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A Study on the Control of AUV's Homing and Docking

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Abstract: AUV(autonomous underwater vehicle) is unmanned underwater vessel to investigate sea environment and resources. To be completely autonomous, AUV must have the ability to home and dock to the launcher. By the way, there are many system uncertainties in AUV modeling and disturbances in the deep sea. So, due to these difficulties, robust control is much necessary to control AUV. Therefore, a sliding mode controller is selected and designed to regulate and track any suggested paths to accomplish the homing and docking procedure. Because AUV system has the non-matched uncertainties, an established idea is applied to solve this problem. Next, by the appropriate cost functions and algorithms, the homing and docking paths are generated in a space. By using these paths, we simulate lane changing problem and the docking procedure in the presence of the ocean current and waves.

Keywords: AUV, Path Generation, Sliding Mode Control.

1. Introduction

Nowadays, the necessity of underwater operation is increasing while the ocean development is progressing actively. Owing to resources in the ocean floor and military purposes, the demand of underwater operation is occurring in many fields. There are many kinds of equipment for deep sea probes. ROV(Remotely Operated Vehicle) and AUV(Autonomous Underwater Vehicle) are representative ones of them. ROV is operated by human through the cable which is connected with a mother ship. Usually, ROV has several manipulators for work and performs the operation in a stationary state or slow moving state. But AUV has a controller for a posture and dynamic motion and also has many kinds of sensors so that it can explore deep sea with high cruising speed. Moreover AUV can operate mission by itself. Therefore many kinds of research about full autonomy of AUV have been studied hard[2,3,4].

AUV must have homing and docking functions in order to be completely autonomous. Homing is an operation that AUV returns to the vicinity of the launcher after a mission. Path planning and tracking control of the planned path are also included in this operation. Docking is another operation that AUV is fixed with the launcher exactly when it is close to the launcher. Docking is more difficult than homing since the position of the launcher can be changed easily by ocean current and waves. Hence, much more precise path considered future position of the launcher is needed.

In this paper, we study about the mathematical model of AUV first. The model in 3-D space has 6 degree of freedom, and many kinds of hydraulic forces and moments should be defined. Also, many coefficients of hydrodynamic equations must be measured by experiments. Secondly we design the robust controller because there are many structure and unstructured uncertainties and disturbances caused by ocean current and waves. Thirdly we plan homing and docking path and simulate the tracking control of the path. Finally, we present the docking failure judging algorithm.

2. Mathematical Modeling of AUV

The objective of this modeling is that how we can represent the dynamic motion of AUV which has 6 degree of freedom in 3-dimensional space[1]. Equations of motion consist of 12 equations for representing AUV's motion in body-fixed coordinate and earth-fixed coordinate(Fig.1). Six equations in local coordinate express linear velocity(u, v, w) and angular velocity(p, q, r) of AUV and the other six equations are for positions(X, Y, Z) and Euler angles(f, q, y) in global coordinate. If we place the origin of the body-fixed coordinate at the AUV's center of gravity, the rigid body equations of motion expressed by forces and moments at center of gravity are derived as follows:

$$\begin{aligned} \tilde{F} &= m(\tilde{v}_G + \tilde{w} \times \tilde{v}_G) \\ \tilde{G} &= \tilde{I} \cdot \tilde{a} + \tilde{w} \times \tilde{I} \cdot \tilde{w} \end{aligned} \qquad (2.1)$$

where $\tilde{v}_G$, m, $\tilde{a}$, $\tilde{w}$, $\tilde{I}$ are the velocity vector of the center of gravity, the mass of AUV, the angular acceleration vector, the angular velocity vector and the inertia tensor of AUV respectively.

