Recovery Motion Control for an AUV Using Fuzzy Decoupling Method

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***Abstract* - The underwater recovery of AUV is a process of 6-DOF motion, which is related to characteristics with strong nonlinearity and coupling. In the recovery mission, the vehicle requires a high demand to the control accuracy. Considering an AUV called BSA, this paper established a simplified kinetic model to describe the motion of AUV in the horizontal plane, which is consisted by some nonlinear equations. On the basis of this model, the main coupling variables and coupling reasons were analyzed during recovery. Aiming at the strong coupling problem between the heading control and sway motion, designed a decoupling compensator based on the fuzzy theory and the decoupling theory, according to the rules of fuzzy compensation, by the input and output membership functions of fuzzy compensator, through compose operation and clear operation of fuzzy reasoning, obtained decoupling compensation quantity. Simulation results show that the fuzzy decoupling controller effectively reduces the overshoot of the system, improves the control precision, and show that the fuzzy decoupling control method has a high application value in the recovery mission.**

***Keywords* - AUV; Recovery; Fuzzy theory; Decoupling compensator**

I. INTRODUCTION

Autonomous underwater vehicles (AUVs) are widely used in hydrographical surveys, security check near the coasts of ports, marine environmental monitoring and salvage operations. The data collected by AUV is very important, which means that the vehicle needs to be recovered safely after missions. Voluminous literatures have been presented in recovery, which could be basically divided in two types:

(1) Surface recovery, which is conducted by a surface mother ship;

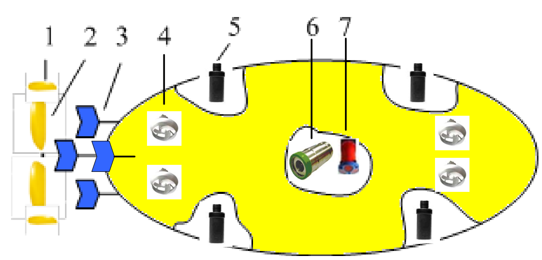
(2) Underwater recovery, which is carried out by using an underwater lifting platform for underwater docking recovery operation.

The latter one is becoming to be AUV clients' favor for its convenience in recovery operation, where the simulation results and pool experiments have demonstrated the feasibility of this method.

The AUV control of recovery mission is working with each link coordinated, it will decrease the regulating quality of the control system if the object exists coupling. The system even can not put into operation in the condition of serious coupling. Therefore, the discussion of the decoupling problem is very meaningful work for both the control theory and engineering practice[1]. In spite of the substantial achievements that the theoretical research have gained, but it is not satisfactory when compare the decoupling theory in engineering application with other branches like the optimal control and the adaptive control in engineering application[2-3]. Investigate its reasons, mainly because the decoupling control system is not only very sensitive to parameter changes but also expensive. Effective way to solve this problem is to study the so-called "non-sensitive" algorithm[4-5]. As we all know, the insensitivity of the fuzzy control system is one of its outstanding advantages, so the fuzzy control can be applied to the decoupling system.

II. AUV RECOVERY CONTROL SYSTEM

The overall layout of the BSA AUV is shown in Figure 1. It is mainly composed by four main thrusters, four auxiliary thrusters, a rudder and an elevator. The main thrusters and control planes are located in the stern of the AUV. The auxiliary thrusters, whose centerlines are designed with a certain angle about its water plane, are placed in the main section of the vehicle. These thrusters can provide sway and heave control forces at the same time. The SBL (Short base line) is an underwater position system which can provide the vehicle's position information relative to the recovery platform where hydrophones are placed. The DVL (Doppler velocity log) is used to measure the AUV's velocity relative to the bottom of water. And the underwater camera is very helpful to obtain a more accurate position measurement with optical method when the vehicle is near the platform where guiding lights are mounted. On the horizontal plane motion, it will produce coupling against sway motion and surge motion through the differential of the left and right main thruster to adjust the heading angle of AUV. It is the main problem that the coupling between the heading angle control and the sway motion control. And it's also the focus of this study. However, we will do a further research in a follow-up article on the coupling between the heading control and the surge motion control.



1 Rudder; 2 Elevator; 3 Main Thrusters; 4 Auxiliary Thrusters;
5 SBL; 6 Underwater Camera; 7 DVL

Fig.1 AUV structure layout

The recovery process of the vehicle can be divided into five stages (Fig.2).

