DaryaBird Mark H29: Design and Implementation of Upgrades on DaryaBird – An Autonomous Underwater Vehicle

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***Abstract*—DaryaBird is an autonomous underwater vehicle (AUV) developed by Kyushu Institute of Technology (Kyutech) Underwater Robotics team. For this year's Robosub Competition, the team aims to reach the finals round. Thus, the design and implementation of upgrades revolve around the different missions that would make the team reach this goal. One of which is the Random Pinger mission. In order to achieve this, the team will focus on the Navigation System of the vehicle. Dead Reckoning and an improved Acoustic Navigation System will be implemented. Additionally, a new module, the Marker Dropper Module, will be implemented to completely cover the Random Pinger Mission. The specific changes and strategies on this are further discussed in this paper.**

I. Introduction

Research and development of Autonomous Underwater Vehicles (AUVs) has been increasing in recent years because of the vast application it offers. Some applications include Underwater Exploration, Search and Rescue Operations, Industrial use such as checking for pipeline conditions, etc. However, in developing an AUV, there are numerous factors that is different from terrestrial vehicles that need to be taken into consideration such as in navigation, sensing and motion control. Navigation and sensing is different underwater since radio waves are absorbed in water, thus GPS cannot be used. Motion is affected by water flow and has a different friction coefficient because of the medium.

The main design strategy of the team in this year's Robosub is to go back to basics, which means use simple and proven designs and algorithms to clear the different missions. A software revamp was also introduced where Matlab was upgraded. The software architecture was implemented as a modular type so that debugging and testing is easier. The acoustic sensing capability of the vehicle was also improved.

II. Technical Specifications

DaryaBird is an AUV that has been developed over time by students and teachers of Kyutech Underwater Robotics Team [1] [2] [3]. The main design goals are summarized as:

- Small and handy enough to complete mission by a few operators
- Frame structure for adding new parts and options
- Selectable operation mode, AUV or ROV mode, depending on the mission.

The specifications of the DaryaBird is given in Table I.

Table I

Technical Specifications of DaryaBird

Structure	4 x Aluminum Pressure Hull Aluminum T-slot Frame Max. Depth: 50m
Dimension	568mm x 534mm x 862mm (HxWxL)
Weight	37.2kg
Thrusters	4 x 110W BTD150 2 x 90W Hibikino Thruster
CPU	PC Board (Intel i7)
Operating System	Windows 7
Software Language	Matlab
Communication	Ethernet and Optic LAN
Sensors	2 x USB Camera 9-axis Attitude Sensor Pressure Sensor (Depth Sensor) Doppler Velocity Log (DVL)
Batteries	1 x LiFePO4 12V 3 x LiFePO4 9V

III. Design and Implementation

A. Design Strategy

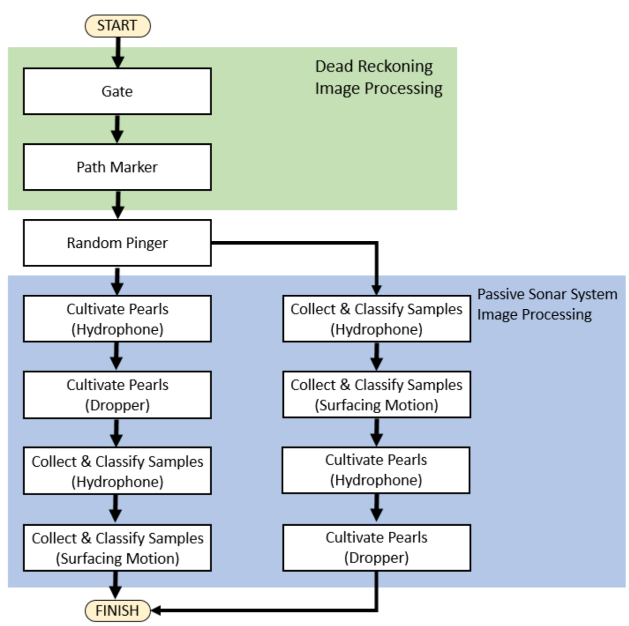


Fig 1. Team's Mission Strategy for Robosub 2017

For the past few years, DaryaBird has focused on making the Mechanical and Electrical components of the vehicle to be stable. Last year, the team tried their hands on High Level Software Development through the use of Image Processing. However, it did not prove to be effective because of various issues on the changing environment. Parameters needed to be adjusted every time. Another problem last year was one of the thrusters broke down for reasons yet unknown. Thus, even the Low Level Control of the vehicle was a problem.