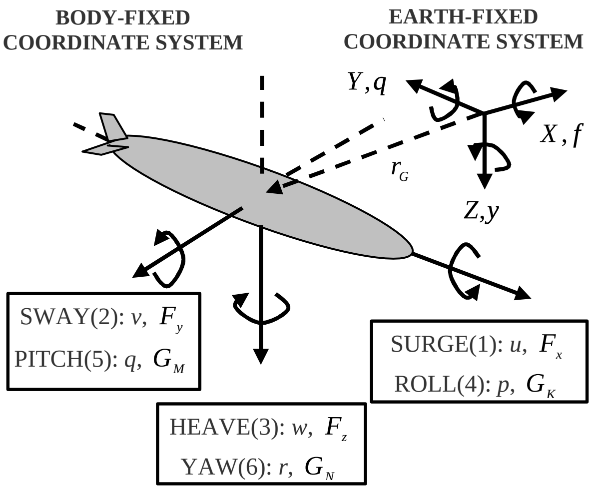

Fig.1 Body-fixed and earth-fixed reference frames

Table 1. Notation used for AUV

D O F		forces & moment	linear & angular velocity	position & Euler angle
1	Motions in the x-direction(surge)	F_x	u	X
2	Motions in the y-direction(sway)	F_y	v	Y
3	Motions in the z-direction(heave)	F_z	w	Z
4	Rotation about x-axis(roll)	G_K	p	f
5	Rotation about y-axis(pitch)	G_M	q	q
6	Rotation about z-axis(yaw)	G_N	r	y

Next, we have to consider about the hydro-static and hydro-dynamic forces and moments which are act on the AUV in the deep sea. At a stationary state the buoyancy generated by difference of the density between the seawater and the AUV and the gravity from the mass are included in the hydro-statics. And at a dynamic state there are added mass effect, drag and thrust forces in the hydro-dynamics. In an AUV modeling, added mass effect is a characteristic term. This is because, unlike an airplane in the air, the densities of the AUV and seawater are similar in the deep sea. Therefore due to this effect, the AUV moves as if its inertia is increased.

In the fluid, when an object is moving, it undergoes the drag forces which are proportion to velocity and the square of velocity. Though there are other drag forces which are proportion to high order of the velocity, but it is sufficient to represent the drag effect up to the square of the velocity[5].

Thrust model is represented at Fig.2. There is a propeller in the axis of progress direction, and rudder and stern plane are used for controlling direction. Especially, stern plane for horizontal motion is divided into two in order to control rolling motion. These hydrodynamic/static forces and moments are summarized in Table 2.

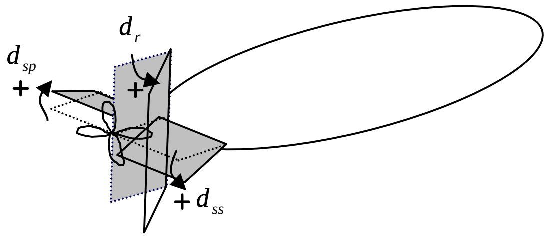

Fig.2 Schematic diagram of the thrust system

Table 2. Hydrostatic/dynamic forces & moments

Hydrostatic	Weight
	Buoyancy
Hydrodynamic	Added mass $\propto$ acceleration
	Drag $\propto$ velocity + velocity^2
	Thrust $\propto$ forward speed ratio + rudder angle + angular velocity $\times$ rudder angle + rudder angle^2

So, we can derive the complete nonlinear underwater vehicle equations of motion as follows :

$$M\dot{v} + C(v)v = \begin{pmatrix} F \\ G \end{pmatrix}_{AI} + \begin{pmatrix} F \\ G \end{pmatrix}_{AC} + \begin{pmatrix} F \\ G \end{pmatrix}_{D} + \begin{pmatrix} F \\ G \end{pmatrix}_{static} + \begin{pmatrix} F \\ G \end{pmatrix}_{T}$$

where M = inertia matrix

C(v) = matrix of Coriolis and centripetal terms

$\begin{pmatrix} F \\ G \end{pmatrix}_{AI}$, $\begin{pmatrix} F \\ G \end{pmatrix}_{AC}$, $\begin{pmatrix} F \\ G \end{pmatrix}_{D}$, $\begin{pmatrix} F \\ G \end{pmatrix}_{static}$ and $\begin{pmatrix} F \\ G \end{pmatrix}_{T}$ are inertia force and moment by added mass, coriolis and centripetal force and moment by added mass, force and moment by drag, force and moment by weight and buoyancy and force and moment by thrust respectively.

