Delhi Technological University: Design and Development of the Littoral AUV Zyra 2.0

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Abstract—**The Delhi Technological University Autonomous Underwater Vehicle project team's main objective is to design and develop an autonomous underwater vehicle for the AUVSI and ONR International Robosub-2014 competition. The competition is held at the TRANSDEC facility, part of SPAWAR Systems Center Pacific in San Diego, California. The paper presents the design and development of a modular littoral autonomous underwater vehicle called 'Zyra 2.0' having four degrees of freedom for performing the following tasks underwater target localization and homing, buoy detection, path following, obstacle detection and obstacle manipulation tasks. The development of the AUV has been divided into five departments namely mechanical design and fabrication, embedded and power systems, control and software, image processing, underwater acoustics. A fully functional AUV has been tested in a self created arena with different tasks spread out in a shallow water environment.**

I. Introduction

Autonomous Underwater Vehicle are powerful and complex systems which are capable of performing underwater (shallow and deep sea) tasks. The range encompasses bathymetry calculation, detection of faults in oil pipelines, recovery and monitoring of submerged installations and even complex tasks like collecting data which aids in understanding global warming. The aim is to design and develop an Autonomous Underwater Vehicle which will serve as a technology demonstrator which is highly compact, multirole and can be used for various missions with the independence of choosing payload. Zyra 2.0 is the product of completely refined mechanical assembly, control systems, embedded systems, vision system and acoustics module. The mechanical model of Zyra 2.0 is designed to be in hydrodynamically stable equilibrium both below and above water surface. The mechanical system consist of main pressure hull, front and back lids, frame, electronics rack. The focus of embedded and the power systems department is mainly on the implementation of acoustic positioning module, actuator board and the designing of a power distribution board for diverting power to various modules on the AUV [1]. Dynamic control is achieved by retrieval of coordinates using various PID control algorithms [2],[3]. 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. The mission plan model is also taken care by the control department as it is responsible for the artificial intelligence of the vehicle [4],[5]. The vision system is designed to perform tasks like buoy detection, bin detection, path detection, entry gate detection. The image processing software consists of various colour filters, edge and line detection algorithms. For the target(sound source or pinger) localization the AUV employs a three dimensional array of hydrophones forming a passive SONAR system. The data acquired through hydrophones is passed through a amplifier, filter and detector circuit before it is converted into its digital form for further processing. The localization task is a sequential task in which first we calculate a set of values of TDOA(Time Difference of Arrival) using the hydrophone signals and using these values we estimate the bearing and the position vector of the sound source with respect to the AUV. For the experimental testing of the AUV an arena is created in a shallow water area and the tasks of entry gate detection, buoy detection, path detection and sound source are spread throughout the arena.

II. Mechanical Design

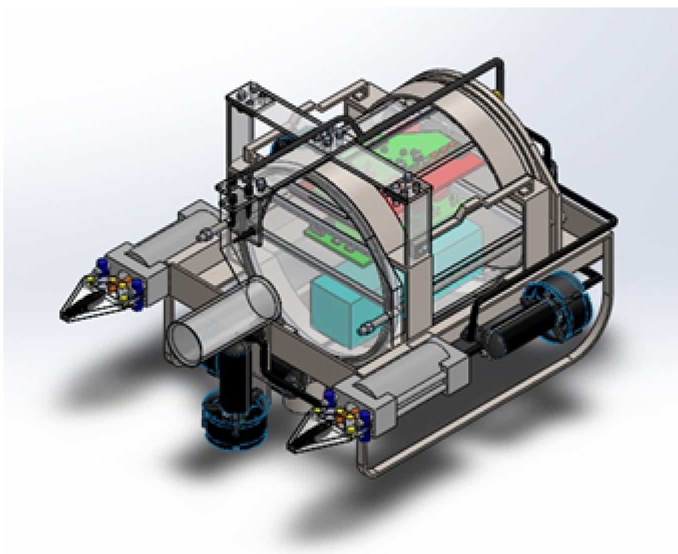


Fig. 1. Solidworks Assembly of Zyra 2.0

Zyra 2.0 is the product of indigenously designed mechanical assembly to embedded and control systems. It has a custom made LiPo battery pack, a novel power distribution board, redesigned actuator control board, battery monitor, leak sensor, an acoustic signal processing module and improved software. 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 is found out to be more than 5.1.

