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An AUV Platform for Robot Behavior Development : Twin-Robot "DaryaBird" and "OCTA", and Their' Mission Strategy

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Abstract: Various kinds of robots have been developed as computers and information processing technology advance. Operations in extreme environments such as disaster areas, space and ocean are getting one of the practical solutions for hazardous missions. The underwater robots are one of the extreme environment robots that are expected as one of solutions for underwater activities; maintenance of underwater structures, observations, scientific research. These activities require robots that can cover large area deep under ocean water. Their efficiencies have been investigated during recent decades and are proven by ocean experiments. However, the robotic system including the support vessels is still large in scale, and is not so easy to handle without number of researchers. In this paper, we describe the design of "DaryaBird" and "OCTA" developed to be easy to handle, small-scaled underwater robots that can operate only with two researchers. In addition, experimental results and mission strategies for Robosub2014 are reported.

Keywords: Autonomous underwater vehicle, MATLAB/Simulink, Modular architecture, Robosub2014

1. INTRODUCTION

Robots are expected to be a common solution for operations in extreme environments. Deep underwater of an ocean for example, is an extreme environment where human beings cannot survive which also makes it the operations costly. As science and technology develop, researchers have been studying seafloor topography and ecosystems of deep ocean water. These researches have mostly been carried out by divers with sensory equipments on boats. Recently, increasing number of researchers use underwater robots. Autonomous underwater vehicles (AUVs) are have advantages for activities in deep oceans [1] and are attractive tool for underwater studies. However, there still are various known issues to be solved: motion control, acquisitions of sensor informations, decision making, navigation without collisions, self-localization etc... A robot should be able to make decisions according to changing conditions from its sensors and actuators. It should then be able to change their behaviors least amount of efforts from the operators. We have been investigating adaptive controller systems [2][3], a navigation system [4] and an underwater manipulator system [5].

There are recent reports about successful underwater observations using AUVs. For example,"Urashima" of Ocean Development Research Institute made its successful voyage of 317km[6]. "r2D4" successfuly dived into 2000 [m] depth underwater and observed active underwater volcanos in Myojin-sho and Rota located near Tokyo and Guam respectively [7][8]. "AquaExplorer" has proved that AUVs are useful for ocean ecologic sys-

