SRM University
Autonomous Underwater Vehicle
Concept and Design of AUV Sedna

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***Abstract*-SRM University Autonomous Underwater Vehicle Team is an undergraduate team of students that develop AUVs for competition and research. The AUV Sedna is developed in a design cycle of six months. CAD modeling and CNC techniques were used for in-house fabrication. The vehicle is equipped with an array of sensors including two vision cameras ,an Inertial Measurement Unit, passive SONAR array and a pair of pressure sensors. These sensors enable the vehicle to navigate seamlessly and enable it to hear, see and measure its speed, acceleration and underwater positioning. In order to interact with the environment, the AUV is equipped with 8 thrusters, an active grabber and a torpedo launcher.**

The development of Autonomous Underwater Vehicles has gained a momentum with the advancement of the field of robotics. The need for rapidly deployable underwater vehicles that can be used in challenging environments is on the rise. Well designed AUV's can provide a reconfigurable platform for various industries such as ocean research, oil and natural gas and many more.

SRMAUV is a group of passionate undergraduate students studying at SRM University, Chennai. The goal of the team is to develop a functioning efficient, robust Autonomous Underwater Vehicle that may be used for research and development along with participating in the annual Autonomous Unmanned Vehicle System International (AUVSI) and the Office of Naval Research (ONR) Robosub Competition at San Diego . The aim of the AUV is to complete an obstacle course of real life tasks presented at the competition. The tasks may involve following path segments ,navigating through gates ,maintaining heading, touching buoys, launching torpedoes, dropping markers, locating acoustic beacons and manipulating objects. To achieve all this the vehicle needs to have swift movement and accurate positioning. The vehicle needs to be aware of its position at all times. Hence vehicle localization plays a prime role. Specific subsystems have been developed to handle underwater tasks.

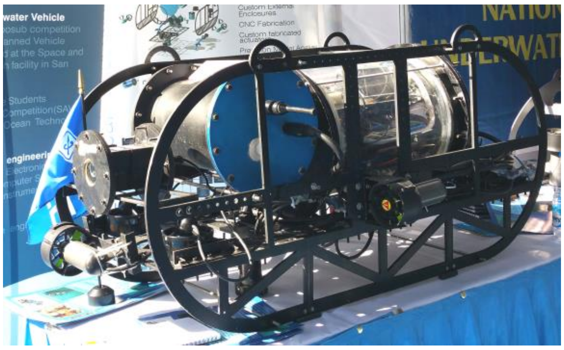


Fig: 1.1 AUV Sedna

MECHANICAL DESIGN

A. OVERVIEW

The mechanical design for Sedna was planned with the goal of making the AUV modular, compact and lightweight. The hull contains a sliding deck with a rack system, facilitating removal and centralized access to the electronic components. The external frame is designed to foster future modification of the AUV with minimal effort. The software tools used in modeling and analysis are SolidWorks, Catia and ANSYS.

Fig: 1.2 Solidworks rendering of AUV Sedna

VEHICLE SPECIFICATIONS:

- **Depth rating :**
    - 50ft (Acrylic Hull)
- **Max speed:** 0.6 m/s
- **Overall Dimensions:** 48" L x 24" W x 21" H,
- **Weight:**45kg
- **Run time:** 1 hours 30 minutes
- 8 x Thrusters for active Yaw, Pitch, Heave, Surge and Roll Control

B. HULL

Acrylic is the material chosen for construction of the hull. Acrylic refers to a family of synthetic or man-made plastic materials, containing one or more derivatives of acrylic acid. The hull has an inner diameter of 290 mm and an outer diameter of 300 mm. It is designed to be watertight in order to insulate the internal electrical systems from water damage. The hull end-cap features waterproof connectors, allowing external components to access the electrical systems inside the hull. The front and back end-caps are machined from Aluminum blocks to facilitate passive heat conduction. The cylinder is made from acrylic to provide a clear view of the hull components for inspection.

