Design and Implementation of PD Controller for an AUV 'ISiMI100'

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Abstract: - This paper presents design and implementation of PD controller for an autonomous underwater vehicle (AUV) called ISiMI100 which is developed by Maritime and Ocean Engineering Research Institute (MOERI). An AUV is a system that is too difficult to control. It has coupling between control input and output. And it is nonlinear, under-actuated system. In this research, we propose a revised PD controller for an AUV. This controller is different from typical PD controller. It is based on strong correlation between control input and a state of an AUV (system output) from dynamics of an AUV. Finally, we validate the algorithm by simulation and Ocean Engineering Basin experiment in KORDI.

Key-Words: - virtual goal, AUV, homing path planning, under-actuated system, tangential line and PD control

1 Introduction

An AUV is a typical system of under-actuated and nonlinear. And there are coupling between control inputs and state of an AUV (system output). So it is a system that is too difficult to control. But recently, an AUV have become main tool to survey underwater in scientific and commercial applications. Then it becomes very important research that design, implementation, path planning, and control for an AUV.
Currently, Maritime and Ocean Engineering Research Institute (MOERI) is developing the ISiMI100 AUV and testing for running in Ocean Engineering Basin [1]~[3]. The ISiMI100 AUV is an upgrade version of ISiMI to endure a depth rating of more than 100 meter.
Many algorithms are developed for path planning and control of a nonlinear system as like an AUV [4]~[5]. In this research, we generated the homing path via virtual goals and use it. For the path tracking, we design a revised PD controller for an AUV. Finally we validate the algorithm by simulation and experiment.

2 Introduction of ISiMI100 AUV

The ISiMI100 is sea-trial version of original ISiMI, which is a tank-test model. The design concept is small AUV to survey the real ocean up to the 100m depth with the functions for AUVs fleet. The ISiMI100 can be easily launched, recovered, and operated without special handling equipment as the original ISiMI. The ISiMI100 is additionally equipped with DVL, ATM, Pinpoint LBL, and obstacle avoidance sonar (OAS) to control AUVs fleet and to survey underwater.

2.1 Appearance and Specifications of ISiMI 100

The ISiMI100 has a torpedo-type appearance as the ISiMI. To minimize the drag force coefficient, front section and middle section were designed cylindrical type, and head cone and tail section was designed based on the Myring hull profile of Fig.2. We can see the hull parameters of ISiMI100 in Table 1.

Fig.1. Appearance of ISiMI100

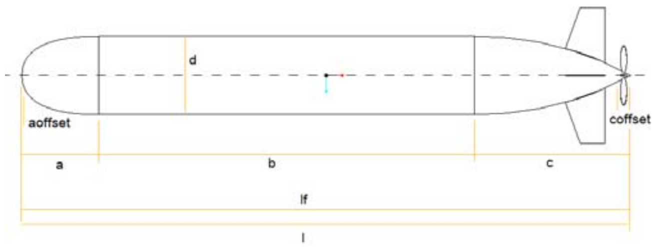

Fig.2. Myring hull contour of ISiMI100

Table 1.Hull parameters of ISiMI 100

Parameter	Value	Unit	Description	Remark
a	197	Mm	Nose-section	
b	960	Mm	Mid-section	
c	398	Mm	Tail-section	

d	200	Mm	Diameter
aoffset	3	Mm	Nose offset
coffset	30	Mm	Tail offset
lf	1555	Mm	Forward length
l	1585	Mm	Total length

2.2 Kinematics and Dynamics of ISiMI 100

The kinematics and dynamics of ISiMI has already been reported in [3]. The 6-DOF nonlinear dynamic equations of IsiMI is given as

$$M\dot{v} = F_{CC} + F_{DL} + F_{rest} + F_{thrust} + F_{fin} \quad (1)$$

where M is the inertia Matrix (including added mass), and the F 's of the tight-hand side are Coriolis and centripetal force, damping force, restoring force, propulsion force, and fin force vector. Detail may be found in [3].