Stage 1: Adjust the heading of vehicle towards the projection of the recovery platform's geometric center in the horizontal plane where the vehicle sails for the first time.

Stage 2: Sail to the projected point directly.

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Stage 3: Dive in the vertical for the first time until its height is 3m above the platform, during which it maintains its bearing and position in the horizontal plane.

Stage 4: Begin to adjust its heading in the direction of the platform's longitudinal line for the second time.

Stage 5: Make submergence for the second time until the AUV arrives in the platform.

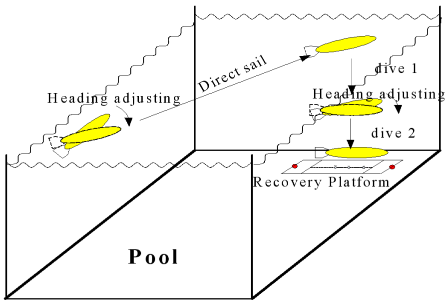

Fig.2 A diagram of AUV's recovery process

III. AUV MODELING

In this part, we established a simplified kinetic model to describe the motion of AUV in the horizontal plane, which is consisted by some nonlinear equations[8]. And this model is used to design a fuzzy decoupling controller and conduct a simulation.

$$\begin{aligned} m(\dot{u}-vr) &= \tfrac{1}{2}\rho L^4 \cdot X'_{rr} r^2 + \tfrac{1}{2}\rho L^3 (X'_{\dot{u}}\dot{u} + X'_{vr} vr) \\ &+ \tfrac{1}{2}\rho L^2 (X'_{uu} u^2 + X'_{vv} v^2) \\ &+ \tfrac{1}{2}\rho L^2 u^2 \cdot X'_{\delta_r\delta_r}\delta_r^2 + X_{prop} \end{aligned} \tag{1}$$

$$\begin{aligned} m(\dot{v}+ur) &= \tfrac{1}{2}\rho L^4 Y'_{\dot{r}}\dot{r} \\ &+ \tfrac{1}{2}\rho L^3 (Y'_{\dot{v}}\dot{v} + Y'_{ur} ur + Y'_{v|r|} v\,|\,r\,|) \\ &+ \tfrac{1}{2}\rho L^2 (Y'_{uv} uv + Y'_{v|v|} v|v|) \\ &+ \tfrac{1}{2}\rho L^2 u^2 \cdot Y'_{\delta r}\delta_r + Y_{prop} \end{aligned} \tag{2}$$

$$\begin{aligned} I_z\dot{r} &= \tfrac{1}{2}\rho L^5 (N'_{\dot{r}}\dot{r} + N'_{r|r|} r|r|) \\ &+ \tfrac{1}{2}\rho L^4 (N'_{\dot{v}}\dot{v} + N'_{ur} ur + N'_{|v|r} |v| r) \\ &+ \tfrac{1}{2}\rho L^3 (N'_{uv} uv + N'_{v|v|} v|v|) \\ &+ \tfrac{1}{2}\rho L^3 u^2 \cdot N'_{\delta r}\delta_r \end{aligned} \tag{3}$$

In which: u--surge velocity, m/s; v--sway velocity, m/s; r--heading angular velocity, rad/s; m--mass, kg; L--length, m; ρ -- sea-water density, kg/m^3; δ_r -- rudder angle, rad; X_{prop} -- surge thrust, N; Y_{prop} -- sway thrust, N; N_{prop} -- heading control moment, $N \bullet m$; $X'_{(\bullet)}$ -- surge non-dimension hydrodynamic coefficient ; $Y'_{(\bullet)}$ -- sway non-dimension hydrodynamic coefficient; $N'_{(\bullet)}$ -- non-dimension hydrodynamic moment coefficient;

IV. COUPLING ANALYSIS AND DECOUPLING CONTROLLER DESIGN

A. Coupling Analysis

Due to the complication and intelligent development of the modern control system, along with the increasing number of variables, the system becomes more difficult to control because of the coupling between variables[6-7]. There are multiple coupling among the recovery motion. It is the main problem that the coupling between the heading angle control and the sway motion control. And it's also the focus of this study. Now through a case to illustrate the coupling between them and analyze the reasons, so as to provide the basis for decoupling controller design.

Case: Without controller, adjusting the AUV heading effects on the sway motion. Through the differential of the left and right main thruster to adjust the heading, that is, equal the thruster thrust and opposite in direction to adjust the heading. Fig.3 shows the effect on sway motion as adjusting heading while the left and right thruster thrust are 100N(the left thruster is positive, the right thruster is negative).

