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Research Article

Research on Coordinated Robotic Motion Control Based on Fuzzy Decoupling Method in Fluidic Environments

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The underwater recovery of autonomous underwater vehicles (AUV) is a process of 6-DOF motion control, which is related to characteristics with strong nonlinearity and coupling. In the recovery mission, the vehicle requires high level control accuracy. Considering an AUV called BSAV, this paper established a kinetic model to describe the motion of AUV in the horizontal plane, which consisted of nonlinear equations. On the basis of this model, the main coupling variables were analyzed during recovery. Aiming at the strong coupling problem between the heading control and sway motion, we designed a decoupling compensator based on the fuzzy theory and the decoupling theory. We analyzed to the rules of fuzzy compensation, the input and output membership functions of fuzzy compensator, through compose operation and clear operation of fuzzy reasoning, and obtained decoupling compensation quantity. Simulation results show that the fuzzy decoupling controller effectively reduces the overshoot of the system, and improves the control precision. Through the water tank experiments and analysis of experimental data, the effectiveness and feasibility of AUV recovery movement coordinated control based on fuzzy decoupling method are validated successful, and show that the fuzzy decoupling control method has a high practical value in the recovery mission.

1. Introduction

Autonomous underwater vehicles (AUV) 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 AUV recovery area, which could be basically classified into 2 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 2nd type is AUV clients' favour for its convenience in recovery operation, where the simulation results and pool experiments have demonstrated the feasibility of this type.

Currently, there are some approaches for the AUV underwater recovery as follows.

(1) Pole docking: this recovery method needs to equip the recovery mechanism which can capture the rope or the pole target. Typical representative is Odyssey IIB which was developed by Woods Hole Marine research institute and the MIT and Starbug MKIII AUV which was developed by Queensland University of Technology [1].

(2) Funnel Docking Station: typical representatives have the FDS Funnel Docking Station which was developed by Eurodocker for REMUS [2] and a Funnel Docking Station that was developed by The Monterey Bay Aquarium Research Institute for the 54 cm diameter (21-in) AUV [3].

(3) The torpedo tube recovery mode: the recovery method is mainly used in the military field, belonging to a kind of independent recovery mode. The first successful case of the torpedo tube recovery mode,

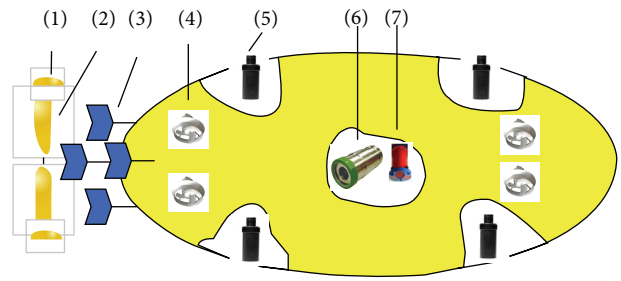
which was a LMRS [4] type AUV, about 5.88 m long, 51 cm diameter, was completed on "Hart Mesa" nuclear submarine in 2007.

(4) The embedded equipped recovery mode: the mode is a deep water recovery technology as follows: build deep space station as a platform, build a boat of AUV, sail the boat back to the nonpressure hull of mother ship, or build a boat in the side of mother ship. Typical representative is the ALVIN [4], developed by the United States, which returns to a huge dry shelter cabin, such as DDS, on the back of the mother ship, during recovery. Another one is DSRV; it adopts the docking during recovery, which also belongs to such a mode of recovery.

(5) The platform recovery mode: the recovery method uses underwater platform to achieve the task of the recovery of AUV. Typical representatives are the Marine-Bird [5], developed by Kawasaki Heavy Industries of Japan and FAU AUV [4] and developed by USA, which adopt Cable Latch Docking, both belonging to this recovery method.

The AUV control of recovery mission is working with each linked coordinate; it will decrease the regulating quality of the control system if the objects have coupling. The system even cannot operate 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 [3]. In spite of the theoretical research which has gained substantial achievements, it is not satisfactory when we compare the decoupling theory in engineering application with other branches such as the optimal control and the adaptive control in engineering application [6, 7].

