공학석사 학위논문

Hovering-type AUV의 경로추종을 위한 제어기 설계 및 실해역 실험에 관한 연구

A Study on Controller Design and Real Sea Experiment for Path Tracking of Hovering-type AUV

지도교수 김 준 영

2016년 8월

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Hovering-type AUV의 경로추종을 위한 제어기 설계 및 실해역 실험에 관한 연구

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Abstract

AUV replacing humans and performing works in deep sea where humans are hard to work is actively developed. AUVs are various on purpose, but among them, Hovering-type AUV can perform works by keeping its position and posture under water. Studies about AUV are being performed domestically, but comparing to other counties, technologies fall behind. So it is needed to accept outside technologies that already reached commercialization and to secure technical skills by developing navigation algorithm.

In this thesis, performances of AUV were verified by making

Hovering-type AUV test-bed and designing various controllers. Developed AUV can control 4DOF motion, using 2 horizontal thrusters and 2 vertical thrusters. Prior to field test, 6DOF equations of motion is developed, simulation program is constructed by using Matlab/Simulink, and essential motion performance of designed vehicle is verified. Besides, PID controller and Fuzzy PID controller are designed for carrying out their missions, and performance of the controllers is verified by simulation. Tests are performed in the field to verify motion performance of the AUV, and the way-point tracking is performed by PID and Fuzzy PID controller to the vehicle. It results in confirming appropriate control performance under current disturbances. Result graphs of experiments were showed, and by analyzing those, performances of controllers were verified.

KEY WORDS: Hovering-type AUV; PID controller; Fuzzy PID controller; Field test.

CHAPTER 1
INTRODUCTION

1.1 Background

As human beings have evolved, it is necessary for them to develop technologies to satisfy their desires and interests for something new. Thanks to technology developments, there are lots of skyscrapers in land, and it is difficult to find no vehicle streets. You can easily see gigantic airplanes in the sky and also gigantic ships on the sea. Gigantic airplanes in the sky and gigantic ships on the sea are easily seen.

In the past there were many plentiful resources in land, but the more technologies developed, the more resources were depleted on and on. In the future it will be not sure how many resources that we can use left in land. Therefore, it is natural that people have been interested in resources in the sea gradually. It has led to interests in under water and attempts to develop and explore unexplored underwater environment.

There is a large limit for human to explore and work underwater environment in person. Possible range that humans can work in the water is a shallow sea 20m or so, but it is impossible for them to work over 20m in depth. That is the reason why a underwater vehicle was made to safely work for exploration, research, and construction on the seabed. Underwater vehicles were developed from manned underwater vehicle to unmanned underwater vehicle. Every underwater vehicle operating in the water is called UUV(Unmanned Underwater Vehicle). These kind of UUVs are suitable for dangerous and difficult works instead of existing manned underwater vehicles or divers. According to human's interference degree, UUV is divided into ROV(Remotely Operated Vehicle) and AUV(Autonomous Underwater Vehicle).

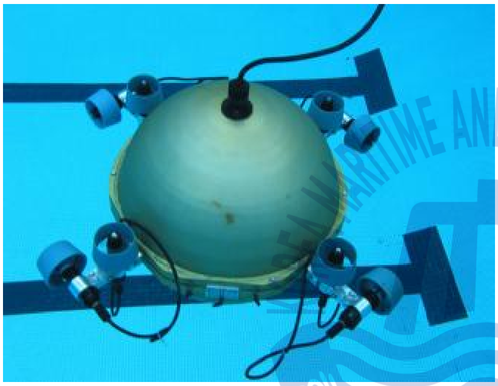
ROV is a remotely controlled by user and has a command ship and a cable for data, control, and power supply. ROV is not suitable for driving because as cable is longer and longer, it is affected by tidal current more and more, and price rises too. There are a small robot to do simple work like underwater shooting and a large robot to bury cables or to install pipes in the water. Most of ROVs have multiple thrusters that are shaped like box or torpedo, and it's operational speed is less than 4 knots. AUV autonomically navigates to perform its task, not being controlled by user. It has its own power inside, instead of having communication or power cable connected to command ship. So, AUV's operational time depends on its battery capacity. Also, it has a computer and various sensors inside because it is not controlled by human. AUV is very effective to explore deep sea or shallow sea that command ship cannot access and also useful to inspect buried cable or pipe plumbing.

According to cruising distance for task, AUV is divided into Cruising type AUV and Hovering type AUV. Unlike Cruising type AUV that sails in a wide range of water and explores seabed landform, Hovering type AUV is used for inspecting the bottom of a ship or underwater structure. Function of attitude control and position control is important to Hovering type AUV for precise work under water, so precise control of thruster is needed. Fig.1 shows example of various types of Hovering type AUV.

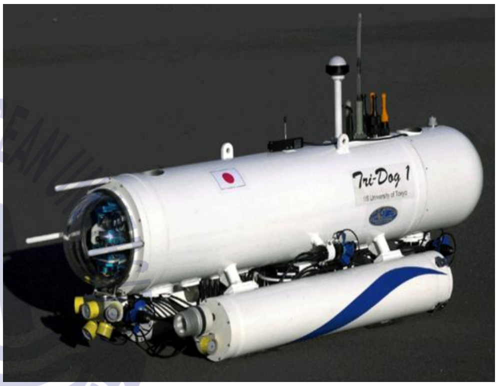
The earlist Hovering type AUV is 'ODIN' of University of Hawaii, and it is composed of pressure vessel that is globular shape of 0.64m in diameter. Like Fig 1, to maintain position underwater, six degrees of freedom movement is controlled by using four vertical thrusters and four horizontal thrusters.

'Tri-Dog1' developed by Ura laboratory of Tokyo University in Japan in 1999, is about two meter long Hovering type AUV. It can control four degrees of freedom by six thrusters and is equipped with two cameras and one subsea landform measurement equipment. In 2004, it succeeded in observing a large caisson around.

'HAUV' of Bluefin Robotics company of USA uses 3~5 thrusters, and maximum water depth is 30m. Navigational sensor includes a ring laser gyro and a Doppler velocity log(DVL). 'HAUV' performs scanning the bottom of a ship and subsea landform by using Image sonar.



(a) ODIN (Hawaii Univ.)



(b) Tri-Dog1 (Tokyo Univ.)

(c) HAUV (BLUEFIN ROBOTICS)

(d) ALIVE AUV

Fig. 1 Hovering-type AUVs

CHAPTER 2
HOVERING-TYPE AUV’ S HARDWARE & SENSORS

2.1 Hardware

Hovering type AUV ‘OCTAGON’ is the shape of octagon like Fig. 2. Stainless steel was used for outer frame to prevent corrosion. Outer frame surrounded pressure vessel and was the shape of octagon to easily attach not only sensors that had been already equipped but also additional sensors. Two horizontal thrusters and two vertical thrusters were attached to outer frame, and DVL was attached to lower part of outer frame and also protected by it. Compression styrofoam was used for boosting buoyancy on the upper part of UUV. UUV’s pressure vessel should have watertight structure to protect battery and electric part from seawater, so two O-rings were used for waterproofing. Pressure vessel is divided into two parts, the lower part of pressure vessel that is composed of battery and electric part, and the upper part of pressure vessel that is composed of antenna, GPS, and TCM-3. Aluminum was used for pressure vessel, and corrosion was prevented by surface treatment. There were thruster, DVL, and six waterproof connectors connected to switch in the lower part of pressure vessel. Pressure sensor was located in the bottom of pressure vessel by making a hole. Six Li-Pos were used for battery that provided power supply to UUV. Four batteries that were arranged in a row provided power supply to four thrusters, and the other two batteries provided power supply to power distribution board. Then power distribution board provided that power supply to DVL, TCM-3, PC power supply, and Pressure sensor.

In this case, DC-DC converter was used to adjust power supply because needed power supply differed from each other. Power supply of PC board was provided by power supply board.

Fig. 2 Hovering-type AUV 'OCTAGON'

Electric part was composed of previously explained power distribution board, DAQ board, and PC board and played a role as head of UUV. There were GPS, antenna for communication, and wireless router for remote communication with the outside PC in the upper part of pressure vessel. Also direction angle sensor, TCM-3 too. If pressure vessel for GPS was aluminum, transmission and reception of data were impossible, so acetal was used for pressure vessel. Switch box was equipped by making a hole in buoyant material located in the upper part of UUV, and switch gave power supply to electric part of UUV and PC board. The upper and lower part of pressure vessel were tested on waterproof function, also GPS housing, switch box too. Specifications of Hovering type AUV 'OCTAGON' is like Table 1.

Table 1 Specifications of Hovering AUV 'OCTAGON'

Parameter	Specification
shape	Open-frame
size	736×736×600[L×W×H][mm]
mass	50Kg
task water depth	10m
thrusters	350watt×4EA
control mode	4-DOF
communication	RS-232, wifi
control board	on-board PC, DAQ board
battery	25.7V-6.6Ah Li-Po × 6EA
sensor	Pressure sensor, DVL, TCM3

Thruster

Control of Multiple thrusters are needed for UUV(Unmanned Underwater Vehicle) to perform given task. Two Horizontal Thrusters and two Vertical Thrusters are used in this paper. The Horizontal Thruster is Model 300 and the Vertical Thruster is Model 280 of Tecnadyne Company. Input voltage of the thruster is 24V~150V and applied voltage of Motor driver is independently 12V. Six 26.5V Li-Po batteries are used to give Input voltage, and using DC-DC converter, 12 voltage is given to motor driver. To make thrust to the thruster, DAQ board is used to give ±5V analog control input. Model 300 thruster's capacity is a maximum of 350watt, and the thruster has 7.7kgf ahead thrust and 3.2kgf astern thrust. Model 280 thruster has thrust of 6.1kgf both ahead and astern. Fig. 3 is a thruster used to AUV.

Fig. 3 Thruster

2.2 Sensors

State value of UUV is haven to measure with sensor for UUV to perform given order. In this paper, multiple sensors are used to control UUV. Pressure sensor to measure depth, GPS and DVL to measure position of UUV, and TCM-3 to measure direction of UUV are used.

Pressure sensor

UUV uses pressure sensor that measures ambient pressure directly, to measure depth of water.

In this paper, PSCE00.5BCIG model of Sensor system company was used. This sensor can measure range of 0.5bar(5m), and according to depth of water, it outputs 1V~5V. Fig. 4 is a pressure sensor for measuring depth of water.

Fig. 4 Pressure sensor

Magnetic compass

Fig. 5 is a gyrocompass for getting information about direction of UUV. Used sensor model is TCM3 of PNI company, and it provides 3 axis angle information by receving 5V input power source. Measured accuracy of Roll, Pitch, and Yaw angles is 0.5° in a state of stop, and sensor resolution is 0.1°.

