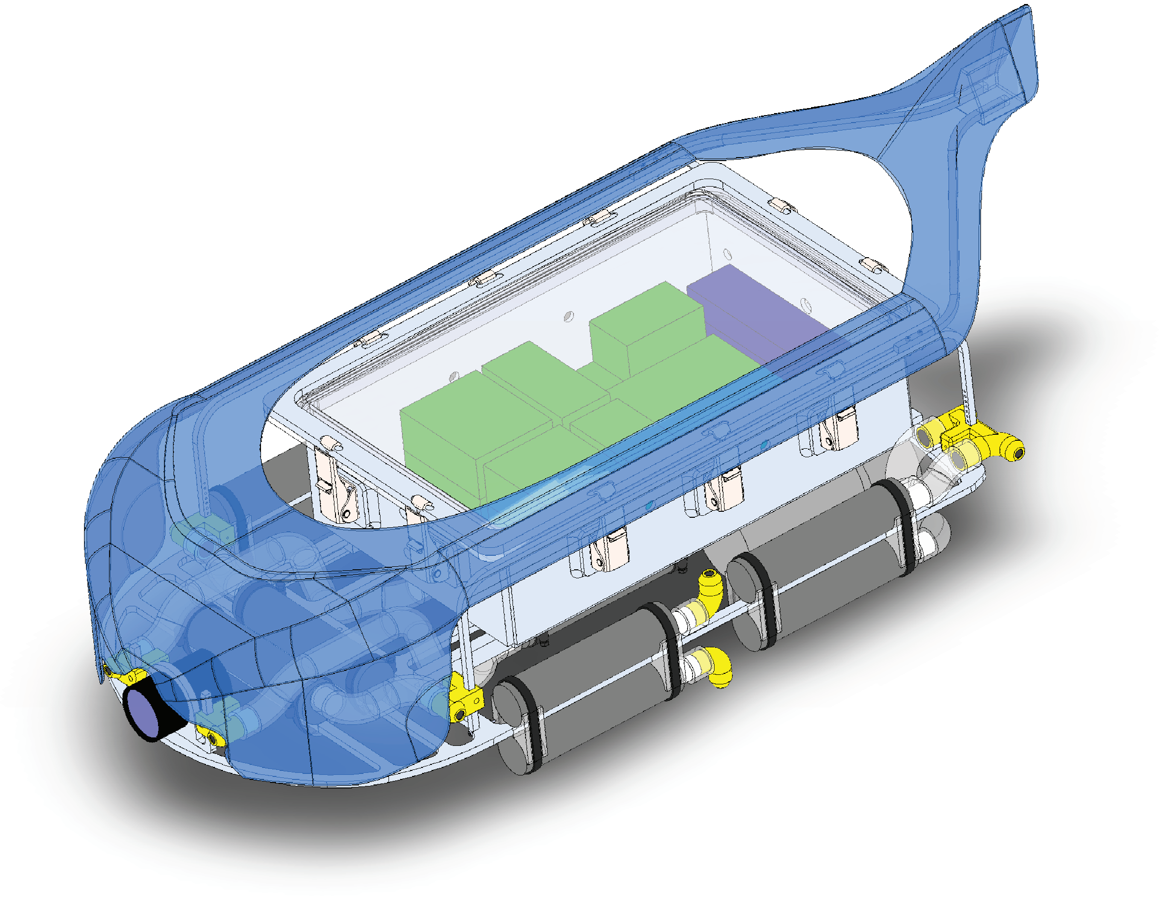
autonomous robotic vehicle project

UNIVERSITY OF ALBERTA



OVERVIEW OF SUBMURSA AUTONOMOUS UNDERWATER VEHICLE

A. Askari, T. Berner, M. Bowthorpe, M. Bujold, V. Ganev, A. Lee,
K. Schmidtke, A. Watts, L. Wiseley, C. Woloschuk, K. Yap-Chung

Abstract

The Autonomous Robotic Vehicle Project (ARVP), from the University of Alberta, was formed with the goal of involving students in the design, construction, and promotion of autonomous robots and robotic technology. This will be ARVP's fourth year attending this competition. This year ARVP introduces its new robot, *SubmURSA*, which is based on a new mechanical platform and improved electronics from those used in the team's previous vehicle, *Bearacuda*. The passive sonar system, which receives the signal transmitted by an acoustic pinger, features four hydrophones and a custom-built PCB to amplify and filter the signal. The time-difference-of-arrival data is measured and sent to the embedded computer which calculates the location of the acoustic pinger. A new main board was designed to accommodate the new NetBurner Microcontroller that will be used this year. The power system was improved by isolating the power systems supplying power to the pumps and the electronics. The software for *SubmURSA* was designed to be as modular as possible, using a custom built framework called "DisCo". This allows for easy communication between different, independent components such as the microcontroller and embedded computer, allowing for more versatility within the system.