This year, the Mechanical and Electrical Modules are maintained. The team wanted to upgrade the Low Level Software Development. DaryaBird have not had a stable Navigation System before, so this year, this was the focus. Dead Reckoning will be applied. In addition, Acoustic Navigation will also be improved and will be made more accurate. With this, the team aims to get as many points as possible. Seeing that the Random Pinger mission has one of the highest points in the competition, the team is determined to accomplish this. This is why there is a high motivation on improving the Navigation System. The specific missions and strategies are further explained in Fig 1 and in the following sections.

1. Gate

This year, the team wants to accomplish the Gate mission as simple as possible. Thus, in order to pass through the gate, a waypoint will be set. This waypoint will then be used as a target location and will be navigated to through Dead Reckoning.

2. Path Marker

Once DaryaBird reaches the waypoint specified, it will use image processing, specifically Hough Transform, to search and align itself to the path marker.

3. Random Pinger

This year, the team wants to take on the Acoustic Mission head on. Last year, the team wasn't able to try it since DaryaBird took a long time on the Buoy Mission. This was due to environmental inconsistencies and the need to change parameters which made buoy detection through image processing very hard. As such, the Buoy Mission was totally eliminated and the Random Pinger mission was focused. More details about the Acoustic Positioning and Navigation will be discussed in the next sections.

4. Cultivate Pearls (Marker Dropper - uncovered)

As part of the Random Pinger Mission (or rather an effect), Cultivate Pearls and Collect and/or Classify Samples missions needs to be accomplished. For Cultivating Pearls, once DaryaBird reaches the pinger, DaryaBird will search for the bins using Speeded Up Robust Features (SURF). Once the bin is found, the vehicle will orient and align itself on top of the bin. Then, the Marker mechanism will be triggered to drop the markers.

5. Collect and Classify Samples (Octagon)

Another part of the Random Pinger Mission, the team plans to just surface inside the Octagon. Once the vehicle reaches the random pinger, the vehicle will stop its motors and slowly surface. With this, accuracy in Acoustic Positioning and Navigation is needed. Thus, to reiterate, the team focused on improving this module.

B. Vehicle Design

1. Mechanical Design

DaryaBird consists of modules that are encased in different hulls. Each module is connected together through the aluminum frame with T-shaped slots on the four sides. The advantage of this kind of design is that the configuration of the vehicle can be changed easily by attaching and detaching the different modules. The Main, Battery, Sensor Hulls are all made out of aluminum and can withstand a maximum depth of 50m. Each module will be described in the following section.

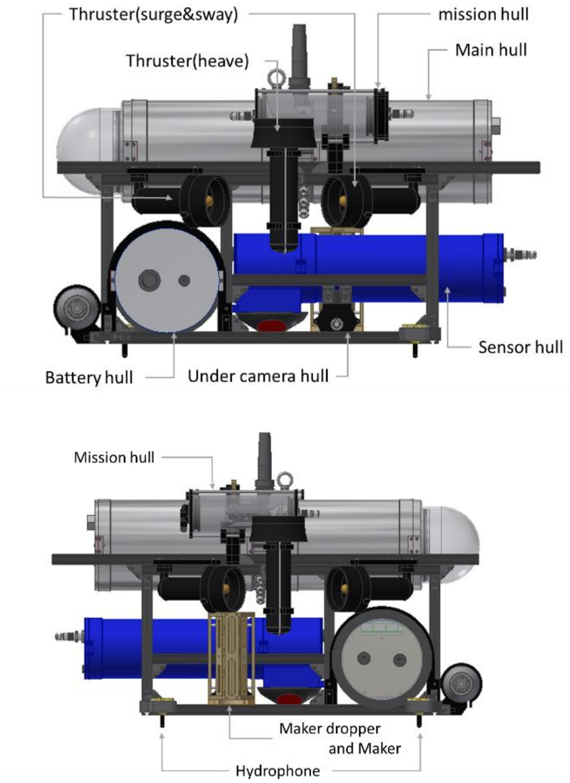


Fig 2. Different Modules (Hulls) of DaryaBird

a. Main Hull and Middle Part

The Main Hull is the most important module in DaryBird. It houses the PC, motor drivers and communication units for controlling the vehicle. The structure of the main hull as shown in Fig 3 and Fig 4 consists of two pressure resistant containers connected in series: 1) containing the motor driver; 2) containing the PC and communication units. The Middle Part connects these two containers. This type of structure makes it easy to add and removed modules for new equipment. Additionally, an acrylic dome is attached to the front of the Main Hull to contain the front-facing camera.

b. Battery Hull

In order to make the battery changing process easier, the battery hull was created. This contains 3 x 9V batteries that supply power to the thrusters, and 1 x 12V battery that supplies power to the PC. The hull contains a transparent window to