3. Controller Design

There are many difficulties in controlling AUV under the sea. Too many nonlinear terms are included in the equations of motion and hydro-coefficients derived by experiments have uncertainties. Besides, unpredictable disturbances such as ocean current or waves have an effect on AUV. Due to above reasons, it is necessary to design robust controller.[6]

3.1 Sliding mode control

In this paper, we use the sliding mode controller. We perform the tracking control of the AUV in the 3-dimensional space. Now the system can be represented as follows :

$$\dot{x} = f(x) + B(x)u(t) \tag{3.1}$$

where $x \in R^{n\times1}$, $u \in R^{m\times1}$, $B(x) \in R^{n\times m}$

In the system, we adopt linear sliding surfaces $s(x)$.

$$s(x) = \begin{bmatrix} s_1(x) \\ \vdots \\ s_m(x) \end{bmatrix} = Sx(t) = 0 \tag{3.2}$$

where S is an m × n matrix.

In sliding mode control, input is divided into equivalent input that makes system stable and switching input that compensates disturbances and uncertainties. Equation (3.1) can be divided into linear part and non-linear part and written as:

$$\dot{x}(t) = Ax(t) + Bu(t) + f(x,u) \tag{3.3}$$

By the way, this equation can be rewritten as:

$$\dot{x}(t) = Ax(t) + Bu(t) + De(x,u) \tag{3.4}$$

Then, if D is the subset of the range B, we say the matching condition is satisfied. By the way, in AUV modeling, the matching condition is not satisfied since D is not subset of the range of B. So we divide the state into matching part and unmatched part in order to set the switching input gain and surface gain easily. In this research, we control the unmatched disturbances by using the regular form transformation.

We derive the transformation matrix T_r that changes system into regular form. By T_r matrix which can be computed via 'QR' decomposition, B matrix is changed into

$$T_r B = \begin{bmatrix} 0 \\ B_2 \end{bmatrix} \quad (Rank(B) = m\ ,\ B_2 \in R^{m\times m}) \tag{3.5}$$

Also, state is transformed and following equations are derived from equation (3.3).

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = T_r x \tag{3.6}$$

$$\begin{aligned} \dot{x}_1 &= A_{11}x_1 + A_{12}x_2 + f_u(x_1, x_2) \\ \dot{x}_2 &= A_{21}x_1 + A_{22}x_2 + B_2 u + f_m(x_1, x_2, u) \end{aligned} \tag{3.7}$$

where $x_1 \in R^{n-m}$ is unmatched state and $x_2 \in R^m$ is a state that satisfies the matching condition .

Then sliding surfaces are also divided into two parts as follows :

$$s = S_1 x_1 + S_2 x_2 \tag{3.8}$$

Substituting equation (3.8) into equation (3.7) yields

$$\begin{aligned} \dot{x}_1 &= \overline{A}_{11}x_1 + \overline{A}_{1s}s + f_u(x_1, x_2) \\ \dot{s} &= \overline{A}_{s1}x_1 + \overline{A}_{ss}s + S_2 B_2 u + S_2 f_m + S_1 f_u \end{aligned} \tag{3.9}$$

where $\overline{A}_{11} = A_{11} - A_{12}S_2^{-1}S_1$, $\overline{A}_{1s} = A_{12}S_2^{-1}$,

$\overline{A}_{s1} = S_1 A_{11} + S_2 A_{21} - S_1 A_{12} S_2^{-1} S_1 - S_2 A_{22} S_2^{-1} S_1$,

$\overline{A}_{ss} = S_1 A_{12} S_2^{-1} + S_2 A_{22} S_2^{-1}$

If we make s zero from the input, equation (3.8) becomes

$$x_1 = -S_1^{-1} S_2 x_2 \tag{3.10}$$

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Using above equation, x_1 is converged after x_2 is converged to zero. Finally, equivalent and switching input are designed as follows:

$$u_{eq} = -(S_2 B_2)^{-1}\left\{\overline{A}_{s1} x_1 + \overline{A}_{ss} s + S_2 f_m + S_1 f_u - f s\right\}$$

$$u_N = -(S_2 B_2)^{-1}\, r \cdot sign(s) \qquad (3.11)$$

where r is switching input gain and f is a stable matrix that has faster response characteristics than state x_1, $x_{2\ s}$ so that s can be converged to zero much faster.