Fig. 5 TCM-3 sensor

GPS

GPS is a satellite navigation system to calculate user's current position by receiving signal from GPS satellite. In this paper, GPS of Fig. 6 was used to get information about UUV's position on the water. The GPS is ASTERX-M model of Septentrio company. Accuracy of sensor is within 1m, and it can be connected to PC directly because it is USB type.

Fig. 6 GPS antenna

DVL(Doppler Velocity Logger)

DVL is a device to measure body's relative velocity using Doppler effect of sound wave reflected from surface of the sea and seabed. Measured velocities are used to find out moving distance and to help other sensors.

In this paper, instead of GPS sensor that cannot use in the water, DVL is used to get some information of UUV's velocity and to find out moving distance. Used DVL is NavQuest 600 Micro DVL of LinkQuest Company like Fig. 7, and it provides velocity of Surge, Sway, Heave. Because moving distance is calculated by integrating UUV's velocity value, cumulative error could occur. Later, location is need to correct with GPS sensor on the surface of the sea making UUV float.

Fig. 7 DVL sensor

DAQ board

DAQ board is a device that changes entered analog signal to digital signal and makes computer decode that signal. DAQ device for signal measurement is composed of ADC(analog-digital converter) and computer bus. Analog signal of sensor should be changed to digital signal before digital device manipulates, ADC is a chip playing this role. Analog signal changes as time passes, and ADC collects regular samples of signal according to predefined speed. These samples are delivered to computer by computer bus and in software are reconstructed to original signals. Computer bus functions as a communication interface between DAQ device and computer to deliver measured data.

Fig. 8 is NI USB-6009 DAQ board of National Instruments company, and it has eight analog input ports and provides bus with power supply through USB power supply. It is used to get measured value of pressure sensor, maximum voltage range of analog input is -10V ~ 10V, and accuracy is 7.73mV.

Fig. 8 NI USB-6009 DAQ board

Fig. 9 is NI-9264 DAQ board of NI company, and it has sixteen analog output channels. It is used for control of four thrusters, and its output range is -10V ~ 10V. In this paper to control thruster, it was given -5V ~ 5V of maximum output range. PC board plays a role as a central processing unit that saves data from sensors and issues an order.

Fig. 9 NI-9264 DAQ board

When designing UUV, to improve usability, the size of pressure vessel was minimized, and used PC board was mini-ITX board. It was 1.5 times smaller than existing PC board. PC was composed of CPU of Inter Core i5, two 4G DDR3 RAMs, and Samsung SSD. To supply power to PC board, power supply board was used like Fig. 10.

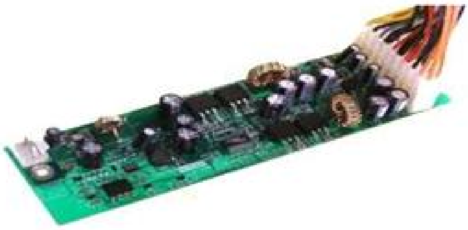


Fig. 10 Power supply board

CHAPTER 3

AUV'S MATHEMATICAL MODEL & DESIGN CONTROLLER

To design AUV, first it is needed to interpret dynamic performance and performance of control using mathematical model.

In this paper, 6 DOF(Degrees Of Freedom) nonlinear equations of motion was induced to interpret AUV's motion, and AUV's dynamic performance was verified by developing simulation program to solve the equation under various inputs and environments.

3.1 좌표계설정 및 무인잠수정의 수학적 모델

To express AUV's motion, it is needed to set up coordinates and to define notation used in equations of motion. Coordinates assume designed AUV as rigid body. Body fixed coordinates were set up to AUV's center of gravity like Fig. 11, and earth fixed coordinates were also set up for user to confirm motion of AUV.

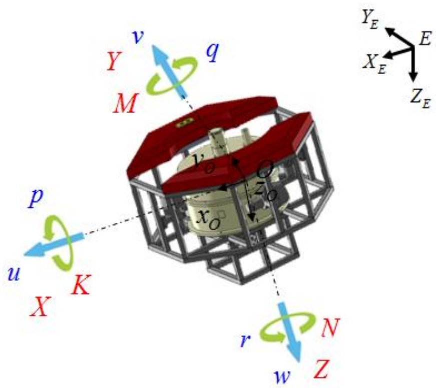


Fig. 11 Coordinate system

Translational motion and rotational motion about each axis of designed coordinates were expressed as 6 DOF equations of motion, and it was expressed in Eq(equation). (1) ~ (2). Coordinate axis and title used in developed formula are like Table 2.

$$
\begin{aligned}
&m[\dot{u} - vr + wq - x_g(q^2 + r^2) + y_g(pq - \dot{r}) + z_g(pr + \dot{q}) = \sum X_{ext} \\
&m[\dot{v} - wp + ur - y_g(r^2 + p^2) + z_g(qr - \dot{p}) + x_g(qp + \dot{r}) = \sum Y_{ext} \\
&m[\dot{w} - uq + vp - z_g(p^2 + q^2) + x_g(rp - \dot{q}) + y_g(rq + \dot{p}) = \sum Z_{ext} \\
&I_{xx}\dot{p} + (I_{zz} - I_{yy})qr - (\dot{r} + pq)I_{xz} + (r^2 - q^2)I_{yz} + (pr - \dot{q})I_{xy} \\
&\qquad + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] = \sum K_{ext} \\
&I_{yy}\dot{q} + (I_{xx} - I_{zz})rp - (\dot{p} + qr)I_{xy} + (p^2 - r^2)I_{xz} + (qp - \dot{r})I_{yz} \\
&\qquad + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] = \sum M_{ext} \\
&I_{zz}\dot{r} + (I_{yy} - I_{xx})pq - (\dot{q} + rp)I_{yz} + (q^2 - p^2)I_{xy} + (rq - \dot{p})I_{xz} \\
&\qquad + m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] = \sum N_{ext}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
\Sigma X_{ext} &= X_{HS} + X_u u + X_{u|u|} u|u| + X_{\dot{u}} ur - X_{\dot{u}} uq + X_{\dot{u}} uw - X_{\dot{u}} uv + \Sigma F_x \\
\Sigma Y_{ext} &= Y_{HS} + Y_v v + Y_{v|v|} v|v| + Y_{\dot{v}} vp - Y_{\dot{v}} vw + Y_{\dot{v}} uv - Y_{\dot{v}} vr + \Sigma F_y \\
\Sigma Z_{ext} &= Z_{HS} + Z_w w + Z_{w|w|} w|w| + Z_{\dot{w}} wq - Z_{\dot{w}} \wp + Z_{\dot{w}} vw - Z_{\dot{w}} uw + \Sigma F_z \\
\Sigma K_{ext} &= K_{HS} + K_p p + K_{p|p|} p|p| + K_{\dot{p}} pr - K_{\dot{p}} pq + \Sigma M_x \\
\Sigma M_{ext} &= M_{HS} + M_q q + M_{q|q|} q|q| + M_{\dot{q}} pq - M_{\dot{r}} qr + \Sigma M_y \\
\Sigma N_{ext} &= N_{HS} + N_r r + N_{r|r|} r|r| + N_{\dot{r}} qr - N_{\dot{r}} pr + \Sigma M_z
\end{aligned} \tag{2}
$$

Left side of Eq. (1) is mass(m), center of gravity(x_g, y_g, z_g), mass moment of inertia(I) of AUV and linear velocity(u, v, w), angular velocity(x_g, y_g, z_g) of body fixed coordinates. Eq. (2) is external force of applying to AUV including added mass force, Coriolis force, restoring force, and thrust force. Hydrodynamic coefficients like $X_{u|u|}$, $Y_{v|v|}$, $Z_{w|w|}$ were got by experiments and empirical formulas.

Table 2 Notations of each axis

Classification	Motion	Displacement	Velocity	Force & Moment
Translational Motion	Surge	x	u	X
	Sway	y	v	Y
	Heave	z	w	Z
Rotational Motion	Roll	Φ	p	K
	Pitch	θ	q	M
	Yaw	ψ	r	N

In this paper, hydrodynamic coefficients of previously announced similar form were used, and it was like Table 3.

Table 3 Parameters of hydrodynamic coefficients

Parameter	Value	Parameter	Value
I_{xx}	6.9	$Y_{v\|v\|}$	-405.41
I_{yy}	26.1	$Z_{\dot{w}}$	-46
I_{zz}	23.2	Z_{w}	0
X_{g}	0	$Z_{w\|w\|}$	-478.03
Y_{g}	0	$K_{\dot{p}}$	-1.3
Z_{g}	0	K_{p}	-0.223
X_{b}	0	$K_{p\|p\|}$	-3.212
Y_{b}	0	$M_{\dot{q}}$	-6.8
Z_{b}	-0.3461	M_{q}	-1.918
$X_{\dot{u}}$	-18.5	$M_{q\|q\|}$	-14.002
X_{u}	-10	$N_{\dot{r}}$	-5.9
$X_{u\|u\|}$	-227.18	N_{r}	-1.603
$Y_{\dot{v}}$	-28	$N_{r\|r\|}$	-12.937
Y_{v}	0		

Hovering type AUV performs 4 DOF(Surge, Heave, Pitch, Yaw) by using 2 vertical thruster and 2 horizontal thruster. So force and moment of thruster can be added to external force of equations of motion, considering position and direction of each thruster. Fig. 12 shows position and direction of thrusters. Marked number 1, 2 are horizontal thrusters, and 3, 4 are vertical thrusters. Force and moment of each axis are like Eq. (3).

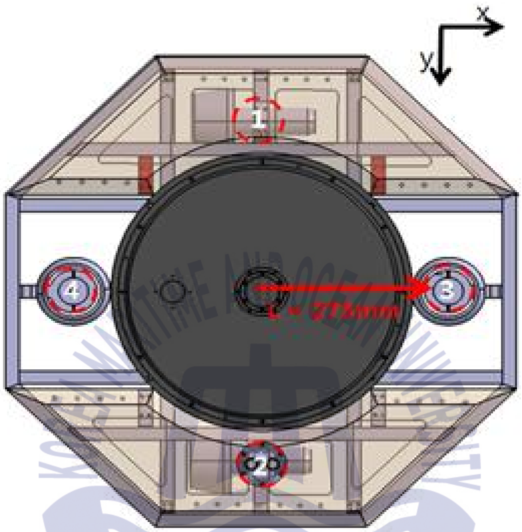


Fig. 12 Thruster configuration

$$\Sigma F_x = F_1 + F_2 \quad (3)$$

$$\Sigma F_y = 0$$

$$\Sigma F_z = F_3 + F_4$$

$$\Sigma M_x = 0$$

$$\Sigma M_y = -l \cdot F_3 + l \cdot F_4$$

$$\Sigma M_z = -l \cdot F_1 + l \cdot F_2$$

F_i is force of i_{th} thruster, and l is distance from AUV's center of mass to thrusters.

