A tracking control method of ASV following AUV

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***Abstract*—A method using autonomous surface vehicle (ASV) is presented in order to track autonomous surface vehicle (AUV). This method uses tracking control based on chasing activity. The heading and speed of ASV is automatically adjusted according to position and speed of underwater robot. And the safe domain of ASV which is not allowed to get out of is built to avoid danger. Sample points are updated dynamically to predict possible position of AUV for stable tracking, in the condition of broken communication which introduces the unknown position. The lake experiment shows that the ASV can autonomously track AUV which trajectory is unknown with stability and continuity by the proposed algorithm in the environment with complex acoustic communication and the results is satisfactory.**

Key Words*—*autonomous surface vehicle; underwater robot; autonomous tracking; dynamic prediction;safe area

I. INTRODUCTION

Autonomous Underwater Vehicles has much application in ocean observation system. And there is an increasing demand for real-time data from the surface to underwater. The AUV tracking problem becomes a key research recently [1-3]. The ordinary method is to use support boat for tracking AUV. However, reliable communications are difficult to be established due to the physical properties of the water, especially when transmitting along great distances. Due to communicating range restriction, it is hard to satisfy requirements of tracking with long distance. The most valid method is to track the AUV with Autonomous Surface Vehicle (ASV). Having an ASV acting as a support boat by following the AUV trajectory, would establish a reliable communication link between both vehicles. Therefore, scientists could own the ability to communicate with AUV which can perform any given mission. This provides a technical support for more complex and challenging AUV missions. [4] introduced a closed-control method of AUV trajectory tracking method for ASV. In fact, in order to communicate with AUV, it does not have to track AUV's trajectory for ASV. ASV only needs to be controlled within a certain distance. It is just the valid communication range. We proposed a new tracking method. The ASV autonomously adjusts speed and heading itself according to relative position and speed between ASV and AUV. Moreover, The ASV can continue to track AUV in the presence of broken communication. For avoidance, the ASV would never sails outside the safe area that has been determined by people.

II. PROBLEM

The communication link is established with acoustic signal. Acoustic modems are deployed on both vehicles. AUV sends its navigation message to ASV periodically. ASV calculated necessary control inputs to adjust itself for tracking AUV based on the navigation data. The tracking sketch is shown in figure 1.

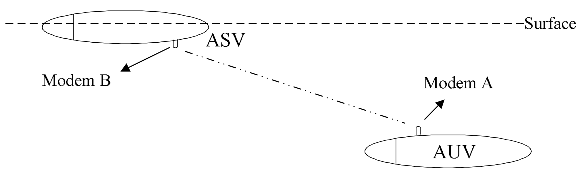

Fig.1 The tracking sketch from ASV to AUV

Letting $S(t)$ denote ASV trajectory, $E(t)$ denote AUV trajectory, $u(t)$ denote the control inputs of ASV. We give the following definition Success tracking control: ASV trajectory which is driven from the control inputs is keeping a valid communication distance from AUV, and ASV always sails into the safe area.

The definition can also be explained as below

$$\left\{u \middle| d(S(u(t)),E(t)) = r_{valid}, S(u(t)) \in SA\right\} \quad (1)$$

where $S(u)$ denotes ASV trajectory, $d(S(u(t)),E(t))$ denotes the distance between ASV and AUV, r_{valid} denotes the valid communication distance, SA denotes the safe area.

III. TRACKING CONTROL

In the surface, ASV's trajectory is in horizontal plane. The trajectory is formed with two inputs: the heading and speed. Thus, the controller of tracking system for both vehicles is made up of two controllers, and heading controller and speed controller. For heading controller, the ASV is needed to be informed about the AUV position coordinates. And for speed controller, ASV should acquire the speed of AUV. Moreover, the heading

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of AUV still should be obtained so that the AUV's trajectory of next time step can be predicted. Thus, the navigation message sent by AUV includes the position coordinates, speed and heading. The main idea of the control strategy is that if the ASV is far enough away from the AUV, then it should go straight ahead on a direction directly to the ASV on full speed; as it approaches the AUV, it should start changing its speed to one that suits it needs, and the direction should be oriented to the AUV.

The rigid body equations of ASV motion are then given as [5]

$$M\dot{v}+C(v)v+Dv=\tau \tag{2}$$

where M , $C(v)$ and D represent the mass, Coriolis, and damping matrices respectively. They are given as

$$M=\begin{bmatrix} m & 0 & 0 \\ 0 & m & mx_g \\ 0 & mx_g & I_z \end{bmatrix}, D=\begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & 0 \\ 0 & 0 & d_{33} \end{bmatrix}$$

$$C(v)=\begin{bmatrix} 0 & 0 & -m(x_g r+v) \\ 0 & 0 & mu \\ m(x_g r+v) & -mu & 0 \end{bmatrix}$$

where m is the mass of the USV, I_z is the moment of inertia about the z (vertical) axis, and the diagonals of D represent damping along the surge, sway, and yaw directions respectively.