Many scholars have researched fuzzy control with strong robustness a lot and used it in decoupling systems. From the perspective of reducing the inputs dimension of the decoupling controller, we distinguish in real-time the coupling relationship of the asymmetrical gas collector pressure by using dynamic coupling analysis method, and then fuzzy decoupling controller is employed to decouple and control the gas pressure of collector. Paper [8] outlined the Zadeh-MacFarlane-Jamshidi trio in their pursuit concerning the theory and application of fuzzy logic. These developments built a theoretical basis to apply single-context decision which makes a problem governed by the knowledge based on coupled fuzzy rules. The developed theorems establish an analytical equivalence to analyze the relationship between the decisions made from a coupled set of fuzzy rules and an uncoupled set of fuzzy rules concerning the same problem domain. These developments have been widely adopted in the field of supervisory control of an industrial fish cutting machine. Paper [9] designed a unique fuzzy self-tuning disturbance decoupling controller for a serial-parallel hybrid humanoid arm to complete the throwing trajectory-tracking mission. Paper [10] proposed a self-learning fuzzy decoupling controller. This method can online generate and modify the fuzzy rules through the method of self-learning. And this kind of controller was applied to the control of aircraft engine.



(1) Rudder
(2) Elevator
(3) Main thrusters
(4) Auxiliary thrusters
(5) SBL
(6) Underwater camera
(7) DVL

Figure 1: AUV structure layout.

The simulation results showed that the control effect was ideal.

2. AUV Recovery System

The overall layout of the BSAV AUV is shown in Figure 1. It is mainly composed of 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 to 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 with guiding lights 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. The main problem is the coupling between the heading angle control and the sway motion control. And it is 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.

3. The Coordination Control Strategy in AUV Recovery

The AUV recovery control system is designed by the hierarchical structure of discrete event perception; it consists of three top-down layers, including layer for mission planning (mission layer), task transfer (task layer), and behavior realization (behavior layer). The mission layer is mainly responsible for the planning of movement coordination control strategy during the whole AUV recovery process, the state, and planning the next state. The task layer is mainly responsible for transferring the planning information

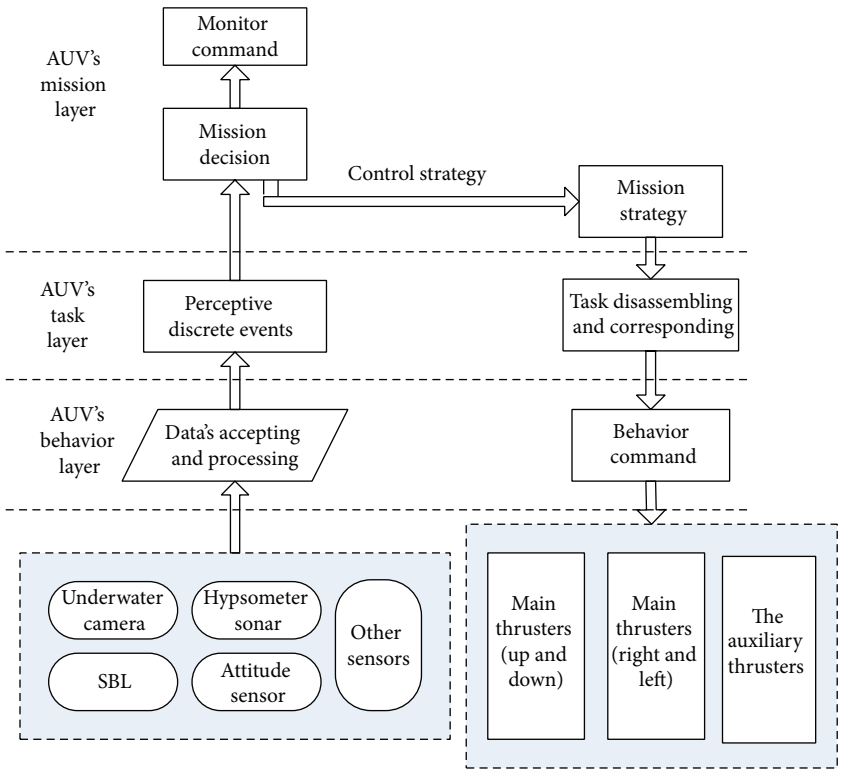


Figure 2: The AUV recovery control system.