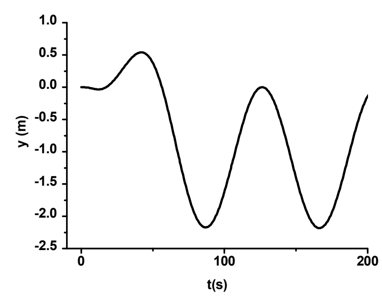

Fig.3 The effect of heading control to sway motion

Beginning analysis from AUV structure and hydrodynamic characteristics. When AUV began to adjust heading, the torque was almost equal size and relatively balanced, so it had a little effect on the surge and sway motion. We can see from Fig.3 that the curve is relatively flat in the beginning 15 seconds. But with the rotation continues, it has a relative motion between AUV bow and stern around the barycenter and the surrounding water. When the speed reaches a certain level, the resistance that rudder suffered significantly increased. However, streamlined bow has a relatively small resistance so that the moment balance is broken. AUV is clockwise (overlooking) when the heading Angle increases, but AUV deviates to the right relative the original center of gravity because of the reaction of the stern strong resistance. With the heading angle increasing, the value of sway motion begins to decrease when it exceeds 90 degrees. So the barycenter presents an elliptical track along with the unceasing changing of the heading angle. The track is shown in Fig.4. It also has effects on surge motion, but it is the main thruster that the surge motion controller has enough power and energy control the effects of this interference. However, the auxiliary thruster exists a problem that insufficient thrust compared to the main thruster. So it is necessary to add decoupling to suppress its effects.

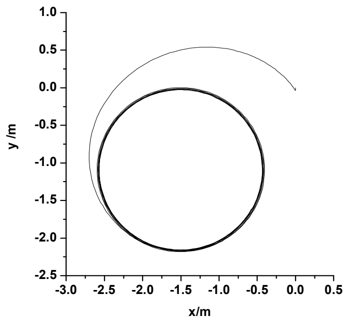

Fig.4 The track of barycenter on the horizontal plane while adjusting heading

B. Decoupling Control System Design

In control theory for multivariable systems, fuzzy decoupling is a kind of theory that combine decoupling theory with fuzzy control theory, which has a low demand to the mathematical model of system. Analysis of the coupling between variables can achieve decoupling control, weaken the influence between each other from a certain extent, coordinate output control quantity of each variable in order to improve the control effect of control system, also have a great significance to solve the problem of multivariable coupling.

In coupling analysis, the simulation results on coupling of sway motion control and heading control in the AUV recovery mission show that when the speed reaches a certain degree and the torque balance is broken, the greater the heading control force, the greater the impact on sway motion. So this paper designed a decoupling compensator and we can see the structure of fuzzy decoupling controller shown in Fig.5. u1 and u2 are output control quantity of the controller, they can be as two inputs of the fuzzy compensator after appropriate adjustment through adjusting parameters k1 and k2. Fuzzy compensator, a two-inputs and one-output fuzzy controller that in common use, compute a output u3 by two inputs that have been adjusted by adjusting parameter, then add u3 that have been adjusted by k3 and k4 to the original output of the controller to constitute control quantity to send to the actuator. Among that, al and a2 can be +1 or -1, which to determine compensation quantity on the variable is positive or negative compensation.

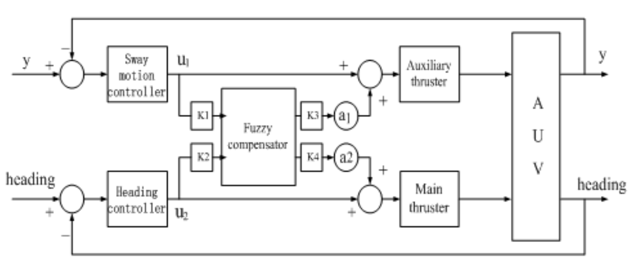

Fig.5 The structure of decoupling controller

The design of fuzzy compensator is critical in decoupling control system design. Firstly, we should fuzz the accurate quantity when we design a fuzzy compensator. The process of fuzz is to map the accurate input to the domain of language value. For two-inputs and one-output fuzzy compensator that more commonly used is concerned, under normal circumstances, the deviation E and the deviation change rate EC of controlled quantity as input language variable and the control quantity to the object as output language variable of fuzzy compensator.