Switching input gain r has a condition below.

$$r \geq \|S_2\| \|\tilde{f}_m - f_m\| + \|S_1\| \|\tilde{f}_u - f_u\| \qquad (3.12)$$

where $\tilde{f}_u, \tilde{f}_m$ are perturbed value of system variables in a constant bound.

And to stabilize state x_1 which does not satisfy the matching condition, for such P_1, Q_1 that satisfy Lyapunov equation $P_1 \overline{A}_{11} + \overline{A}_{11}^T P_1 = -Q_1$ following equation (3.13) must be satisfied.

$$\| f_u \| < \frac{1}{2} \frac{l_{\min}(Q_1)}{l_{\max}(P_1)} \| x_1 \| \qquad (3.13)$$

3.2 Application of sliding mode control to AUV

Now, we apply the SMC technique to the AUV system. Nonlinear terms that we know exactly in equations of motion are compensated by equivalent input, and system parameter uncertainties are compensated by switching input by handling them as disturbances.

There are four inputs, F_x, G_K, G_M, G_N , so it is possible to control x-direction force, x/y/z-direction moments in body-fixed coordinate. In homing and docking, we have to control linear velocity u in body-fixed coordinate and global position X,Y,Z as well as Euler angle f,q,y . By the way, linear velocity v, w have very small value only when q,r have some value. Therefore we adopt the state as $u, p, q, r, X, Y, Z, f, q, y$.

To determine the S_1 and S_2, we have to decide twenty four values at the same time. But this process is very complex and it is difficult to choose the value which has the physical meaning. So, to solve this difficulty, we design the controller by classifying several control modes.(Table. 3)

Table 3. Control Modes

Mode	States	Input
Mode I	u	F_x
Mode II	q, q, Z	G_M
Mode III	r, y, Y	G_N
Mode IV	p, f	G_K

Mode (I) is a mode that regulates the linear velocity u of AUV in local coordinate. Mode (II) and (III) control the vertical motion on diving plane and the horizontal motion on the steering plane in the global coordinate respectively. Mode (IV) is a mode to control the rolling motion of AUV.

4. Homing and Docking Algorithm

The reason why we classify algorithm into two stages is that the information from sensors are changed seriously. In the homing stage, LBL(Long Baseline) type sensor is used to get the position information. But in the docking stage, SSBL(Super Short Baseline) type sensor and CCD camera are used. Data transfer speed of LBL type sensor and accuracy is lower than that of docking sensors, so the same control strategy should not be applied to two stages. The sensors commonly used in two stages are gyro, compass, and speedometer and so on.

4.1 Homing algorithm

It is essential for homing to generate path to the launcher. Because the renewal of position information of LBL sensor is somewhat slow, we plan the path so that AUV reaches appropriate site, 10 m front of the launcher, at one data receiving.

The path is generated by using the cubic spline function with following boundary conditions

$$\vec{r}(t) = x(t)\hat{i} + y(t)\hat{j} + z(t)\hat{k} \qquad (4.1)$$

$$\vec{r}(t)\big|_{t=0} = [x(0)\ y(0)\ z(0)], \quad \vec{r}(t)\big|_{t=1} = [x(1)\ y(1)\ z(1)],$$

$$\left.\frac{d\vec{r}(t)}{dt}\right|_{t=0} = [\dot{x}(0)\ \dot{y}(0)\ \dot{z}(0)], \quad \left.\frac{d\vec{r}(t)}{dt}\right|_{t=1} = [\dot{x}(1)\ \dot{y}(1)\ \dot{z}(1)]$$

where, $\vec{r}(t)$ is position vector and $x(t) = a_x t^3 + b_x t^2 + c_x t + d_x$. $y(t)$ and $z(t)$ are also represented in the same way.