The body shall be propelled by four thrusters and has a 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. The front lid is made

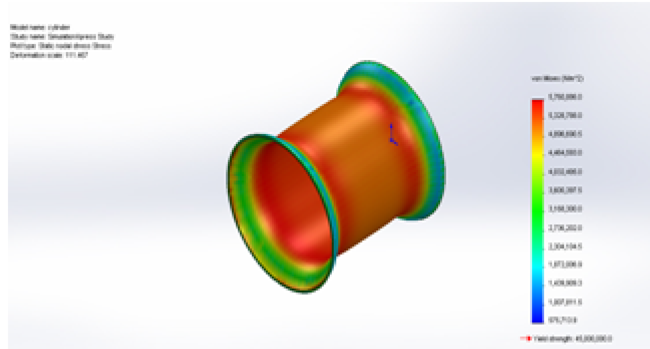


Fig. 2. Solidworks simulation of the main hull-Von Mises Stress distribution

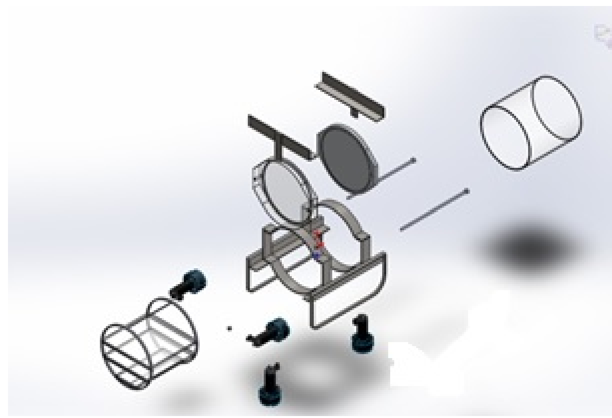


Fig. 3. Exploded view of assembly

of virgin cast acrylic .Its transparency ensures clear and unobstructed view for the forward camera that is 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 as a heat sink.

A. Electronics Hull

The main hull of Zyra 2.0 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. 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 the whole frame and prevent cracks. Some of its components are made up of Stainless Steel GR316 and others are of

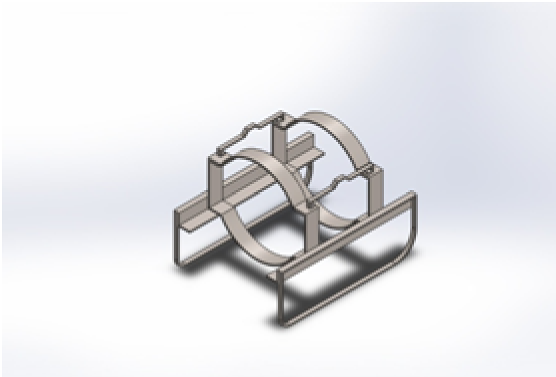


Fig. 4. Solidworks model of main frame

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. The hull is waterproofed using Toggle Clamps instead of Rods for faster opening and closing of the rear lid.

B. Vehicle Dynamics

Thrusters: Four strap-on BTD-150 thrusters from Seabotix Inc. are used to manoeuvre the vehicle. Two thrusters facilitate motion in the horizontal direction as well as yaw motion when operated in differential mode, while other two facilitate the vertical motion. These thrusters provide a two blade bollard thrust of 2.9 kgf and require power in the range of 80-110 watts depending on the conditions outside. 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.

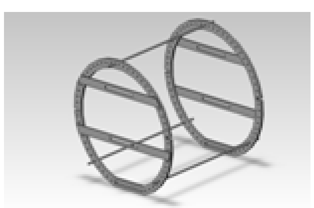


Fig. 5. Solidworks model of electronics frame

C. Degrees OF Freedom

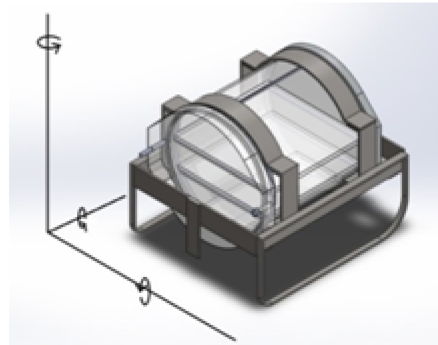


Fig. 6. Zyra 2.0's Degrees of Freedeom

The four thrusters are installed in such a way that the vehicle has four degrees of freedom namely heave, yaw, pitch and surge.

D. Stability

The AUV is designed in such a way so that the centre of gravity and centre of buoyancy lie in the same vertical line.Fig.7 displays the stability parameters.

