DTU AUV Design and Development of the Autonomous Underwater Vehicle 'ZYRA'

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***Abstract*-Autonomous Underwater Vehicle are powerful and complex systems which are capable of performing underwater (shallow and deep sea) tasks like bathymetry calculation, detection of faults in oil pipelines, collection of deep sea water samples, counting of fish and even complex tasks like collecting data which aids in understanding global warming.**

This paper presents the design and development of a littoral autonomous underwater vehicle named 'ZYRA' (5th generation vehicle) which has been developed by a team of undergraduates of Delhi Technological University. The design and development as well as rationale behind the design of various systems such as the Control systems, mechanical design, embedded and power systems, vision and acoustics location estimation system which form the integral part of ZYRA has been discussed in the paper.

I. INTRODUCTION

The aim is to design and develop an Autonomous Underwater Vehicle which will serve as a technology demonstrator, having following features:

- Highly compact, multirole, customizable platform which can be used for various missions with independence of choosing payload and thus deciding mission backup time.
- Target localization using image processing and passive SONAR.
- Dynamic control by achieving co-ordinates using PID Control algorithms.
- Pilot Software to control an AUV.
- Underwater Communication / retrieval of data.
- Implementation of grabber, dropper, torpedo firing and other underwater actuators.

ZYRA is the product of completely redefined mechanical assembly to embedded and control systems. This year it has a new custom made LiPo battery pack, a novel power distribution, redesigned actuator control board, battery monitor, leak sensor, an acoustic signal processing module and improved software.

II. MECHANICAL DESIGN

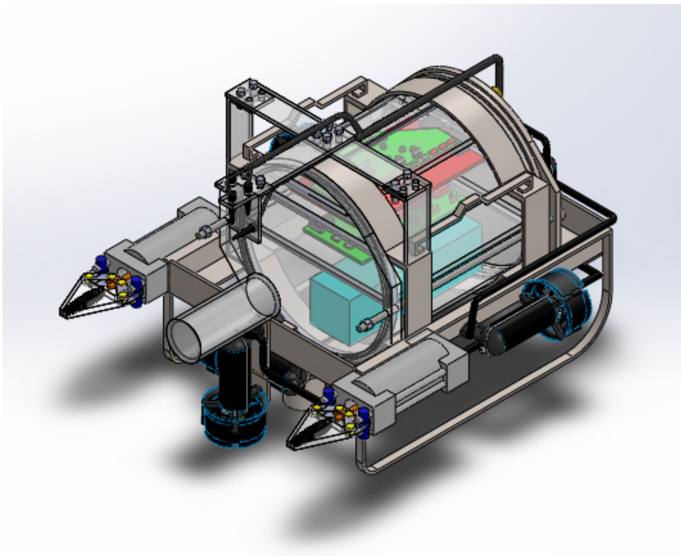


Fig1: Assembly of 5TH Generation model

The mechanical model of ZYRA is designed to be in hydro dynamically stable equilibrium both below and above water surface. The mechanical system consist of main pressure hull, front and back lids, frame, electronics rack. The vehicle will feature a smooth contoured cylindrical pressure hull. The fabrication material chosen for pressure hull is Virgin Cast Acrylic (Clear) because of its excellent workability, strength, shock resistance and comparatively low density. Simulation is done on hull at underwater depth of 10 m and Factor of safety so found out is more than 7.8.

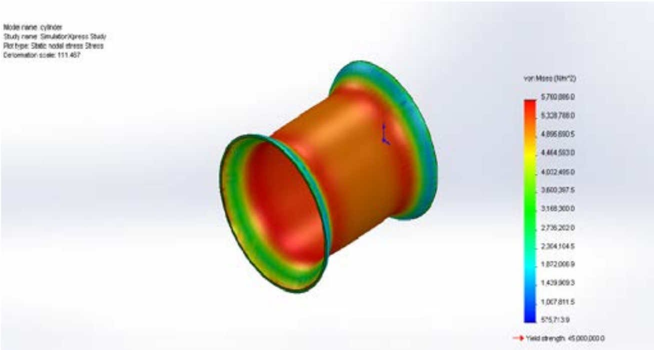


Fig 2: Solid works simulation of main hull

The body shall be propelled by six thrusters and has net positive buoyancy. The frame is so designed to ensure easy mounting of thrusters, sensors, grabbers etc. The profile of the vehicle makes it highly manoeuvrable.

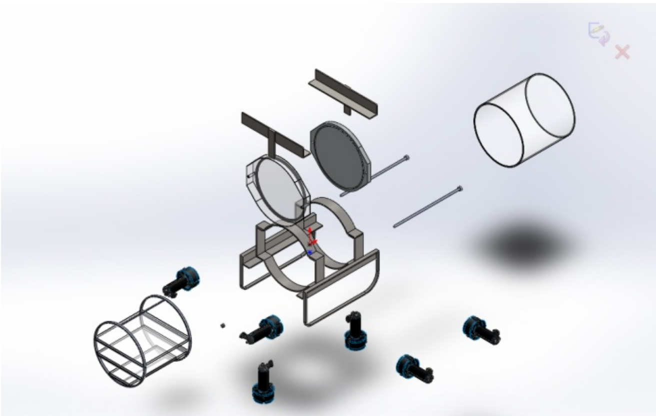


Fig 3: Exploded view of assembly

The front lid is made of virgin cast acrylic .Its transparency ensures clear and unobstructed view for the forward camera that will be mounted inside the hull. Back-lid will be made of aluminium. Its smooth surface will ensure easy and efficient installation of connectors and aluminium being a good thermal conductor will also help in heat sink**.**

III.ELECTRONICS HULL

The main hull of ZYRA is of cylindrical shape. The shape of the vehicle has been decided after calculations, keeping various hydrodynamic parameters in mind to improve the overall performance of the robot.