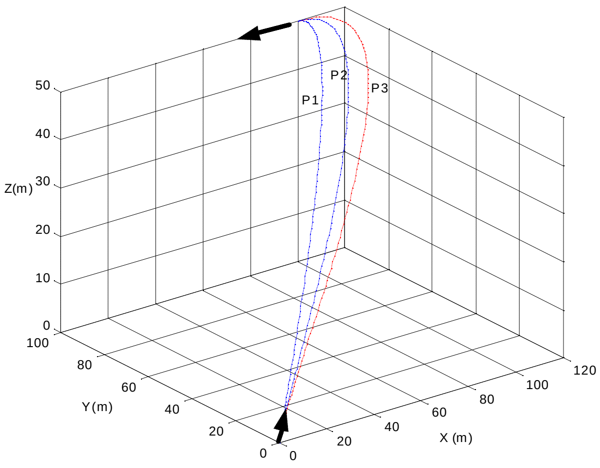

Fig. 3 Homing path generation

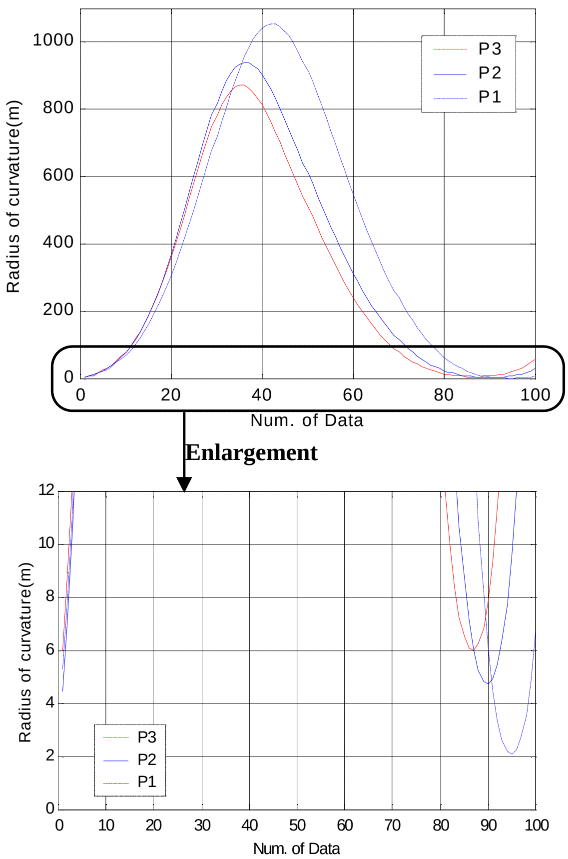

Fig. 4 Radius of curvature along homing paths

There are two additional conditions to generate the path. One is the radius of curvature and the other is total path length. So we generate the minimum length path by using optimization technique (SQP) with the restriction of radius curvature (6 m). In the Fig. 3, 4 we generated three paths P1, P2, P3. By the way P1, P2 are shorter than P3, but the minimum radius of the curvature is lower than 6 m. Therefore we have to choose P3 since the AUV can not track the P1 and P2.

4.2 Docking algorithm

In docking process, There are many difficulties because the launcher is not stationary. Primary reason is that a mother ship is moving by the ocean current and waves . So the launcher is also moving in sine motion of vertical direction and in linear motion of horizontal direction with constant velocity.

From this point of view, docking should be performed in two stages. At the first stage, accurate path is derived by anticipating the future docking point. That is, we anticipate the exact docking position by getting the information about velocities and positions of AUV and launcher, and then generate exact path by iteration. At the second stage, we do not generate path. AUV will track the docking target by vision system in real time.

4.2.1 Strategy of the first stage

First, we make path and calculate the consumed time ($T_{tracking}$) to launcher. But, while AUV track this path, the launcher will be moved from the first position, so AUV can't dock into the launcher. Therefore we should calculate the future position of the launcher during $T_{tracking}$. Next, we derive new path by using the future position of the launcher, and recalculate $T_{tracking}$. Then we check whether the docking point of the new path is same with the future position of the launcher. If this is not same, same process is repeated until two positions will be exactly the same.