The kinematics and dynamics of ISiMI100 is not developed yet. But the appearance of ISiMI100 is very similar to that of ISiMI. So we can use most coefficient of ISiMI except a few items. And we can adopt the equation (1) as the one of ISiMI100.

3 Homing Path Planning Algorithm

We just focus on the design of controller and implementation. So in this section, we describe an algorithm for homing path planning in simple. Position as well as orientation should be considered for AUV's homing to docking station. In this research, we utilized the minimum turning radius of an AUV and tangent line.

It is a way point which is generated by tangent line for via-point to goal position. So we call the way point a virtual goal (VG).

For a homing path of an AUV, we model all of obstacles to minimum circles that surround the obstacles. Then we make two circles which has a flow from start position (x_s, y_s, θ_s) and goal position (x_g, y_g, θ_g) as like Fig.3.

In next step, starting with a start position, we draw tangent line between circles that are adjoined. And then we create points of contact. If there is no obstacle, 16 tangent lines are created between start position and goal position as like Fig.4.

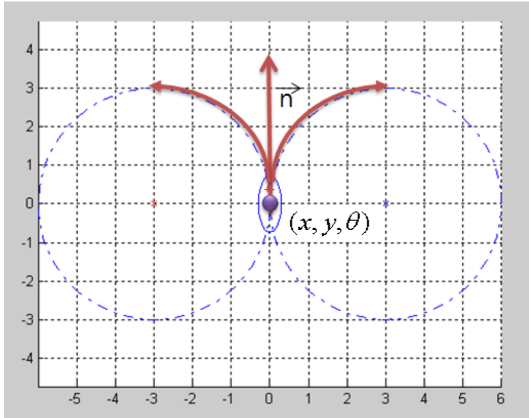

Fig.3. Two circles generated from AUV position (x, y, θ)

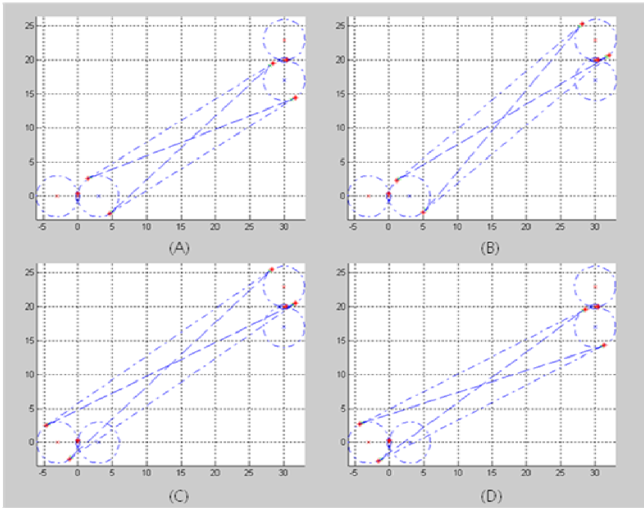

Fig.4. Candidate tangent lines for virtual goal

Fig.4. is shows the candidate tangent lines for virtual goal. Then we can make candidates of optimal path that connect remaining virtual goals with start position and goal position. The equation (2) is a cost fuction. A path that minimizes the cost function (2) is selected as optimal path.

$$\underset{i=1\sim n}{Min}(J_i) = W_d \Delta d + W_\psi \delta\psi + W_{\delta R} \delta R \quad (2)$$

In which J_i is cost for path of i th, W_d , W_ψ , $W_{\delta R}$ is weighting factor for distance, yaw angle, and control input, respectively. Δd is distace to goal, $\delta\psi$ is cumulative yaw angle and δR is cumulative control input.

The simulation result of path planning with no obstacle is shown in Fig.5. In this result, start position is $P_0 = [0,0,90^\circ]$ and goal position is $P_f = [30,20,0^\circ]$. There are two virtual goals except start position and goal position. This result show that an AUV can reach the goal position with desired orientation. In this case, the path is optimal path for an AUV.