The input and output language variables of fuzzy compensator is represented as a fuzzy subset, X={NB，NM，NS，O，PS，PM，PB}，in this subset, NB，NM，NS，O，PS，PM，PB respectively denote negative big, negative middle, negative small, zero, positive small, positive middle, positive big. The membership function shown in Fig.6, Fig.7 and Fig.8. Fuzzy Compensation rule table shown in table 1, Y_{prop} and N_{prop} are two input language variables, namely sway thrust and transgenic bow thrust moment, U is the output language variable.

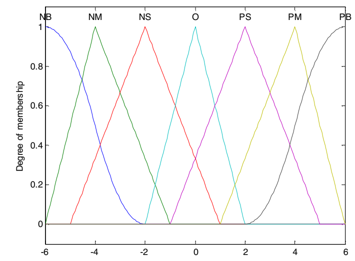

Fig.6 Membership function of deviation

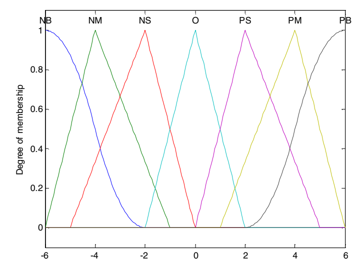

Fig.7 Membership function of deviation change rate

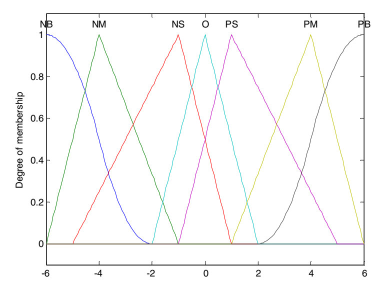

Fig.8 Membership function of the output

Table 1 Compensation rules

U		N_{prop}						
		NB	NM	NS	O	PS	PM	PB
Y_{prop}	NB	NS	NS	NS	O	PS	PS	PS
	NM	NM	NM	NS	O	PS	PM	PM
	NS	NB	NM	NS	O	PS	PM	PB
	O	O	O	O	O	O	O	O
	PS	PB	PM	PS	O	NS	NM	NB
	PM	PM	PM	PS	O	NS	NM	NM
	PB	PS	PS	PS	O	NS	NS	NS

According to the rules of fuzzy compensation, by the input and output membership functions of fuzzy compensator, through compose operation and clear operation of fuzzy reasoning, obtained decoupling compensation quantity and made fuzzy decoupling compensation table, as shown in appendix. In practical engineering, we can get the corresponding compensation value through interpolation to query fuzzy decoupling compensation table after the fuzzification operation of the output of heading controller and sway motion controller. The compensation value multiplied by a certain factor, then add to the output of sway motion and heading controller can form the final control quantity of the actuator.

V. SIMULATION

Simulation Case 1: Two simulations were carried out here to demonstrate the effective of the proposed controller. In the first one, a heading command was issued from 0 degree to 60 degree using the left and right thrusters, where the vehicle was initially static at the surface. In comparison, another simulation was conducted under the same condition using the decoupling compensator.

The hydrodynamic coefficient of model and some adjusting parameters of fuzzy decoupling compensator are setted as follows: k1=3, k2=1, k3=0.15, k4=0.1, a1=1, a2=1; The quantitative factor of sway thrust Y_{prop} and heading control moment N_{prop} are set K_Y=0.02, K_N=0.05, the scale factor K=1. Fig.9 shows the deviation of effects on sway motion before and after decoupling compensation. Two-inputs and one-output of compensator shown in Fig.10 and Fig.11. Fig.12 shows the compensation force that sway motion control obtained while adjusting heading.

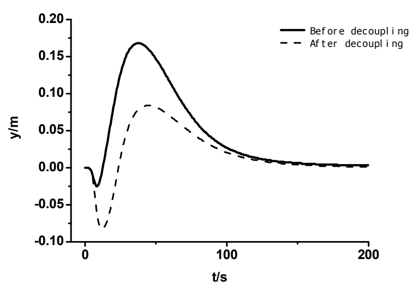

Fig.9 The comparison of transverse movement before and after decoupling compensation