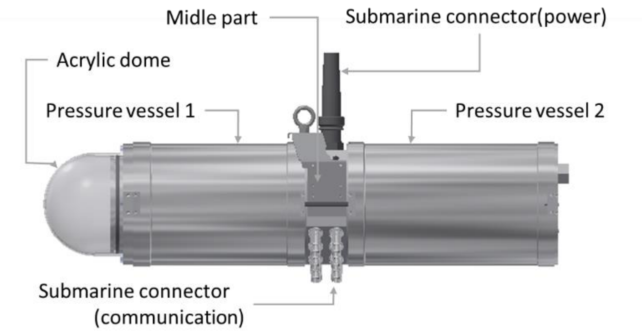


Fig 3. Main Hull Parts

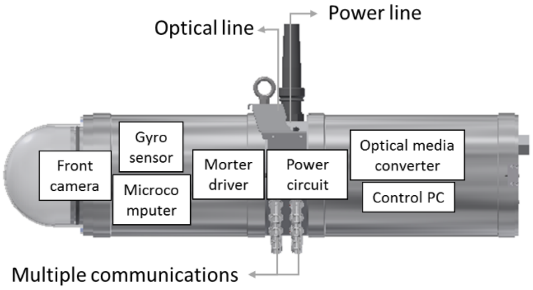


Fig 4. Main Hull Contents

view the battery levels.

c. *Sensor Hull*

The Sensor Hull houses the Doppler Velocity Log (DVL) and pressure sensor. It is the blue anodized hull of DaryBird. The pressure sensor is located at the back of the hull while the DVL is located in front, facing downward. The components are arranged in such a way that the center axis of the DVL overlaps with the center-of-gravity of the vehicle.

d. *Bottom Camera*

A resin-based mini hull located at the bottom of the vehicle houses the Bottom Camera. This container is fixed near the Yaw axis to maintain the location of the center-of-gravity of the vehicle.

e. *Thrusters*

DaryaBird has 6 thrusters: two 90W Hibikino Thruster for generating heave motion, four 10W BTD150 for generating surge, sway and yaw motions. The 4 thrusters each have an offset angle wherein, when combined, can generate multiple directional vectors with respect to the forward direction resulting to forward, backward, turning left, and turning right motions.

f. *Mission Hull*

Similar to the Bottom Camera Hull, the Mission Hull is a resin-based container that houses a variety of equipment based on the mission or experiment that needs to be done. There are two containers with varying sizes. These hulls have large buoyancy, thus, attached to the top of the robot as additional buoyancy component. In this year's Robosub, the Mission Hull will contain the circuitry of the Marker Dropper and Acoustic Control Unit. Details of each component will be described in the following section.

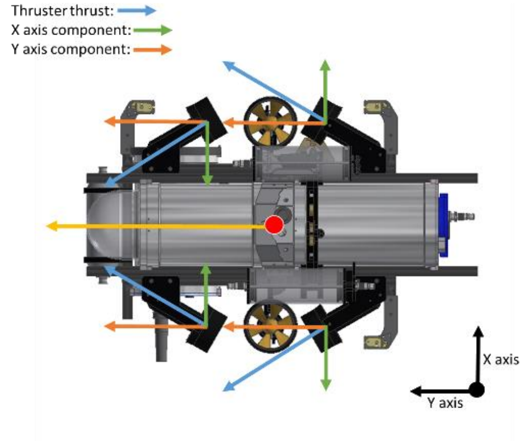


Fig 5. Thruster Kinematics Example – Forward Motion

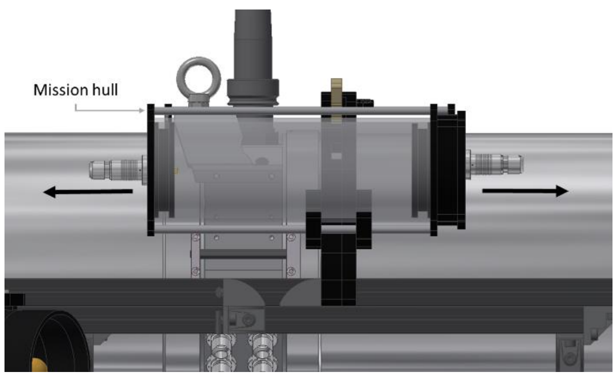


Fig 6. Mission Hull's Buoyancy Stabilization

1) *Marker Dropper Module*

This module is for the *Cultivate Pearls* mission. The main body of the device is loaded with four markers. The mechanism uses a pneumatic actuator, similar to the Grabber Module created for last year's Robosub. The markers are stacked on top of each other. When one is dropped, the mechanism loads the next marker. The actual Marker design is composed of a weight and three wings so that it goes straight down after it is released from the Dropper.