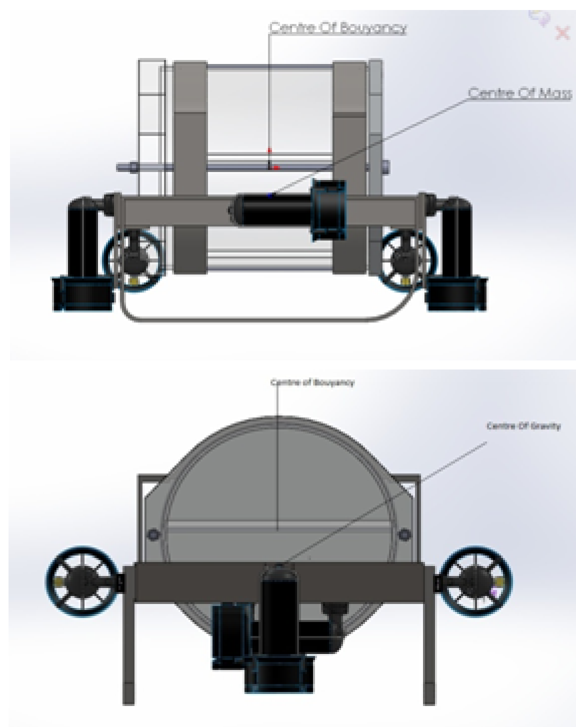


Fig. 7. Centre of buoyancy and gravity in same vertical line

TABLE I
CHARACTERISITICS OF ZYRA 2.0

Property	Value
Dimensions	70cm x 40cm x 50 cm
Diameter of Hull	30cm
Dry Weight	35Kg
Length of Hull	37cm
Propulsion	2 horizontal + 2 vertical thrusters
Velocity	0-1.5m/s

E. Robustness

Fig.2 displaying Von Mises Stress Distribution and Fig.8 showcase the robustness of the mechanical design.

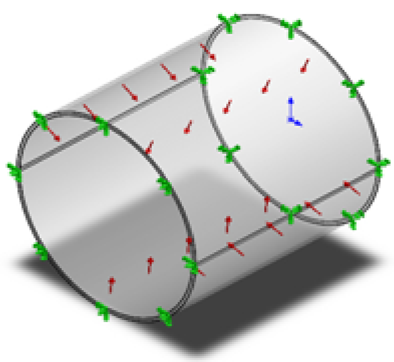


Fig. 8. Depicts the fixture and face of pressure application

III. EMBEDDED AND POWER SYSTEMS

As discussed before for the AUV Zyra 2.0 the focus of electronics department is primarily on implementation of SONAR and signal processing module, actuator board for control of four SeaBotix thrusters. 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.

A. 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 2.0 with clean, isolated, and regulated power at 5V, 12V, and 18.5V.

B. Actuator Control

The actuator board used for Zyra 2.0 is custom designed. It takes in care the electromagnetic interference from the thrusters which distorts the motor control signal coming from the microcontroller unit LPC-2148(ARM). 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.

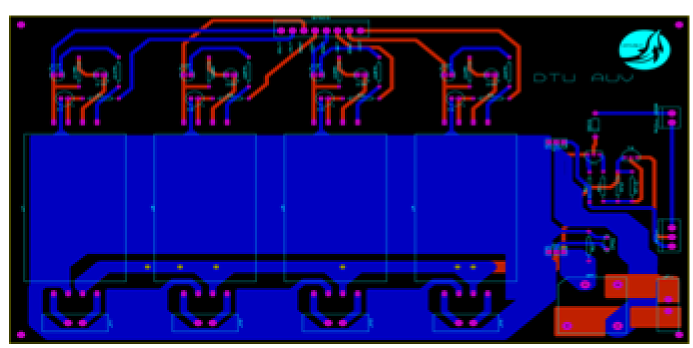


Fig. 9. Schematic for Actautor board

The motor controllers from Dimension Engineering are capable of functioning at ultra-high frequency of 32 KHz thus making it 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 2.0which in turn actuate the required thrusters. A hermetically sealed switch is responsible for killing the power to the propulsion system.A normally open reed switch is responsible for killing power to the propulsion system. The advantage is it can be easily operated from outside the main hull.

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. Learning from past experiences, the

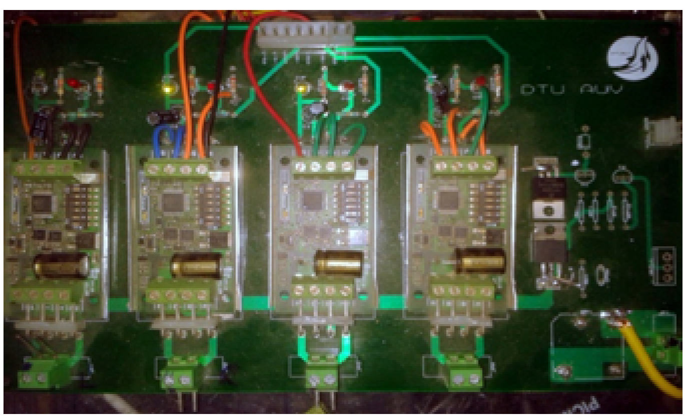


Fig. 10. Actuator Board

propulsion system of Zyra 2.0 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.