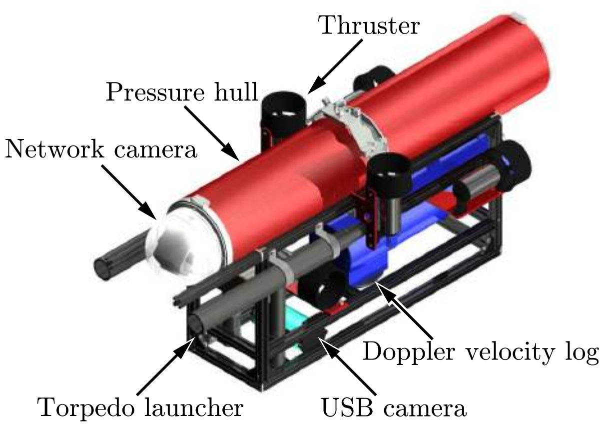


Fig. 1 Exterior view of DaryaBird

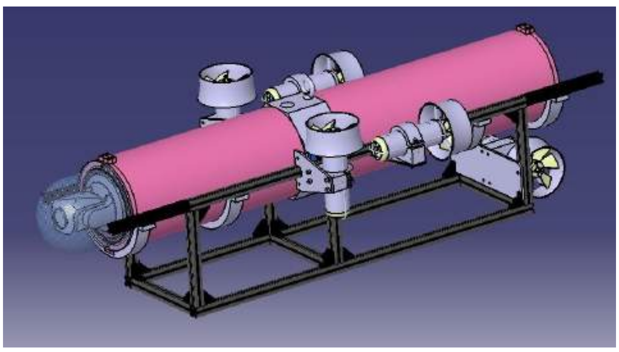


Fig. 2 Exterior view of OCTA

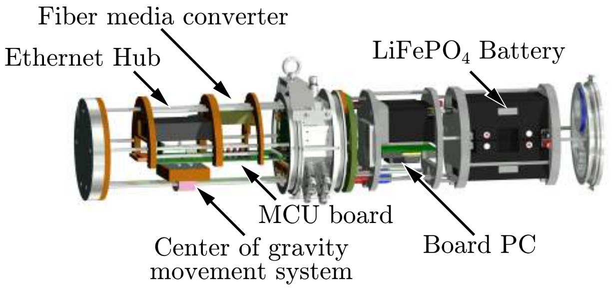


Fig. 3 Interior view of DaryaBird

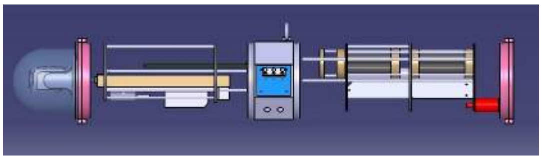


Fig. 4 Interior view of OCTA

Table 1 Specifications of DaryaBird

Structures	Aluminum pressure hulls × 2 Aluminum T-sloted frame 50[m] depth pressure resistant
Dimensions	H457 × W381 × L1044 [mm]
Weight	34 [kg]
Thrusters	110[W] (BTD150) × 5
Controller	Board PC (Intel Core-i5) Windows 7 MCU board(dsPIC30F6014A)
Communication	Ethernet and Optic LAN
Sensors	Pressure sensor (Depth sensor) Doppler velocity log Camera (Ethernet and USB) Attitude sensor Hydrophone
Batteries	$LiFePO_4$ 12[V], 9[Ah] ×3
Others	CoG movement system Torpedo launcher Marker Dropper

tem by tracking experiments of a Sperm Whale using AquaExplorer[9]. However, these robotic systems including the support vessels are still large in scale, and are not easy to handle by a few researchers. We have been developing underwater robots and these technical issues in Kyushu Institute of Technology (KIT) and Nippon Bunri University (NBU).

AUV ’DaryaBird” and “OCTA” have been developed by KIT and NBU Underwater robot teams aiming for easy-to-handle module contracture. The main concepts of DaryaBird and OCTA are:

1. small and handy enough to complete mission by a few operators without support vessels.
2. Frame structure for adding various options.
3. The operation mode, AUV or ROV mode, is selectable depending on mission.
4. Module system for easy maintenance.

These robots are being developed to overcome cooperative tasks. In this paper, we describe the hardware and software design of the DaryaBird and OCTA and mission strategies for Robosub2014.

Table 2 Specifications of OCTA

Structures	Aluminum pressure hulls × 2 Aluminum T-sloted frame 50[m] depth pressure resistant
Dimensions	H458 × W330 × L1030 [mm]
Weight	32 [kg]
Controller	Laptop PC(Intel Atom 1.33[GHz]) Windows 7 MCU board(dsPIC30F6014A)
Communication	Ethernet and Optic LAN
Sensors	Pressure sensor (Depth sensor) Gyro sensor Water quantity sensor Network camera
Batteries	NiMH (29.4[V], 3000 [mAh]) ×3

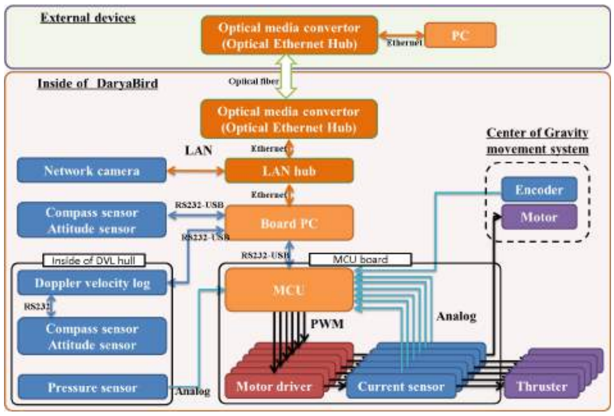


Fig. 5 System architecture of DaryaBird

2. OVERVIEW OF UAV “DARYABIRD” AND “OCTA”

DaryaBird means “gull” in Persian. OCTA stands for Oita Coastal survey Takemura-laboratory Autonomous underwater vehicle. The specifications of DaryaBird and OCTA are shown in Table 1 and Table 2. These robots can function as AUV by recognizing the surrounding environment and the situation. They can also funcion as ROVs using remote control system by connecting to external PC with optical cable. To observe a surrounding environment and internal state, these robots are equiped with number of speed sensors, a pressure sensor that measures the depth, a magnetic gyro sensor that measures attitude angle and azimuth angle, a set of current sensors. A network camera and sound localization device are in-