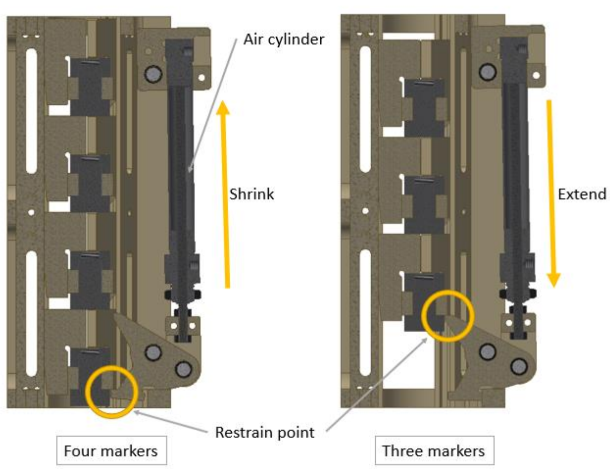


Fig 7. Marker Dropper Mechanism

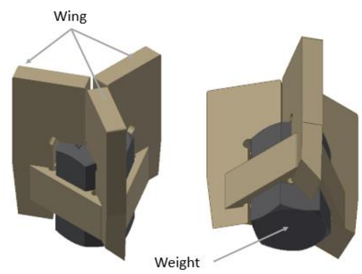


Fig 8. Marker Design

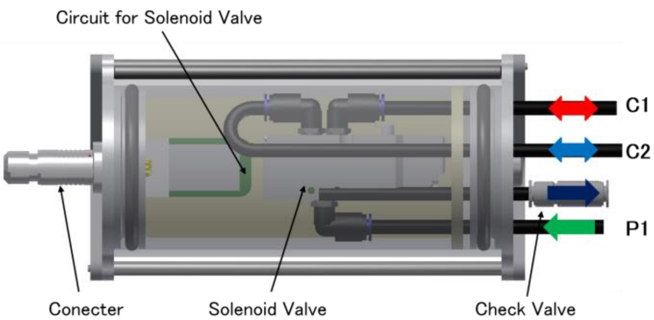


Fig 9. Marker Dropper Mission Hull Contents

2) Hydrophone Module

DaryaBird is equipped with 3 hydrophones for the Acoustic Missions. These are attached to the four corners of the vehicle so that the distance between them are maximized. Since it is recommended that there are no objects obstructing the reception of sound waves around the hydrophone, a specialized mount was created. With this design, it is possible to attach the hydrophones at the bottom of the vehicle and at the same time, putting the vehicle on the ground.

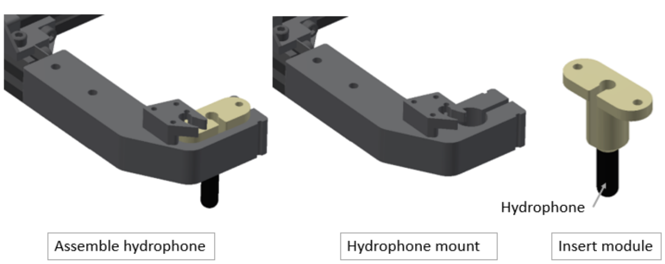


Fig 10. Hydrophone Module

2. Electrical System

For the past years, the Electrical System of DaryaBird has proven to work as expected. Thus, this year, the team decided to improve mostly on Software Development and the Electrical System is left as is. The main circuit board consists of three units, motor control unit, power source and communication unit. Motor controller unit and power source unit are connected with the backplane board as shown in Fig 11. Motor controller unit signal lines are connected to the communication unit. Detailed system architecture of DaryaBird is given in Fig 12. Sensors and motor driver standard communication is done through RS232. Communication unit has two functional modules. First, the signal level conversion module (ADM3202) convert RS232 to TTL level. Second is FT4232H module to interface USB 2.0 to UART.