C. Electronics Rack

Modularity of the vehicle has been the priority while developing the vehicle. Electronics Rack is designed such that it holds all the electronics and can be removed from Zyra 2.0 without disturbing the rest of the system

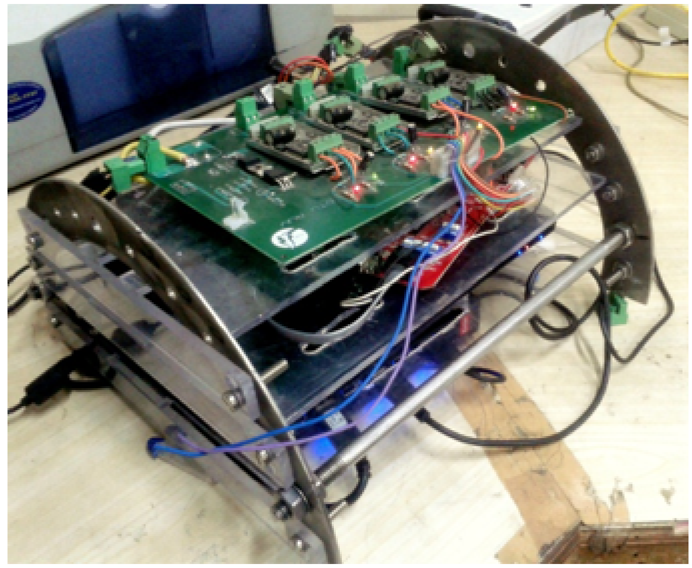


Fig. 11. Electronics rack for Zyra 2.0

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

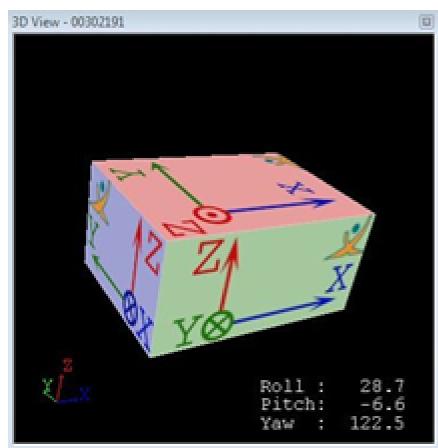


Fig. 12. Orientation data received from IMU used as an input in Control system module.

IV. Mission Module

Mission plan module of Zyra 2.0 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

TABLE II
COMMERICIAL OFF THE SHELF(COTS) PRODUCTS USED IN ZYRA 2.0

Devices	Model
Kontron Motherboard	986LCD-M/mITX
Battery	Li-Po 18.5V , 18000mAh
Motor Controller	Syren 10
Camera	Microsoft LifeCam-3000 and Logitech HD Pro C920
Propulsion	SeaBotic BTD-150
Pressure Sensor	Applied Measurements Pi9933
IMU	XSENS MTi-28A
Actuator Controller	LPC-2148(ARM)
Servo HiTec	HS5646WP
Hydrophones	Reson TC-4013

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.

V. 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 performed 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 Qt Creator 3.0. 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.

This year we have shifted all our codes to open source softwares. We have integrated all the codes in Qt SDK 5.2 using Qt Creator 3.0.The Computer Vision module is developed using OpenCV library of C++.