IV. METAL FRAME

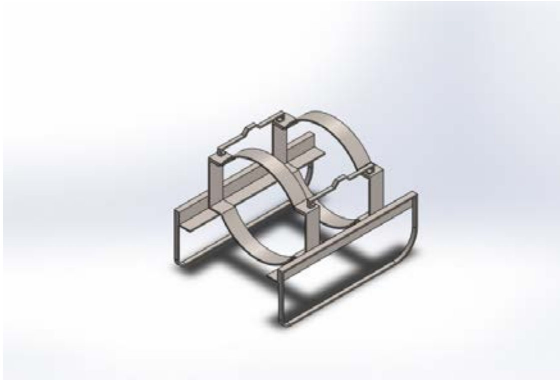


Fig 4: Solid works model of main frame

Main frame is designed to ensure easy installation of thrusters, grabber, hydrophone array etc. The main consideration while designing it was that unwanted stresses on hull are uniformly and efficiently transmitted to whole frame and prevent cracks. Some of its components are made up of Stainless Steel GR316 and others are of Aluminium. The reason for this approach is to have a suitable combination of weight, buoyancy, resistance to corrosion along with low maintenance, high strength and ease of fabrication.

V. VEHICLE DYNAMICS

Six strap-on BTD-150 thrusters from Seabotix Inc. are used to manoeuvre the vehicle. Two thrusters facilitate motion in the horizontal direction, while other two facilitate the vertical motion. Two additional thrusters are being used to control strafe and rotations about z-axis i.e. yaw. They are chosen because of their high thrust to weight ratio and safeguards for power surges and ground shifts. These thrusters provide a two blade bollard thrust of 2.9 kgf and require power in the range of 80-110 watts depending on conditions outside.

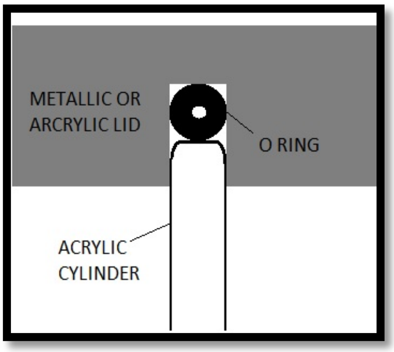


Fig 5: O-ring mechanism

VI. ELECTRONICS FRAME

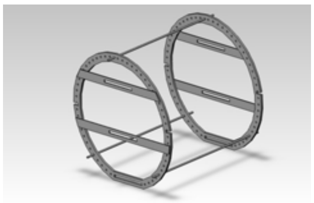


FIG 6: Solidworks model of electronics frame

All electronic components are housed inside the electronics hull. Components are placed in racks inside the main hull so as to facilitate easy removal of component in case of a technical fault. The rack is so designed to ensure easy addition of new shelves later as per requirements and least length of wires. Battery is placed at lower most shelf to ensure lower centre of gravity and improve stability and resist roll.

VII. UNDERWATER CONNECTORS

Connectors from Samtec provide effective leak proof electrical connections from systems outside to the main circuitry present inside the hull and are easy to install and dismantle.

VIII. GRABBER MECHANISM

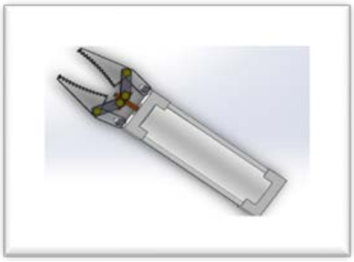


Fig 7: Grabbing mechanism

Grabber mechanism uses a servo motor with rack and pinion mechanism which moves the polycarbonate jaw and holds the object.

IX. HYDRODYNAMICS

ZYRA is a 0.6m long hydro dynamically stable AUV, designed and built by DTU AUV.

Type	Volume Flow Rate	Environment Pressure
Faces	<0>@tube-1	<1>@tube-1
Value	Volume Flow Rate: 1.7200 m^3/s Temperature: 293.20 K	Environment Pressure: 101325.00 Pa Temperature: 293.20 K
Result	Max Velocity	0.646 m/sec

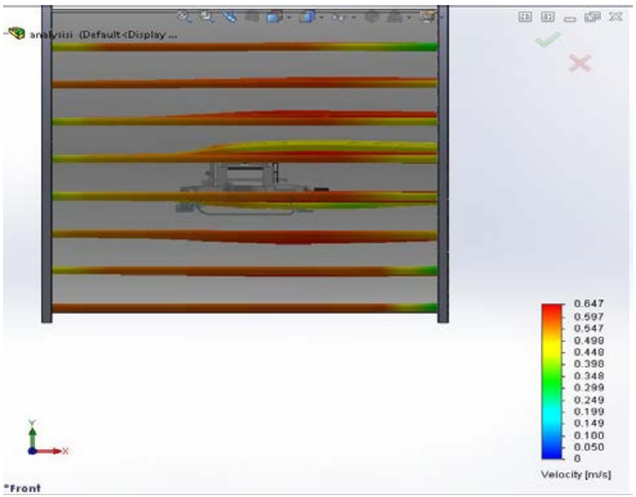


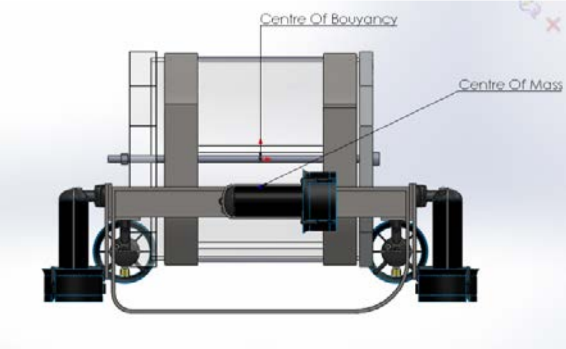
FIG 8: Flow Simulation of Zyra

TABLE I
CHARACTERISTICS OF ZYRA

Dimensions	60cm x 40cm x 51 cm
Diameter of the hull	30cm
Dry weight	32 kg

Propulsion	4 horizontal + 2 vertical thrusters
Horizontal velocity	0.5 m/s max.