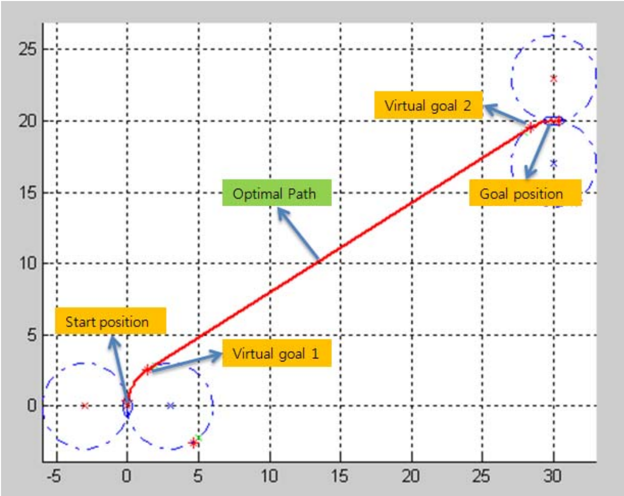

Fig.5. Path planning result with no obstacle

4 Controller Design

4.1 Typical PD Controller

The AUV under consideration is a typical under-actuated system that has 6-DOF. A state variable for the AUV η is 6×1 vector and control input is 3×1 vector. Then proportional gain and derivative gain is 3×6 matrix. So generally, path tracking controller for an AUV is designed as like (3) ~ (4).

$$u = K_P e + K_D \dot{e} \qquad (3)$$

$$e = x_d - x_a \qquad (4)$$

where u is control input, K_P, K_D is proportional gain, derivative gain respectively. x_d is desired state and x_a is actual state. And e is state error for PD control.

But we must obtain 36 gains for controller. It is too difficult to obtain 36 gains. Furthermore, it is impossible that all of gains are optimal values.

4.2 Revised PD Controller Design for ISiMI100

In this case, typical PD controller design procedure is not enough. In this research, we utilize a strong correlation between control input and state of an AUV (system output) from dynamics of an AUV. And we can design PD controller using the correlation.

In the equation (1), if state of an AUV η is determined, some part of the equations is constant(see (5)). Then all terms of left-hand side of the equation (6) is constant. And there are control inputs in the right-hand side. As a result we can obtain strong correlation between control input and state of an AUV from the equation (6).

$$F_{CC} + F_{DL} + F_{rest} = F_{const} \qquad (5)$$

$$M\dot{v} - F_{const} = F_{thrust} + F_{fin} \qquad (6)$$

The equation (6) consists of 6×1 vector. First row is about motion of x-axis. And they are about motion of y-axis, z-axis, roll, pitch, and yaw in sequence. The equation (7) is first row of the equation (6) that is 6×1 vector.

$$\begin{aligned}
&(m - \frac{\rho}{2} l^3 X_{\dot{u}})\dot{u} + mz_g \dot{q} - my_g \dot{r} - mvr \\
&+ my_g pq + mz_g pr - mx_g q^2 - mx_g r^2 \\
&- \frac{\rho}{2} l^2 (X_{v|v|} v|v| + X_{w|w|} w|w|) \\
&- \frac{\rho}{2} l^4 (X_{q|q|} q|q| + X_{r|r|} r|r|) \qquad (7) \\
&+ (W - B)\sin\theta \\
&= \frac{\rho}{2} l^2 (a_X + b_X u_T + c_X u_T{}^2 + d_X u_T{}^3) \\
&+ \frac{\rho}{2} l^3 U^2 X_{\delta_R} \delta_R
\end{aligned}$$

If state of an AUV η is determined, left-hand side of the equation (7) is constant. A forward movement ratio u_T (is mean forward velocity) and a rudder input δ_R are in the right-hand side of the equation (7). Thus, we can show that there is correlation between control inputs δ_R and motion of x-axis. If we perform the same process repeatedly, we can obtain all of correlation for 6-DOF as shown in Fig.6.