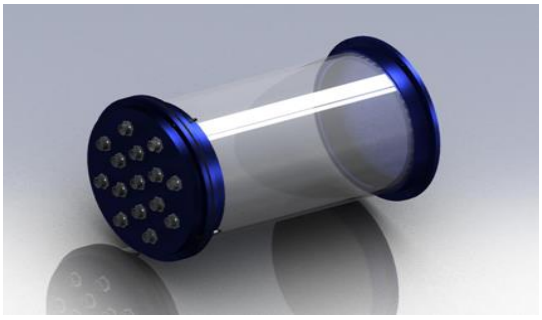


Fig: 1 Acrylic Hull

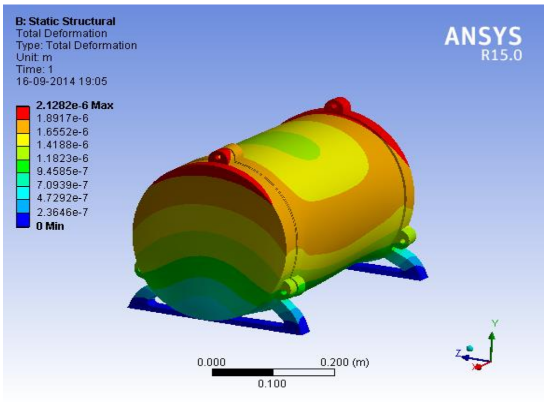


Fig: 2 Hull Deformation analysis

C. EXTERNAL FRAME

For the frame to be modular, a drill pattern is applied over its surface. The frame is made of aluminum and hard-anodized for structural stability. It was designed in such a way that the total deformation, von mission stress and strains are always minimum. All the components are directly secured to the frame. The frame design provides an unobstructed flow for the thrusters. Structural analysis using ANSYS is done to ensure structural rigidity. The frame consists of 2 side plates made up of Al-6061-T6 having a thickness of 6mm.The dimension of each plate is 1100mm x 500mm the width of the frame is 500mm. The frame accommodates 8 thrusters for Surge, Heave, Yaw and Pitch Control. Handles attached to the frame are provided for easy transportation of the AUV.

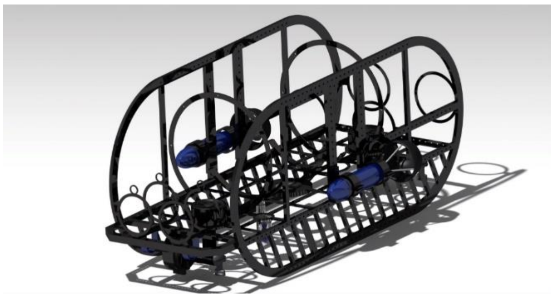


Fig: 3 Frame

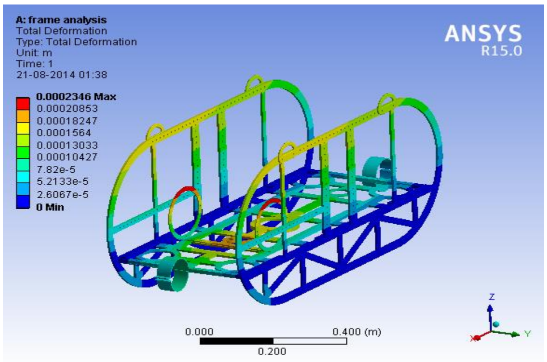


Fig: 4 Frame Deformation analysis

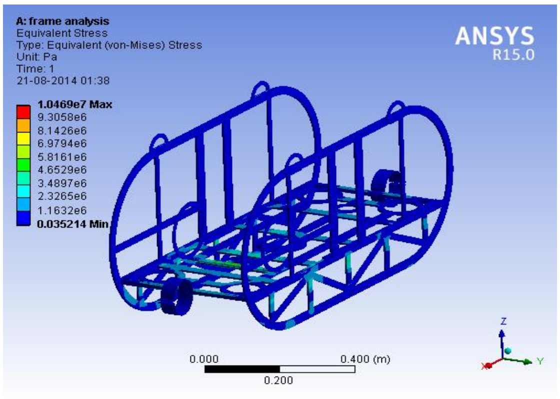


Fig: 5 Frame Stress analysis

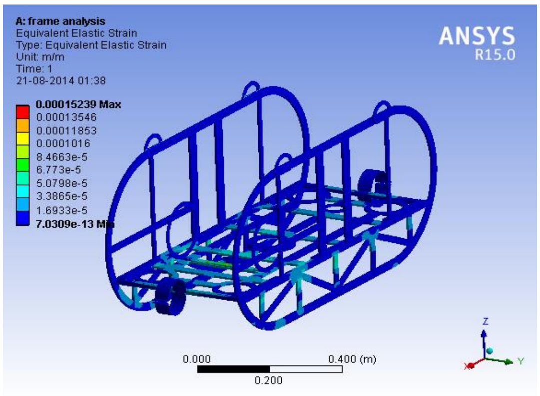


Fig: 7 Frame Strain analysis

D. PNEUMATIC SYSTEMS

The pneumatics systems are used to drive the following manipulators attached to the frame :