X. STABILITY:



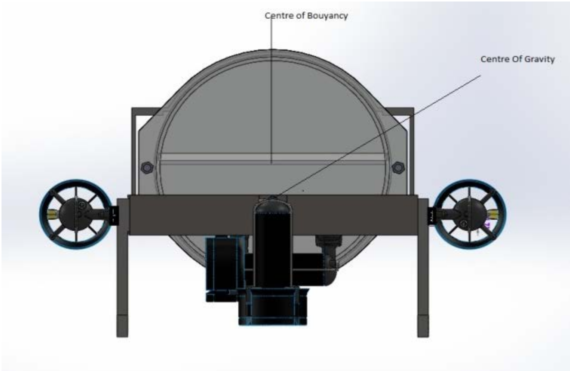
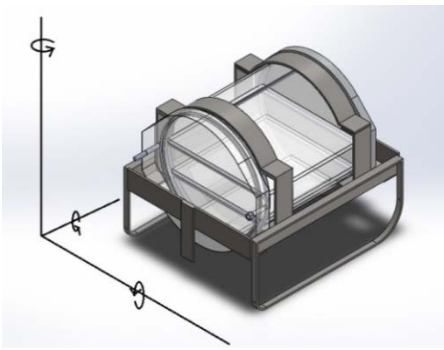


FIG 9 Centre of buoyancy and Gravity in same vertical line

The AUV is designed in such a way so that the Centre of Gravity and Centre of buoyancy lies in the same vertical line.

XI. DEGREES OF FREEDOM:

The six thrusters are installed in such a way that the vehicle has 6 Degrees of Freedom including rotational motions like roll, pitch and yaw.



XII. ROBUSTNESS

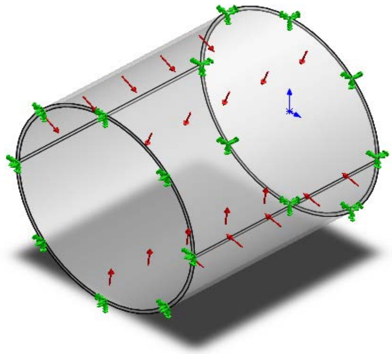


FIG 10 depicts the fixture and face of pressure application

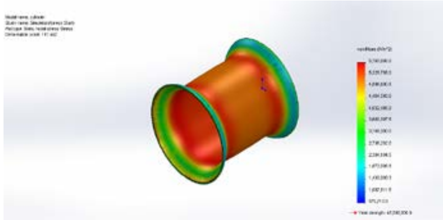


FIG 11 Von Mises Stress distribution

Based on the specific parameters the lowest factor of safety (FOS) is found out to be 5.18 , thus ZYRA can dive safely till 60 ft.

XIII. EMBEDDED AND POWER SYSTEMS

For this year AUV, "ZYRA" the focus of electronics department is primarily on implementation on acoustic positioning module and actuator board for control of 6 SeaBotix thrusters and weapons system. A new power distribution board is designed for voltage regulation and to provide power directly to all the systems through one particular board which would eliminate the need of further bucking of voltage and hence concentrates the heat dissipating unit in one particular section of hull which can be placed near the metal ends to allow heat exchange with the water.

XIV. POWER SYSTEMS

The electrical power system is comprised of lithium polymer (LiPo) battery, encased within the main electronics hull. The battery is rated at 18000 mAh at 18.5V. The battery protection board monitors voltage of each cell and shuts off the power if the voltage drops to 16V, also the overcharge and current drawn is monitored by the same. It is connected to a Power Distribution Board (PDB) which is responsible for diverting power to various modules on the bot. The PDB is equipped with fuses in case of battery/circuit failure, multiple capacitors to smooth out ripples, and eliminates high frequency noise. The PDB divides the power and provides regulated power supply to sensitive electronics. It provides Zyra with clean, isolated, and regulated power at 5V, 12V, and 18.5V.

XV. ACTUATOR CONTROL

The actuator board used for ZYRA is custom designed. It takes in care the electromagnetic interference from the thrusters which distort the motor control signal coming from the microcontroller unit dsPIC30F2010. This microcontroller is responsible for taking in signals from the central processing board through packetized serial interface. The microcontroller is capable of processing at 30MIPS.

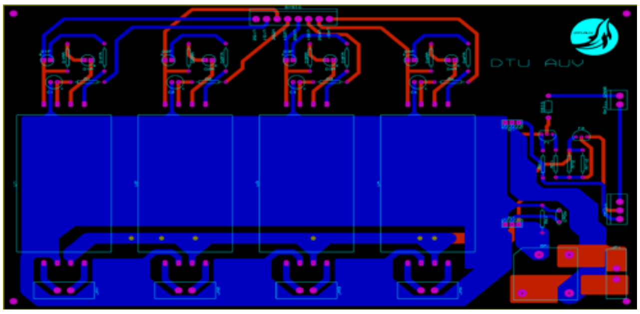


Fig 12 : Schematic of Actuator Board

The motor controllers from Dimension Engineering are capable of functioning at ultra-high frequency of 32 KHz thus making inaudible for human ears and eliminate the irritating humming noise. The controllers can be configured to use either in tank style differential drive or analog voltage control. The microcontroller unit receives signals specifying direction and speed of the Zyra which in turn actuate the required thrusters. A hermetically sealed switch is responsible for killing the power to the propulsion system. Along with hard kill a soft kill is also incorporated in the code.