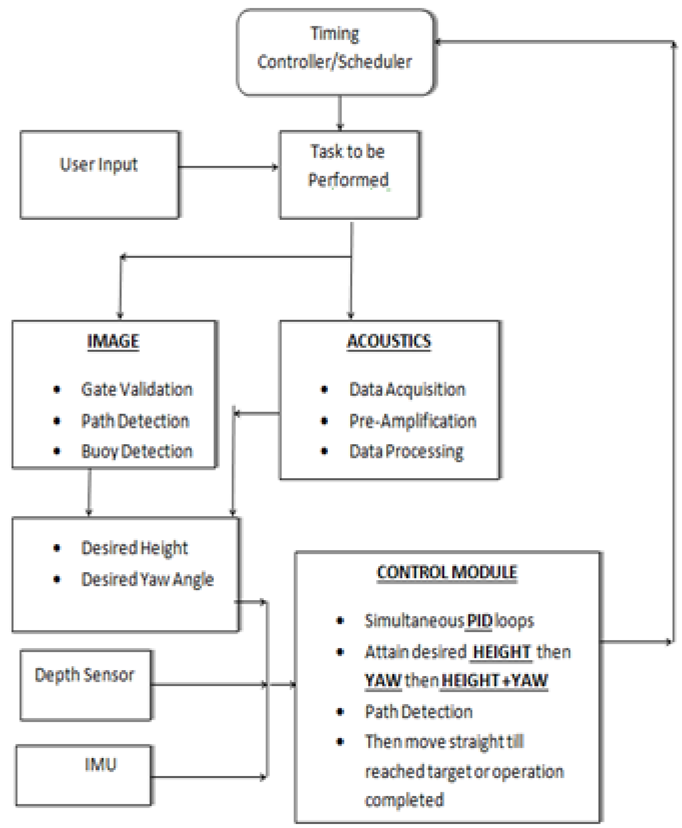


Fig. 13. Various software modules working in tandem to achieve mission control

The Computer Vision module was developed using the OpenCV library of C++ integrated with Qt SDK using Ubuntu 12.04. The high parallelism during execution of programs on multi-core processors in Ubuntu (Linux) gives the vision module the required real-time computational power. The module incorporates concepts involving the various image processing algorithms for particle analysis, image segmentation, binary morphology, Hough transformation and Machine Vision. The major change this year is that the navigation system works on absolute yaw (angle) control and we have used the User Datagram Protocol (UDP) for communication of the AUV. The previous generation vehicles had a less accurate navigation system partly based on heuristics.

We have used an Android phone as our IMU (Inertial Measurement Unit) using an application for Android operating System to get the orientation of the AUV as an alternative of our IMU. The Android phone uses the UDP communication for sending and receiving data packets between the Android phone and the single board computer.

VI. Software and Machine Vision

The software team is responsible for mission planning, machine vision and developing several software tools to enhance the debugging and operability of the vehicle. This year the team has shifted all the codes to open source softwares keeping in mind the following objectives: 1)Enhancing the parallel processing capability and modularity. 2)Reducing mission task execution time. 3)Development of debugging and replacement modules in case of critical hardware failure.

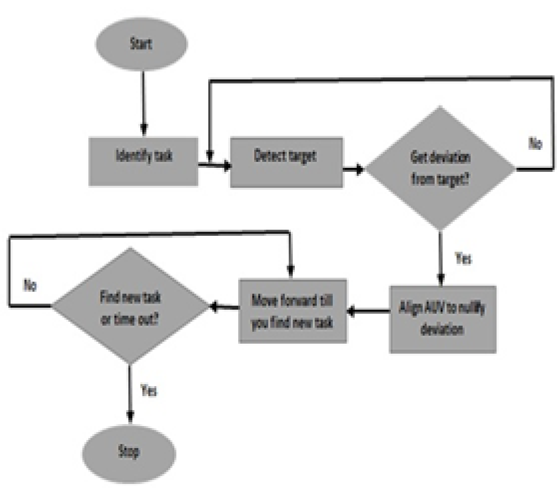


Fig. 15. Generalized flow chart for target detection using Image Processing

A. Software stack on SBC

The software stack has been built on Ubuntu Core GNU/Linux distribution, using Ubuntu 12.04. The vehicles computer is composed of Kontron Motherboard 986LCD-M/mITX, 4 GB of RAM and an Intel Atom Processor clocked at 1.60GHz . The entire software stack has been written in C/C++. The software stack performs mission planning, image processing, and handling the communication between the hardware modules, power board and inertial measurement unit.