- Grabber Mechanism
- Dropper Mechanism
- Torpedo Mechanism

(i)Active grabber mechanism:

The grabbing mechanism is powered by a pneumatic piston which allows controlled grabbing and release using compressed air. The pneumatic grabber is utilized to grab underwater mission objects.To grab, the piston extends and the grabber arms close around the PVC object, securing it for transport to the second recovery area.

To release, a second set of valves is opened to force air into the other half of the piston, opening the grabber.

A CO2 cartridge is provided to contain compressed air .Here we use a Rexroth PRA-D32 pneumatic cylinder which can effectively functional even at higher pressures.

Fig: 8 Active Grabber

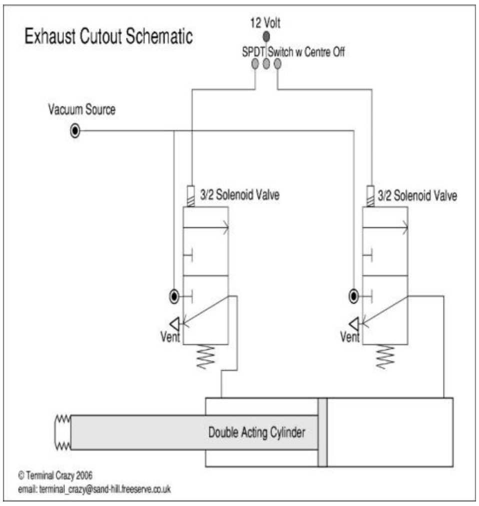


Fig: 9 Electrical Circuit for grabber

(ii)Dropper mechanism:

Two droppers are mounted below the hull. A magnetic coil is used to actuate the dropper using an electric pulse. This provides for dropping markers in competition bins. The dropper is made heavy so it can fall directly in line with the marker bins. Custom electromagnet actuation is used for this purpose.

The dropper actuation mechanism weighs at 0.5 kg.

Fig: 10 Dropper

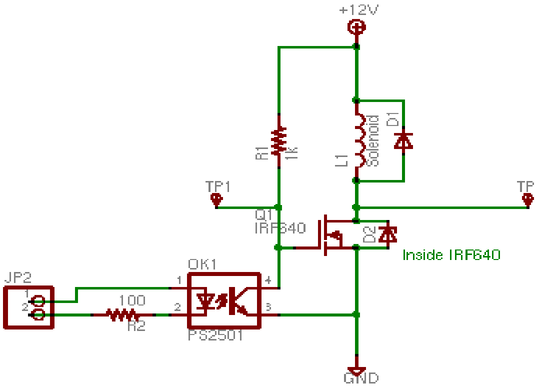


Fig: 11 : Electrical Circuit for Dropper

(iii) Torpedo

Two independent pneumatic torpedo-shooting mechanisms are provided which have been 3D printed with a drag-optimized profile. The torpedo is activated using a pressure release valve that is solenoid controlled. Neutrally buoyant torpedoes provides stable water dynamics and easy recoverability.

E. Custom enclosures:

Custom sensor/electronics/battery enclosures are designed using CAD software and optimal precision CNC fabrication techniques are chosen for fabrication using aluminum

Battery Pod

A battery pod houses the Li-Po batteries onboard Sedna. Pressure release valves and connector slots are provided on the periphery. The pod is water tightened using an axial sealing mechanism and can easily be swapped to provide continuous vehicle operation.

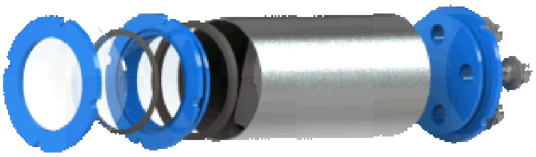


Fig: 6 Battery Pod

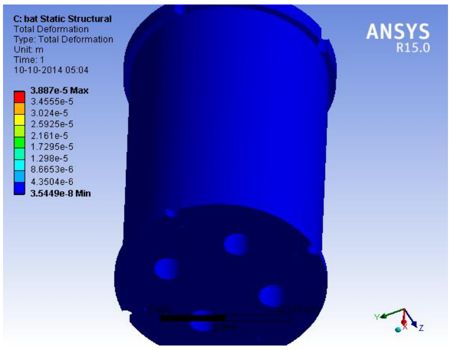


Fig: 13 Battery pod Deformation analysis

Camera Enclosure:

Two custom camera enclosures have been fabricated for the front and bottom vision cameras. Clear acrylic front panels provide an unrestricted field of view.