Analog voltage is used to control the speed of thrusters with another signal to specify the direction of motion. PWM motor controller of dsPIC30F2010 is used to generate variable duty cycle PWM signal which is filtered and smoothed into an analog signal (0V-5V) via a high capacitance, RC filter. The added advantage of mounting syren-10 on the actuator board is that any particular controller can be replaced in case it gets damaged and thus prevailing re-usability of the board.

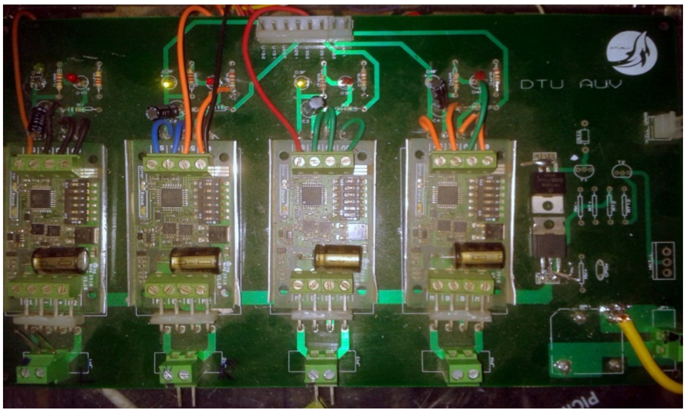


Fig 13: Actuator Board.

Learning from past experiences, the propulsion system of ZYRA have been completely redesigned. The communication of Master Computer and Micro-controller have been changed from RS-232 protocol to TTL. Instead of the fact that RS-232 is noise tolerant, the communication to UART is done using USB-TTL chips.

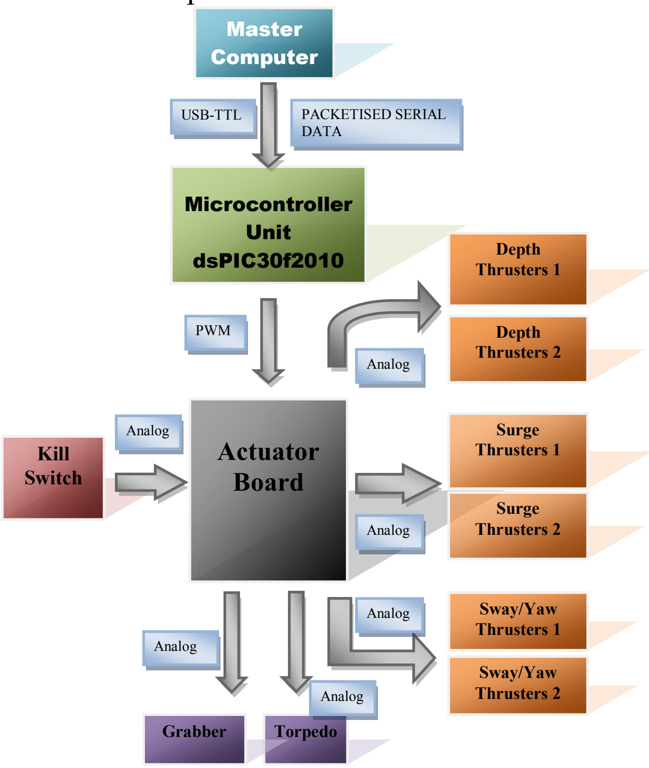


Fig 14 : System Architecture of navigation control

XVI.ELECTRONICS RACK

Modularity of the vehicle has been the priority of the team. Electronics Rack which holds all the electronics and can be removed from ZYRA without disturbing the rest of the system has been developed.

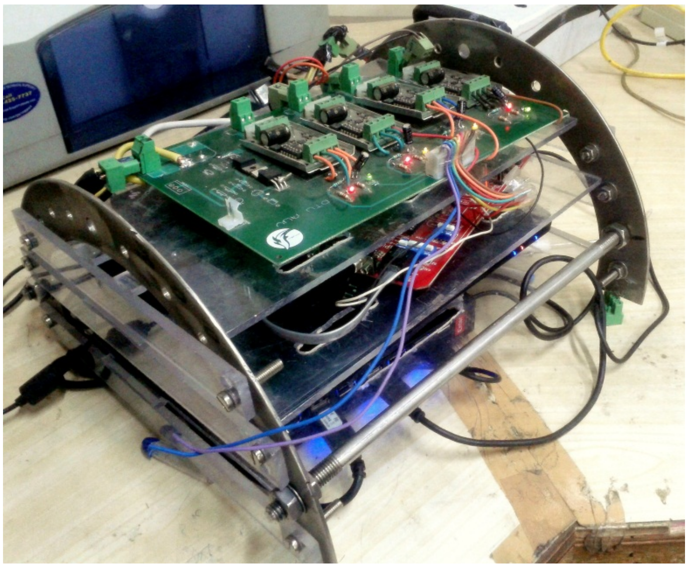


Fig 15: Electronics Rack of ZYRA

The level of various racks can be varied according to payload.