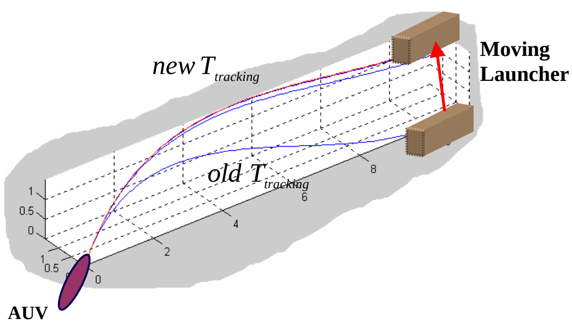

Fig. 5 Docking path algorithm (1st stage)

4.2.2 Strategy of the second stage

The second considerable problem is the vertical oscillation motion of the launcher. This is because

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the mother ship is surged by waves. JAMSTEC[8] experimented that how much the launcher which is 6500 m under the sea oscillate when the mother ship vibrates vertically. The result was the launcher oscillates with the same period and 0.15 m of amplitude, when the mother ship moves vertically with 2.2 m of amplitude and 7 sec of period.

So, at the second stage, when the AUV approaches close location from the launcher (5m in front of the launcher), AUV tracks the target of the launcher by using visual tracking technique in the real-time. But, in simulation, we assume that the frequency and amplitude of sine motion in vertical plane are known and then we make the sinusoidal path in order to test AUV's sinusoidal tracking ability. Fig.6 shows the docking path example using above method. The first stage is up to separation plane.

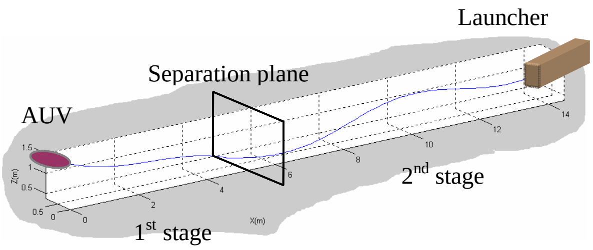


Fig.6 Whole docking

5. Simulation

Control frequency is 10 Hz and boundary layer method is applied. Input limits are:

Propeller rps : Max. 20 rps

Rudder angle : Max. 30 degree

5.1 Lane changing

First, we simulate the lane changing problem in 3-dimensional space. The reference conditions are:

Local velocity : $u = 2\ m/\sec$

Global position : $Y = 2\ m$, $Z = 2\ m$

Fig.7 show the error values during lane changing. Input values (propeller rps, $d_{rol}(= d_{sp} - d_{ss})$, $d_s(= d_{sp} + d_{ss})$), are also represented in Fig. 8. Fig.9 represents sliding surfaces of each control mode.