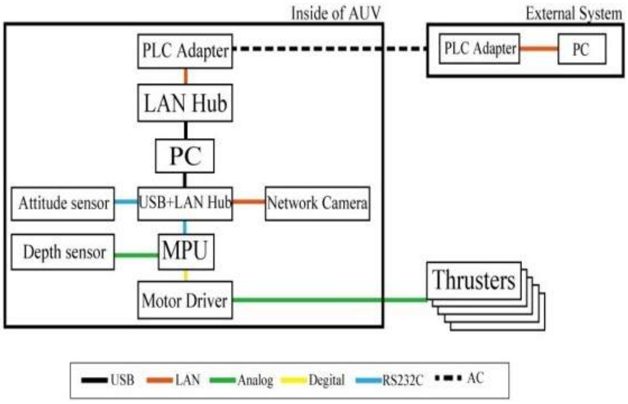


Fig. 6 System architecture of OCTA

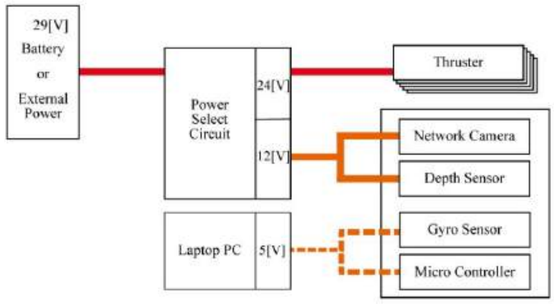
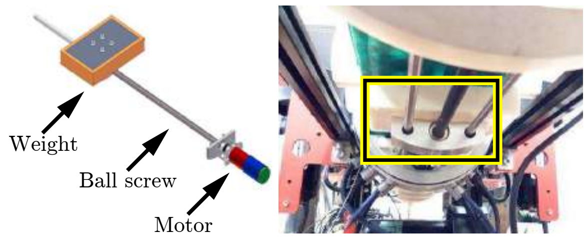


Fig. 7 Power supply system of OCTA



(a) over view (b) front view

Fig. 8 Center of gravity movement system

Fig. 9 Thruster (SeaBotix:BTD150)

stalled as external sensors. For propulsion, five thrusters (BTD150: SeaBotix 24[V] DC 110[W]) are mounted on the center and the rear. Motions such as surging, swaying, heaving, rolling and yawing are controlled using these five thrusters. Center of gravity movement system is installed for controlling pitching motions.

Fig. 5 and Fig. 6 shows the system architecture of DaryaBird. The robot is designed for a versatile testbed and software development, therefore, a small computer with high processing performance that is enough small enough for the pressure hull is installed. The operating system is Windows 7 with remote desktop function. Robots are controlled by using information from cameras, hydrophones and other sensors in autonomous mode. Mathworks MATLAB/Simulink is used as controlling system. DaryaBird is able to be controlled by remote commands while it is connected with tethered cables. A micro controller is introduced for motion control. Measured data in the dsPIC are transmitted to the PC through a FT232: RS232C-USB converter connected to USB hub.

A difference between DaryaBird and OCTA is power supply system. OCTA has two sets of power supplies. Fig. 7 shows power supply system for OCTA. Battery or External Power (AC100 [V] power) is selective. NiMH Batteries (29.4 [V], 3000 [mAh]) are used. NiMH battery and AC power is selected automatically using relay switching system and power circuit with self-holding circuit. Magnetic read switche is used for ON/OFF power switch.

3. HARDWARE AND SOFTWARE

This section deals with hardware and software architecture of DaryaBird.

3.1 Pressure hulls and frames

Fig. 3, Fig. 4 shows inside of pressure hulls. Pressure hall is jointed to center part. Center part holds electrical parts such as connectors and circuit boards for thrusters, sensors and motor drivers. The center part is designed for less connector trouble. Connectors are normally mounted on the outer side of the hulls. When robot needs a maintenance, all the connectors must be carefully removed one by one wihch require extra caution and time. Center part system allows these connectors to be centored in the middle of the robot, resulting easier access to the internal parts. Moreover, these pressure hulls are designed to hold the pressure up to 50 meters of depth. These two pressure hulls are supported by aluminum T-slotted frame. External devices can be attached or dettached on any place on the frame by using T-slot.

3.2 Actuators

The five thrusters shown in Fig.7, (BTD150: SeaBotix 24[V] DC 110[W]) control the motion of the robot. One is mounted at the bottom-center of the robot and four thrusters are attached around the body of the robot as shown in Fig.1. Surging, swaying, heaving, rolling and yawing motions of the robot are controlled using these five thrusters.