The vector $\tau=\left[\tau_{u,}\tau_v,\tau_r\right]'$ represents the input forces. The vehicle used in this work is underactuated in the sway direction. Define s_e and ψ_{eI} where $\dot{s}_e=u_e=u-u_d$ and $\dot{\psi}_{eI}=\psi_e=\psi-\psi_d$,The states under consideration in this analysis are the error dynamics. Assuming that the sway movement can be ignored, the error dynamics may then be determined as

$$\begin{aligned} &\dot{s}_e=u_e \\ &\dot{u}_e=\frac{1}{m}(\tau_u-d_{11}u)+r(v+rx_g)-\dot{u}_d \\ &\dot{\psi}_{eI}=\psi_e \\ &\dot{\psi}_e=r-\dot{\psi}_d \\ &\dot{r}=\frac{(\tau_r-d_{33}r+d_{22}vx_g)}{(I_z-mx_g^2)} \end{aligned} \tag{3}$$

A) Heading controller

The relative orientation between the AUV and ASV changes in real time a result of AUV's movement. The heading controller adopts a control mode made up of closed loop adding open loop. It is quite simple: the heading control of the tracking system for ASV and AUV is closed loop, as shown in figure 2.

Let $\dot{\psi}_d$ =0，the heading error system can be obtained according to equation(3)

$$\begin{bmatrix} \dot{\psi}_{eI} \\ \dot{\psi}_e \\ \dot{r} \end{bmatrix}=\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\dfrac{d_{33}}{I_z-mx_g^2} \end{bmatrix}\begin{bmatrix} \psi_{eI} \\ \psi_e \\ r \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{I_z-mx_g^2} \end{bmatrix}\tau_r \tag{4}$$

It is obvious that the system is controllable, we can design a control law for surge speed control using state feedback as follow

$$\tau_r=-k_{r1}\psi_{eI}-k_{r2}\psi_e-k_{r3}r \tag{5}$$

This control law consists of proportional, integral, and derivative terms to stabilize the heading error. The pole of the system can be set as any negative part in order to guarantee the stability.

The objective heading ψ_d can be figured out with both position coordinates of AUV and ASV. It is a common calculation algorithm which will not be described here.

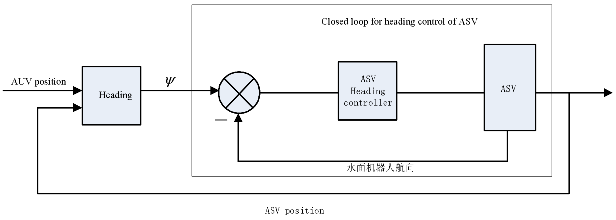

Fig.2. The heading controller of the tracking system

B) Speed controller

In general, AUV moves with uniform speed in most time. Consequently, a closed loop controller is used in the speed controller in order to keep the distance in a proper range for communication and safety. The controller is two-stage controller, as shown in Fig.3. The

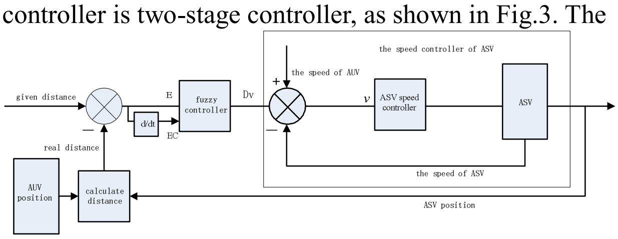

Fig.3. The speed controller of the tracking system

first stage is a fuzzy controller that compares the AUV position with the position of the ASV. The inputs are distance error denoted by E and its rate denoted by EC while the output is the speed adjustment. We use value of the speed adjustment as an increase of speed of the ASV. The second stage is the speed closed loop controller of ASV. The input of the second state is a reference speed given by AUV speed（denoted by v_u ）added to the increase of speed(denoted by D_v), calculated by the first stage. The controlled quantity of ASV can be expressed as below.

$$u = v_u + Dv \tag{6}$$

While the AUV and ASV positions differ, the available speed of the last should be higher than the first one. The fuzzy control is built with simple "if-then" rule as shown in table 1.PB, PS, NS and NB means positively big, positively small, negatively small and negatively big respectively.

TAB.1. THE RULE OF THE FUZZY CONTROLLER IN THE FIRST STAGE.

Dv \ E / EC	PB	0	NB
PB	PB	PS	NS
0	PB	0	NB
NB	PS	0	NB

Let $\dot{s}_d = \dot{u}_d = 0$, the speed error system can be obtained according to equation (3)

$$\begin{bmatrix} \dot{s}_e \\ \dot{u}_e \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -\frac{d_{11}}{m} \end{bmatrix} \begin{bmatrix} s_e \\ u_e \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{m} \end{bmatrix} \tau_u + \begin{bmatrix} 0 \\ -\frac{d_{11}}{m} u_d \end{bmatrix} \tag{7}$$

It is obvious that the system is controllable, we can design a control law for surge speed control using state feedback as follow

$$\tau_u = d_{11} u_d - k_{u1} s_e - k_{u2} u_e \tag{8}$$

This control law consists of proportional and integral terms to stabilize the surge speed. The pole of the system can be set as any negative part in order to guarantee the stability.