3.2 Coordinate system setting & AUV's mathematical model

In this paper, PID controller and Fuzzy PID controller were used to control position of AUV. Also, composition matrix was applied to distribute appropriate thrust to hovering type AUV using many thrusters.

Force and moment about each axis were expressed by using composition matrix T like Eq. (4) ~ (5) considering position and direction of thruster explained by 3.1

$$\tau_T = TF_T \tag{4}$$

$$T = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & -l & l \\ l & -l & 0 & 0 \end{pmatrix} \tag{5}$$

$$\tau_T = [\Sigma F_x, \Sigma F_y, \Sigma F_z, \Sigma M_x, \Sigma M_y, \Sigma M_z]'$$

$$F_T = [F_1, F_2, F_3, F_4]'$$

Using this equation, thrust F_T to control AUV is like Eq. (6).

$$F_T = T^{-1} \cdot \tau_T \tag{6}$$

3.2.1 Design PID controller

PID controller is one of the powerful controllers because it can process ideal integral compensation and derivative compensation and also is composed of active circuit. Most of modern industrial systems have been controlled by PID controller. This is because it is comparatively stable under extensive operating condition, design of control device is easy and can be easily understandable, and operation is simple. Because performance of PID controller depends on gain of proportional K_P, gain of integral K_I, and gain of derivative K_D, how to decide this three variables is very important. But finding parameter of PID controller is not easy, these values are calculated by experience and ability of control system designer in the way of trial and error. If normal closed loop control system is designed by PID controller, structure of closed loop control system looks like Fig. 13.

According to Fig. 13, PID controller is composed of proportional term P, integral term I, and derivative term D.

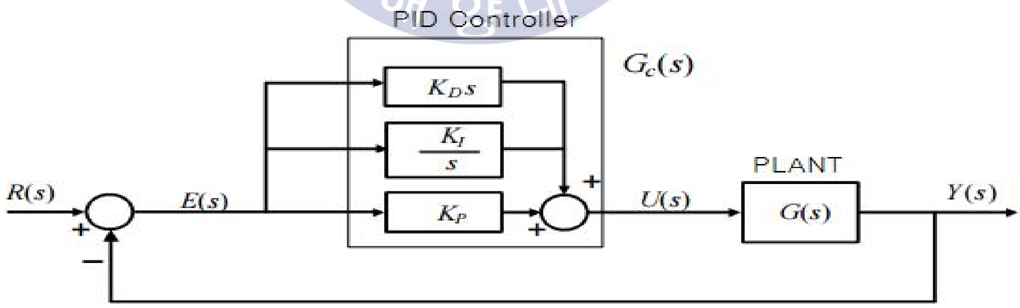


Fig. 13 Structure of closed loop control system composed of PID controller

Output equation in time domain is like Eq. (7).

$$u(t) = K_P\, e(t) + K_I \int e(t)dt + K_D \frac{de(t)}{dt} \tag{7}$$

This equation is a general form of PID controller, $u(t)$ is Control Input, and e is a gap between Desired Value and Current Value. If proportional gain is increased, rising time of respond decreases, and also steady-state error decreases, but there is a disadvantage of overshoot increase. Steady-state error can be reduced, but it requires large controlled variables and can make system vibrate. If integral gain is increased, rising time of respond slightly decreases, and steady-state error disappears. But if it is used independently, it makes system unstable, so it is usually used with proportional control term. If derivative gain is increased, rising time of respond and overshoot decrease. It is used with proportional-integral control term, instead of being used independently.

It was needed to calculate force and moment of each axis to keep position of AUV, and PID controller was designed for deciding this force and moment. Developed AUV can control 4 DOF motion, so control input outputting from controller becomes force of x, z direction and moment of y, z direction.

Depth controller was designed by considering depth and motion of pitch direction as PD controller. Designed depth controller is like Eq. (8).

$$\tau_n = K_{pn} e_n + K_{dn} \dot{e}_n \tag{8}$$

$$\begin{cases} n = 1\ ,\ Heave\ ,\ e_1 = Z_d - Z \\ n = 2\ ,\ Pitch\ ,\ e_2 = \theta_d - \theta \end{cases}$$

Z_d is desired depth, Z is current depth, θ_d is desired pitch angle, θ is current pitch angle, K_p is proportional gain, and K_d is derivate gain. Also, PID controller to control heading angle and velocity of AUV is expressed by Eq. (9).

$$\tau_n = K_{pn}e_n + K_{in}\int e_n dt + K_{dn}\dot{e}_n \tag{9}$$

$$\begin{cases} n = 1,\ Yaw\ ,\ \ e_1 = \psi_d - \psi \\ n = 2,\ Surge\ ,\ \ e_2 = u_d - u \end{cases}$$

ψ_d is desired heading angle, ψ_d is current heading angle, u_d is desired velocity, u is current velocity, and K_i is integral gain. Gain value that was used for PID controller in this paper selected optimal response value of AUV through the rule of trial and error.

3.2.2 Design Fuzzy PID controller

Fuzzy theory is different from original computer logic method, true and false, so it has ambiguous values between true and false because it is approximate logic.

In short, Fuzzy theory is not true and false two-valued logic. If true is 1 and false is 0, real number between 1 and 0 is showed for ambiguity. Fuzzy control method is used for having difficulty in mathematical modeling or nonlinear system. Fuzzy control does not require mathematical modeling in nonlinear system control, and satisfying good controller can be designed by 'IF-THEN' format of linguistic rules as reflecting human experience or expert knowledge.

Most Fuzzy control systems use output error of system and error's rate of change as input, it is similar to PID control in that control rule is composed of the same principle as PID control. But unlike PID controller that has a linear relationship with plant, control input of Fuzzy controller is decided in nonlinear method, so it show better control characteristic because it can overcome a wide range of motional condition, compared to motional condition that PID controller overcomes.

Like Fig. 14, general Fuzzy controller is composed of Fuzzifier, Rule base, Fuzzy inference engine, and Defuzzifier. Each factor affects efficiency of Fuzzy controller and control system motion.

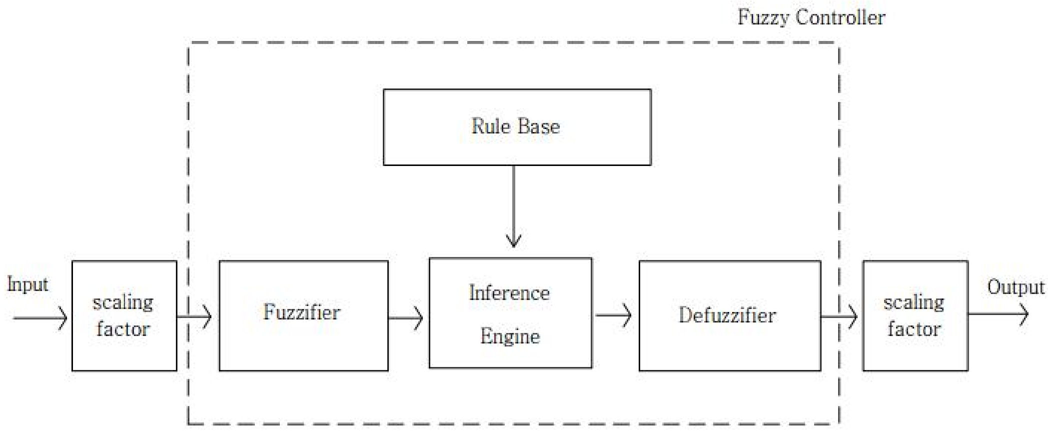


Fig. 14 Fundamental structure of fuzzy controller

Fuzzy control could be divided into various types, and in this paper, combination of two algorithms was applied to decide gain value of designed PID controller using fuzzy theory. Among control objects, membership functions of input variable and output variable of heave motion and heading motion are like Fig. 15 ~ Fig. 18. Also, fuzzy rule for controlling depth and heading angle of AUV was set like Table 4 ~ Table 8, and output value became PID controller's gain value. At this time, fuzzy rule could be decided by considering difference between desired value and current value and the difference value's rate of change with time.

In this paper, there were rules of control gain (K_p, K_i, K_d) for heading control and of PD controller's control gain (K_p, K_d) for controlling depth. Like above, there were rules of pitch angle and velocity control to calculate each control gain. Also, the rule was inferred from Mamdani method, and centroid method was used for defuzzification.