I. INTRODUCTION

THE Autonomous Robotic Vehicle Project (ARVP) was founded in 1997 as a means for students at the University of Alberta to develop, apply and promote robotic technology. Members of ARVP are interdisciplinary and come from various faculties such as the Faculty of Engineering and the Faculty of Computing Science. Through ARVP, these students gain the necessary skills and understanding of the different processes involved in the design, construction and testing of autonomous robots to prepare them for a possible career in the field of robotics. From 1997 to 2006, ARVP was involved exclusively with ground-based autonomous vehicles and had great success. Since then, ARVP has shifted its focus to underwater-based autonomous vehicles. This year, ARVP accepted the challenge put forth by the 14th International RoboSub Competition, hosted by the Association for Unmanned Vehicle Systems International (AUVSI) and the Office of Naval Research (ONR). The challenge is to build a fully autonomous underwater vehicle (AUV) that can perform the following tasks:

- Follow a predetermined path
- Bump into a series of coloured buoys in a predetermined pattern
- Travel over an "L"-shaped pipe
- Drop a marker into a bin
- Launch a torpedo towards a stationary target
- Locate an acoustic pinger
- Grab an object and surface in a predetermined area

This is the first year of competition for ARVP's new AUV, *SubmURSA*. This year, *SubmURSA* will be attempting to hit the buoys in the correct order, travel over the "L"-shaped PVC pipe, locate the acoustic underwater pinger and surface within the correct octagon.

II. MECHANICAL

WITH the development of *SubmURSA*, many of the lessons learned from the team's previous AUV, *Bearacuda*, were taken into account and improvements were sought, while successful areas were maintained. The main faults with *Bearacuda* were its large mass and a pressure hull interior that was difficult to access. The design of *SubmURSA* successfully addressed these two problems. A summary of the specifications of *SubmURSA* is outlined in Table I

Fig. 1. *SubmURSA* frame with uprights and IMU arms

A. Mechanical Design

The mechanical platform was designed using 6061-T6 aluminum as the primary construction material. There are two main components in the platform: the frame and the hull. The frame consists of custom cut aluminum bars and plates as shown in Fig. 1. As can be seen, the base frame has uprights on the sides and rear as well as rails in the middle. The uprights serve a dual purpose. They hold the inertial measurement unit (IMU) the required distance away from any electromechanical components, preventing inaccurate readings due to the magnetic fields these components create, and they provide a mounting point for the thermoplastic shell that aids in the aerodynamics and aesthetic appeal of the platform. The pumps and thrusters, which propel *SubmURSA*, as well as the custom camera mounts, located in front of and underneath the platform, are attached to the crossbars of the base frame. Additionally, there are two rails mounted on the base frame in which the removable pressure hull is able to slide in and out. The advantage of the sliding

TABLE I
SUMMARY OF SPECIFICATIONS

Size	0.94m x 0.43m x 0.36m
Weight	19.32 kg
Top Speed	1.86 m/s
Running Time	35 minutes

pressure hull and the mounted propulsion pumps is that it allows these elements to be adjusted until static balancing is achieved.

A solid model of the vehicle and all of its submodules was created in SolidWorks to ensure proper design space was allocated for all internal components. A complete engineering drawings package, including an assembly guide, was created from the solid model, which provided a means of communication between ARVP and the University of Alberta Machine Shop during the manufacturing phase of the platform.

B. Pressure Hull

One of the major issues with *Bearacuda*, which was a primary focus of design for *SubmURSA*, was the pressure hull. Key areas of visibility and accessibility were addressed in the development of *SubmURSA*, and the requirements regarding these two areas have successfully been met.

The new hull is designed with a clear lid to keep the enclosed electronics visible while the craft is sealed. A sheet of clear polycarbonate is heated and blown into a dome-like shape to create the lid. As part of the design, only a minimum dome height was specified, and, as a result, this simple forming method is suitable. This lid improves the visibility of the hull because the team can now visually inspect all electronics without unsealing the hull. With the design of indicator lights on almost all printed circuit boards, the clear lid allows for quick electronic error analysis so that any emergency situation can be assessed immediately. Additionally, the dome shape of the lid prevents the collection of water on the craft, which prevents water from spilling into the craft.