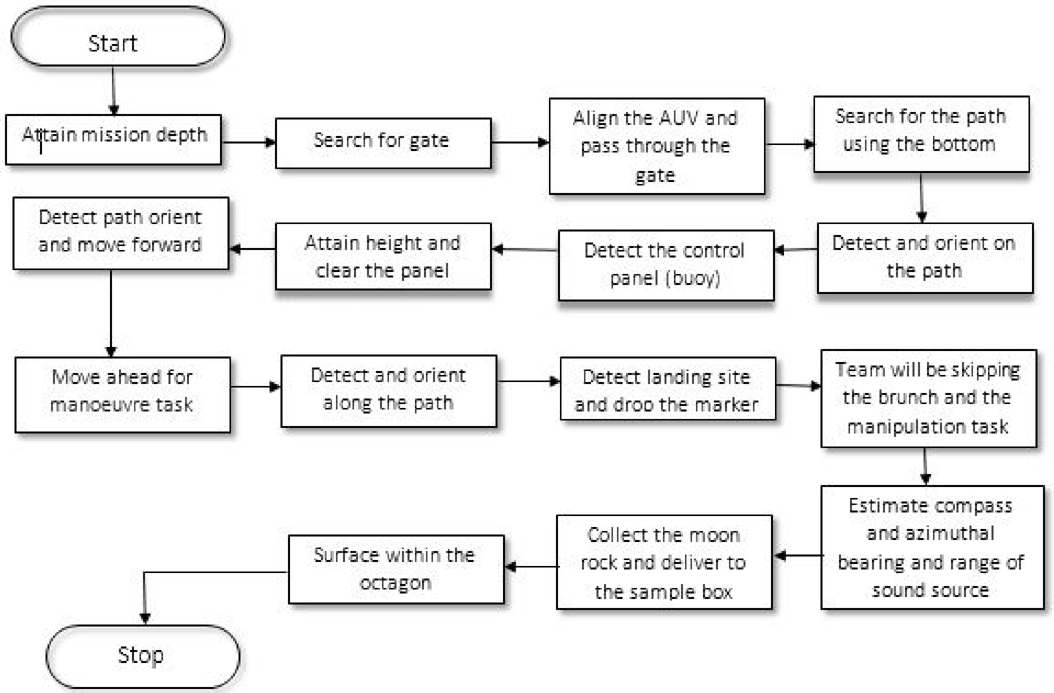
B. Middleware

The objective of the middleware is to formulate a neat and clean interface for various processes to interact with each other. The inter process communication for various processes and multiple sensor modules on the on-board computer operate on the shared memory managed on Qt SDK 5.2 using QSharedMemory Class. A central mission control module then takes the decisions according to the sensor values received from these processes.

C. Vision

The team has integrated all the codes in Qt SDK 5.2 using Qt Creator 3.0. The Computer Vision module is developed using OpenCV library of C++. We are using two cameras (Logitech C920) one facing downwards and the other forward facing camera. These cameras are USB 2.0 enabled and interfaced to the SBC. The front facing camera is used for localization while the bottom camera is used for orienting the vehicle along the path placed at the bottom.

1) Image Preprocessing: Images tend to get degraded as the vehicle goes underwater. Since as the depth increases, the amount of light on objects decreases and light distribution becomes non-uniform. To tackle this issue, the input images are converted to YCbCr color space and Contrast Limited Adaptive Histogram Equalization (CLAHE) is performed on the Luminescence(Y) channel of the image which improves the local contrast, at the same time limiting the amplification which can over-amplify the noise too. Normalized cross correlation techniques and Pyramidal Mean Shift filter is also used to enhance the target image before further processing.



(a)

Fig. 14. ROBOSUB Mission Controller's Approach .

The AUV is capable of doing the tasks described below. Fig.15 gives the generalized flow chart for target detection using vision module.

D. Gate Validation

Starting with the Gate Detection, our vision algorithm receives video feed from the front facing camera and gives the heading relative to the AUV as the output. To accomplish this the Cr channel from the image in YCbCr is taken. Over this image, Canny Edge Detection is performed and perpendicular Hough Lines are found. The center of the symmetry of the resulting image thus gives the correct heading relative to the vehicle.

E. Path Detection

For Path Detection video feed from the downward facing camera is analyzed and heading relative to the AUV is given as output. The captured image is converted to HSV and segmented for specific color. Further, morphological operations are performed to remove any unnecessary noise. Contours are then found on the resulting image to find the connected components. Smaller contours are removed pertaining to noise. A minimum bounding rectangle is formed over the detected contours and the angle of the edge having the longest length is taken as the angle of the path.

F. Buoy Detection

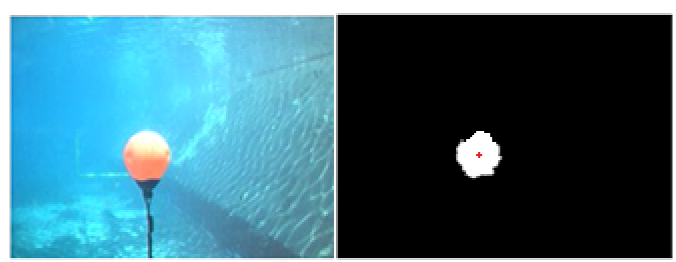


Fig. 18. Original Image and Processed Image for Buoy Detection

Algorithm for buoy detection is similar to path detection. Video feed from the front camera is taken and the captured image is converted to HSV and segmented for specific color. Over the resulting binary image, morphological operations are performed to remove any unnecessary noise. On the resulting image, the center of the largest blob is found using central moments. The position of the center gives the relative heading for the AUV.