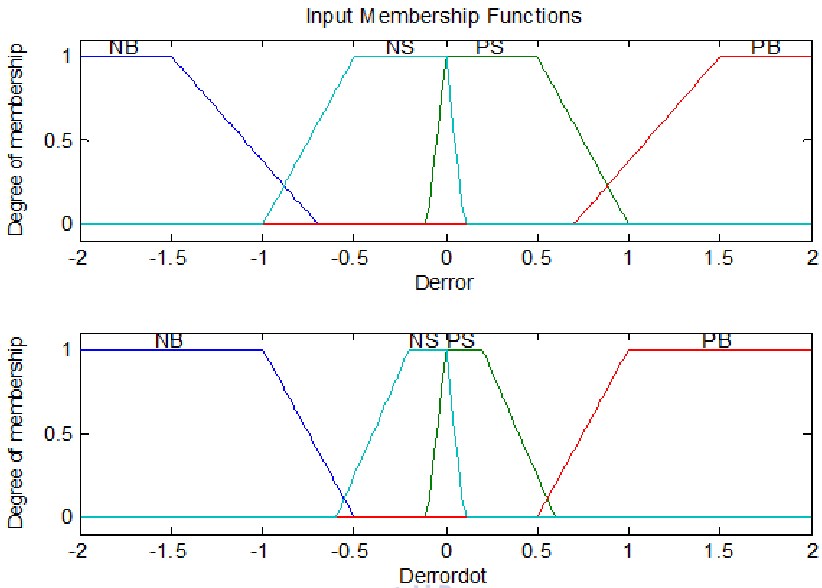


Fig. 15 Detph input membership functions

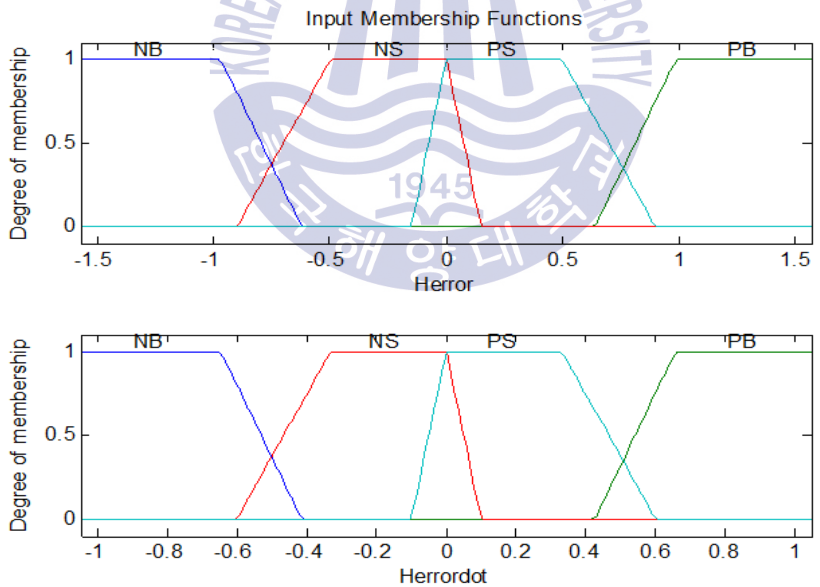


Fig. 16 Heading input membership functions

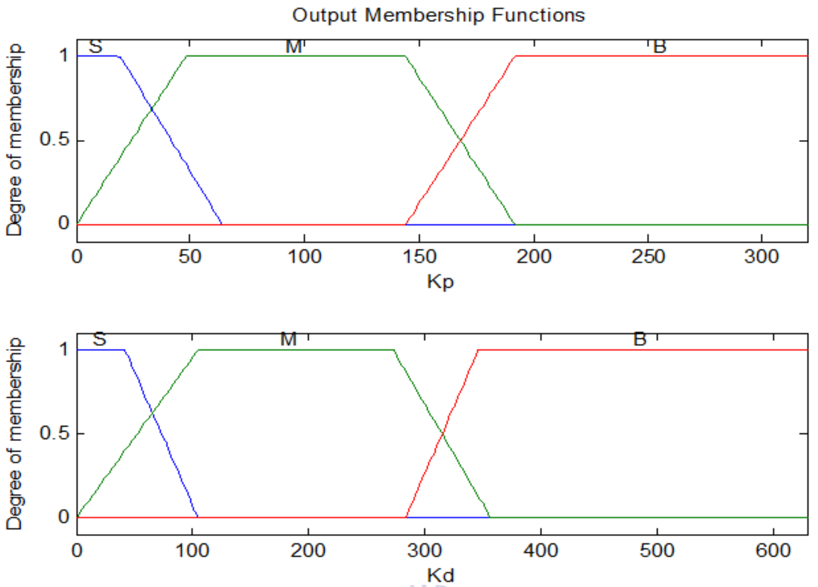


Fig. 17 Depth output membership functions

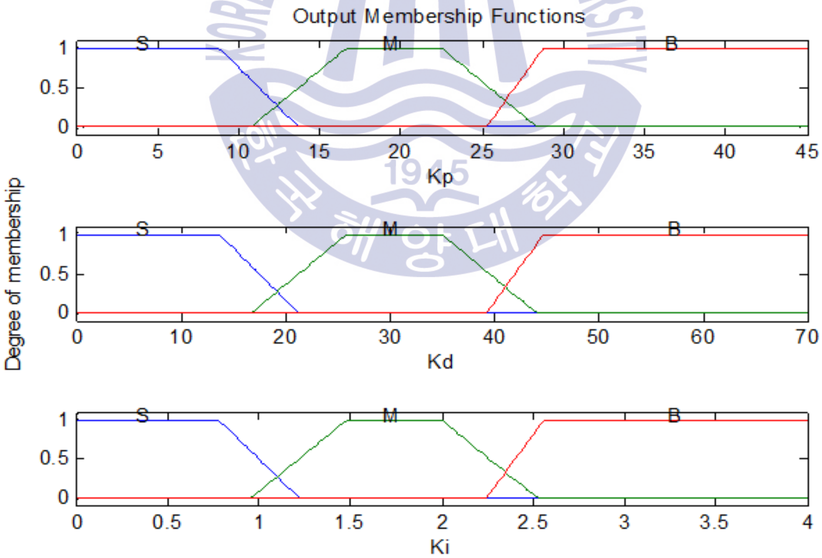


Fig. 18 Heading output membership functions

Table 4 Fuzzy rules - gain K_p of depth control

$\dot{e}$ \ e	NB	NS	PS	PB
NB	B	M	M	B
NS	B	S	S	B
PS	B	S	S	B
PB	B	M	M	B

Table 5 Fuzzy rules - gain K_d of depth control

$\dot{e}$ \ e	NB	NS	PS	PB
NB	B	B	B	B
NS	M	S	S	M
PS	B	S	S	M
PB	B	B	B	B

Table 6 Fuzzy rules - gain K_p of heading control

$\dot{e}$ \ e	NB	NS	PS	PB
NB	B	M	M	B
NS	B	M	M	B
PS	B	B	M	B
PB	B	M	M	B

Table 7 Fuzzy rules – gain K_i of heading control

$\dot{e}$ \ e	NB	NS	PS	PB
NB	M	M	M	S
NS	M	M	M	S
PS	M	B	M	M
PB	S	B	B	M

Table 8 Fuzzy rules – gain K_d of heading control

$\dot{e}$ \ e	NB	NS	PS	PB
NB	B	B	B	B
NS	M	B	B	B
PS	M	B	B	M
PB	B	M	M	M

NB(Negative Big), NS(Negative Small), PS(Positive Small), PB(Positive Big), S(Small), M(Medium), B(Big) are member.

3.3 Simulation results

Prior to tank experiments and field tests, performance of designed controller needs to be verified under various conditions. So, simulation about control performance was performed by using designed controller and equation of motion in chapter 3.1.

In this paper, numerical simulation program was constructed by using Matlab/Simulink. Simulation was performed to verify designed AUV's performance of motion and controller as follows. Because hovering type AUV needed to reach target point through way points to explore certain areas, target heading angle was decided for using LOS(Line Of Sight) method, and simulation was also performed to verify performance of designed PID and fuzzy PID controller. Current model is assumed as vector which has 2-dimensional direction and velocity, direction of current is 20° , and velocity of it is 0.1m/s.

Simulation was performed by starting from first position (0,0,0), moving on 1m under water, passing already given 5 way points (50,0,1), (50,50,1), (0,50,1), (0,100,1), (50,100,1) with keeping 1m depth, and reaching final position (50,100,0).

Fig. 19 is moving path of AUV in X-Y plain. Each gird point's arrow in graph means current direction. When AUV passed each target point and heading angle changed to next target point, it was moved back by current, but it was confirmable that all two controllers found given target points well.

Fig. 20 is AUV's 3-dimensional moving path. AUV moved on 1m under water from first position (0,0,0), found next target point's heading angle, and then moved on and on. Also, after AUV reached 5 target point, it floated on the surface of water.

In Fig. 21, AUV moved on target depth 1m under water, went on keeping the depth, and floated on the surface of water after it reached final way point.

Fig. 22 is the result graph of controlling AUV's pitch angle. Because depth direction motion and y-axis rotation affect each other, pitch angle needs to be controlled in AUV's motion. In this paper, considering hovering type AUV's characteristics, pitch angle was set up 0° when AUV moved on depth direction. As shown in Fig. 23, at first there was vibration within about 0.05°, and then the result converged 0°.

Fig. 24 is AUV's heading angle during finding given target point, at this time AUV's target heading angle is decided by using LOS method. The results of simulation showed that PID controller and Fuzzy PID controller had similar control performance. The results also showed that two controllers performed way point control well under current disturbance. However, because modeling error and value of hydrodynamic coefficient are different from Octagon's, control performance is need to be verified by field tests.