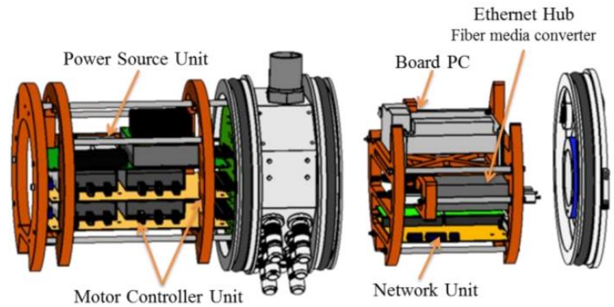


Fig 11. Electrical Circuit Unit

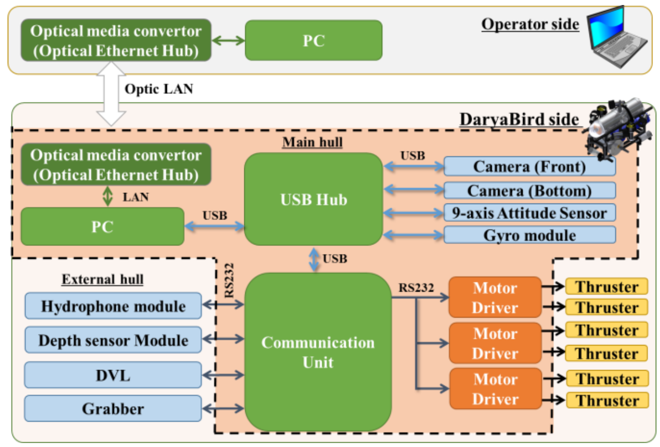


Fig 12. DaryaBird's System Architecture

3. Dead Reckoning Navigation System

This year, the team decided to go back to basics and apply Dead Reckoning as DaryaBird's Navigation System. Dead Reckoning is a method of measuring the translational and angular velocity of a vehicle using sensors, calculating the amount of movement done, adding these to the precious state quantity to estimate its position. For DaryaBird, three sensors are used – DVL, Gyro and Compass. Generally, Dead Reckoning is erroneous over time due to the process of computing the values by integration. Thus, the team will use Image Feedback Analysis to correct the error.

4. Acoustic Positioning System

Acoustic positioning system is grouped into three classes such as Long Base Line (LBL), Short Base Line (SBL) and Super Short Base Line (SSBL). LBL is extremely accuracy compared with other methods but this method requires some ultrasonic beacon at the bottom of sea and its calibration. SBL and SSBL requires only one beacon. SBL detects the position of sound source from time difference of arrival. SSBL does it from phase difference and receiver array of AUV become compact. Moreover, SBL and SSBL are suitable for AUV because these methods don't require the calibration [4] [5]. In this competition, SSBL method is applied for AUV for ease of operation.

a. Calculation of sound source direction with SSBL

First, the acoustic wave that arrive close two hydrophones is approximated by plane-wave as shown in Fig 13. Therefore, the two acoustic waves arrive the hydrophones at the same angle θ and these waves have phase difference $\delta\emptyset$. The arrival angle θ is given by the following equation.

$$\theta = \cos^{-1}\left(\frac{\delta\phi\ c}{2\pi f d}\right) \quad (1)$$

Where, c is underwater sound velocity [m/s], f is signal frequency [Hz] and d is distance between hydrophone [m].

The range of phase difference $\delta\phi$ is from –π to +π [rad] from Eq. (1) and the range of θ that was required is from 0 to π [rad]. Thus, distance d is expressed in the following equation.

$$d \leq \frac{\lambda}{2} \quad (2)$$

Where, λ is the wavelength in the water [m].

Next, three hydrophones need for three-dimensional estimation at least. The arrival angles θ_x and θ_y at OXT and OYT plane are given by following equations as shown in Fig 14.

$$\theta_x = cos^{-1}\left(\frac{\delta\phi_x\ c}{2\pi f d}\right),\quad \theta_y = cos^{-1}\left(\frac{\delta\phi_y\ c}{2\pi f d}\right) \quad (3)$$

The arrival angles θ_z at OZT plane is calculated from the following equation.

$$cos^2\,\theta_z = 1 - cos^2\,\theta_x - cos^2\,\theta_y \quad (5)$$

From Eq. (5), distance between pinger and hydrophone R is as follow:

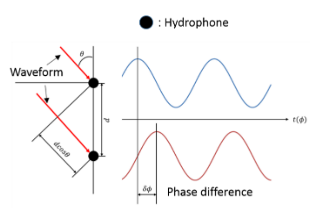
$$R = \frac{z_t}{\cos\theta_z} = \frac{z_t}{\sqrt{1 - cos^2\,\theta_x - cos^2\,\theta_y}} \quad (6)$$

Where, z_t is relative depth between pinger and hydrophone. The position of sound source x_t and y_t are described by:

$$x_t = R\,cos\,\theta_x\,,\quad y_t = R\,cos\,\theta_y \quad (7)$$

The arrival angles θ_{xy} at OXY plane is given by following equations.

$$\theta_{xy} = tan^{-1}\frac{y_t}{x_t} \quad (9)$$



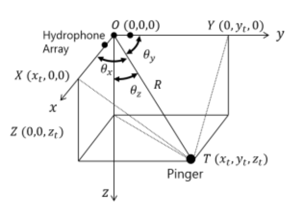


Fig 13. Detection of phase difference
Fig 14. Acoustic positioning with SSBL

b. Detection of Phase Difference

The method of acoustic positioning resistant to the reflected wave and noises is required because the acoustic wave is affected by multipass and noises in water. The accuracy of detecting phase difference greatly affects the estimation accuracy of the sound source direction in mothed of SSBL. To improve the estimation accuracy, detection of the phase difference employs calculating by following Cross Correlation Function (CCF).

$$R_{xy}(m) = \frac{1}{M}\sum_{n=1}^{M} x(n)y(n+m) \quad (10)$$

x is value of reference signal voltage. y is value of received signal voltage. The Eq. (10) defines the similarity of the signal x and y. The argument m is obtained as the phase difference when R_{xy} is maximum.