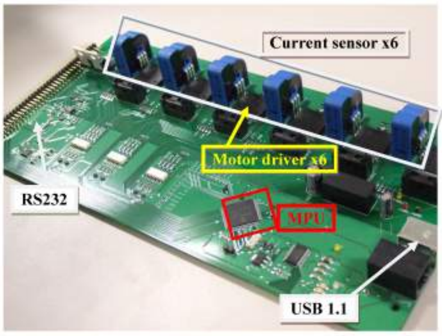


Fig. 10 MCU board named “iDriver”

Fig. 11 LiFePO $_4$ Battery

3.3 MCU board

We have developed a main circuit board as shown in Fig. 10 called ’iDriver’ enabled to control six motors. It consists of six motor drivers with six current sensors. Communication is performed by USB1.1, RS232 and I2C. Microcontroller dsPIC30F6014A manufactured by Microchip Technology Inc is used as main processing unit of iDriver. Isolation between motors and microcontroller is used to guarantee the safety of the microprocessor.

3.4 Batteries

A significant difference in DaryaBird and OCTA is batteries. DaryaBird has LiFePO $_4$ batteries shown in Fig. 11. LiFePO $_4$ is a relatively safe type of Lithium battery. It has good energy density (available power per weight). OCTA has NiMH batteries. NiMH batteries are potentially advantageous for high current drain applications, due to their low internal resistance.

3.5 Sensors

3.5.1 Pressure sensor

The FP101 is a high accuracy pressure sensor that can be used to measure gauge or absolute pressure as shown in Fig. 12. It has measuring range of 0kPa to 300kPa, and its corresponding maximum depth is about 20m. The sensor outputs a voltage between 1 to 5 DC volts signal corresponding to the measured pressure. This sensor is used in DaryaBird to monitor the depth where the robot is operating.

Fig. 12 Pressure sensor (YOKOGAWA Electric Corporation: FP101A)

Fig. 13 Doppler Velocity Log (Teledyne RD Instruments: Explorer DVL)

(a) over view

(b) front view

Fig. 14 Network camera(Canon: VB-C300)

3.5.2 Current sensor

In order to provide isolated current feedback, a hall effect closed loop DC current transducer LEM LTS 6-NP device has been installed as shown in Fig. 10. It consists of 5V supply with 2.5[V] nominal output representing 0A. This can be used to measure the primary r.m.s. current up to 6 A and primary current in ± 19.2 A. This type of sensors is installed to measure the current consumed by thrusters to limit their torques.

3.5.3 Doppler Velocity Log (DVL)

Another significant difference in DaryaBird and OCTA is a DVL. The Doppler sends out a 4-beam ’Pings’ and measures the resulting response in terms of frequency shift. This translates to a Velocity relative to the reflection point. Thus, DaryaBird is able to monitor how fast it travels.

3.5.4 Camera

To ensure robot control without any collision, Canon VB-C300 network camera is used which has pan tilt motion installed. This camera incorporates a 70 wide angle lens capable of encompassing a fairly large area even when operated in stationary position. This camera is mainly used to recognize the obstacles under water and to search for the landmarks.

Fig. 15 Attitude sensor (PNI Sensor Corporation: TRAX)

Fig. 16 Launched torpedo

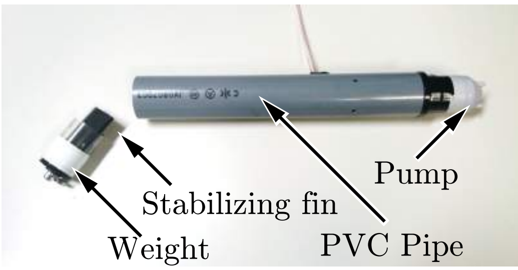


Fig. 17 Marker and dropper

3.5.5 Attitude sensor

As attitude sensor, 'TRAX (see Fig. 15)' made by PNI Sensor Corporation is installed for the control of motion in front hull. The TRAX is able to measure rolling, pitching and yawing motions. Acquisitioned data are transmitted through USB.