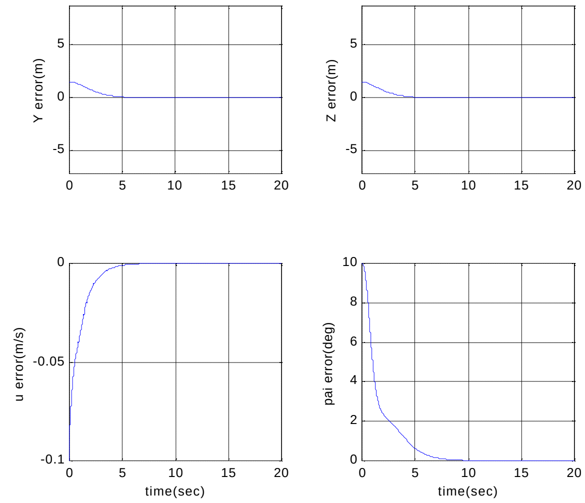


Fig. 7 Error values during lane changing

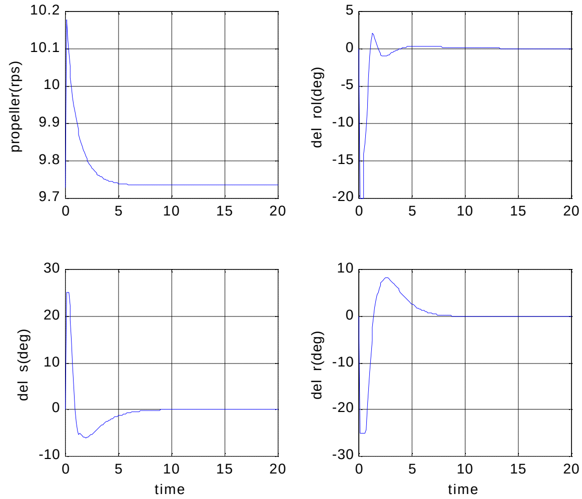


Fig.8 Input values during lane changing

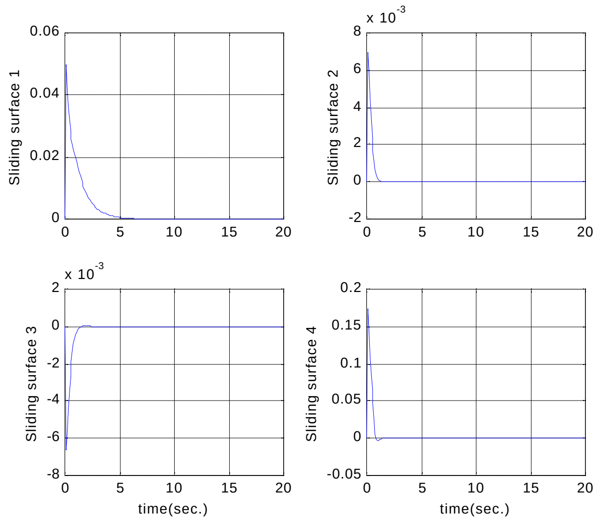
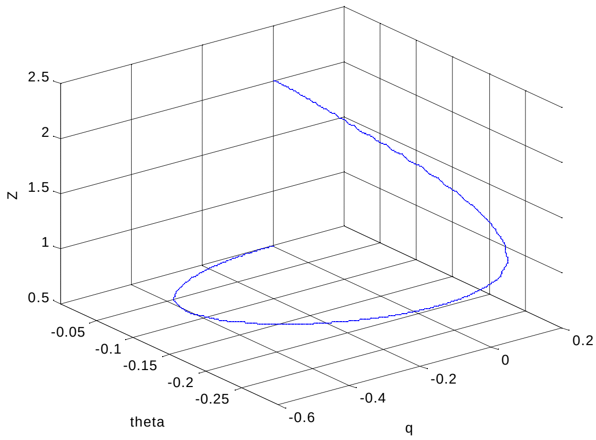
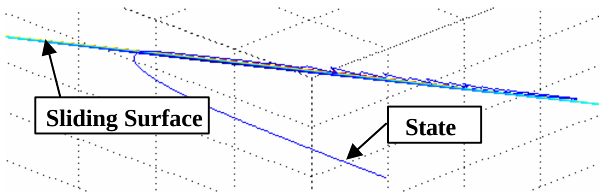


Fig. 9 Sliding surfaces of control modes during lane changing

The state that forms sliding surface S_2 for control mode(II) is represented in the three dimensional space(Fig. 10). It can be known that a chattering is on the sliding surface and the state is converged on the plane.



(a) States plot

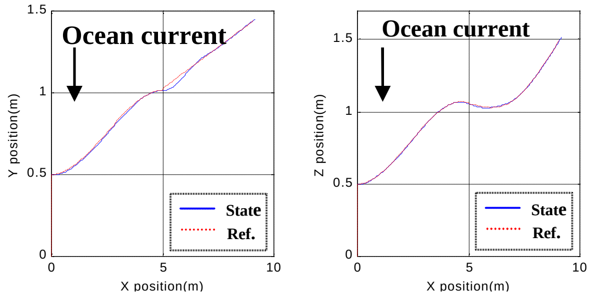


(b) Sliding surface

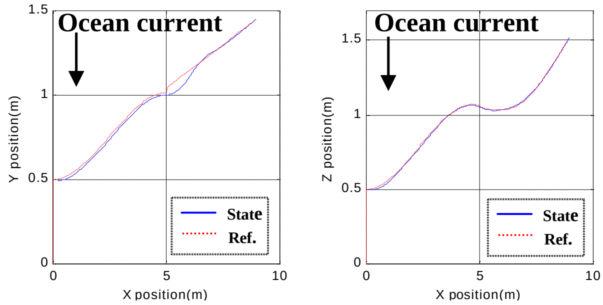
Fig. 10 Sliding surfaces concept of S_2 during lane changing

5.2 Docking simulation

Next, when the velocity of the ocean current is 0.1 or 0.2 m/sec toward negative Y and Z direction and the AUV is 10 m in front of the launcher, the docking simulation results are represented in Fig. 11. Here to impose more disturbances the launcher is moving toward completely opposite direction of ocean current with same velocity and it also has vertical sine motion whose period and amplitude are 7 sec and 0.25 m respectively. In the Fig. 12, it is known that error from the docking path is less than 5 cm. Due to the anticipating algorithm there is somewhat large error up to 10 seconds, but we can see the error is getting less and less. At last, it is shown that the AUV can track the path well and dock in the launcher with success.