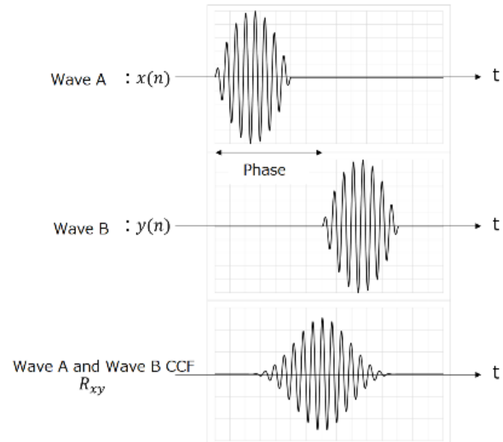


Fig 15. Reference waveform for CCF

5. Acoustic Navigation System

The block diagram of the acoustic positioning system is shown in Fig 16. This system consists of hydrophones, amplifier, bandpass filter and micro processing unit (MPU) as shown in Fig 17. Table II gives the specification of the acoustic positioning system module. Its length of pressure hull is 200 [mm], the diameter is 75 [mm] and dry weight is 0.9 [kg]. The underwater cable and hydrophone cable are attached on the cap of the hull. This system has three hydrophones and these are arranged at interval d as shown in Fig 18.

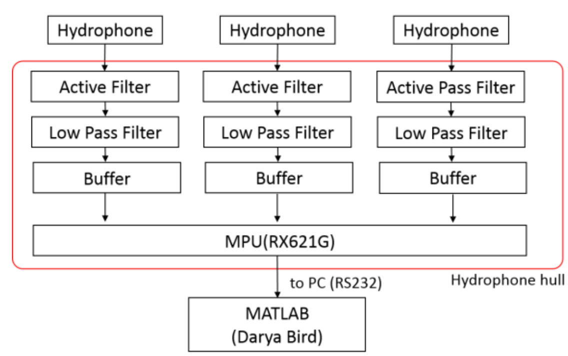
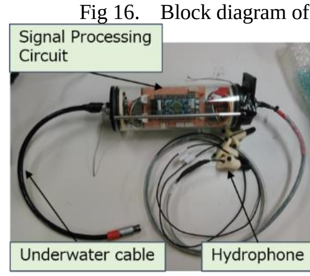


Fig 16. Block diagram of acoustic positioning system



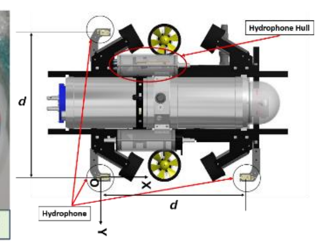


Fig 17. Acoustic positioning system module
Fig 18. Arrangement of hydrophones

Table II
SPECIFICATION OF ACOUSTIC POSITIONING SYSTEM

Number of hydrophones	3
Bore diameter	70 [mm]
Outside diameter	75 [mm]
Length	200 [mm]
Weight	0.9 [kg]
Processor (MPU)	RX62G
A/D converter	12bit 250 [kHz] 3ch
Frequency range	20 [kHz] – 30[kHz]
Power	DC 5 [V]
Communication	Serial (TTL)

In this system, the waveform of sound source is chirp signal and the wavelength λ of the chirp signal is given by following equation. Where, the sweep time T is 1 [mesc] as shown in Table 1. Therefore, the value of wavelength is as follow:

$$\lambda = \frac{c}{f} = \frac{c}{1/T} = \frac{1500}{1 \times 10^3} = 1500\ [\text{mm}] \tag{13}$$

From the Eq. (2), the required length of base line is less than 750 [mm]. Considering the size of AUV, the length of base line is set to 500 [mm].

The acoustic wave received by each hydrophones is converted into an electrical signal. The signals are performed amplification and noise removal by the signal processing circuit. The amplification factor can be changed by the programmable gain amplifier. The filter consists of secondary high pass filter and low pass filter and it functions as a bandpass filter that passes 20 to 30 [kHz]. The signals filtered by bandpass filter is shaped into the square wave. MPU takes a sample the signals and digitizes by 12bit 250 [kHz] A/D converter. The sampling data is sent to AUV's single-board computer and phase difference is calculated by CCF.