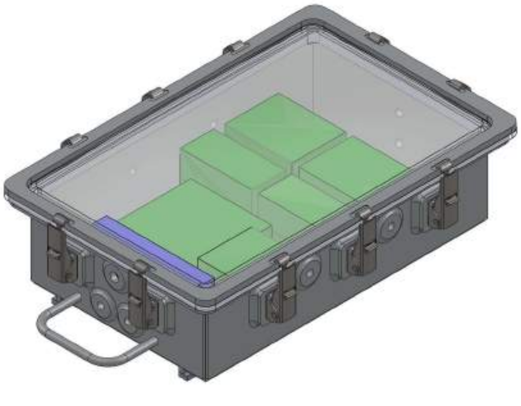


Fig. 2. *SubmURSA*'s assembled pressure hull

The complement of being able to quickly assess the situation of the vehicle is the speed of access to the problematic components. With *Bearacuda*, a minimum of 10 minutes was required to access the electronics. This quickly became a problem for the team with regards to qualifying and competition runs each year. The hull sealing method of *SubmURSA* was completely redesigned so that approximately 30 seconds is required to seal or unseal the hull. This sealing method relies on the use of ten Southco draw latches distributed around the hull. These ten latches provide a clamping force in excess of 15kN, which allows a dual O-ring seal to be used as a measure of safety, while still maintaining a safety factor of 2:1.

The main component of the pressure hull is an aluminum box, with dimensions 421mm x 262mm x 137mm, in which almost all the electronics are housed. The box is welded together, which results in a large usable volume. This allows for the adjustment of electronic components until an ideal placement is found. Additionally, the reuse of this hull can accommodate different electronics configurations due to the lack of rails and platforms confining placements in the hull. The internal electronics are connected to external components via threaded holes in the sides of the hull, as illustrated in Fig. 2. In the final assembly of the vehicle, these holes are filled with Subconn connectors and custom made cables connect these connectors to external components. Since the Subconn connectors in this platform all have the same thread size, the placement of the electronics can be adjusted as required.

The pressure hull is mounted to the main frame of *SubmURSA* through the rails shown in Fig. 1. As can be seen in Fig. 2, there are two rails underneath of the hull. These two rails slide into the rail mounts on the frame, and the hull sits snugly on top of the rails on the frame. The hull is secured in place by a locating clip on the left rail, and can easily be inserted or removed using the access handle on the rear.

C. Propulsion

During the design phase of *SubmURSA*, it was decided that centrifugal pumps would be used as

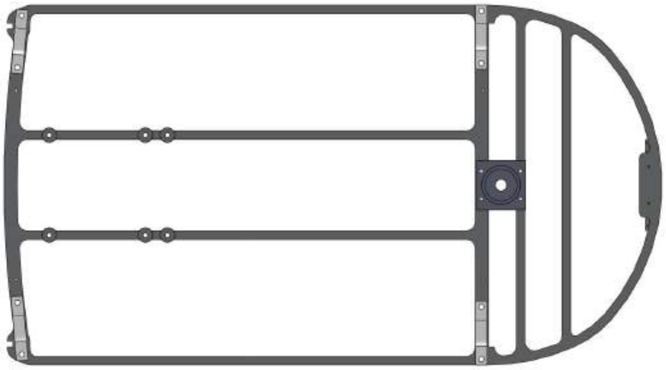


Fig. 3. *SubmURSA*'s underside component layout

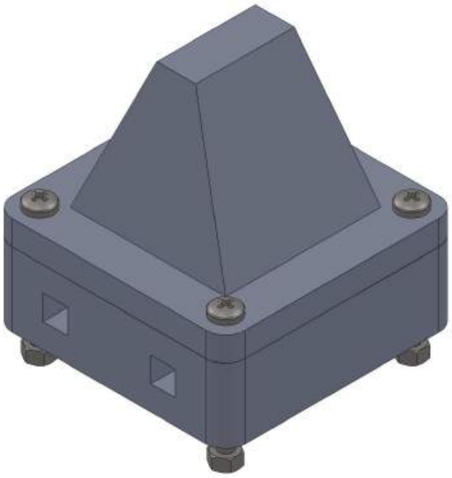


Fig. 4. Inertial Measurement Unit chamber

the means of propulsion for the vehicle. In the original design, 12 LVM Congo 111 centrifugal pumps were selected, with the use of 12 adjustable nozzles distributed around the platform to allow the craft to move with four degrees of freedom — heave, surge, sway, and yaw.