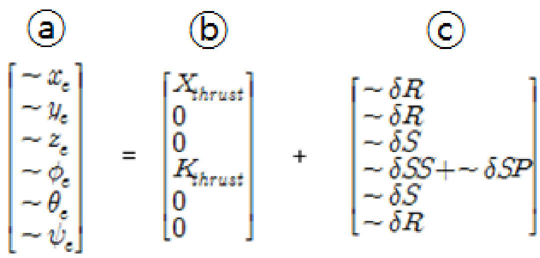

Fig.6. Correlation between input and output

Consequently, we can show that there are correlation between the rudder that is control inputs and x, y, ψ .

Also, we can show that there is correlation between the stun and z, θ. Even if errors exist about x, y, z axis, as it needs a driving force to overcome errors, we can show that RPS is related to all of x, y, z values. Therefore, as we design PD controller about each control input, equations can be written as the equation (8) ~ (10). Each control gains are obtained by using a trial-and-error method. Due to the energy storage and power consumptions, an AUV should be kept from over-control. Also, path tracking control for homing to docking station may allow some errors. So we adjust higher proportional gain than differential gain to consider more safety than the fast tracking.

$$rps = (K_{P1}e_x + K_{D1}\dot{e}_x) + (K_{P2}e_y + K_{D2}\dot{e}_y) + (K_{P3}e_z + K_{D3}\dot{e}_z) \quad (8)$$

$$\delta R = (K_{P4}e_x + K_{D4}\dot{e}_x) + (K_{P5}e_y + K_{D5}\dot{e}_y) + (K_{P6}e_\psi + K_{D6}\dot{e}_\psi) \quad (9)$$

$$\delta S = (K_{P7}e_z + K_{D7}\dot{e}_z) + (K_{P8}e_\theta + K_{D8}\dot{e}_\theta) \quad (10)$$

5 Simulation Results

We simulate the algorithm by using Matlab program. We could obtain a proportional gain -2 and differential gain -4 in many simulations. Finally, we selected the values for simulation and experiment.

The result of path tracking is shown in Fig.7. In this result, start position is $P_0 = [-13, 0, 0^\circ]$ and goal position is $P_f = [15, 0, 0^\circ]$. The red solid line is reference path and the blue dotted line is simulation result.

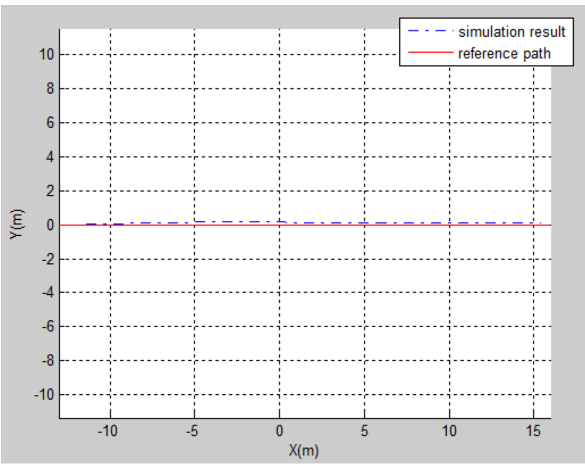

Fig.7. Path tracking simulation result for straight line

The error between reference path and simulation result is about 0.13m at goal position in Fig. 8.

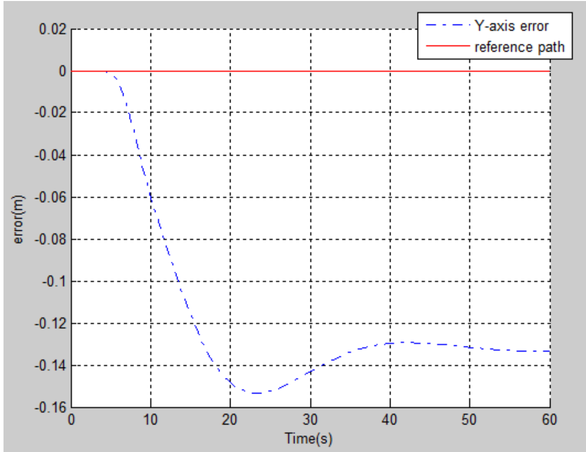

Fig.8. Path tracking simulation error for straight line

The result of path tracking is shown in Fig.9. In this result, start position is $P_0 = [-15, 5, 0^\circ]$ and goal position is $P_f = [10, -2, 270^\circ]$. The reference path is made by virtual goal method. The red solid line is reference path and the blue dotted line is simulation result.