TABLE II COTS Used in ZYRA

Device	Model
Kontron Motherboard	986LCD-M/mITX
Battery	Li-Po 18.5V , 18000mAh
Actuator Controller	dsPIC30F2010 (dsPICDEM 2)
Motor Controller	Syren 10
Camera	Microsoft LifeCam-3000 Logitech HD Pro C920
Propulsion	SeaBotic BTD-150
Pressure Sensor	Applied Measurements Pi9933
IMU	XSENS MTi-28A
Data Acquisition	NI PCI-4462 NI USB-6210
Servo	HiTec HS5646WP
Hydrophones	Reson TC403

XVII. SOFTWARE PLATFORM

The use of Labview, developed by National Instruments, has been decided to develop our software framework. The software is designed to run in decentralized multi-threaded agent architecture, with the threads handling pressure sensor, acoustics, cameras, control system, IMU, each performing input and output operations in continuous loops. It's GUI based coding, ease of onsite debugging and quickly changeable mission strategy is the main reason for it to be preferred over conventional 'C' based coding. Even though vision sub modules have been tested on OpenCV and acoustics modules on MATLAB, everything has been finally integrated into Lab View to keep a uniform software platform.

ZYRA has interactive Graphical User Interfaces (GUIs) developed for acquiring data from all sensors, adjusting control parameters, implementing individual codes, as well as for the mission control using Lab View. This helps quick onsite editing of codes / mission parameters, payload & target selection even by a person with very minimal knowledge of the coding languages. This complies with the basic idea a highly modular, flexible and multiple application AUV platform.

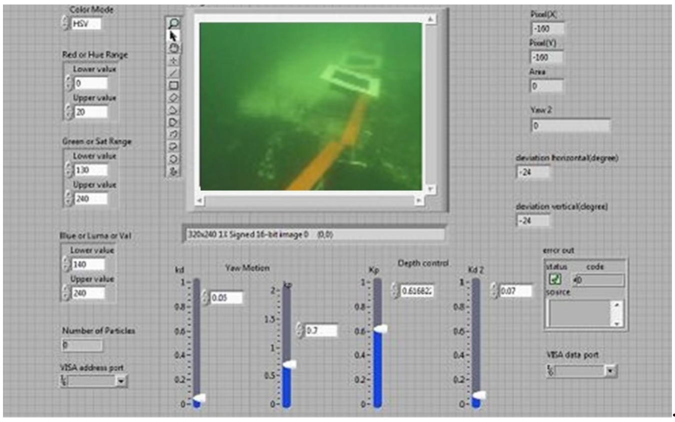


Fig16 : Operator status screen during AUV mission run .

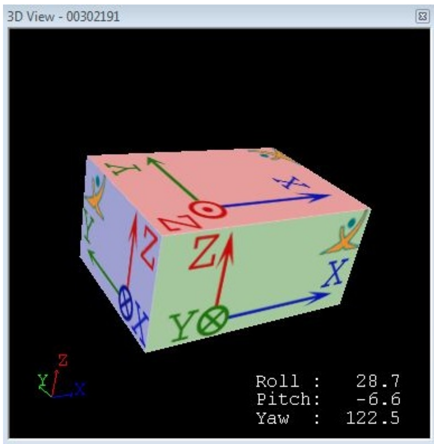


Fig 17 : Orientation data received from IMU used as an input in Control system module.

XVIII. MISSION PLAN MODULE

Mission plan module of ZYRA is responsible for the artificial intelligence of the vehicle. It is at the highest level in the software hierarchy, coordinating the global state of the AUV and the state of each subsystem. It makes calls to sensor modules like vision, sound etc. determine the position and orientation of the AUV and to identify targets in the arena. The mission plan module coordinates the state of the AUV as it goes through the entire mission arena. It has a scheduler/ timing module which times each operation and is capable of making smart decisions of leaving a task and moving to the next one based on mission time elapsed and pre-written contingency plans. Once the AUV determines what type of action is to be performed, it calls the control module which commands the actuators to function precisely.

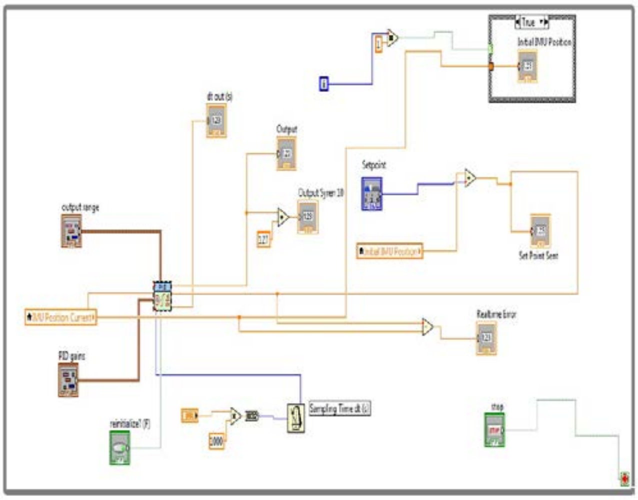


Fig 18 : GUI based PID loop coding in Labview.