However, a theoretical maximum speed of 0.307m/s was found through mathematical modeling and was deemed unsuitable for competition. As a result, the propulsion mechanism was changed to a pump/thruster combination system, in which two Seabotix BTD-150 thrusters are used for surge and yaw, while eight pumps are used for heave, sway, and yaw. This combination increases the maximum speed of the craft due to the larger thruster output.

The main advantage the pumps offer is the adjustability of their output nozzles. To change the direction of flow of the pumps' output, the nozzles simply have to be translated or rotated to achieve a balanced and adequate propulsion in a specific direction. This allows the craft's movement to be idealized without a significant change to the static balancing, a distinct advantage over the previous thruster-based system, where adjusting the output of the thrusters changed the centre of gravity of the craft.

D. External Components

The external components of the platform — apart from the propulsion mechanisms — include the hydrophones, the cameras, and the IMU. All of these components are connected to the pressure hull, and its interior, through the use of custom-made cables and Subconn connectors.

The locations of the four hydrophones are chosen as a rectangular array, with two front-facing hydrophones placed near the front of the vehicle, and two rear-facing hydrophones placed near the rear. This serves the purpose of maximizing the distance between each hydrophone while still maintaining symmetry of the vehicle. Additionally, due to the omni-directional nature of the SQ26-11 hydrophones, this array allows for a listening sphere surrounding the vehicle.

On *SubmURSA*, two cameras are located near the front of the craft. Both cameras lie immediately in front of the pressure hull, with one forward facing, and the other downward facing. The cameras are individually mounted, which allows for the changing of a camera module in the case of failure, as well as specific upgrading of either camera to suit the team's needs in the future.

The placement of all underside components is more accurately displayed in Fig. 3. As can be seen, the four hydrophones sit on the corners of the main rectangle of the frame, and the downward facing camera sits in the front.

E. Mechanical Validations

Before *SubmURSA* was manufactured, several calculations were performed in order to validate the design before the costly manufacturing stage. This mechanical platform had the main objective of improving the areas in which *Bearacuda* had failed,

TABLE II
IMPROVEMENTS OF *SubmURSA* OVER *Bearacuda*

	Bearacuda	***SubmURSA***
Mass	34kg	19.32 kg
Hull Volume	37.0L	18.6L
Running Time	29.9 minutes	35 minutes
Pressure Hull Sealing Time	10 minutes	0.5 minutes
Cost	$5451	$1522

while maintaining the previous successes. A summary of the improvements provided by *SubmURSA* are described in Table II.

Additionally, the mechanical validation calculations also outlined the key areas of buoyancy, velocity, depth, and sealing strength of the vehicle, with the team's requirements being met or exceeded, as is delineated in Table III.

III. ELECTRICAL

THE electronics subteam completely upgraded and redesigned the electronics of *SubmURSA* in order to create a more modular system. This modular design allows for easy replacement or bypassing of certain systems in the event of system or circuit board malfunctions or failures.

A. Main Board

The main board, shown in Fig. 5, is responsible for communications between all external subsystems except for the vision component which is handled by the embedded computer. The main board features a MOD5270 from Netburner which is running microLinux. The micro controller can load the kernel (version 2.6.34-uc0) and the applications from the on-board SD card. The microcontroller communicates with the motor controllers using TTL and with the IMU using RS232. In addition, for ease of debugging, a 6 pin male header allows for a TTL-USB cable to be directly connected to the main board.

Power is supplied to the main board from the electronics power board. LEDs indicate whether power is being supplied to the board which is also protected by a fuse. The main board has a 3.3V voltage regulator that can supply up to 800mA. The main board also supplies power for the sonar subsystem, the IMU, the digital compass, and the depth sensor. A 5V supply line is provided by the motor controllers, negating the need to step up the 3.3V supply line with additional circuitry.

The kill switch is implemented on the main board; triggering the external kill switch will pull an input of each of the motor controllers to ground, shutting down the motor controllers and all propulsion.