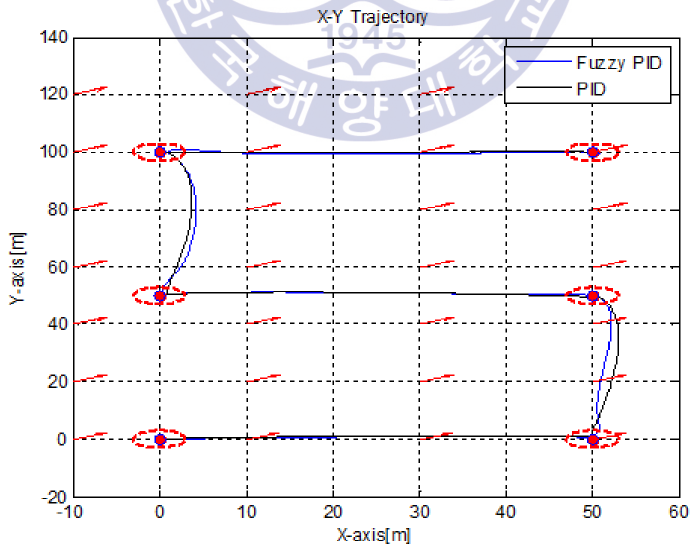


Fig. 19 X-Y trajectory

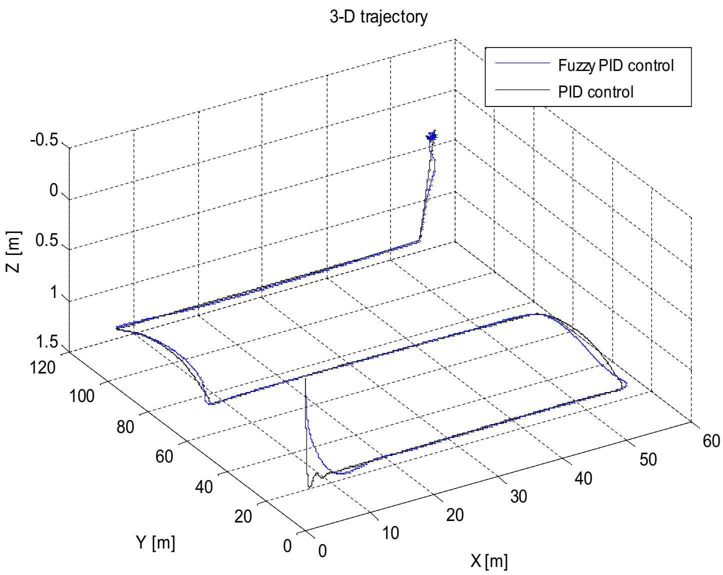


Fig. 20 3D trajectory

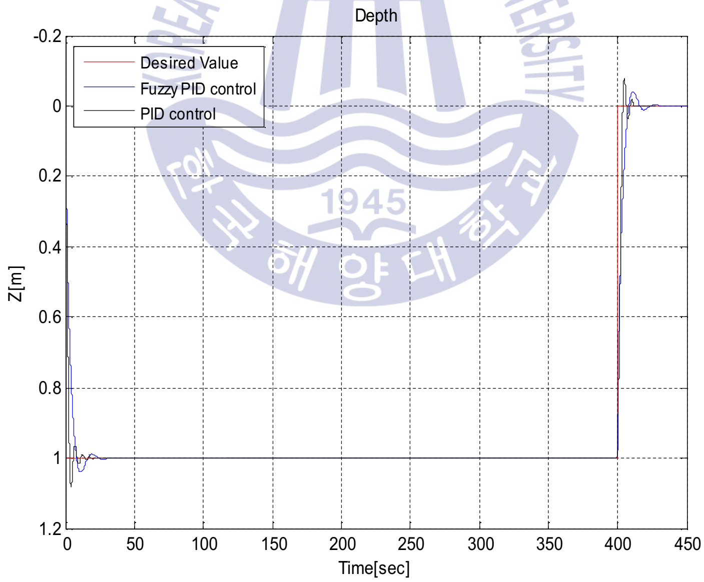


Fig. 21 Result of depth control

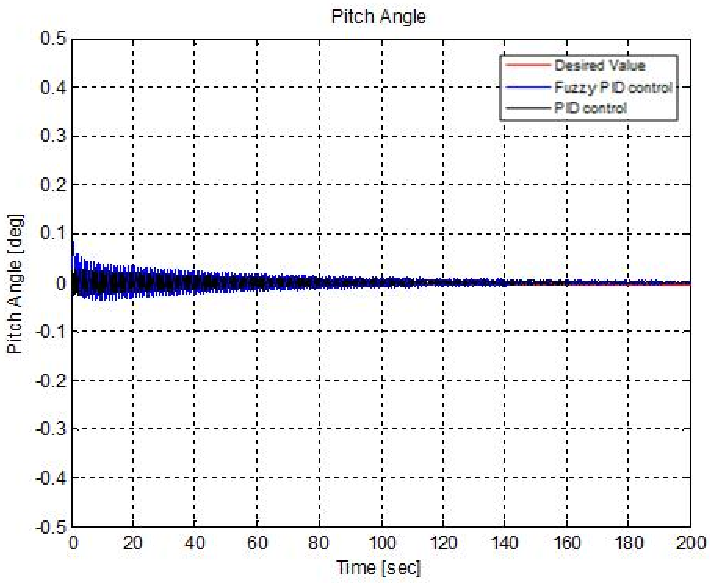


Fig. 22 Result of pitch angle control

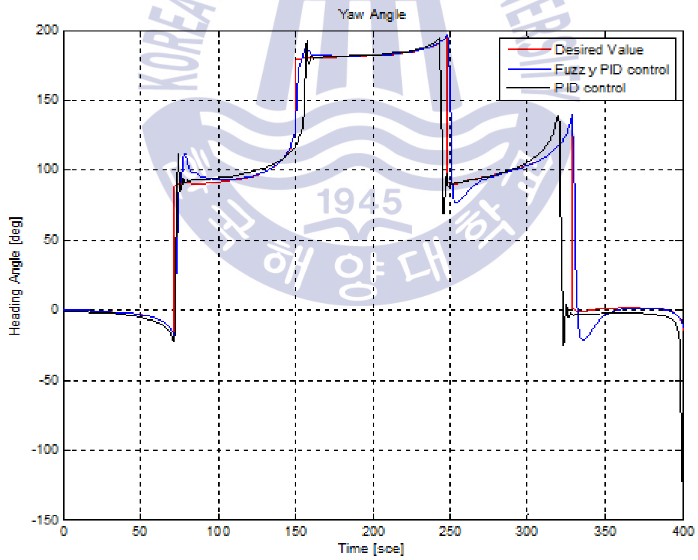


Fig. 23 Result of heading angle control

CHAPTER 4
FIELD TESTS

In this paper, field tests were performed to verify performance of Hovering type AUV and performance of designed controller.

Field tests were performed in Korea Maritime and Ocean University yacht mooring like Fig. 24. Final goal of these field tests was Way-point(WP) control that AUV pass from way point to start point as keeping target depth. Way point control was performed by using PID controller and Fuzzy PID controller.

LOS method was used to plan navigation path, DVL was used to calculate AUV's position, and TCM-3 was used to measure heading angle. About 0.5% of position error in flat water was confirmed through advanced test about DVL measurement error analysis. In this test, position value including error of DVL was supposed as real position of AUV.

Fig. 24 Korea Maritime and Ocean University

4.1 PID Control

4.1.1 Depth control

To identify control performance whether AUV follows target depth or not, depth control was performed. Fig. 25 is the results of depth control. Target depth set up 1m, and 40 seconds later, AUV floating to the surface of the water was confirmed.

AUV had an overshoot at 4 seconds because of inertia, later, it converged on target depth at about 10 seconds. The reason why value of depth oscillates is disturbance applying to AUV or change of input value of thruster.

Depth controller was designed for converging on error range within ±5cm, and like below graph, AUV had error within ±3cm, so performance of controller was considered superior.

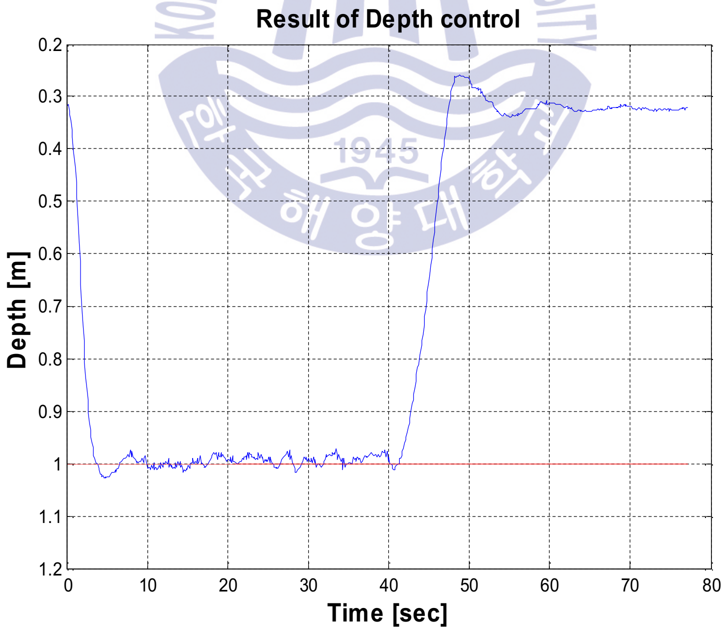


Fig. 25 Result of depth control

4.2.2 Heading control

The most important thing in way point control is to find target way point as having small error. So, to identify control performance about heading angle, heading control was performed. Fig. 26 is the results of heading control.

Experiments that followed target heading angle and went straight were performed during about 50seconds. Initial heading angle of AUV was about −140°, and 3 seconds later it converged on target heading angle 0°. When heading controller was designed, error range was ±5°. If it was satisfied in the field, performance of controller was considered superior. Like below graph, heading error range was within ±3°, so performance of controller was considered superior.

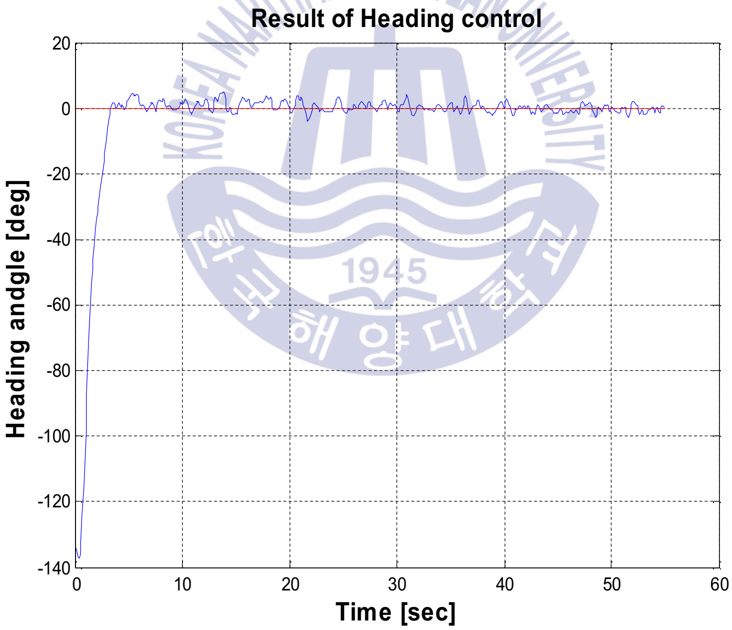


Fig. 26 Result of heading control

4.1.3 Way-point control

Way point control was designed for that AUV passed five way points, (0,0,1), (10,0,1), (10, -10, 1), (0, -10, 1), (0, 0, 1), and it came back to start point (0, 0, 0). Fig. 27 is the graph of AUV X-Y plane path, and it means moving distance that integrates speed of AUV measuring from DVL.

Considering movement of AUV and current disturbance in the field, it was difficult to reach exact way point, so effective area was set up. Effective areas were marked with circle at each way point of Fig. 27.

Fig. 28 is the graph of AUV's 3D path, and it shows that AUV moves on 1m under water into heave direction, and that it floats to the surface of the water after passing way point as keeping the depth.

While performing way point control, Fig. 29 shows the results of depth control. It can be confirmed that AUV oscillates between ±0.04m from target depth and keeps it's depth.

Fig. 30 is the graph of AUV's heading angle change as target angle changes through LOS method. AUV starts from -20°, and heading angle is designed for moving to first way point. After, heading angle is also designed for moving to each way point, and it can be confirmed that AUV oscillates in the range of target angle and follows that angle. It is the course of repetition that AUV follows target value under current disturbance.

Fig. 31 is the graph of Pitch angle when AUV moves under water. The results of AUV movement show that 12° pitch angle appears when AUV moves under water, and 4° pitch angle appears when it converges on target depth. The reason why each blade of two vertical thrusters has opposite direction, and thrust of input voltage is also different. One thruster has forward direction blade, and the other has reverse direction blade. Thrust of forward direction blade makes the lower force than the other blade's. To minimize pitch angle, the value of input voltage was founded through a lot of tests, and the results are Fig. 32.