ELECTRICAL DESIGN

A. Overview

The electrical infrastructure consists of Power Management Systems, Acoustic Signal Processing and Sensor payload Electronics, so as to cater the needs of constantly evolving software and mechanical components. The design ensures modularity in the electrical system for allowing boards to be reused through multiple design iterations and provides support for future unforeseen requirements. The Mini-ITX motherboard, microcontroller carrier board, Batteries and Power Supply Units are the main electrical components which are enclosed within the hull. In addition, a number of sensors and protection circuits have also been incorporated to make the system robust.

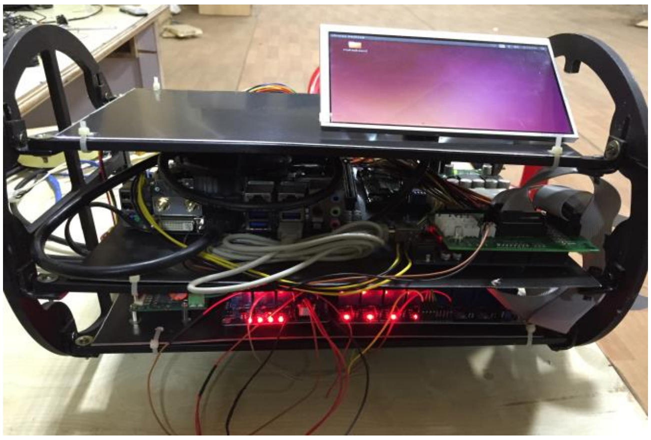


Fig: 14 Sedna's Backplane

B. Power Management System

A dedicated Power Management System is developed to support the on-board electronics and sensor payload. A Battery Management System is developed for optimal power distribution among various boards such as the onboard CPU, thrusters and the microcontroller board. A Battery Management and Protection board is custom designed to provide even discharge of Lithium Polymer (Li-Po) batteries. A visual feedback system to provide battery level information for thrusters and electronic peripherals is developed. Special care has been taken to ensure water leakage detection and overheating. Each component is protected with resettable fuses. Sedna is powered by five 11.1V (3S), 8Ah Lithium Polymer batteries in parallel.

a. Power Monitoring:

A custom board has been designed to monitor the power level of each battery which is also provided with a Hall Effect current sensor to continuously measure the current. A point contact temperature sensor is placed on each battery to continuously measure the temperature. A graphic LCD displays the status of the batteries, power lines and hull temperature. LED strip lighting provides visual feedback for software debugging.

b. Power Distribution:

A M4-ATX (250W) power supply unit provides power to the mainboard computer which is equipped with features like programmable voltage output and time out auto shutdown features. A DC-DC boost converter receives the raw voltage from batteries and converts it to different levels of voltage (5v, 12v, 18v) required by microcontrollers, actuators and sensor payloads. These channels are monitored and displayed on the LCD and protected in case of an overcurrent or overvoltage.

Components	**Avg. Power Required (w)**	**Quantity**	**Total (w)**
Thrusters	60	8	480
Computing Unit	55	1	55
Display Unit	10	1	10
Total Power Required			**545**