B. Motor Controllers

SubmURSA utilizes four Sabertooth dual 12A motorcontrollers and one dual 10A motor controller. The 12A units are used to power the pumps while the single 10A unit controls the two thrusters. The motor controllers receive their instructions via a packetized serial protocol from the microcontroller. This allows for multiple units to be placed on the same serial line, decreasing the number of serial ports required overall. The motor controllers for the pumps are powered using two custom propulsion power boards, shown in Fig. 6, while the motor

Fig. 5. The main board

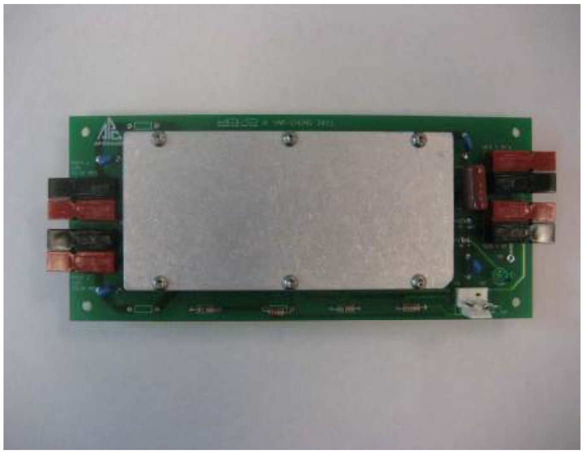


Fig. 6. The motor controllers' power board

TABLE III
SUMMARY OF MECHANICAL VALIDATION

Calculation	Objective	Result	Conclusion
Buoyancy	% buouyancy $\geq$ 0.5%	0.5%	Meets Requirement
Maximum Velocity	Between 0.5 m/s and 1.5 m/s	1.86 m/s	Exceeds Requirement
Depth	Reach depth of 16ft without yielding	Factor of Safety = 2	Exceeds Requirement
O-Ring Seal	Maintain seal up to 16ft	Factor of Safety = 2	Exceeds Requirement

controller connected to the thrusters is powered directly by a single lithium-polymer battery.

C. Sensors

In order to achieve a proper bearing, the electrical team chose Ocean Servers OS5500, a combination inertial measurement unit (IMU) and digital compass. This device also allows the incorporation of a pressure transducer as a means of obtaining the depth. The OS5500 has connectors for both USB and RS232 communication and offers an ASCII interface to allow programming with the microcontrollers. *SubmURSA* is capable of taking internal temperature values from multiple sources and can be measured by the motor controllers and the IMU.

D. Sonar Board

The passive sonar system, shown in Fig. 7, uses four SQ26R1 hydrophones with built in preamplifiers to 'hear' the acoustic pinger. The captured signal from the pinger first passes through a high-pass filter to remove the 60Hz power signal. The signal then passes through a variable preamplifier to boost the signal as it was determined that the built in pre-amplifier did not supply a large enough gain to process the signal.

Fig. 7. The sonar board

After the preamplifier, the signal is split into two sections. One section passes through a zero-crossing detector which converts the sinusoidal wave into a square wave where the positive sections of the sinusoidal wave correspond to the positive sections of the square wave and the negative sections of the sinusoidal wave correspond to the negative sections of the square wave. Both sections of the signal are then passed through their own rectifier to eliminate the negative portions of each signal. Finally, the two signals from each of the four hydrophones are sampled by an analog to digital converter. The eight digital signals are then passed via SPI to the microcontroller for processing.

The frequency of each signal is calculated by measuring the distance between the square waves from the zero-crossing detectors or by digitally filtering the raw rectified signal. The time at which the desired frequency is detected by one of the hydrophones is noted. The length of time between the moment when each hydrophone picks up the desired frequency is calculated as the time-distance-of-arrival (TDOA). The TDOA data is then sent via a UART-USB converter to the embedded computer.

E. Lithium-Polymer Battery Charger

SubmURSA uses single-cell 3.7V lithium-polymer batteries for powering the main board and it's associated peripheral boards. To recharge these batteries, a custom-built compact charging circuit was constructed. The lithium-polymer battery charger (or LiPo charger) is inspired by a similar design marketed by SparkFun which uses the same MCP73831 Charger Controller IC as is used in *SubmURSA*'s LiPo charger. It has a selectable charge rate via a jumper, with 250mA or 500mA options. An LED indicates the current charge state, illuminating when the cell is being charged, and turning off when the charge is complete. The power input is a standard mini-B USB connection, which allows power to be supplied to the charger via a USB 'wall-wart' charger or a computer's USB port.