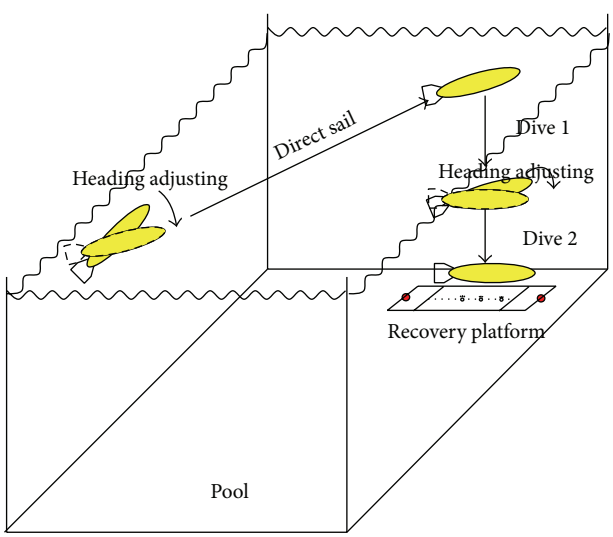


Figure 3: A diagram of AUV's recovery process.

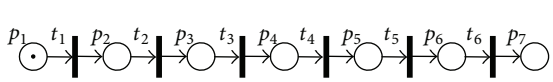


Figure 4: The Petri network structure of mission layer.

in various stages of recovery of AUV to the specific controller implementation. The behavior layer is the lowest layer system structure; it is mainly responsible for that data acquisition, fusion, and controller action execution, as shown in Figure 2.

During the AUV recovery of the whole process, after starting recovery command, AUV in unmanned condition approached the recovery platform, finally seated to the recovery platform, and completed the underwater recovery mission. We can see that in Figure 3. For such a complex process control containing a lot of conflict and concurrent events, it is wise to introduce Petri net theory into the design of the mission layer and task layer of the control system.

Firstly, we design the mission layer. The entire recovery process of AUV consists of heading adjusting, then direct sailing, dive, heading adjusting, dive, and several discrete events. The transition between the various discrete events is continuous and dynamic. The Petri network structure is shown in Figure 4. Then Table 1 shows the transition meanings of the Petri net structure library of mission layer, in which we have the following:

region A: the horizontal circle is at the top of coordinate origin, and the circle's radius is 0.5 m;

region B: the horizontal circle is above the platform 3 m and the circle's radius is 0.1 m;

region C: the region is above the platform 3 m (Z = 2 m in depth).

The task layer of AUV control system is a transition layer between the mission layer and the behavior layer. It includes the processing of data information and the coordinating of control strategy.

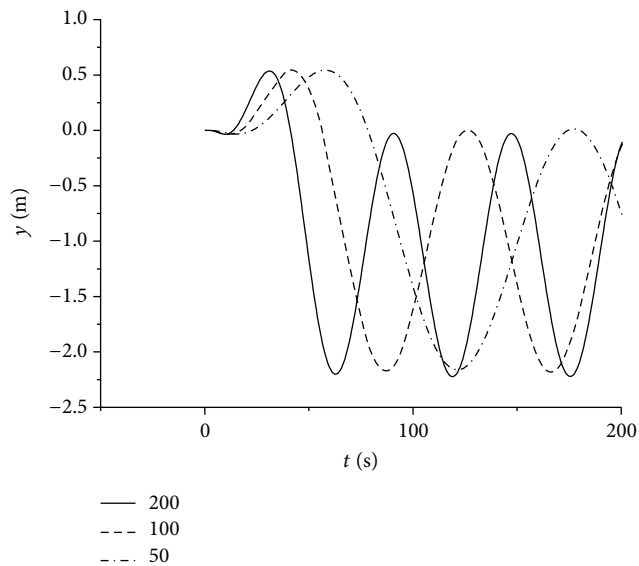


Figure 5: The effect of heading control to sway motion.