3.6 Torpedo launchers

A torpedo launcher is mounted on DaryaBird's frames. It is made by a PVC pipe with an electric kerosine pump and a magnet. Fig. 16 shows overall view of the launched torpedo. A torpedo consists of a kerosine pump, a motor drivers, a lead switch and an acrylic pipe. In order to launch a torpero, DaryaBird initially commands MPU to run motor of the pump, then, the torpedo gets pushed out of the PVC pipe. After that, lead switch that moved away from the magnet is turned on resulting torpedo thuster to be on.

3.7 Marker droppers

Marker dropper is mounted on the inside of frame of DaryaBird. A marker is a weight with stabilizing fin and fixing magnet. A dropper is made by an electric kerosine pump and a PVC pipe. Daryabird commands MPU to drive motor of the pump and the pump pushes the marker out of the pipe.

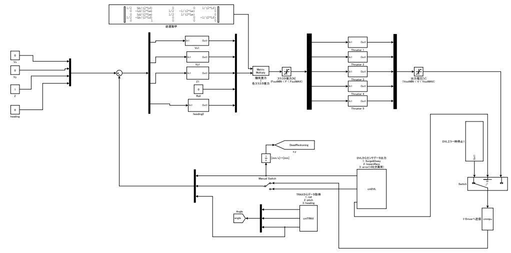


Fig. 18 Example of Simulink model of the DaryaBird

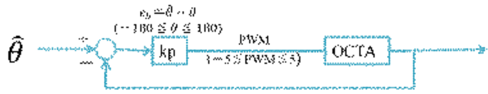


Fig. 19 Block diagram of OCTA Yaw control

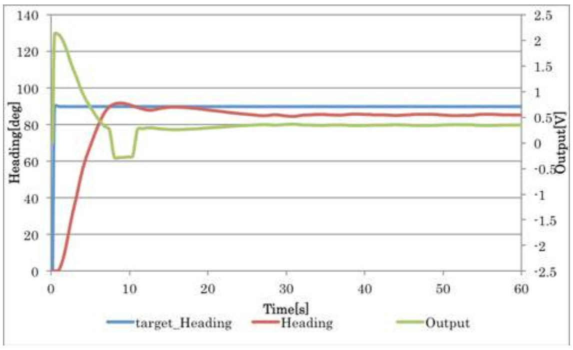


Fig. 20 Control experiment of yaw ($K_P = 0.75$, $b = 0.25$)

3.8 Sofware design of DaryaBird

The controller system of DaryaBird is made by Mathworks MATLAB/Simulink. Simulink is an extension to MatLab that allows engineers to rapidly and accurately build computer models of dynamic physical systems using block diagram notation. Fig. 18 shows a part of a DaryaBird's simulink model.

3.9 Software design of OCTA

For Autonomous control mode, OCTA's controller is adopted by PID controller. At this time, manipulated value is thrust PWM signal, and controlled variables are position of the robot. Figure 8 shows the designed controller which is realized by using position variable feedback loop. For the introduction of PID controller into the OCTA yaw direction, the following discretization equation is given by

$$e_k = \hat{\theta} - \theta_k \quad (1)$$

$$u_{k+1} = K_p e_k + K_I \sum_{i=0}^{t} e_i + K_D(e_k - e_{k-1}) \quad (2)$$

where $u(t)$, $\hat{\theta}(t)$, $\theta(t)$, $e(t)$ are manipulate value, target value, observation value and error value, respectively. K_P, K_I, K_D are proportional gain, integral gain differential gain in OCTA, respectively. Also, suffix 'k' means number of time series. In this experiment, we are using only K_P value. That means, at fist experiment, we are using P control. 'b' describes bias value of the PWM signal, because PWM signal where is -0.5 to 0.5 cannot move the thrusters. Therefore, we remove these area PWM signals.

We set $K_P = 0.75$, $b = 0.25$. Fig. 20 shows result of control experiment. The blue line describes target angle (90 [deg]). The yellow line is value of the heading sensor. The gray line describes output of PWM signal transition. X-axis means time series [sec]. Y-axis means heading angle [deg] (left axis) and PWM output voltage [V], respectively. In the graph, around 10 [sec], the robot reach the target, and almost overshoot doesn't happen. However, our controller is only P control, some constant error remained. Therefore, next works we adjust K_I and K_D parameters.

