAUS Log Replay

During a mission run, AUV6 and the vision server record logs that can be replayed to facilitate debugging.

## CAN/TCP Server

The CAN/TCP server consists of an interface between the CAN bus and a TCP/IP socket. It allows the different software components to communicate with the hardware seamlessly.

## CAN Workbench

The CAN workbench is a tool allowing to diagnose the CAN bus. The team is able to monitor every messages sent on the bus. The workbench also displays information about connected devices, identification, parameters and the values broadcasted.

## Vision Server

The vision server is an application that processes images and returns high-level description of the environment. This high-level description contains the type of objects that have been detected as well as their characteristics, such as color-based identifiers, distance relative to the vehicle and orientation. This information is sent via TCP/IP to the control system and other tools. The vision server uses a pipe and filter architecture to process images, applying vision filters to every input to transform an image in order to detect the different obstacles.

## Vision Client

The vision client allows the streaming of the raw output from the cameras and the output from the different filters activated. Furthermore, it's able to modify various filter and camera parameters.

## Conclusion

The year 2011 resulted in a giant leap forward for team SONIA. The mechanical team pushed the boundaries of their abilities. A challenging design resulted in a beautiful and successful vessel. In parallel, the electrical team achieved an unprecedented level of integration, both with the mechanical and software aspect. Finally, the software team succeeded in creating a control system that is precise, reliable and repeatable.

The team is proud of its actual vehicle and of its achievements throughout the year. SONIA is eager to be in the field to compete with other teams to challenge the course and use its submarine to its full potential.

## Acknowledgement

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Thanks to the AUVSI and to the ONR for organizing this challenging event.

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

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- **Bronze:** Accedian Networks, Aicas realtime, Centre Sportif École Petite-Bourgogne, Département de génie électrique (ETS), Hydro-Québec, KGE, Kvaser, MicroStrain, Ore Offshore, Parc Jean-Drapeau, Réseau des ingénieurs du Québec, Seacon, TD Meloche Monnex, Tektronix, Thomas & Betts, Vector
- **Personnal Contributions:** Martin Morissette, Félix Pageau


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- **Sub-Team Leaders:** Olivier Allaire, Simon Bolduc , Louis-Philippe Lacroix
- **Treasurer:** Jacques Bertrand
- **Graphic Designer:** Isabelle Carrier
- **Movie Director:** Ève Lévesque
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- **Software Engineering Team:** Mathieu Benoit, Simon Bolduc, François Campeau, Pier-Luc Caron St-Pierre, Marc-André Courtois, Nikolas Durette, Stéphane Franiatte, Martin Gamsby, Pablo Herrera, Jean-François Im
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