Fig. 15 : Power distribution

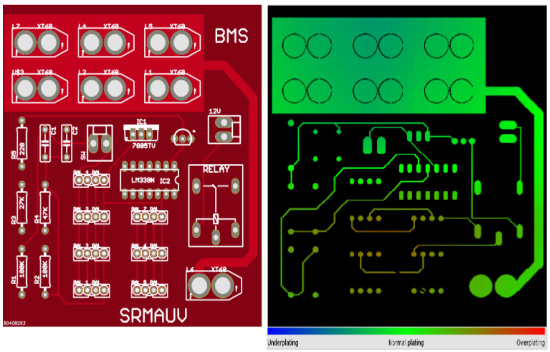


Fig: 16 Battery Management Board

C. Onboard Computer

Computer design for Sedna is governed by the vehicle’s need to perform complex computer vision and machine learning in real time in spite of restrictive space requirements. The software system is powered by an Intel Haswell CPU Core i7-4785T quad core processor with a maximum Thermal Dissipation Power (TDP) of 35W on a Gigabyte GA-Z97N-WIFi motherboard along with a 256 GB SATA Solid State Drive (SSD). The Motherboard requires a non-fluctuating and uninterrupted DC power supply to deliver optimum performance, and it is provided by M4-ATX (250W) PSU. A USB hub interfaces the embedded sensors and actuators as well as other serial devices, i.e. Battery Management System (BMS), AHRS-8 and cameras. The main purpose of the Arduino board is interfacing Sedna’s various sensors and thruster.

Fig: 17 Gigabyte GA-Z97N-WIFi Mini-ITX Motherboard

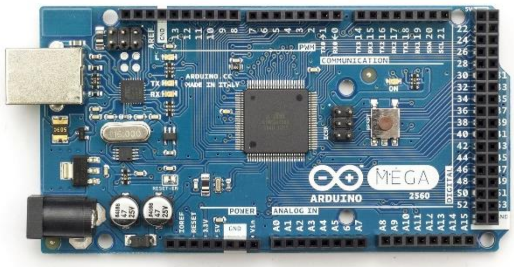


Fig: 18 Arduino Mega 2560

D. Sensors

Sedna is equipped with a suite of sensors used for sensing the environment and providing orientation feedback as well as odometry information.Sensors for current, temperature, inertia, angular velocity, pressure and leakage are used in Sedna. Two vision cameras are provided for driving the image processing software stack. The sensor suite provides 6 degree of freedom state space solution. A brief description of the sensors is given below:

a. Pressure Sensor

The vehicle uses UltraStable™ US300 Series and SWITZER 717-V series submersible pressure transducer to obtain analog pressure data. The sensor returns the pressure exerted by the mass of water above the vehicle. Using Pascal's Law, the depth of the vehicle is extrapolated.

Fig: 19 UltraStable™ US300 Series Pressure sensor

b. Inertial Measurement Unit (IMU)

Sedna is equipped with a MEMS based Sparton AHRS-8 system It is fully temperature compensated and uses Advance sensing technology (3-axis magnetic, 3-axis MEMS acceleration, and 3-axis MEMS gyro) to compute yaw, pitch and roll measurements. It provides critical inertial data at a rapid rate of 100 Hz. The IMU is used to provide vehicle angular velocities and linear acceleration that is used to compute the pose of the vehicle.

Fig: 20 Sparton AHRS-8

c. Camera

Sedna uses two Microsoft LifeCam cinema cameras, one forward and other at bottom. Cameras are used to drive the vision system of the vehicle and are housed in custom fabricated external enclosures that provide a clear field of view to the camera lenses.

Fig: 21 Microsoft LifeCam cinema

d. Current Sensor

A low noise producing current sensor is used in Sedna. Hall Effect current sensors (ACS 709) are used by the power board to get a feedback of current being consumed from the batteries, It continuously monitors the current going in and out of the battery.

Fig: 22 ACS709 Hall Effect Current Sensor

e. Temperature Sensor

Sedna utilizes a LM35 digital thermometer temperature sensor. The digital thermometer has the capability of deriving power directly from the data line, thus eliminating the need for an external power supply. The sensor monitors the temperature within the hull in areas where higher temperatures might be a cause of concern.

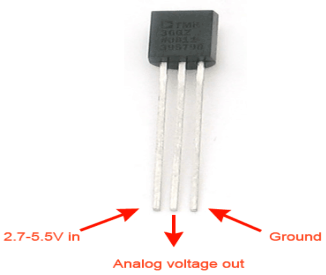


Fig: 23 LM35 Temperature Sensor

f. Leak Sensor

Sedna has integrated leak sensors to detect possible water leaks. It consists of an array of wires. When these wires become wet, an electrical short occurs which is transmitted by a binary signal to the microcontroller and it is processed and desired action is taken. In addition, LED strips are integrated as state indicators. These indicators are especially useful during autonomous runs for understanding the vehicle's current state.