Second, we introduce to heave directional controller. The depth sensor transmitted analog voltage into motor driver. In the data sheet of depth sensor, analog voltage 1.0 [V] convert to 5.0 [V], that means sensor value is calculated as 5.0 [m/V]. Depth D [m] is calculated as follows:

$$D = (O_S - O_n) \times 5.0, \quad (3)$$

where, O_s and O_n are output voltage of analog pressure sensor value and natural air pressure [1 atm] output value of analog pressure sensor, respectively. Now we set that bottom direction is positive value. Fig. 21 shows raw sensor data. The data is calculated depth using (3). X-axis describes data number, and Y-axis describes depth [m]. It is clear fom the graph that raw data have a lot of noise. Therefore, we makes filter using FFT. And, Fig. 22 shows filtered data. It has also still noise around 0.05 [m]. However, in our experience, we don ' t need precise control around 0.05 [m], therefore, we ignore small noise.

For the introduction of PID controller into the OCTA depth direction, the following discretization equation is given by

$$e_k = \hat{D} - D_k \quad (4)$$

$$u_{j+1} = K_p e_j + K_I \sum_{i=0}^{t} e_j + K_D(e_j - e_{j-1}) + b \quad (5)$$

Where, $u(t)$, $\hat{D}$, $D(t)$, $e(t)$ are manipulate value, target value, observation value and error value, respectively. K_P, K_I, K_D are proportional gain, integral gain differential gain in OCTA, respectively. Also, suffix 'j' means number of time series. In this experiment, we are using only K_P value. That means, at fist experiment, we are using P control. ' b ' describes bias value of the PWM signal, because PWM signal where is -0.5 to 0.5 cannot move the thrusters.

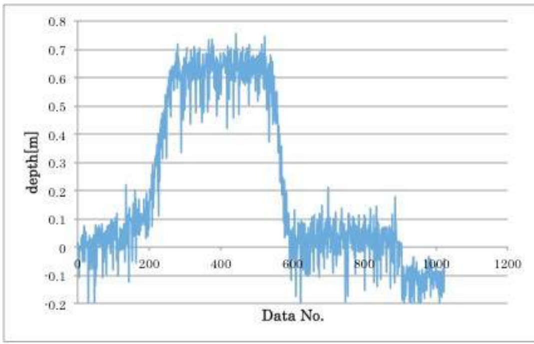


Fig. 21 Raw data of depth sensor

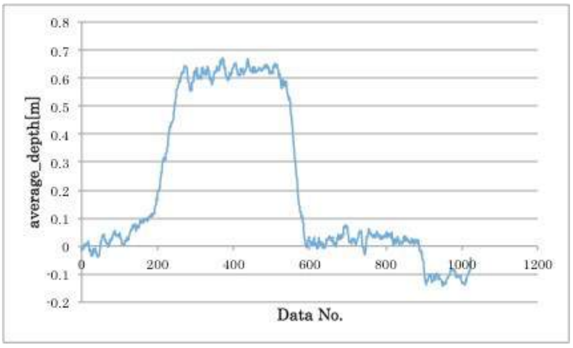


Fig. 22 After filtered data of depth sensor

We set $K_P = 0.8, b = 0.25$. Fig. 23 shows result of control experiment of depth. The blue line describes target depth (0.3 [m]). The yellow line is value of the depth sensor. The gray line describes output of PWM signal transition. X-axis means time series [sec]. Y-axis means depth [m] (left axis) and PWM output voltage [V], respectively. In the graph, the constant error is remaining, the robot cannot reach the target. However, Fig. 24 shows the experiment result when we set $K_P = 0.9$, $b = 0.25$. The robot can reach the target, however, the robot happen to move hunting. And, the robot also have overshoot around 0.1 [m]. Therefore, we decide the parameter of $K_P = 0.8$ and $b = 0.25$.

As seen above, we experienced yaw and depth control, these controller have still constant error, therefore, we should tuned more parameter. And also, we should make the model of the robot using limit cycle experiment and approximated motion equation.

4. MISSION STRATEGY

Mission is performed by 6 different tasks to achieve the goal. These tasks are including of Validation gate, Path tracking, Control Panel (Buoy), Maneuvering (PVC to pass over/around), Landing Site (Bins) and Brunch (Firing torpedoes).