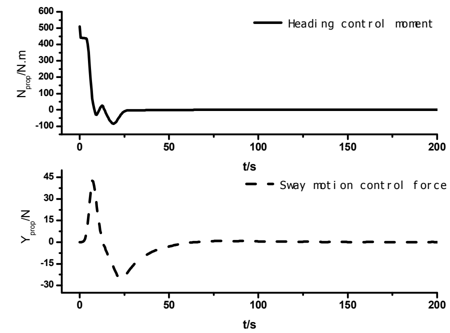

Fig.10 Two-inputs of the compensator

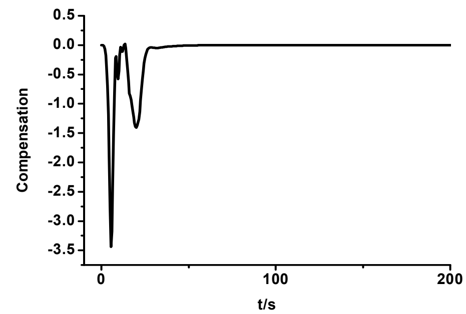

Fig.11 Output of the compensator

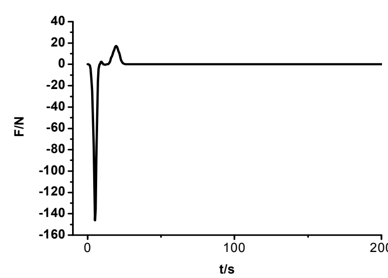

Fig.12 The compensation force of sway control

We can see from the simulation result that heading control has a relatively large effect on sway motion before decoupling. It is dangerous to high-accuracy motion like AUV recovery. After decoupling, although there is a certain deviation on the opposite direction, the overshoot is reduced half in a whole.

VI. CONCLUSION

In this paper the coupling relationship between sway movement and heading control in AUV recovery process was studied. Based on BSA - AUV platform, this paper proposed a underwater recovery strategy and analyzed the coupling variable and coupling reason in recovery motion control through simulation. It has a high demand to sway and surge motion control in AUV recovery process. But the actuator(auxiliary thruster) of sway motion controller has a problem that insufficient thrust compared with the actuator(main thruster) of surge motion controller. Therefore, this paper mainly focus on the influence that the heading control act on sway motion. And according to the coupling mechanism formulate fuzzy decoupling rules and design fuzzy decoupling compensator. Simulation results have shown that the sway movement was eliminated to a permitted range with the help of a fuzzy decoupling controller, which was considered to be very effective in the AUV recovery motion control.

Acknowledge

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APPENDIX

Table 1 The non-dimensional hydrodynamic coefficients of the AUV

U		N_{prop}												
		-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6
	-6	-2.13	-2.20	-2.13	-2.25	-2.13	-1.09	0.00	1.09	2.13	2.25	2.13	2.20	2.13
	-5	-2.79	-2.79	-2.79	-2.85	-2.20	-1.09	0.00	1.09	2.20	2.85	2.79	2.79	2.79
	-4	-3.16	-3.11	-3.16	-3.00	-2.13	-1.09	0.00	1.09	2.13	3.00	3.16	3.11	3.16
	-3	-3.97	-3.97	-3.90	-3.00	-2.25	-1.07	0.00	1.07	2.25	3.00	3.90	3.97	3.97
	-2	-4.85	-4.41	-3.91	-3.00	-2.13	-1.09	0.00	1.09	2.13	3.00	3.91	4.41	4.85
	-1	-2.85	-2.94	-2.64	-2.41	-1.65	-1.09	0.00	1.09	1.65	2.41	2.64	2.94	2.85
Y_{prop}	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	1	2.85	2.94	2.64	2.41	1.65	1.09	0.00	-1.09	-1.65	-2.41	-2.64	-2.94	-2.85
	2	4.85	4.41	3.91	3.00	2.13	1.09	0.00	-1.09	-2.13	-3.00	-3.91	-4.41	-4.85
	3	3.97	3.97	3.90	3.00	2.25	1.07	0.00	-1.07	-2.25	-3.00	-3.90	-3.97	-3.97
	4	3.16	3.11	3.16	3.00	2.13	1.09	0.00	-1.09	-2.13	-3.00	-3.16	-3.11	-3.16
	5	2.79	2.79	2.79	2.85	2.20	1.09	0.00	-1.09	-2.20	-2.85	-2.79	-2.79	-2.79
	6	2.13	2.20	2.13	2.25	2.13	1.09	0.00	-1.09	-2.13	-2.25	-2.13	-2.20	-2.13