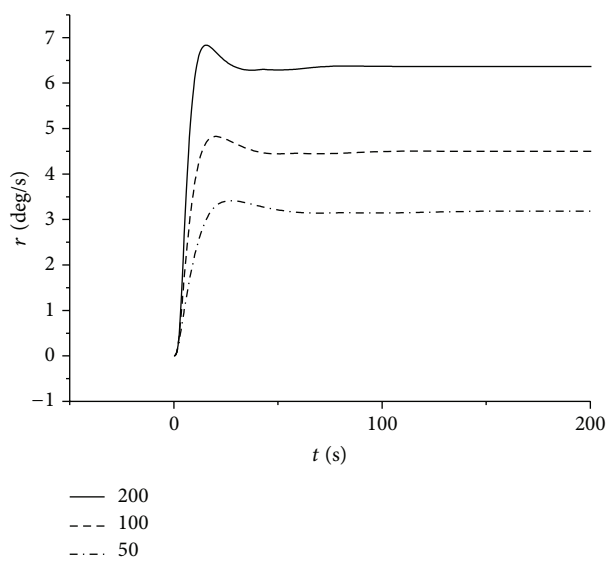


Figure 6: The change of heading angle velocity.

Coupling variables of the control of recovery of AUV mainly exist in the horizontal movement, and the movement, horizontal motion control is the key point of this research. Starting from the design of single degree of freedom controller, and the decoupling control of coupling variables, we can design the horizontal motion coordination controller, and finally we can get the recovery control system of AUV.

4. Coupling Analysis and Decoupling Controller Design

4.1. 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 [11, 12]. There are multiple couplings among the recovery motion. The main problem is the coupling between the heading angle control and the sway motion control. And it is also the focus of this study. Now through a case to illustrate the coupling between them and the reasons, then provide the basics for decoupling controller design.

Table 1: The transition meanings of the Petri net structure library of mission layer.

The meaning of Library	The meaning of transition
P_1 standby state	t_1 starting system
P_2 the ready for heading adjusting	t_2 heading adjusting to the target value
P_3 the ready for direct sailing	t_3 sailing to A region
P_4 sailing at A region and ready for dive	t_4 dive to B region
P_5 sailing at C region with position deviations	t_5 heading adjusting
P_6 sailing at C region and ready for docking	t_6 seated to the recovery platform
P_7 the success of recovery of AUV	

Without the controller, adjusting the AUV heading can affect 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. Figures 5 and 6 show the effect on sway motion and longitudinal motion as adjusting heading while the left and right thruster thrust are 200 N, 100 N, and 50 N (the left thruster is positive and the right thruster is negative).

First, we can analyze AUV structure and hydrodynamic characteristics. When AUV began to adjust heading, the torque was almost equal in size and relatively balanced, so it had little effect from the surge and sway motion. We can see from Figure 5 that the curve is relatively flat in the first 15 seconds. But as 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 of the original barycenter 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 Figures 7, 8, and 9. It also has effects from surge motion, but it is the main thruster that the surge motion controller has enough power and energy to control the effects of this interference. However, the auxiliary thruster has a problem that the thrust is insufficient compared to the main thruster. So it is necessary to add decoupling to suppress its effects.

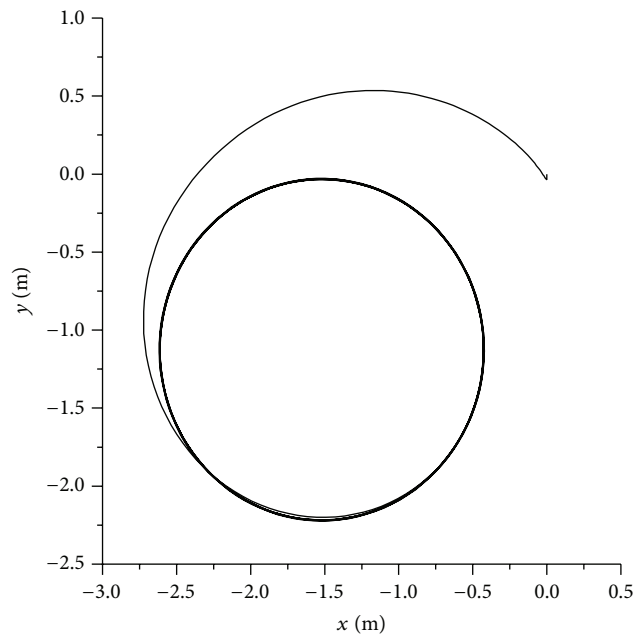


Figure 7: The track of the horizontal plane while adjusting heading with 200 N.