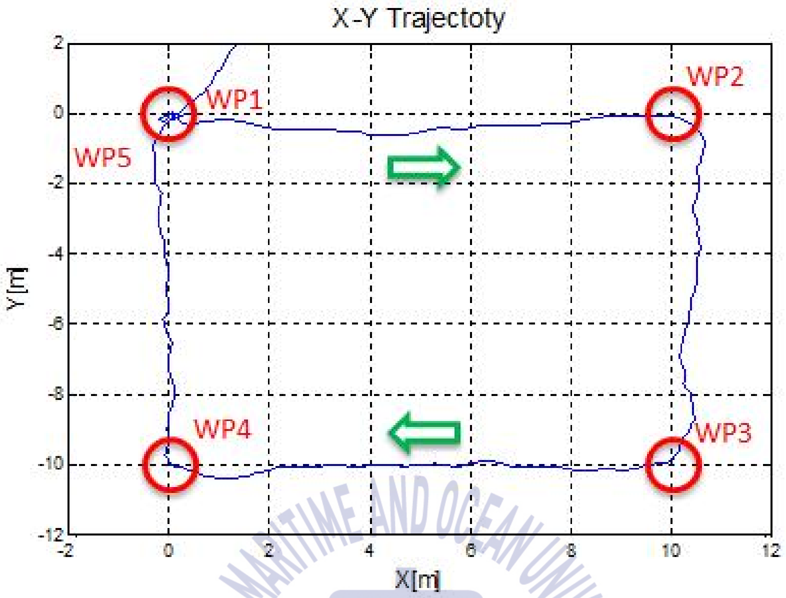


Fig. 27 X-Y trajectory

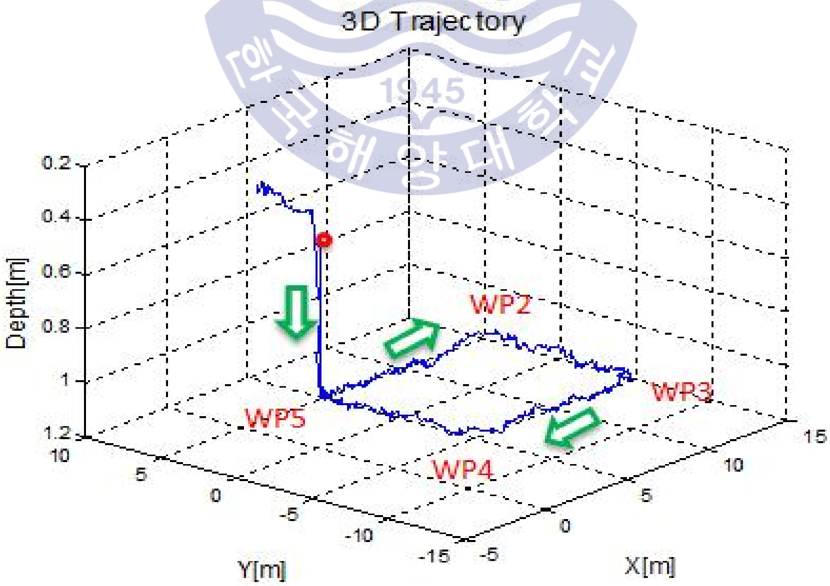


Fig. 28 3D trajectory

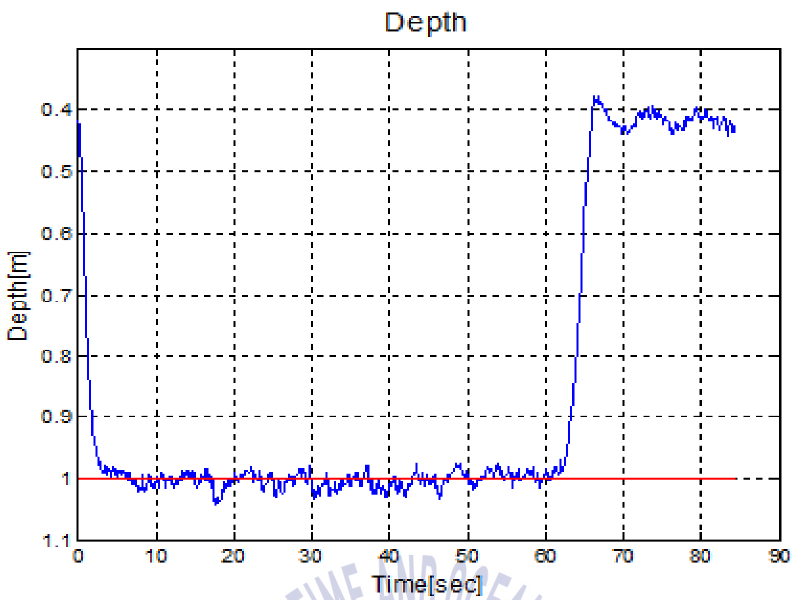


Fig. 29 Result of depth control

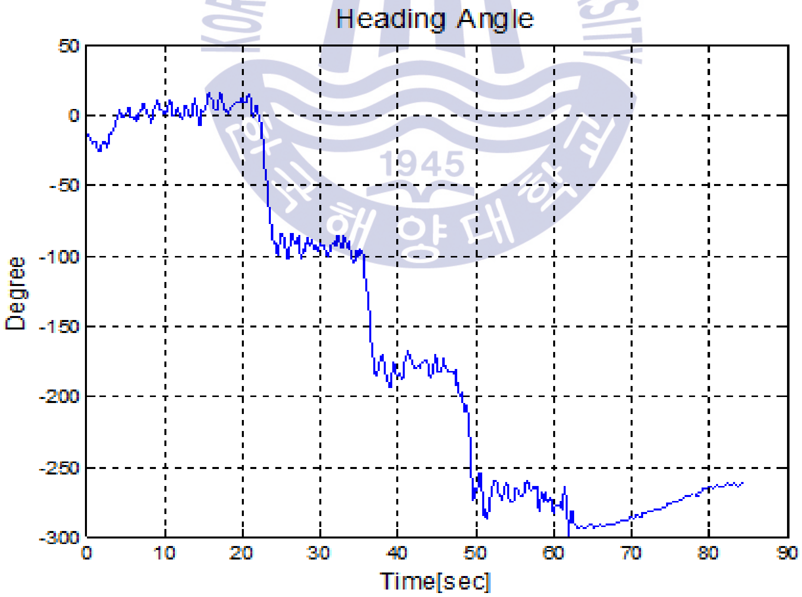


Fig. 30 Result of heading control

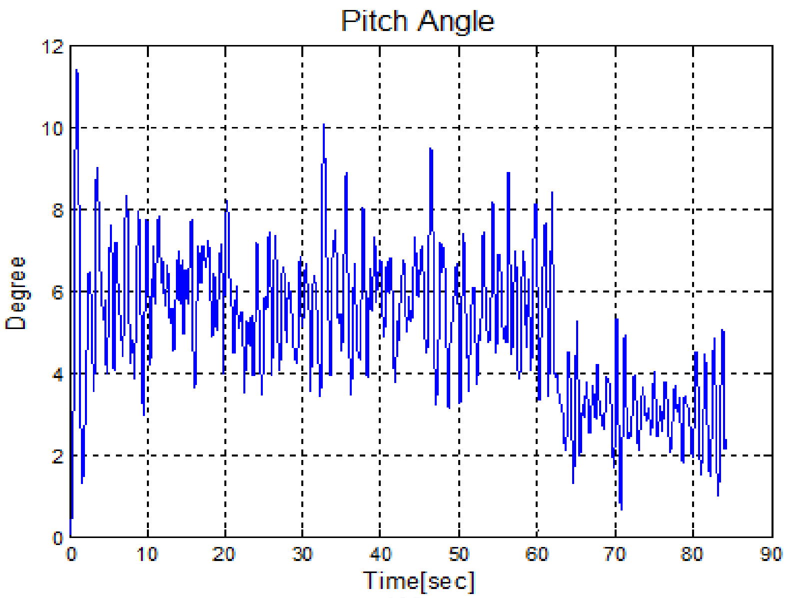


Fig. 31 State value of pitch angle

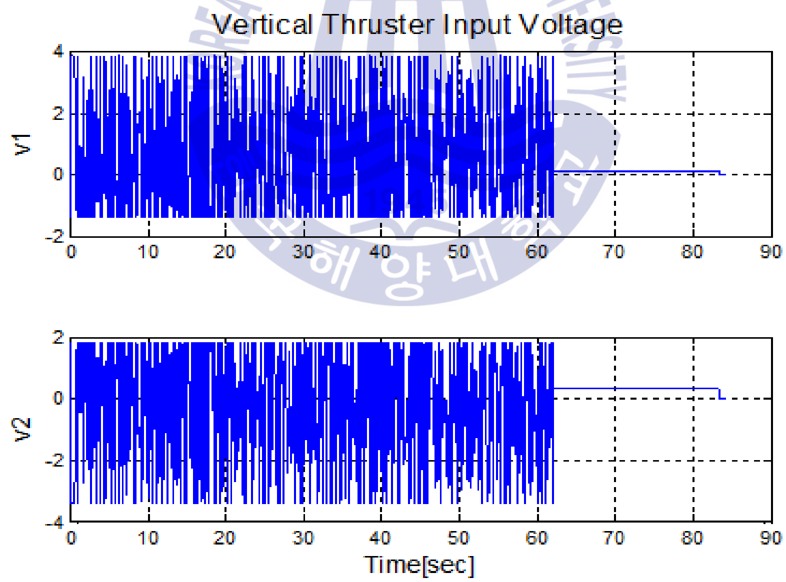


Fig. 32 Thruster control input voltage

4.2 Fuzzy PID Control

In this chapter, heading control, depth control, and waypoint control were performed by designing Fuzzy PID controller. Purpose of designing Fuzzy PID controller is to verify performance of controller through movement of AUV by designing various controllers. At this time, Fuzzy PID controller was designed by using LabVIEW program. Input variable membership function, output variable membership function, and applied fuzzy rule used in depth controller and heading controller will be explained below.

4.2.1 Depth control

Depth control was performed in the similar condition of 4.1.1. Membership function of input variable e_{depth}, $\dot{e}_{depth}$ used in Fuzzy depth controller was divided into 5 sections like Fig. 33. 5 sections were NB(Negative Big), NS(Negative Small), M(Medium), PS(Positive Small), and PB(Positive Big). The values are like Fig. 33.

Unlike depth controller of using PID controller, the depth controller of using Fuzzy PID controller was designed for converging within ±2cm. This was because Fuzzy PID controller made gain value change according to designed sections like Fig. 34, unlike PID controller that had fixed constant as gain. Output variables, gain P, gain I, and gain D, were composed as membership functions like Fig. 34. There was not value of gain I in figure. This was because very small value was used, and also there was a limit to expressing as graph.