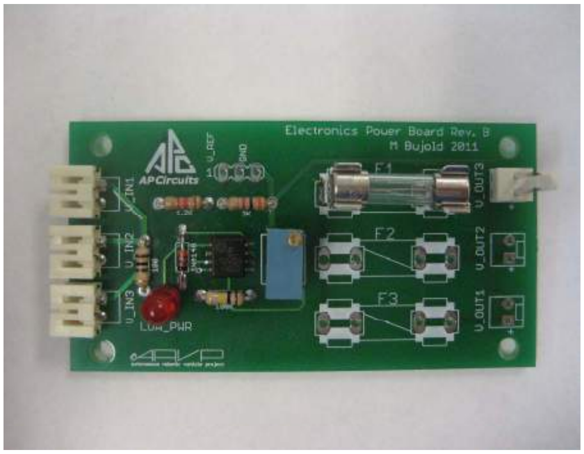


Fig. 8. The electronics power board

F. *Electronics Power Board*

The Electronics Power Board (EPB), shown in Fig. 8, is essentially a bus-board for distributing power from the lithium-polymer batteries to any boards that require a 3.7V power source. It incorporates three battery input headers and three fused power output headers connected in parallel. Since discharging lithium-polymer batteries below 3V can damage the cells and therefore prevent them from accepting a full charge, a simple voltage monitoring circuit activates a red LED to indicate if the voltage has fallen below a preset threshold. This threshold is adjustable by a trim pot on the board, and is typically set at approximately 3.3V.

G. *Propulsion Power Board*

The Propulsion Power Board is based around the VICOR V24A12C400BL voltage regulator. It draws power from 5Ah 18.5V lithium polymer batteries and distributes them to the 8 LVM Congo 111 centrifugal pumps which run at 12V and draw approximately 6A each. *SubmURSA* utilizes two of these boards, each of which power a total of four pumps per board. Each board has inputs for two 18.5V batteries and outputs up to 400W at 12V. Other features include a 3.3V line for battery sensing, additional resistor ports for stepping up/down voltage and a "parallel-out" port for running multiple VICOR V24A12C400BL voltage regulators in a Master/Slave parallel configuration.

IV. SOFTWARE

THE *SubmURSA* software consists of a number of independent components that communicate with each other using small packets of information. These components are divided between the micro-controller (MC), the embedded computer (EC) which is powered by the circuit board shown in Fig. 9, and a laptop/development computer. An important benefit of our design is that two components can easily communicate with each other regardless of whether they are running on the same device or on different devices that are networked together. Fig. 10 is a general overview of the more important components and how they interact with each other. In order to achieve this flexibility, the software utilizes a framework called "DisCo" which was developed at the Department of Computing Science at the University of Alberta, with the goal of providing a unified communication framework between components in robotic systems.

A. *Drivers*

The software system contains a collection of independent pluggable driver components that are responsible for interfacing with the hardware devices. The drivers were designed to be abstract so that the rest of the system can be independent of their implementation. Each of the drivers is a component responsible for initializing a device, communicating with it using the appropriate protocol, and interfacing that device with the higher level components. In order to keep the design modular the driver components are split into two main classes: low-level drivers and high-level drivers.