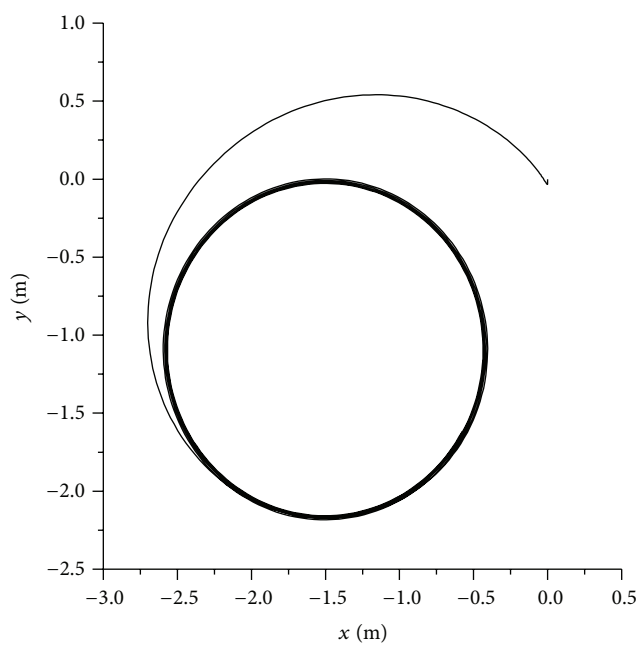


Figure 8: The track of the horizontal plane while adjusting heading with 100 N.

4.2. Design of Decoupling Control System. In control theory for multivariable systems, fuzzy decoupling is a kind of theory that combines 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

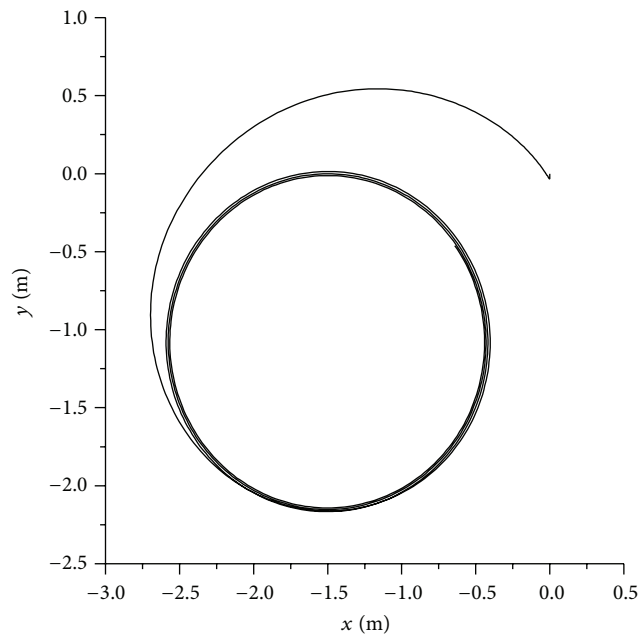


Figure 9: The track of the horizontal plane while adjusting heading with 50 N.

efficiency of control system, and also have a great significance to solve the problem of multivariable coupling.

In coupling analysis, the simulation results in coupling of sway motion control and heading control in the AUV recovery mission which shows that when the speed reaches a certain degree and the torque balance is broken, the greater the heading control force, the greater the impact from motion. So this paper designed a decoupling compensator and we can see the structure of fuzzy decoupling controller shown in Figure 10. The u_1 and u_2 are output control quantity of the controller, and they can be as two inputs of the fuzzy compensator after appropriate adjustment through adjusting parameters k_1 and k_2. For fuzzy compensator, a two-input and one-output fuzzy controller that is in common use, compute an output u_3 by two inputs that have been adjusted by adjusting parameter, and then add u_3 that have been adjusted by k_3 and k_4 to the original output of the controller to constitute control quantity to send to the actuator. Among that, al and a_2 can be +1 or −1, which is to determine whether compensation quantity on the variable is positive or negative compensation.

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-input and one-output fuzzy compensator which is more commonly used, we concern, 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 membership function is shown in Figures 11, 12, and 13. In fuzzy compensation rule table shown in Table 2, Y_{prop}