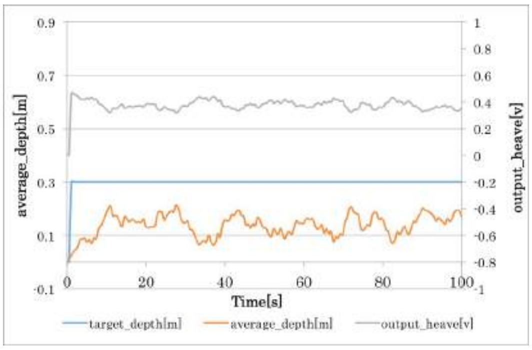


Fig. 23 Control experiment of depth ($K_P = 0.8, b = 0.25$)

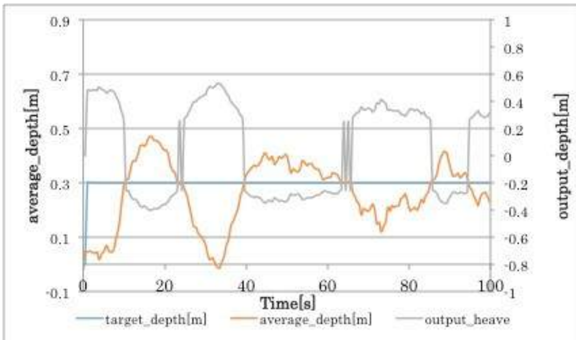


Fig. 24 Control Experiment of depth ($K_P = 0.9, b = 0.25$)

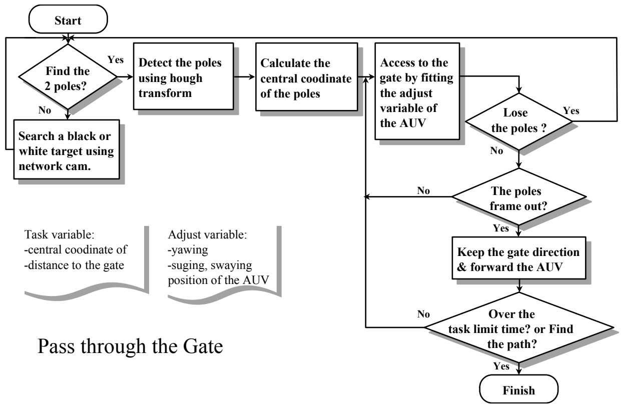


Fig. 25 Flowchart of Validation gate

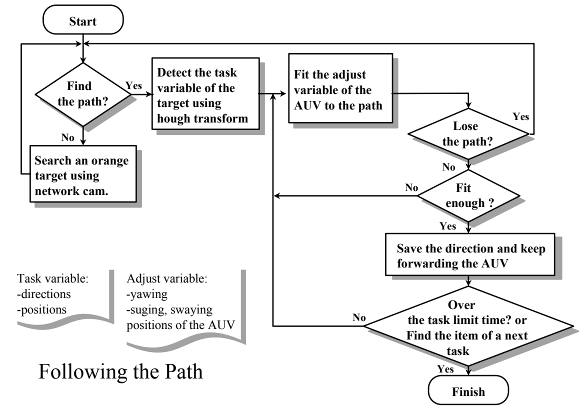


Fig. 26 Flowchart of Path

4.1 Validation gate

This algorithm is developed in order to pass the robot through the gate properly. The flowchart of this algorithm is explained in Fig. 25. At the beginning direction of the gate is given to the robot as the initial conditions when the robot ready to launch. At first, robot is submerged in to the decided set depth. Then the coordinates of the center of the gate is calculated by Hough transformation. The actual range is set up using calibration of a known range and an acquired image on the network camera. To perform this task well and fast, robot should pass the gate and find the path object next to the gate and hence this is planned to carry out within few seconds.

4.2 Path

Path following algorithm guides the robot reach to the buoys placed away from the gate. The flowchart of the algorithm is shown in Fig. 26. When the AUV is in search mode for the path, the AUV emerges a few meters up for easy search. A distance and a direction to the path from the AUV are computed using Hough transformation. When the robot reached to the buoy, this task is finished perfectly and robot beings to next process.

4.3 Control Panel (Buoy)

In this task robot has to move in front to the color buoy decided by the competition organizers. Fig. 27 shows the flowchart of the training algorithm. Directions and positions of the 1st buoy are calculated by the computer system using the Hough transformation of circle. A distance between the buoy and the AUV is estimated by the size of image of the buoy from the acquired image. If 1st buoy detecting task is finished, robot challenges for the 2nd buoy. It tries to 2nd buoy as just like in 1st buoy. When this whole task is finished, robot will go to perform the next task of obstacle course.