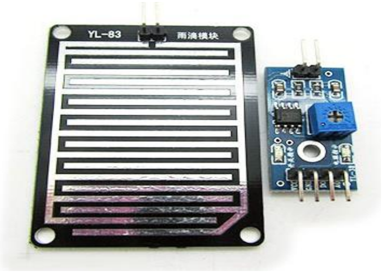


Fig: 24 Leak Sensor

E. Batteries

Lithium polymer batteries built with Li-Po Nano-technology substrate complex are used for providing power to Sedna. The advantage of using these batteries is that there is less voltage sag and a higher discharge rate. The batteries are connected to a Battery Management System, which efficiently supplies power to the thrusters, microcontroller carrier board, CPU and other components used in the AUV. It can power the AUV for 120 minutes continuously.

Fig: 25 Zippy Flightmax 8000mAh

F. Kill Switch

Sedna is provided with a kill switch which is used to shut down the entire AUV system, in an emergency. When the kill switch is activated, it stops power supply to electronic components completely and disables the thrusters. The kill switch minimizes the risk of the AUV getting damaged when an emergency is detected. Emergency situations include water leakage which may cause short circuiting, attacks caused by marine animals and destructive human activities which may inflict severe damage on the AUV.

G. Dropping & Torpedo Circuitry

The vehicle uses a pneumatic cylinder assembly for dropping markers. The piston is actuated using a double acting cylinder, which is connected to a solenoid valve allowing the marker to fall into the bin. This design was chosen due to its low offset and high accuracy.

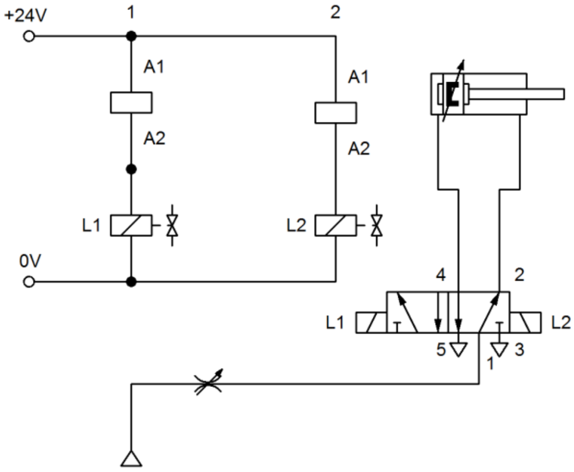


Fig: 26 Dropping & Torpedo Circuitry

G. Thrusters

Sedna uses 4 BTD150 Seabotix thrusters and 4 Blue Robotics T100 series thrusters systemized in three main groups: Two horizontal thrusters for surge, four vertical thrusters for heave and two side thruster for heading and sway control. Each of these thrusters are controlled using an independent motor driver. This enables uniform and accurate propulsion, since it allows for individual control of each thruster's rotation speed. The depth rating of the thrusters is 150 meters in fresh water.

Fig: 27 Thrusters (Seabotix BTD150 and Bluerobotics T100)

H. Hydrophone Array

The Acoustics System enables real-time detection and estimation of the Direction of Arrival (DoA) of underwater impulsive audio signals produced by the pinger. The main objective is to compute the angle and elevation of the source of signal. Signal Processing hardware from National Instrument and a 3-dimensional array of four Sparton PHOD-1 hydrophones are used for the acquisition and real-time processing of the signals. Once the event (impulsive signal) is detected, its DoA is estimated using Generalized Cross Correlation (GCC) with Phase Transform weights (PHAT) to measure the Time Difference of Arrival (TDoA) between pairs of hydrophones. Parameterized predictions of TDoA's are compared to actually measured TDoA's such that the parameter can be obtained by a Least-Squares minimization. Using real-time techniques, there is no loss of information from the environment for the processes of signal detection and DoA estimation occur in parallel.

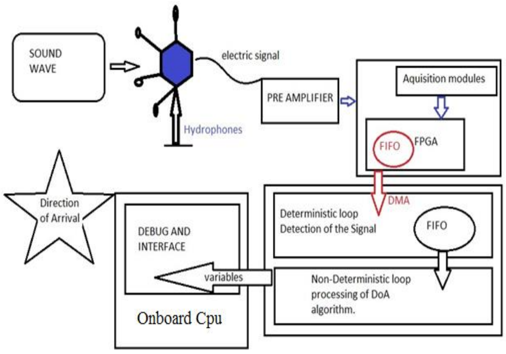


Fig: 28 Acoustics System

Fig: 29 PHOD-1 Hydrophone

SOFTWARE DESIGN

The Software stack of Sedna is built on top of the **Robot Operating System** (ROS) by Willow Garage. ROS is installed on top of **Debian Linux** operating system, running on an Intel core i7 processor. A Mini-ITX on-board computer is provided inside the pressure hull.