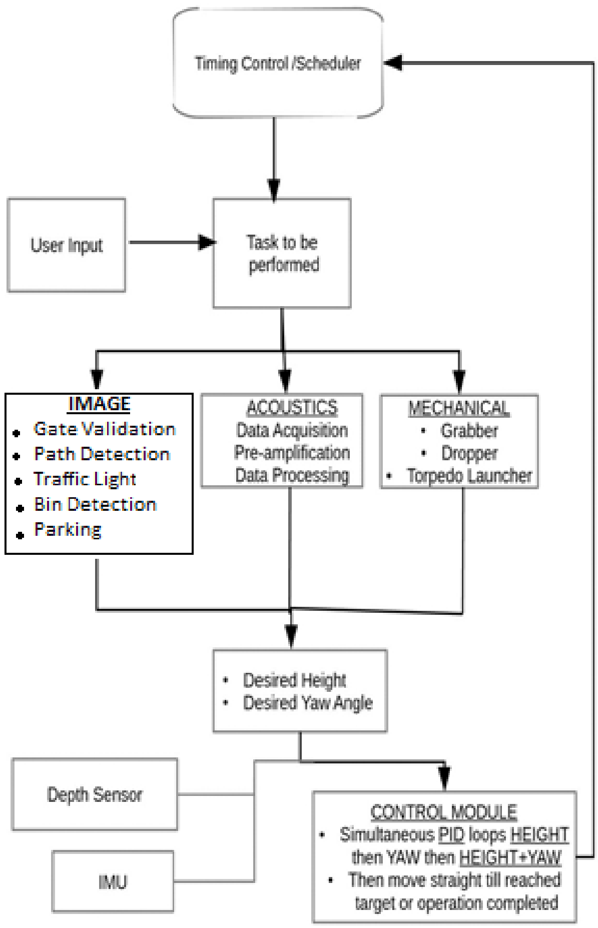


Fig 19 : Various software modules working in tandem to achieve mission control.

XIX. CONTROL MODULE

Control module is called by the mission plan module as and when required to change the orientation and position and orientation of the AUV based on the operation being pe8rformed and input from vision, acoustic, depth and other sensor modules. Control module maintains the orientation of AUV using continuous PID loops running simultaneously. It relies on the mechanical stabilization for both roll and pitch movement, and thus, only the yaw, depth and horizontal movement of AUV is controlled by this module. The PID control algorithm has been coded in Lab View. This method has proven to be more efficient, less processor intensive and easily implementable. The system attempts to maintain its state using dynamic feedback from the IMU, pressure sensor and the acoustic and vision modules. User interfaces have been specifically developed to tune and adjust the PID parameters easily.

XX. MISSION CONTROL APPROACH TOWARDS THE ROBOSUB PROBLEM STATEMENT

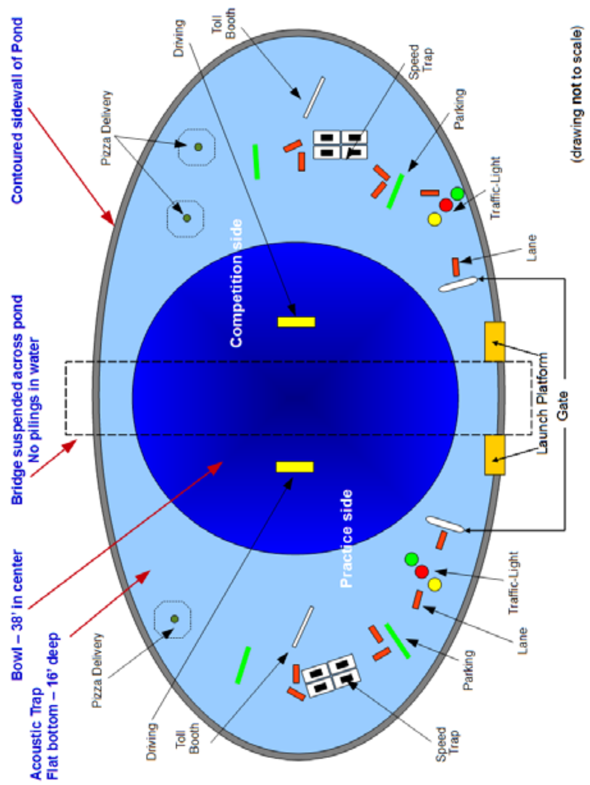


Fig 20 : Arena for ROBOSUB Competition.

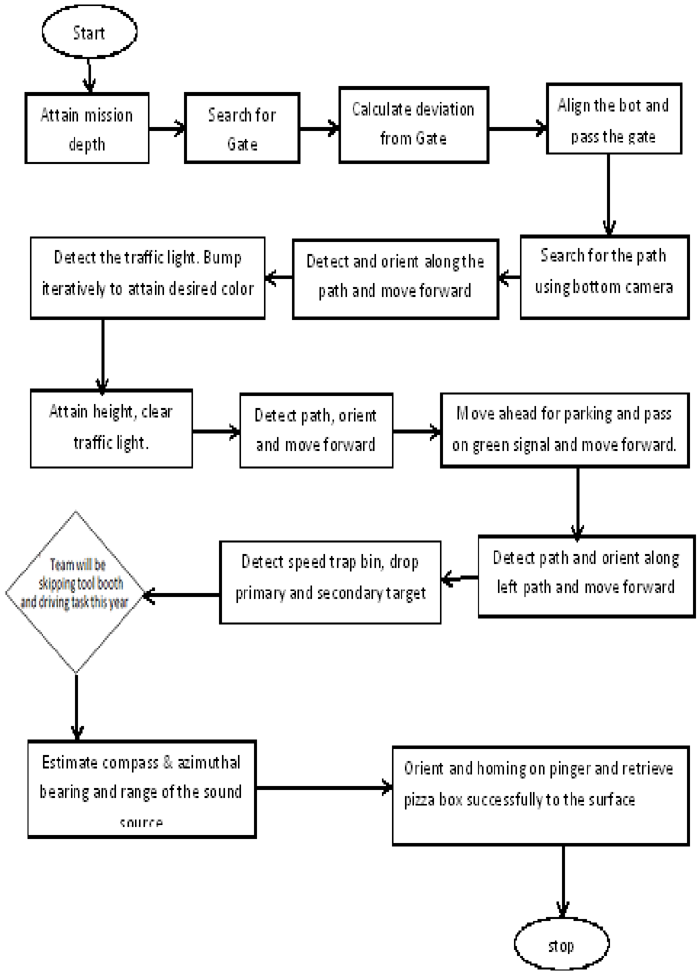


Fig 21: Flowchart showing ROBOSUB mission controller's approach on how to complete the whole track of the ROBOSUB competition's problem statement .