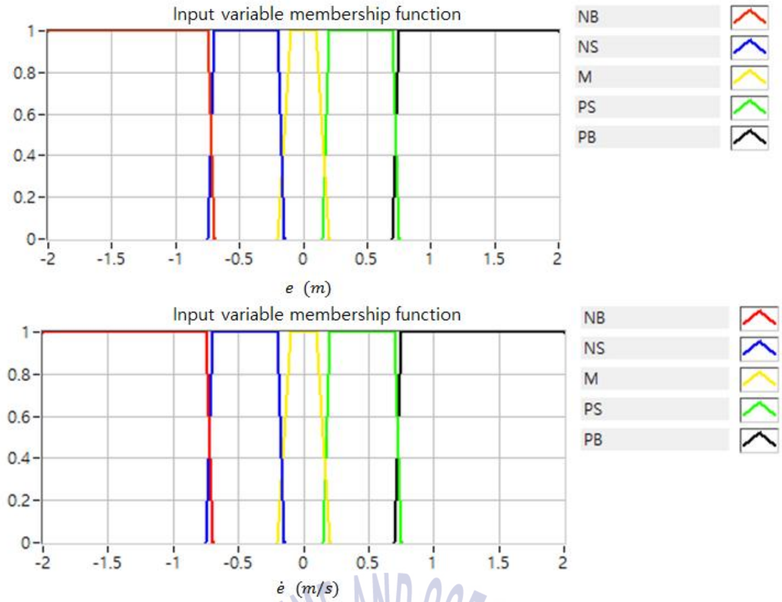


Fig. 33 Detph input membership functions

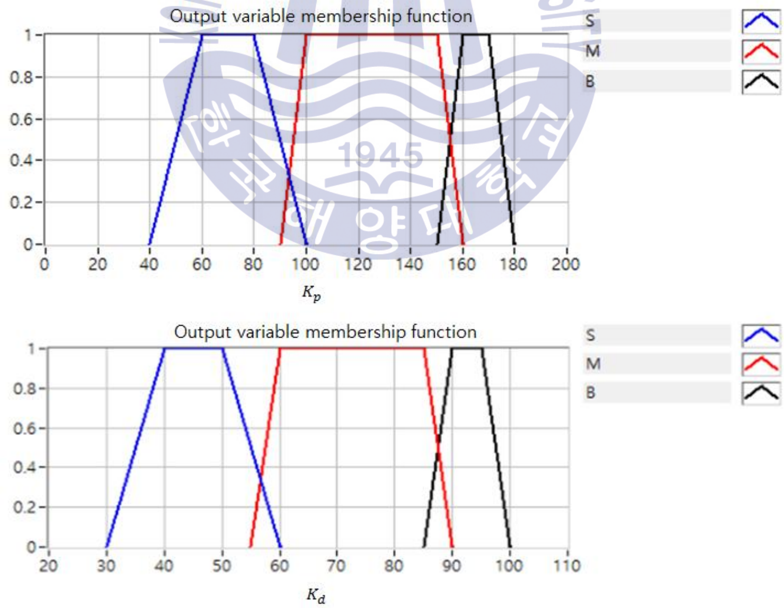


Fig. 34 Depth output membership functions

The range of output variable was S(Small), M(Medium), B(Big). Fuzzy type was mandani and centroid method was used as defuzzy method. When membership function was composed, one of several methods, trapezoid shape was used, and fuzzy rule was composed by using and/or method. Designed fuzzy rule is like Table 9 ~ Table 10.

Table 9 Fuzzy rules – gain K_p of depth control

$\dot{e}$ \ e	NB	NS	M	PS	PB
NB	S	S	S	S	M
NS	S	S	M	M	M
M	B	M	M	M	B
PS	M	M	M	M	S
PB	M	S	S	S	S

Table 10 Fuzzy rules – gain K_d of depth control

$\dot{e}$ \ e	NB	NS	M	PS	PB
NB	M	S	S	S	M
NS	S	S	M	M	M
M	M	M	M	M	M
PS	M	M	M	M	S
PB	M	s	S	S	M

Fig. 35 is the results graph of depth control for 100 seconds using Fuzzy PID controller. 1m was set up as target depth. After AUV started to move and 5 seconds later, it reached steady-state. AUV followed target depth well within about ±2cm, and through this, performance of depth controller applying Fuzzy theory was verified.

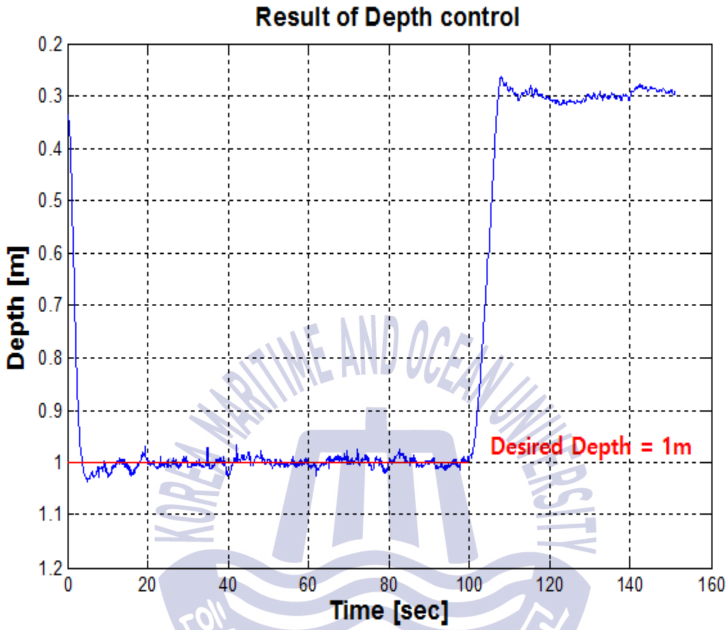


Fig. 35 Result of depth control

4.2.2 Heading control

Membership function of input variable e_{yaw}, $\dot{e}_{yaw}$ used in Fuzzy heading controller was divided into 5 sections like Fig. 36. 5 sections were NB(Negative Big), NS(Negative Small), M(Medium), PS(Positive Small), and PB(Positive Big). The values are like Fig. 36. X-axis of the graph showed angle range of e_{yaw}, $\dot{e}_{yaw}$, and it was expressed by radian. Output variables, gain P, gain I, and gain D, were composed as membership functions like Fig. 37. And fuzzy rule is like Table 11 ~ Table 12.

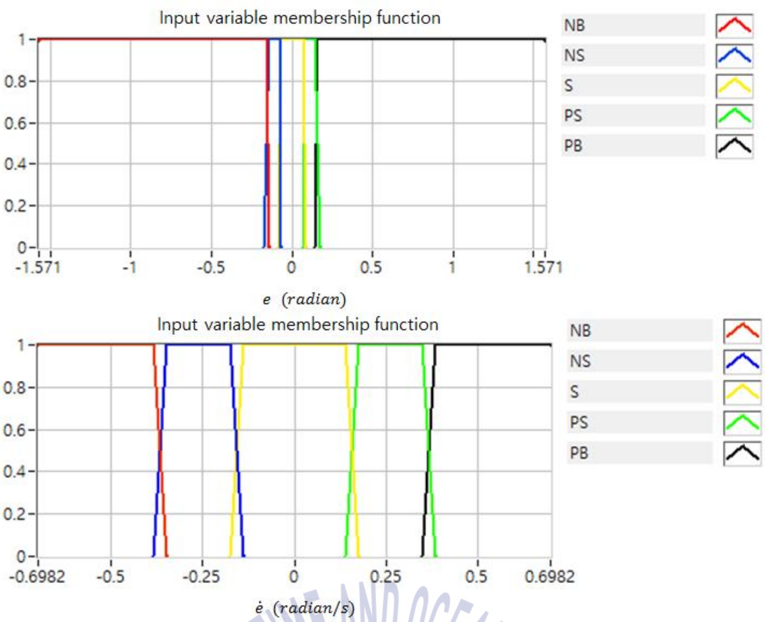


Fig. 36 Heading input membership functions

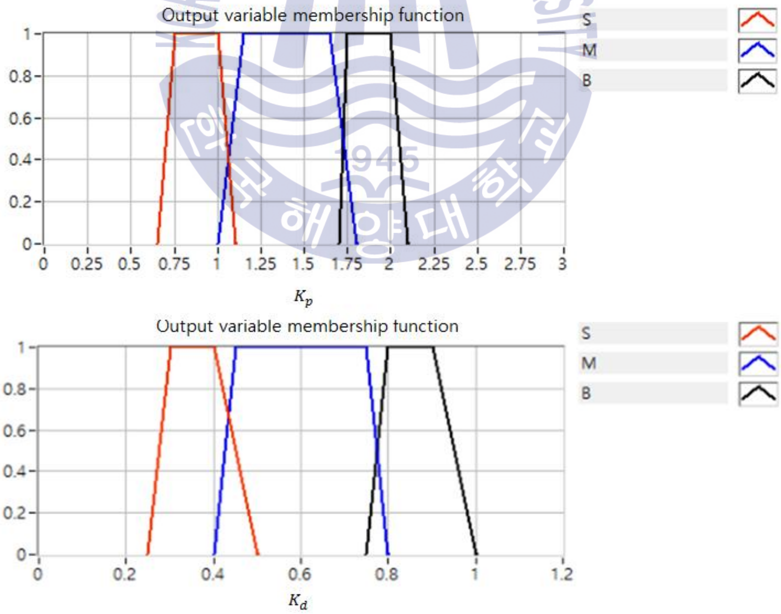


Fig. 37 Heading output membership functions

Table 11 Fuzzy rules - gain K_p of heading control

$\dot{e}$ \ e	NB	NS	M	PS	PB
NB	B	S	S	S	M
NS	B	S	M	M	M
M	S	M	M	M	B
PS	M	M	M	S	B
PB	M	S	S	S	B

Table 12 Fuzzy rules - gain K_d of heading control

$\dot{e}$ \ e	NB	NS	M	PS	PB
NB	B	S	S	S	M
NS	S	S	M	M	M
M	S	M	M	M	B
PS	M	M	M	S	S
PB	M	S	S	S	S

Fig. 38 is results graph of moving forward for about 50 seconds and performing heading control using designed Fuzzy PID controller. Experiments started with AUV pointing to about -120° heading angle, and 10 seconds later, it followed target heading angle 0° as having error within ±3°. Performance of Fuzzy PID controller was verified as AUV converged on target error range within ±5°

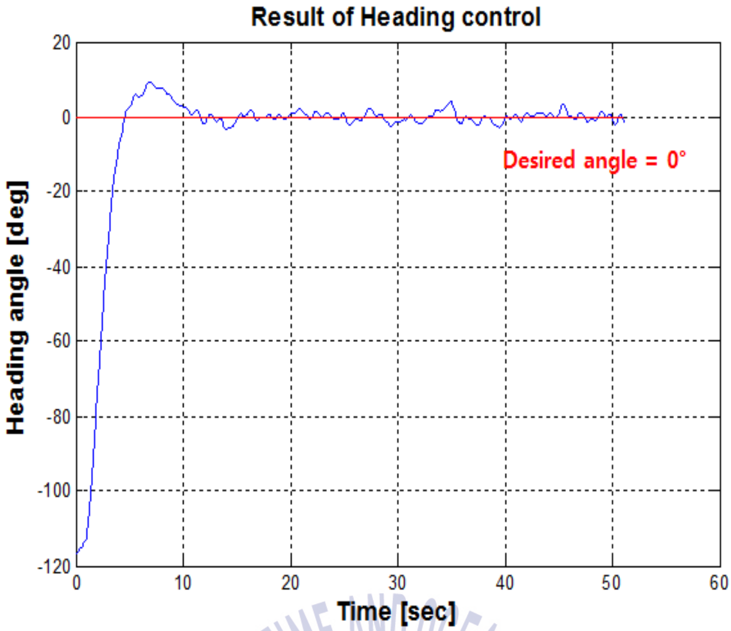


Fig. 38 Result of heading control

4.2.3 Way-point control

Performance of Fuzzy PID controller was verified by results of depth control and heading control, and way point control was performed like Fig. 39 that showed path of X-Y plain. Position of (0, 0, 1) was called WP1, and path that passed each WP and come back to original position was set up.