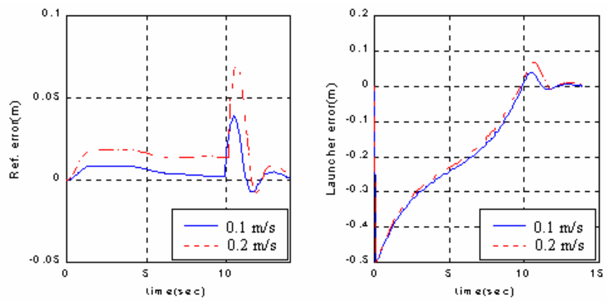


(a) Under 0.1 m/s current

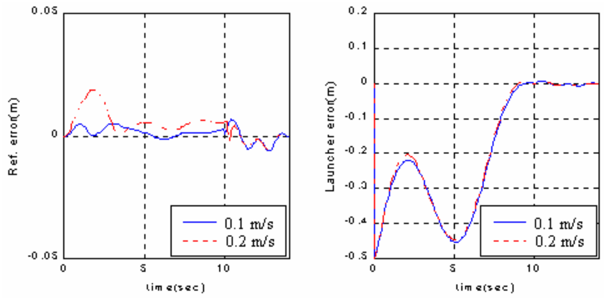


(b) Under 0.2 m/s current

Fig. 11 Motion plot in a docking simulation (With the ocean current)



(a) Horizontal plane (x-y plane)



(b) Vertical plane (x-z plane)

Fig. 12 Reference tracking error & Launcher error in a docking (With the ocean current)

6. Docking Failure Judgement

We generate the docking path in real time. But AUV may not follow the path due to the environment problems, so it may be separated from the path. That is, if the path is generated when AUV is not in the point where the docking is possible, AUV can not follow the path. Therefore, it is necessary to judge whether the position of AUV is proper to dock or not. The algorithm of the docking failure judgement is described in Fig.13. There are two circles which have 6m radius, the minimum radius of AUV's turning ability, and pass through P1 and P2 or P3 in 2-D space. Then, we can consider two tangent lines at P1. If the direction vector of AUV is between two tangent lines in *X*-*Y* and *X*-*Z* plane, AUV can dock into the launcher. Otherwise AUV can not be docked and retry the homing and docking process again.

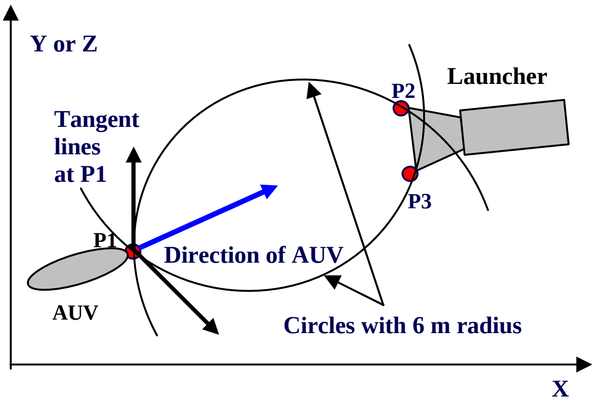


Fig. 13 Docking failure judgement

7. Conclusion

In this paper we derived the mathematical model of AUV that has six degree of freedom and designed the sliding mode controller in order that AUV can track the path in spite of the system uncertainties and disturbances. To make the homing and docking path in three dimensional space, we used the cubic spline function and generated the shortest path in the consideration of minimum radius of curvature by using the optimization technique.

In the controller design, we converted the system equation to regular form since the system does not satisfy the matching condition. By using the sliding mode controller we simulated the lane changing problem and docking process. The simulation results showed the successful docking in the presence of the ocean current.

Finally, we presented the simple failure judgement algorithm in real time.

Acknowledgements

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