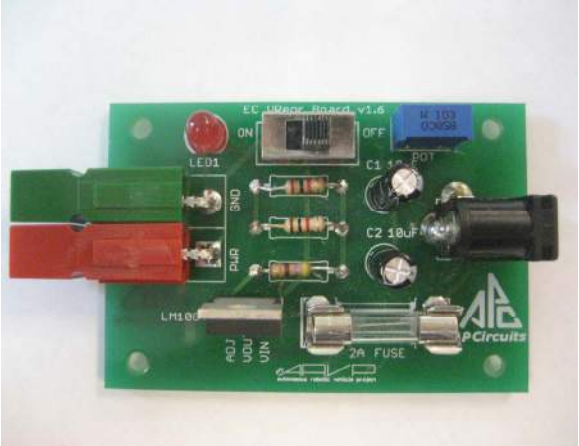


Fig. 9. The embedded computer power board

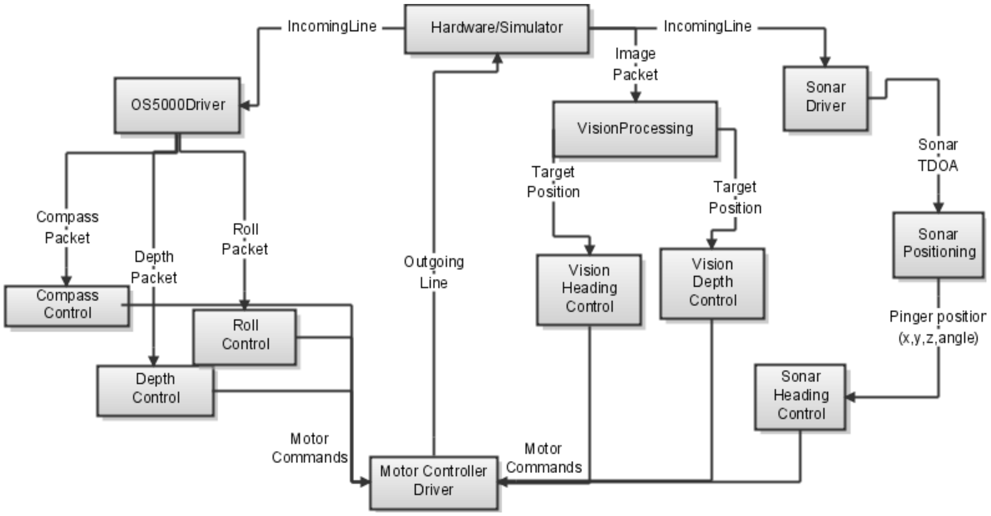


Fig. 10. Main components comprising

The low-level drivers consist of several components that help the high-level drivers communicate with the actual hardware - a serial communication driver component, a GPIO driver component, and a PWM driver component. Additionally, there are two other low level drivers used during development/testing: simulated drivers which can be used for interfacing the higher level drivers with simulated hardware and a “log driver” which allows for “replaying” one of *SubmURSA*’s previous runs for debugging purposes.

The high-level drivers are responsible for decoding data received from the devices as well as encoding data that needs to be sent to them. Examples of high-level drivers include: the IMU/digital compass driver, the Sonar driver, the Motor Controllers driver, and the Frame grabbing driver.

B. Vision

In the past, the Vision module implemented a simple RGB-thresholding algorithm in order to determine which pixels in the frame are close enough to the colour of the target object. A major difficulty with this approach is that the colours can differ significantly at different times of the day. This year several modifications have been made to address this problem.

The current version of the Vision software considers not only colours but also uses information about the shape of the object being tracked. This is accomplished in two different ways: by utilizing a TLD (simultaneously **T**racking, **L**earning and **D**etecting) algorithm described in Kalal’s work [4] and implemented in OpenTLD [3] and by using normalized cross-correlation of the hue between the target image and a template. An important advantage of both of these methods over the old RGB-thresholding system is that they both work by simply taking a sample image of the object as a template and do not require any other input, whereas the old system required manual adjustment of the thresholds based on the current lighting conditions.

The main advantage of the TLD algorithm is that it is not as affected by the changing lighting conditions as the colour-based approach is. Another useful feature is that the algorithm can calculate how confident it is that the object has been found. The disadvantages are that it is computationally expensive, only works on objects that have enough distinct features in their shape so that they can be singled out from the rest of the image, and only works when the entire object is in the frame. It was found that TLD produces good results for the buoy and “L-lane” but not for the path.

Since the TLD algorithm is not applicable in all situations, a colour-based approach is still needed. In order to reduce the time required for calibration, the old method was modified so that it can automatically calibrate itself based on a single sample image of the object. Therefore, the software team implemented a system that uses normalized cross-correlation (as implemented in the OpenCV[1] library) between the hue of the image from the camera and the hue of the sample image. Then, it uses adaptive thresholding in order to single out the object being tracked. This method is used for cases where the confidence of the TLD results is too small and for the path elements, which cannot be handled by the TLD algorithm.

C. Sonar

In order to be able to locate the acoustic pinger the software team implemented a passive sonar system that uses the four time differences of arrival (TDOAs) and applies multilateration to estimate the position of the acoustic pinger relative to *SubmURSA*'s position. Since the location of the acoustic pinger is being searched for in three dimensions and there are four hydrophones, an analytical solution of the multilateration equations is found using the work done by R. Bucher and D. Misra [2]. Once the Sonar component knows the estimated relative position of the acoustic pinger, it calculates the relative heading and updates the horizontal controller's target heading so that *SubmURSA* is aimed towards the acoustic pinger.

D. Navigation

The software team developed a generic PID controller in order to be able make decisions about how to control *SubmURSA*'s actuators based on the current mission requirements and sensor readings. The controller component itself is independent of the item being actually controlled, allowing it to control different items and making it easier to maintain. The higher level components can use the controllers by requesting that the target of the controller is changed as well as starting or stopping individual controllers and changing the gains and other parameters.