XXI. IMAGE PROCESSING

The Computer Vision module was developed using the "NI Vision" library in NI LabView. The high Parallelism during execution of programs on multi-core CPUs in LabView gives the vision module the required real-time computational power. The module incorporates concepts involving image processing, particle analysis, image segmentation, binary morphology and machine vision. The major change this year is that the navigation system works on absolute yaw (angle) control. The previous generation vehicles had a less accurate navigation system partly based on heuristics.

XXII. GATE VALIDATION

The forward facing camera is used in this task. The image is segmented for the specific color. An edge filter is then applied to the binary image thus formed. The Center of Symmetry of vertical edges thus gives the correct heading (in degrees) to the vehicle.

Fig 22: Original Image

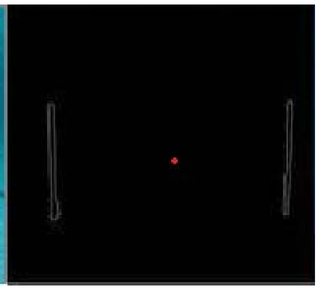


Fig 23: Image after edge detection

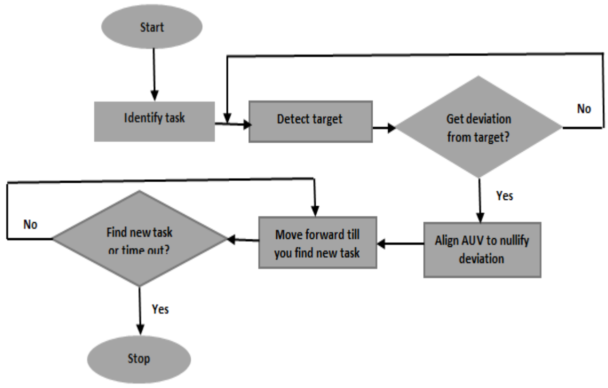


Fig 24: Generalized flow chart for target detection using Image Processing.

XXIII. PATH DETECTION

For path detection our vision algorithm receives video feed from the downward facing camera and outputs a heading relative to the AUV. To accomplish this we employed "colour based segmentation" along with "blob analysis".

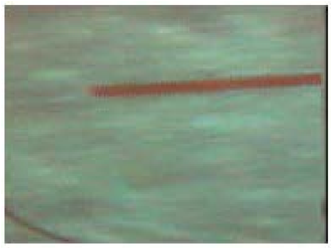


Fig 25: Original Image

Fig 26: Processed Image

XXIV. TRAFFIC LIGHT DETECTION

The next task we have to do is "Traffic light detection". Algorithm for traffic light detection is similar to that of path detection. This algorithm receives video feed from the forward facing camera. Similarly to path, the goal of this algorithm is to output a target pixel, or a target point. Color based segmentation is used for this purpose. The HSV colour space is used for all segmentation based operations. The algorithm segments out the red colour, giving a binary image. Then the binary image is passed through filter to remove noise .The particles in the binary image are then analysed and the centre of the largest connected particle gives the current heading. The vehicle tries to approach the flare keeping the centre at 0 degrees.


Fig 27 .Original Image

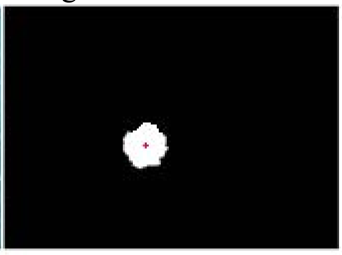


Fig 28. Processed Image

XXV. BIN DETECTION

The downward facing camera is used for bin identification. The algorithm implements concepts of pattern recognition and is able to differentiate between the given geometrical patterns. The centre of the bins is found by calculating the centre of symmetry of the edges found in the captured image of the bin. (The white-black edges are only considered). The marker is then dropped after the vehicle aligns according to the centre given by the algorithm.


Fig 29: Original Image


Fig 30: Processed Image

XXVI. UNDERWATER SOUND SOURCE LOCALISATION

ZYRA has an acoustic navigation system which employs a Square/Tetrahedron array of hydrophones for data acquisition to calculate azimuthal & compass bearing and estimate hyperbolic location of the sound source in far-field approximation using Time difference of arrivals (TDOAs).

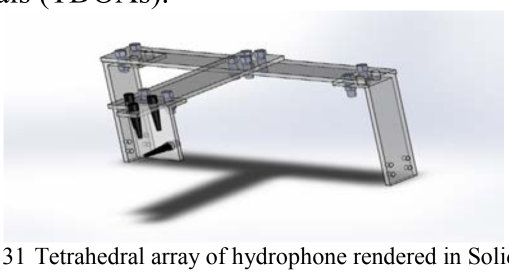


Fig 31 Tetrahedral array of hydrophone rendered in Solid Works

Above figure shows a tetrahedral array of hydrophones which have been used for the localization of the sound source. A symmetric array such as the above helps in eases calculation while making the time difference of arrival measurements.