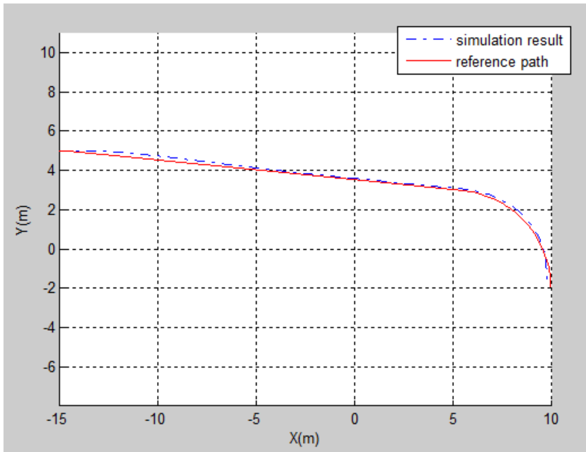

Fig.9. Path tracking simulation result for added turning motion

The reference path is assumed desired uniform velocity. So we can show the increasing error at starting part in Fig.10. Because initial velocity of an AUV is zero. But the error is growing less and less. Finally, the error is 0.2m at the goal position. The Y-axis error at the goal position is 0.4m. But it shows maximum value at the turning motion.

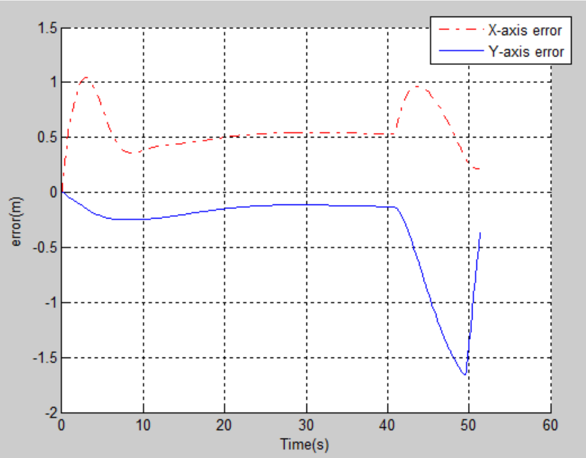

Fig.10. Path tracking simulation error for added turning motion

6 Experiment Results

In this section, we report a path tracking experiment of ISiMI100 based on simulation results in the Ocean Engineering Basin of KORDI. To obtain real position and velocity of ISiMI100, we used image tracking system of CPMC. The image tracking system of CPMC can track the underwater robot less than a few mm errors.

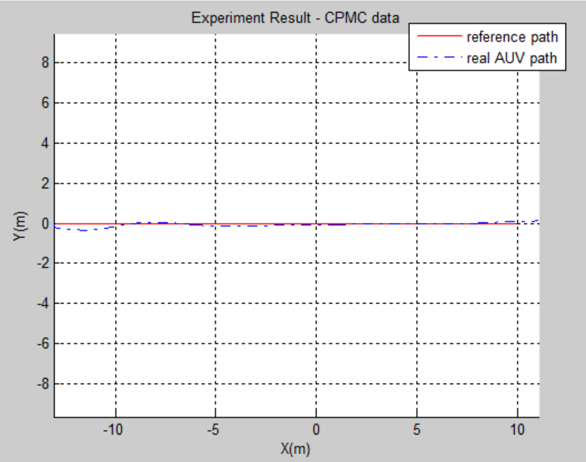

Fig.11. Path tracking experiment result for straight line

We can show path tracking experiment result. In this case, reference path is straight line. Start position is $P_0 = [-13, 0, 0^\circ]$, and goal position is $P_f = [10, 0, 0^\circ]$. Because of attribute of underwater experiment, an AUV can not depart the exact start position. In spite of that, an AUV overcome the initial error, and reach the goal position that has less than 0.05m error in Fig.12.