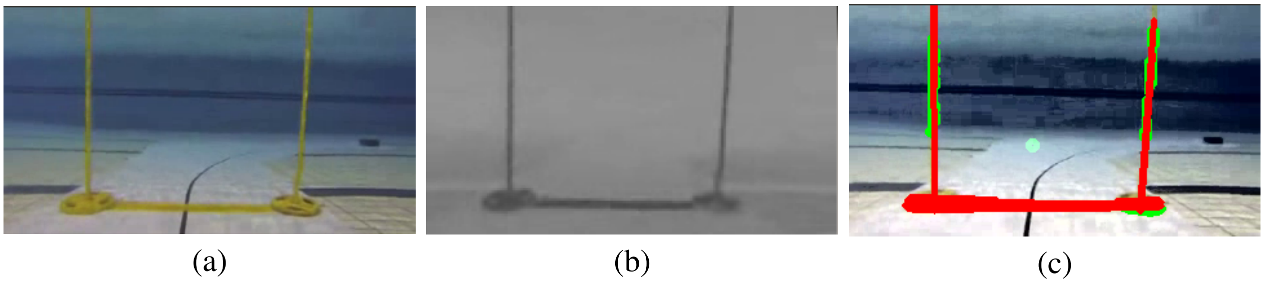


Fig. 16. Visual comparison: (a) Input image, (b) Cr channel from YCbCr space and (c) Gate detected after applying the algorithm

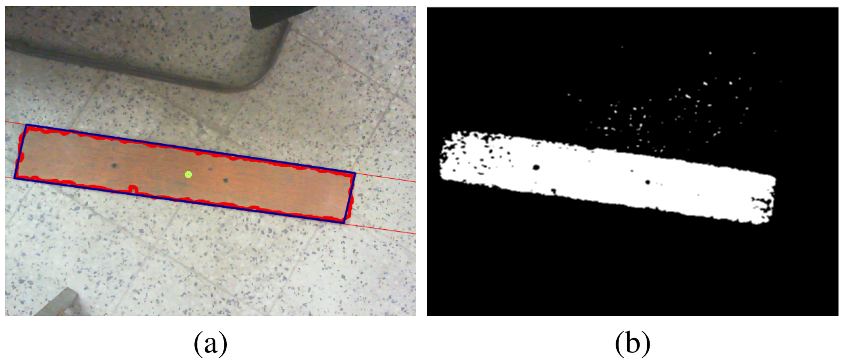


Fig. 17. Visual comparison: (a) Original image with path detected and heading calculated, (b) Corresponding binary image.

VII. UnderWater Acoustics

Zyra 2.0 has an acoustic navigation system which employs a three dimensional array of hydrophones for data acquisition to calculate azimuthal and compass bearing and estimate hyperbolic location of the sound source in far-field approximation using Time difference of arrivals (TDOAs). Fig.19 shows a tetrahedral array of hydrophones which has been used for the localization of the sound source. Such a symmetric array eases calculation while making time difference of arrival(TDOA) calculations and helps in reducing symmetric noise at different hydrophones.

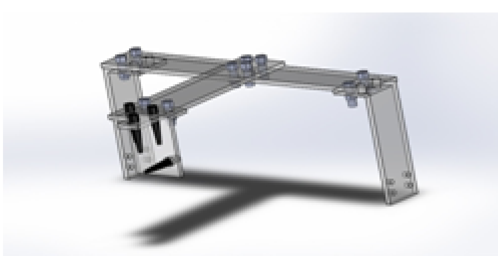


Fig. 19. 3-D hydrophone array

The localization task has been broken down into two parts as follows :

A) TDOA(Time Difference of Arrival Estimation)

B) Position Estimation

A. TDOA Estimation

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 TDOAs give bearing estimation for far field approximation. The mathematics of the method is discussed as belows: Let $S_1(t)$ and $S_2(t)$ be two signals at two different hydrophones and Δ be the Fast Fourier transform of the signals, then

$$X_1(f) = \Delta(S_1(t))$$

$$X_2(f) = \Delta(S_2(t))$$

GCC-PHAT is defined as:

$$GPHAT = \frac{X_1(f)[X_2(f)]^*}{|X_1(f)[X_2(f)]^*|}$$

where * is the complex conjugate of a function

$$TDOA = argmax(\Delta^{-1}(GPHAT))$$

In environments of high levels of reverberation GCC-PHAT helps to improve robustness and accuracy in calculating the time difference of arrival as we can see from Fig.20 that GCC-PHAT enhances the peak and whitens the region around it.