The software stack has been designed from scratch this year and provides the following benefits:

- Modular design with optimal task distribution
- Abstract asynchronous inter-process communication mechanisms
- Redundancy in process life-cycles in case of crashes
- Shared memory system for vehicle parameter variables
- Improved front-end controls for easy debugging of missions

The Robot Operating System is an industrial-grade robotics framework which provides various services and tools that significantly reduce design cycle time. The software stack of Sedna is modularized into various processes that are completely independent of each other, yet are able to communicate using an asynchronous messaging protocol.

The software subsystems of Sedna are divided as such:

- Mission Planner
- Motor Controller
- Vision Server
- Action Server/ Action Client
- User Front End
- Telemetry

All these systems are integrated into the ROS infrastructure in the form of nodes with asynchronous communication among them. Topics provide data communication over TCP or UDP and Services provide an XML-RPC request-response call. The software team is mainly responsible for developing software for mission planning, computer vision and active vehicle localization.

ARCHITECTURE

The software architecture of Sedna is divided into two parts:

- A **High Level Architecture** which involves abstract planning algorithms like mission planners and direct waypoint navigation functions. It also includes the vision server which is responsible for image processing and object recognition on the camera images. Most of these algorithms run of the onboard computer.
- A **Low Level Architecture** where the onboard sensors and actuators of the vehicle are interfaced to the microcontroller. The directives from the high level software are fed to the microcontroller which controls the thrusters of the vehicle.

SYSTEMS INTEGRATION:

Sedna's architecture is a highly distributed and abstraction is achieved in the form on "nodes" with asynchronous inter-process communication mechanisms between them.

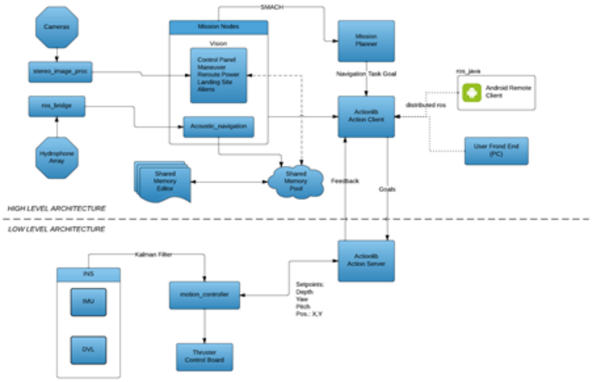


Fig. 30: Software Architecture

The various subsystems are started all at once at runtime and are actively involved in asynchronous IPC once started. The system is fault tolerant with a node being immediately restarted if any system error causes its shutdown.

DESIGN METHODOLOGY

Sedna's software is developed in various layers of abstraction. The low level software comprises the PID controllers, the microcontroller kernel and the communication protocols to interface the microcontroller with the on-board computer. The rest of the software is mostly the high level architecture which sends commands to the low level controllers, e.g. navigational commands.

Sensor data is collected through various sensors

CONTROLLER DESIGN

Robust vehicle control is achieved in Sedna through a combination of 6 carefully Proportional Integral Derivative (PID) controllers. The autonomous operation of the AUV is brought about using set-point directives to the PID control loops. The microcontroller board is programmed with a custom kernel that constraints operating frequencies of the control loops along with loops for collecting sensor data and relaying information to the on-board computer.

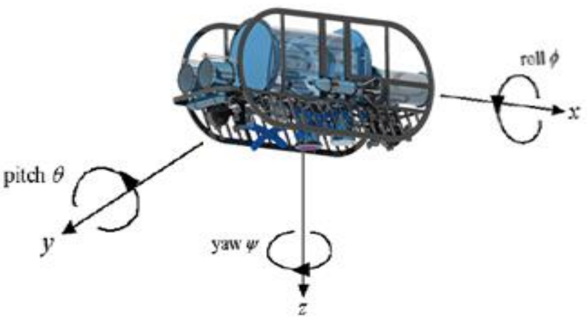


Fig: 31 6 Degrees of Freedom Control

Pose of the vehicle is determined from the inbound IMU data .Each PID controller maintains pose of the vehicle using set-point directives from the High Level Software. The controller computes the error in each of the Yaw, Pitch, Roll, Surge and Sway Axis. A high frequency error minimization algorithm with average weighting of output corrects the pose error to achieve the target set-point.