6. *Software Architecture*

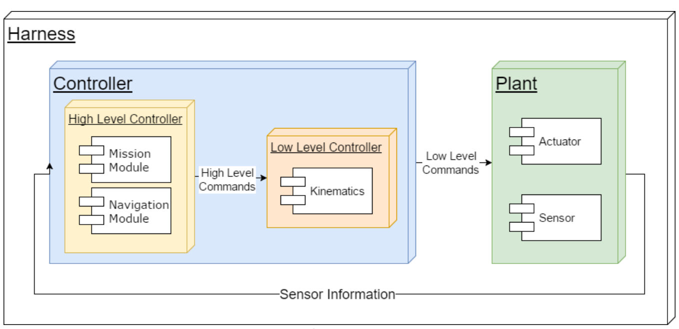


Fig 19. Software Architecture

This year, DaryaBird's software was upgraded from Matlab 2014a to Matlab 2016b. With this, blocks and structure was also updated. The main parts of the program are the Controller and Plant. The Controller includes the Low Level and High Level Controller. The High Level Controller generates high level commands such as move forward, turn right, stop, etc. based on the mission or task currently being executed. Stateflow charts for Mission Control, Image Processing and Navigation Commands are contained in this level. Then these commands are passed to the Low Level Controller to be converted to commands that can be used by the plant. The Low Level Controller uses feedforward PID Controller shown in Fig 20 for surge and sway motions. For controlling heave and yaw, P-PI controller as shown in Fig 21 is used.

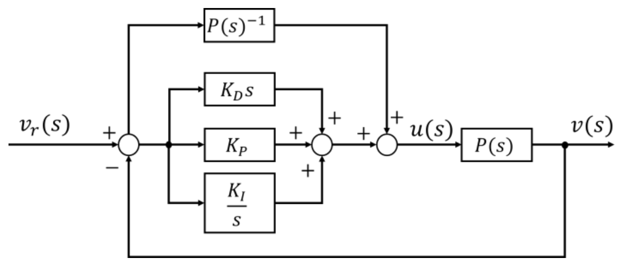


Fig 20. Velocity control system (Surge & Sway)

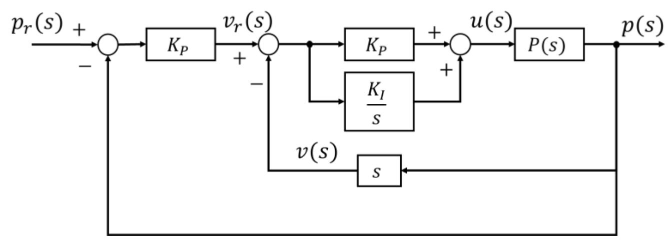


Fig 21. Positon/Angle Control system (Heave & Yaw)

The Plant includes the sensor and actuator models of the vehicle. It basically receives commands from the Controller and sends back sensor information. Each sensor and actuator has their own model file and assembled together in the Plant.

The Controller and Plant is put together using a Harness. Depending on the main purpose of the program, a harness can be created with a High Level Controller that is specific to its purpose and a Plant that is consistent among all the harnesses (since the team is working with one plant or vehicle).

DaryBird runs solely on Matlab and Simulink. In the past years, each event/competition/research has one file that includes everything, from Controllers to Sensors. It proved to be very hard to maintain since each file has its own settings for the same vehicle. So if there was a change or improvement in one file, it is hard to pinpoint and apply to all the other files. Thus, this year, the team used Matlab's project structure to make the program modular. Each element in the Plant such as the sensors and actuators model have their own files. This makes it easier to debug and test their current conditions individually. This also paves way to easier program maintenance. Since the files are maintained separately, different harnesses can be created by using the same plant entities. So if a specific sensor model is updated, the change will propagate to the other harnesses since it links to the same file.

7. *Sensor System*

a. *Attitude Control Sensors*

Until recently, DaryaBird has performed attitude control using angular velocity information obtained from the Gyro Sensor. Actual angle is computed by integrating the measured velocity. With this process, accuracy of the angle computed degrades over time. Thus, if two sensors – compass and gyro, are used and fused, a more accurate angular information can be obtained. This improvement is needed since navigation will mostly be controlled through Dead Reckoning. This is also needed in Acoustic Navigation in order to follow the direction of the pinger accurately.