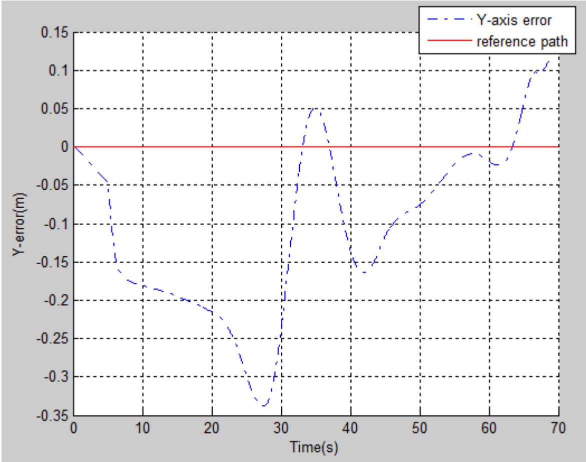

Fig.12. Path tracking experiment error for straight line

The result of path tracking experiment result is shown in Fig.13. In this result, start position is $P_0 = [-15, 5, 0^\circ]$ and goal position is $P_f = [10, -2, 270^\circ]$. The reference path is made by virtual goal method. The red solid line is reference path and the blue dotted line is experimental result.

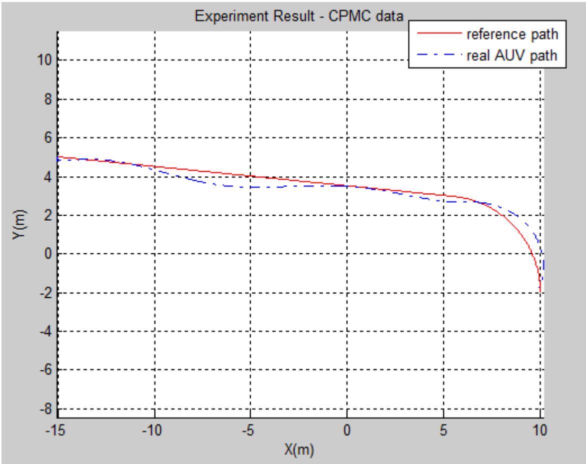

Fig.13. Path tracking experiment result for added turning motion

There are x-axis and y-axis errors in Fig.14. In this result, reference path is made based on desired uniform velocity. So x-axis error is increased at starting part. But it is overcome soon. Because of drift, y-axis error is bigger than other part at starting part of turning motion. But final y-axis error is less than 0.1m.

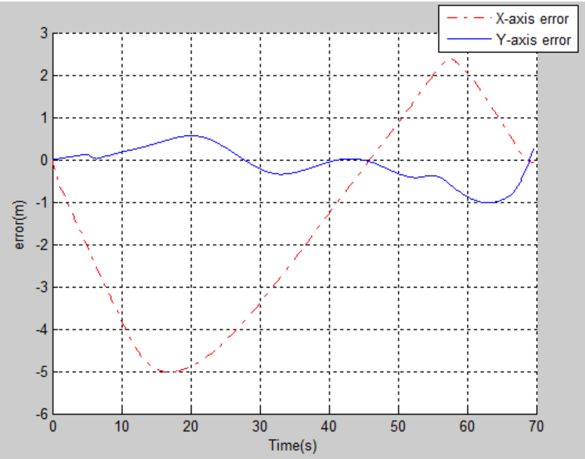

Fig.14. Path tracking experiment error for added turning motion

7 Conclusion and Future works

In this research, we proposed the design method of revised PD controller that is easy and simple to implementation. The PD controller utilized a strong correlation between control input and output from dynamics of an AUV. And we can show the performance of the controller by simulation and experiment results.

Actually, we need many cost and time for an experiment of an AUV in ocean or Ocean Engineering Basin. But we develop the simulator that is similar to real experiment through the result of this research.

In the near future, we will consider unexpected situations as a drift to simulation. And we will revise the controller to robust for disturbance.

Acknowledgement

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