IV. AUTONOMY OF ASV FOR TRACKING

A)Self-prediction on AUV trajectory

The acoustic communication is usually broken off due to complex hydrology condition. It is possible to lose the information of AUV in the process of tracking. Therefore, the ASV is ought to be provided with this autonomous ability. The self-prediction of AUV trajectory in real time is need for ASV. The motion of AUV is a slowly variable movement. And as a matter of fact, the trajectory of AUV for a short time after is only related to its current position and the trajectory of a short time before. A dramatic slide model is employed in [6]. With moving of the AUV, sample points are updated dynamically to predict possible position of the AUV in a short period of time by using the fitting of a polynomial.

B)Self-security in tracking

ASV is probable to encounter the bank in the event of unexpected accident. For example, the AUV is sailing much near the bank and the acoustic communication is failure for a while. And in this situation, the ASV might collide with the bank resulting in disaster. To avoid the danger, the ASV is needed to be provided with the ability of self-security. The ability ensures that the ASV always moves in the safe area at any time. We define a safe area which is a quadrilateral marked with 'A', 'B', 'C' and 'D', as shown in figure 4. The inside of the quadrilateral is the allowable region for ASV movement.

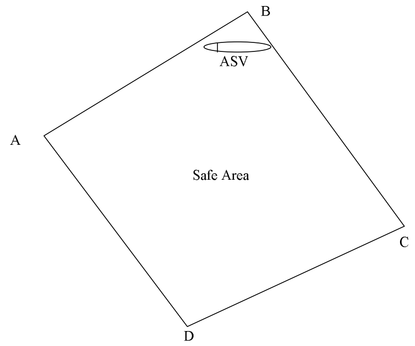

Fig.4. The quadrilateral marked with 'A', 'B', 'C'and 'D'

The linear equation of analytic geometry is used in autonomy algorithm of self-security. The condition of the ASV in the quadrilateral is that ASV lies below the 'AB' line and the 'BC' line, and above the 'AD' line and 'DC' line. Otherwise, the ASV will be in an insecure area. The ASV autonomously judge whether its position of next sample time is in the safe area based on the condition. A 180° angle will be carried out for turning if the next position of the ASV lie in an insecure area.

V. THE EXPERIMENT

In order to test the validity and particularity of the presented tracking method, the experiment on lake was been carried out in October, 2011. The tracking program of the method had been put in the ASV. The tracking system includes a AUV, a ASV and two acoustic modem which are installed on each vehicle. The UWM2000 modems of Linkquest were used. The effective range of the modem is 2000m,

We set a safe area of quadrilateral defined by four zeniths for ASV before the experiment, as shown in figure 5. The two vehicles were deployed nearly at the initial time. AUV started to sail following the planned trajectory after ASV was prepared. The acoustic modem named MA of AUV sent navigation message to ASV in each four seconds. The tracking program started running once ASV received the navigation message. ASV was at a distance of 500 m from AUV when the tracking procedure started. And ASV was located outside of the

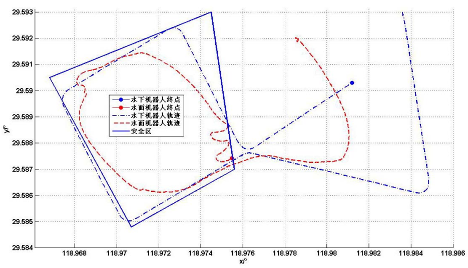

Fig.5. The tracking trajectory of the lake experiment

quadrilateral. ASV always sailed inside the safe area when it went into the quadrilateral from the outside because of the self-security ability. There are about 200 occurrences of broken communication during 300 times communication in all due to complex hydrology condition. Although some broken communication lasted long, even about five minutes. The position of AUV was predicted by ASV with the ability of self-prediction. That ability made ASV still track AUV reliably even if in the presence of broken communication. ASV automatically adjusted the speed and heading according to the output of the tracking program. In the end of the trajectory, we can see that ASV never went out of the quadrilateral for ASV had turned in an opposite direction near inside the right boundary before it would cross the boundary. The lake experiment showed that the presented method is useful and reliable to track AUV for ASV.

VI. CONCLUSION

The results obtained by the lake experiment really satisfy the requirement of tracking application. The performance of the presented method is desirable. ASV takes proper adjustment in heading and speed to reach AUV and keep a desirable distance, not only in continuous but also in broken communication. Besides that, ASV is controlled by the program not to go out of the safe area. It is much useful to track AUV for ASV.

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