4.4 Maneuvering (PVC to pass over/around)

The flowchart of the obstacle course algorithm is shown in Fig. 28. Relative positions between the Lover Lane and the AUV are estimated using Hough transformation of the green targets from acquired image. The AUV keeps the direction fixed and move forward until finish this task without any collisions. This task is planned to finish within few second and go to the next task of Laurel wreath recover. If detecting a green target is difficult while training term, the task is excluded from our mission.

4.5 Landing Site (Bins)

Fig. 29 shows task is performed in order as shown in fig.18-6. Directions and positions of the nest are calculated by the binarization and Hough transform of an area of the nest. A distance between the nest and the AUV is

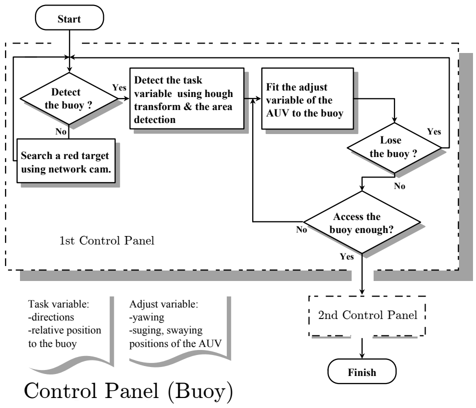


Fig. 27 Flowchart of Control Panel

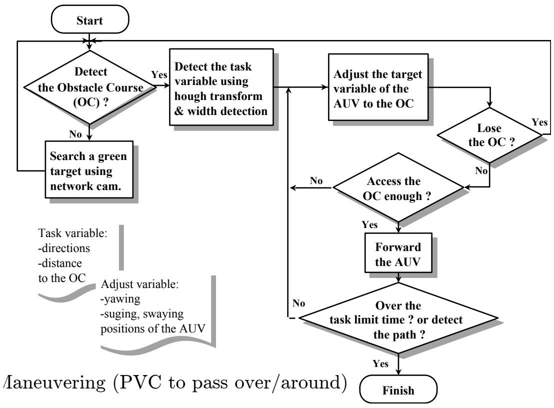


Fig. 28 Flowchart of Maneuvering

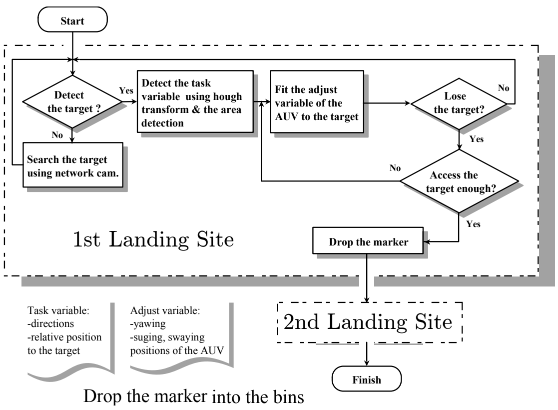


Fig. 29 Flowchart of Landing Site

estimated by the size of image of the nest from acquired image. Two torpedoes are fired off when the AUV close enough to the nest. The finish of the task is decided by the limit time, and fire off forcibly torpedoes. If detecting a green target is difficult while training term, the task is excluded from our mission.

4.6 Brunch (Firing torpedoes)

This task is performed in order as shown in Fig. 30. Directions and positions of the nest are calculated by the binarization and Hough transform of an area of the nest.

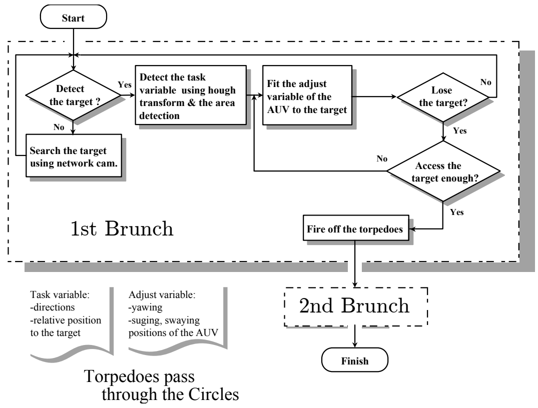


Fig. 30 Flowchart of Brunch

A distance between the nest and the AUV is estimated by the size of image of the nest from acquired image. Two torpedoes are fired off when the AUV close enough to the nest. The finish of the task is decided by the limit time, and fire off forcibly torpedoes. If detecting a green target is difficult while training term, the task is excluded from our mission.

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