Fig. 40 is the graph of AUV's 3D path, and it shows that AUV moves on 1m under water into heave direction, and that it floats to the surface of the water after passing way point as keeping the depth. Fig. 41 is the results graph of depth control, and AUV follows target depth 1m with about ±3cm error.

Fig. 42 is the results graph of heading control, and AUV follows target heading angle from beginning heading angle of about 50°. At this moment, error is about ±10°.

It is better than the results of using PID controller, but it is not better than the results of 4.2.2 heading control. This was because depth control and heading control experiments were performed in the inner harbor where there was no current, and way point control experiments were performed in the place largely influenced by current. When way point control experiments were performed under circumstances of current, it had about ±10° error that was bigger than in the inner harbor experiment's error. It will be overcome by designing robust controller to disturbance like current and equipping additional truster.

Fig. 43 is the graph of gain value used in depth control and heading angle control through designed Fuzzy PID controller. Gain value changed a lot by designed fuzzy rule in the section of big e and $\dot{e}$. When AUV reached steady-state, it had steady gain value. From above results, robust performance about disturbance of Fuzzy PID controller was verified.

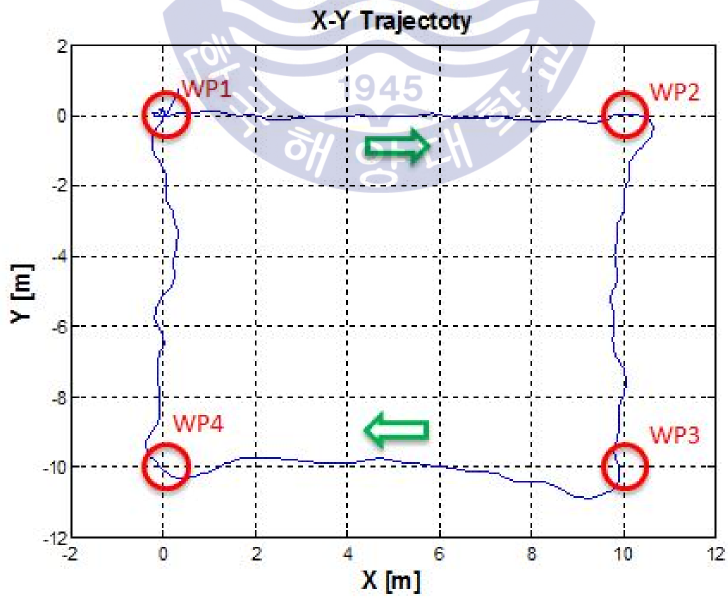


Fig. 39 X-Y trajectory of hovering AUV

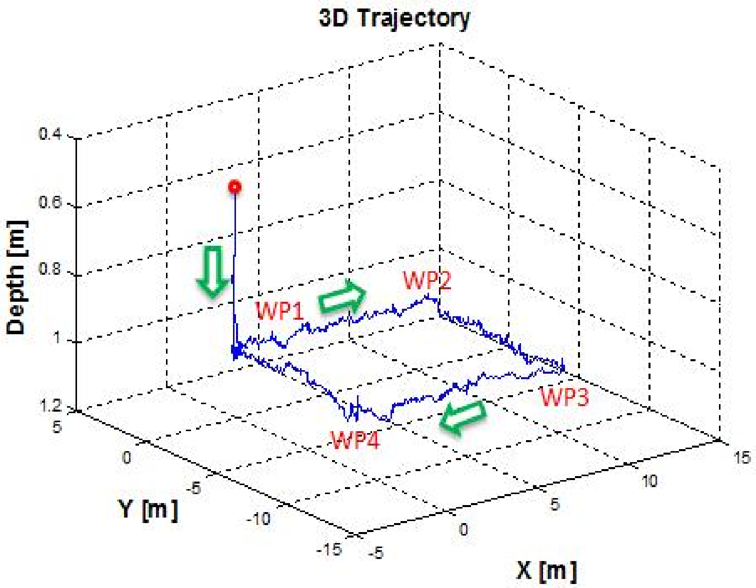


Fig. 40 3D trajectory of hovering AUV

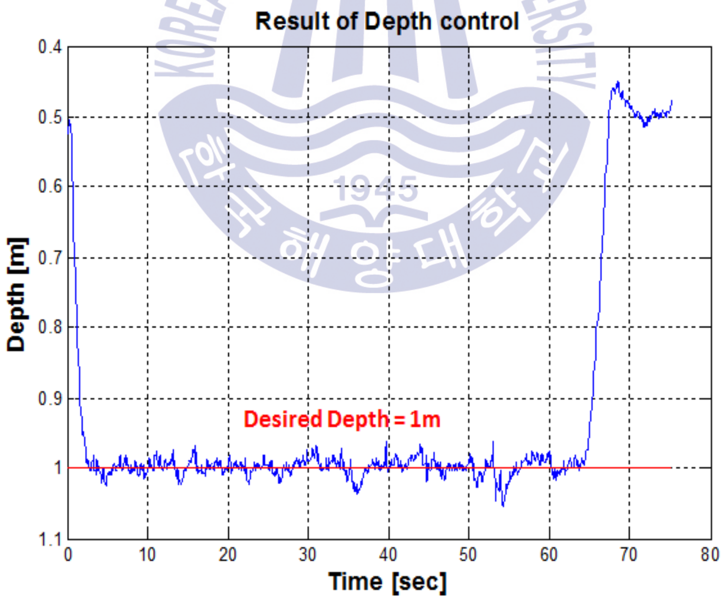


Fig. 41 Result of depth control

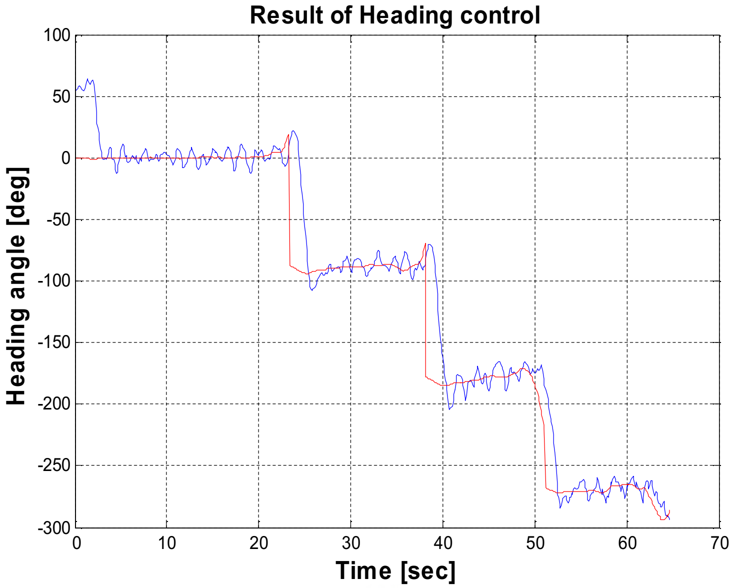


Fig. 42 Result of heading control

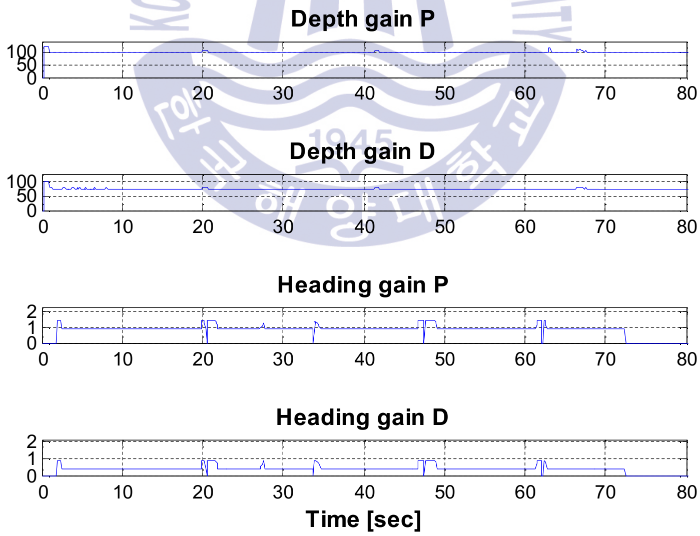


Fig. 43 Gain value

CHAPTER 5
CONCLUSION

In this paper, AUV's test bed was developed to verify algorithm's performance and various underwater sensor tests, through this, fundamental motion performance tests and way point experiments were performed. Also, dynamic simulation program using mathematics model was performed to verify motion performance and control algorithm about designed AUV, and designed controller's performance was verified.

In this paper, numerical simulation was performed to verify performance of PID controller and fuzzy PID controller which was able to adjust gain value by fuzzy theory. Also, method of control allocation was applied to distribute appropriate control input value to thruster.

Depth control, heading angle control, and way point control were performed in the field under current disturbance using designed control algorithm and navigation system to verify AUV's motion performance and control performance, and consequently valid control performance could be gained.

In the field tests, fuzzy PID controller that could adjust gain value by designed fuzzy system rule in real time under current disturbance and basic PID controller were used for fundamental tests. Really, tuning PID controller's gain value under strong current was one of the hardest works, on the other hand, in the case of Fuzzy PID, tuning work was easy.

In the future, filter is need to be designed and algorithm is also needed to be developed to measure precise path. Study about controlling under disturbance of fields will be performed by using more strong controller.

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