MISSION PLANNER

The high level planning software is developed using a State Machine implemented in Python using the SMACH (State Machine) library. The competition tasks are described using a set of states with a number of inputs and results associated with each state. The state machine transitions with the successful completion of a task and failure to complete a task would be logged into the system. Each state also has a time-out feature which helps to transition onto the next state in case a task is taking too long to complete.The competition tasks are divided into a set of states that are executed sequentially or iteratively. The design of mission planners is very rapid because of the high level design approach used for developing the state machines. Also, the states of the state machines can be bundled in containers and be reused as abstract state machines inside another state machine.The main link between the High Level and the Low Level architecture of Sedna is the Action Server and the Action Client interface. The Action server is used to send goals to the Action Client which executes them until completion. Benefits of using the action sever include execution of pre-emptive goals, active goal completion feedback and fault tolerance.

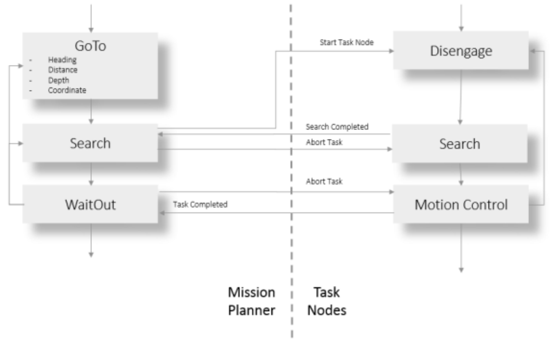
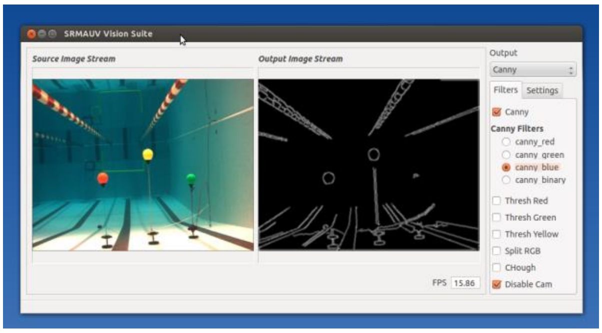


Fig. 32: Mission Planner Flowchart

I. VISION SERVER

The vision server of Sedna is the main system for image processing. The images are obtained using a set of two cameras onboard the vehicle, one for forward and another for bottom vision .



Output: Canny

☑ Canny

○ canny_red
○ canny_green
● canny_blue
○ canny_binary

☐ Thresh Red
☐ Thresh Green
☐ Thresh Yellow
☐ Split RGB
☐ CHough
☑ Disable Cam

FPS 15.86

Fig. 33: Vision Debugging Suite

The image processing software employs a series of algorithms to detect and segment underwater objects. The main task of the vision server is to compute the geometrical co-ordinates of various underwater objects and relay the information back to the vehicle controllers. An example image processing pipeline to detect a colored Buoy can be summarized as follows:
We white balance the input image to improve the contrast. For providing lighting invariance we make use of an appropriate color space. This is followed by segmentation of objects in the image using color thresholding. A set of erosion and dilation filters is implemented to smoothen out the resultant binary mask. Circular Hough Transform is applied on this binary image to detect circular contours. The biggest circular contour is then selected which corresponds to the target buoy. To this image we apply cvMoments to compute the inertial center of the buoy. Finally the computed information is relayed over a ROS Topic so that other subsystems can utilize it

Vision Debugging Suite

The Vision Debugging Suite is a Vision Front-end that is used to dynamically view the results of the image processing pipeline. The vision server provides active controls to vary the image processing parameters using the Dynamic Reconfigure API under ROS.
The Vision Suite GUI is designed using the Qt framework. There are provisions to add various filter chains and analyze the collective effect on the input image. This is very helpful to debug image analysis errors and vary the input parameters accordingly. The result of the process in viewed in real-time.
The vision suite is extensible and new features can be added with seamless integration to the old software. The messaging system that is employed is based on ROS messages. The GUI interface can be used to change the Dynamic Reconfigurable Server parameters. Another feature provided by the Vision Suite is saving a visual feed to the disk. This feature employs rosbag services to log the data. The saved visual feed can also be played back for inspection at a later point of time.

ACKNOWLEDGEMENT

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