Heading and depth control are done by monitoring the current sensor values, from the digital compass and the depth sensor, and feeding them to the respective controller instances which determine the appropriate power for the actuators.

When performing a vision oriented task, the vision processing component produces a location for the object being tracked and sends it to the appropriate controller. The target of the vision controllers is always the middle of the frame. *SubmURSA* only moves forward when the actual position of the object is within a certain threshold (usually set to 10% from the center of the frame) of the target and the rest of the time it only corrects its orientation and vertical position.

Similarly, for the sonar mission, the Sonar component updates the target of the heading controller by taking into account both the current heading (from the digital compass) and the heading of the pinger relative to *SubmURSA*, as calculated by the Sonar component.

E. Mission Planning

The Mission Planner component is responsible for running and controlling the various missions that *SubmURSA* performs. Each mission has a completion condition and/or a timeout time. Whenever a completion condition has been reached, the current mission terminates and the Field Commander moves onto the next mission. If, however, a mission is taking too long and reaches its timeout then the Mission Planner terminates it and moves on. This is done so that *SubmURSA* does not spend too much time on a single mission without getting a chance to perform the other missions.

Each mission has various parameters which are all stored in XML files that are automatically reloaded when changed. This allows for a quick update of the parameters during development/testing.

F. Graphical Display / Remote Control

During testing, the data coming from the sensors is visualized, including live video, annotated with image processing information (Fig. 11). This allows for easy assessment of what *SubmURSA* is doing at the moment. It is also possible to replay a recording of previously collected data.

A remote control interface is also implemented, allowing for manual control of *SubmURSA* when testing/troubleshooting. It can issue a target value for the depth controller and it can also control the direction of *SubmURSA* by either supplying a direct turning effort command or by adjusting the target of the heading controller which in turn will make *SubmURSA* turn in the required direction.

V. ACKNOWLEDGEMENTS

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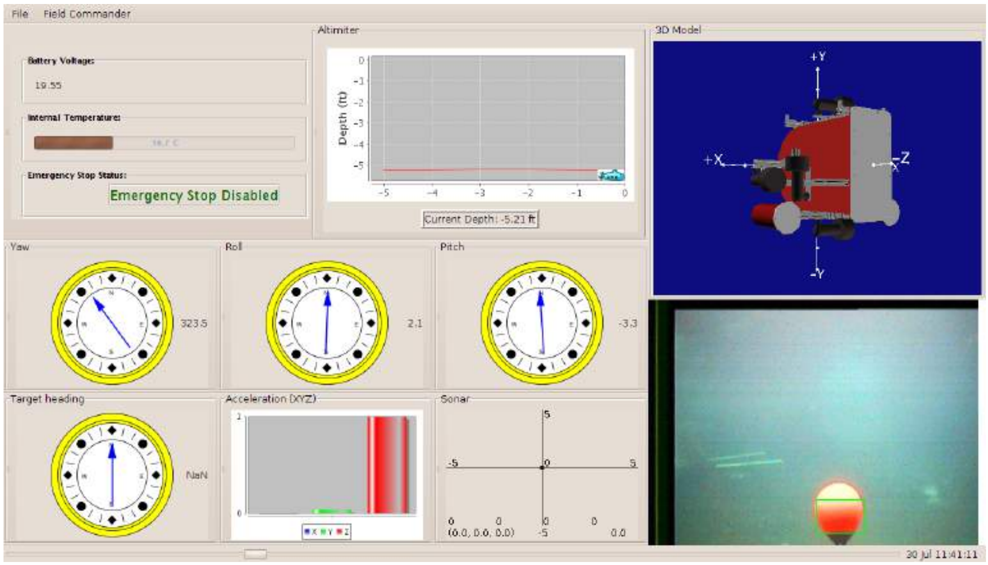

Battery Voltage: 19.55

Internal Temperature:

Emergency Stop Status: Emergency Stop Disabled

Current Depth: -5.21 ft

Fig. 11. Visualization of sensor data

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VI. 2010-2011 TEAM MEMBERS

Team Leader: Chris Woloschuk
Platform Team Leader: Aassem Askari
Platform Team: Thomas Berner, Kris Yap-Chung
Electrical Team Leader: Chris Woloschuk
Electrical Team: Mike Bujold, Kristopher Schmidtke, Asher Watts, Kris Yap-Chung
Sonar Team Leader: Meaghan Bowthorpe
Sonar Team: Allen Lee
Software Team Leader: Veselin Ganev
Software Team: Lily Wong
COPPER Team Leader: Lee Wiseley

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