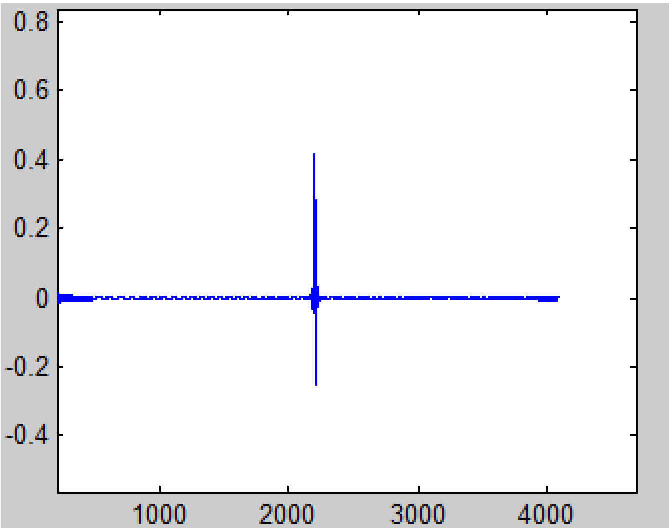


Fig. 20. Typical GCC-PHAT function

B. Position Estimation

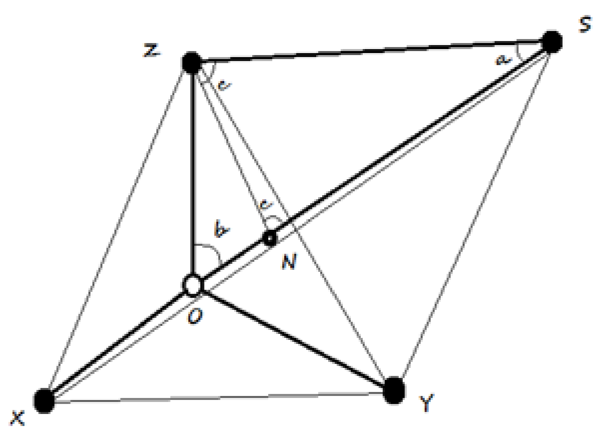


Fig. 21. Geometrical model of the localization system

We have to note a few terminologies here. X, Y and Z are my sensor positions respectively on the x,y and z cartesian axes. The point S represents my sound source. Since TDOA measurements require 2 hydrophones, we will be dealing with source hydrophone triangles such as ΔOZS.

$\angle(ZOS) = b$ is my bearing, we have defined $\angle(ZSN) = a$ and $\angle(ZNS) = c.ZN$ has been drawn such that $ZS = NS$.

The path difference $x = c\tau$ where c is the speed of sound and τ is the TDOA. We define OZ=OX=OY=d.

We define (vectorially), $OS = rs$ and $ZS = rz$ and in a similar fashion we define r_x and r_y.

The basic TDOA equations are:-

$$||r_i| - |r_j|| = X_{ij}$$

Where i and j run over x ,y and z and x is my path difference. Note that X_{ij} is symmetric due to the modulus on the left hand side.

A little manipulation with the parallelogram law of addition and TDOA equations would show us that for that triangle OZS we can derive the quadratic in $|r_s|$ as :

$$A = 4sin^2(a/2)$$

$$B = \pm 4sin^2(a/2)X_{zs}$$

$$C = (X_{zs})^2 - d^2$$

In $A^2x + Bx + C = 0$, x is the dummy varaible(different from X_{ij}) , where

$$x = |r_s|$$

Now clearly ON is the path difference that is $ON = X_{zs}$.

Determine ZN = f by cosine rule and finally using sine rule in triangles OZN and NZS.

$$sin(a/2) = \sqrt{1 - \frac{d}{f} sin^2(b)}$$

The discriminant of the quadratic gives us the condition that :

$cos(a/2)\epsilon - \frac{d}{X_{zs}}, \frac{d}{X_{zs}}$ or in a better sense $\frac{d}{X_{zs}} < 1$.

The idea is to find $|rs|$ from the quadratic and calculate $p = |rs|sin(b)$ and z- coordinate of source using $z(s) = |rs|cos(b)$.

And finally for X_{xs} or for X_{ys} using the fact that,

$$|r_y| = \sqrt{|r_s|^2 - 2dy(s) + d^2}$$

And that $y(s) = psin\psi$, ψ being measured in the XY plane from X axis we find out by using this in the TDOA equation in triangle OYS.

$$sin\psi = \frac{d^2 - X_{ys}{}^2 \pm |r_s| X_{ys}}{2dp}$$

The beauty of this method lies in the fact that we haven't used any approximations for calculating the exact positions .

Although there is the possibility of multiple roots from the quadratic yet only one of the solutions will be feasible satisfying all other conditions . Any error if encountered will be on part of the TDOA analysis method, it will only be multiplied by a scalar constant while calculating the overall error.

VIII. Conclusion and Current Progress

In this paper the development of the AUV Zyra 2.0 is presented to perform various shallow water tasks. The idea and logic behind the mechanical design ,embedded and power systems design, control algorithms and software platforms , image processing techniques and the geometric mathematics involved in the localization process of the pinger have been explained in detail.Zyra 2.0 is now in the testing phase. Prior to vehicle assembly, the mechanical systemswere thoroughly leak tested, and the electrical systems were bench tested.

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