Hydrophones are basically piezoelectric material which responds to any physical disturbances in water. The acquisition of signals is done through NI Data Acquisition Card which pre-amplifies the received weak and feeble signals and then Analog to Digital conversion.

The Generalized cross-correlation technique using phase transform (GCC-PHAT) is employed to calculate the time difference of arrival corresponding to the correlation peak. Estimated TDOA's give bearing estimation for far field approximation. In environments of high levels of reverberation GCC-PHAT helps to improve robustness and accuracy in calculating the time difference of arrival [3], [4]. We can see from the above MATLAB simulation that GCC-PHAT enhances the peak and whitens the region around it, whereas in the Cross Correlation simulation the region around the peak displays some ripples, also the peak is not that well defined as it is in the GCC-PHAT. Both the methods show similar performance under noise, GCC-PHAT is better in case of added reverberations.

Estimation of range is done by solving the hyperbolic TDOA equations using 'Chan and Ho' method which is non-iterative and gives an explicit solution. It is an approximate realization of maximum likelihood estimator and is shown to attain

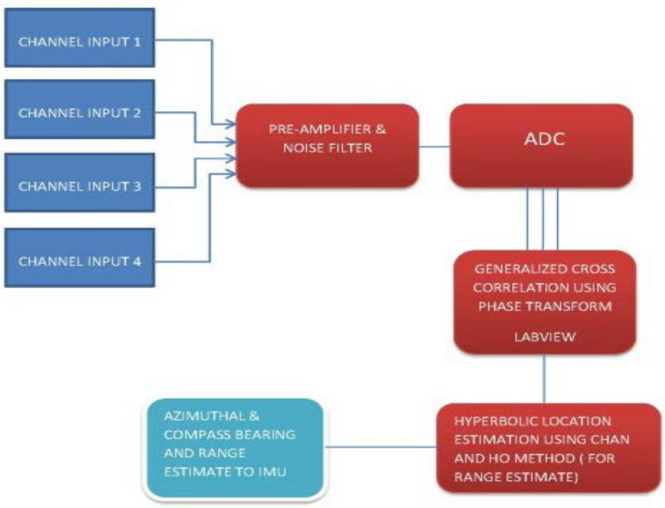


Fig 32 Acoustic System Flowchart

the 'cramer-rao' lower bound near small error region

It is clear that a pair of hydrophones yields one equation so to localize a source in 3-D we need three equations i.e. a minimum of 4 hydrophones are required to successfully locate the source in far field

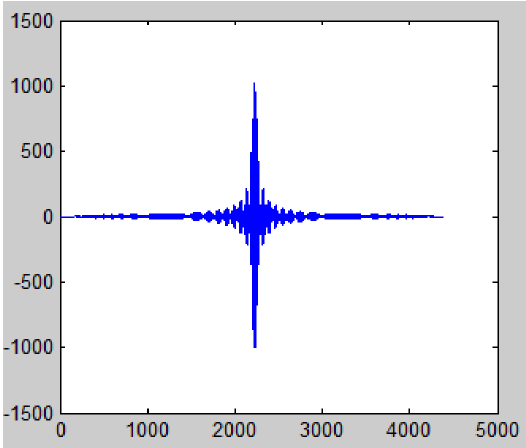


Fig 33. Typical Cross Correlation function simulated in MATLAB

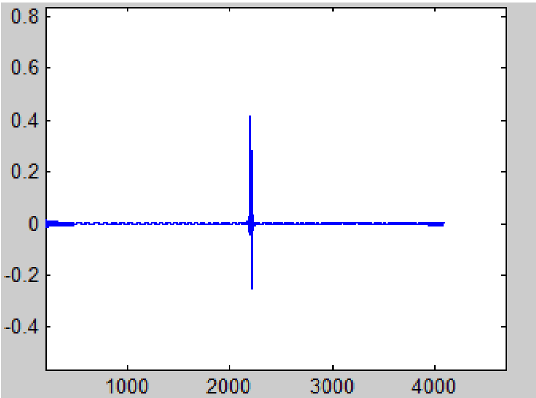


Fig 34. Typical GCC-PHAT simulation in MATLAB

XXVII. ACKNOWLEDGMENT

Team DTU AUV wishes to extend its thanks to past and present sponsors, namely ONGC, Yamaha, Samtec, NIOT, Seabotix and National Instruments. Further thanks to our faculty advisors P.B.Sharma and Prof. R.K.Sinha. We are grateful to Mr. Anil for providing his pool for testing. Without these individuals' support, DTU AUV's work would not have been possible.

XXVIII. VEHICLE STATUS

ZYRA is right now in testing phase. Testing phase was started late in June 2013 only after the novel actuator board started working error free and mechanical systems were totally leak proof . Team is spending at least 3 hours in pool daily and is working on schedule to participate in Robosub 2013.

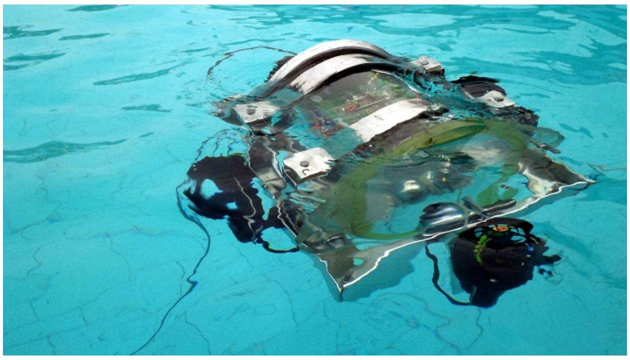


Fig 35. ZYRA inside pool for testing.

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