C. *Experimental Results*

a. *Experiment on Sound Source Detection*

An experiment of sound source detection with developed acoustic positioning system module was carried out. The acoustic Pinger and DaryaBird are set up as shown in Fig 22. The hydrophones are mounted on the AUV. The diameter of experimental pool is 6 [m] and the depth is 1.5 [m]. The distance between pinger and hydrophones is 4.0 [m] and the relative depth is 1.0 [m]. θ_{xy} shows the relative angle between pinger and hydrophone and it can be adjusted by rotating the AUV. In this experiment, the measuring relative angle is set in total nine points from -90 [deg] to +90 [deg] in steps of 22.5 [deg]. Furthermore, the number of samples of each angle are 15.

Fig 23 show the angle estimated by the acoustic positioning system with respect to the actual relative angle. The results indicate a significant correlation between the relative angle and the estimated angle. The Average in the figures shows average value of 15 sampling data. In this experiment, the maximum average error was 6.6 [deg] and the maximum standard deviation was 5.2 [deg].

The detection accuracy was verified in the experiment and the result suggest that this system can detect the sound source direction within an average error of 10 [deg].

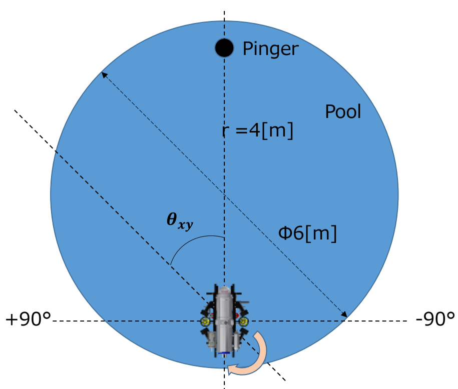


Fig 22. Experiment Setup

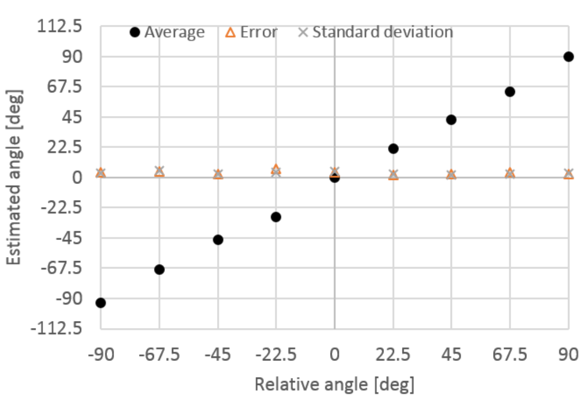


Fig 23. Result of Sound Source Detection

b. *Logging and Debugging*

This year, a new logging system was implemented. For the past years, in order to compare the values with each other, the team had to get the data individually from the *logsout* variable. Also, within a run, the team cannot determine the state DaryaBird is in on a specific time. Thus, debugging was very tedious. To facilitate easier logging and debugging, this year, the team used Signal and State Logging features of Matlab. The data after each run can be imported to the Simulation Data Inspector and compared with each other over time.

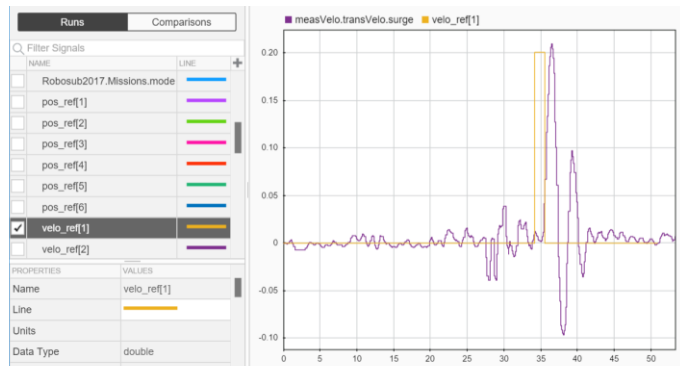


Fig 24. Simulation Data Inspector Sample Logging

c. *Overall Team Experiment for Robosub*

Since most of the team's members have job hunting duties from the start of the year, the team was not able to hold that much experiments during the first few months of the school year. During April 2017, the team held bimonthly experiments. It gradually increased to a weekly experiment during May. Then starting June, the experiments were held twice a week.

The school has a mini circular pool as shown in Fig 25 where the team usually holds the experiments. It is 1.5m deep with a diameter of 6m. The team also plans on using another campus' pool that measures 50x15m.

Fig 25. Kyutech Underwater Robotics Team Pool, Wakamatsu

Fig 26. Demo of DaryaBird to High School students last April 2017

APPENDIX

[1] W. Hori, R. Satoh, S. Nam, J. Ahn, N. Fujii, K. Matsuoka, Y. Soejima, Y. Takemura and K. Ishii, "An AUV Platform for Robot Behavior Development: Twin-Robot “DaryaBird ”and “OCTA ”, and Their’ Mission Strategy," *AUVSI&ONR’ s 17th Annual RoboSub Competition,* 2014.

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