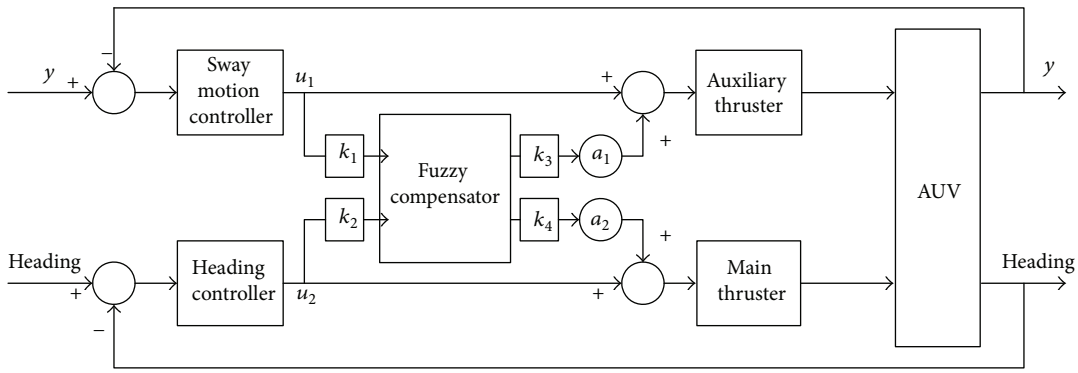


Figure 10: The structure of decoupling controller.

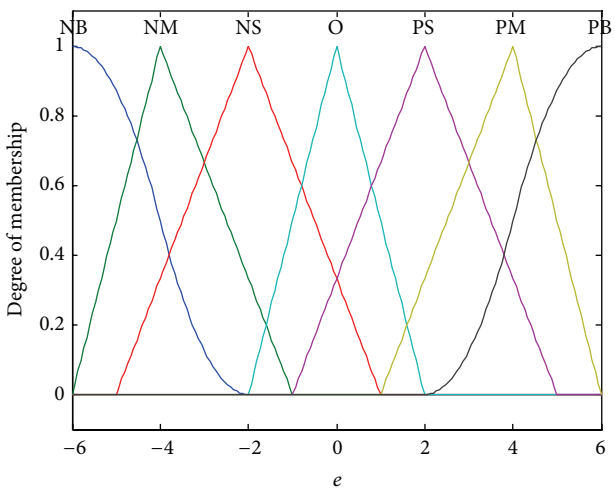


Figure 11: Membership function of deviation.

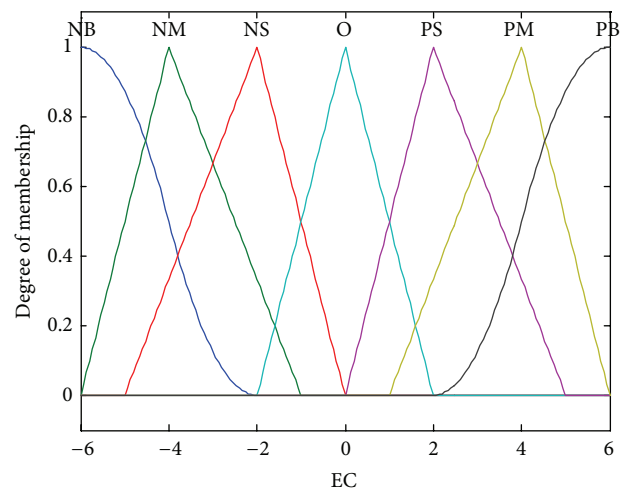


Figure 12: Membership function of deviation change rate.

Table 2: Compensation rules.

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

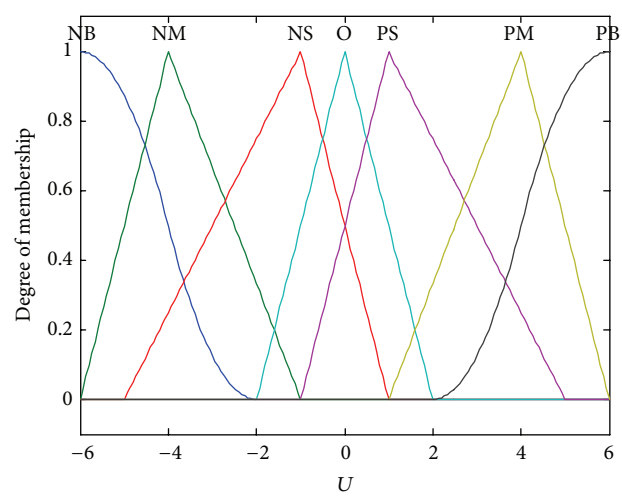


Figure 13: Membership function of the output.

and N_{prop} are two input language variables, namely, sway thrust and transgenic bow thrust moment and U is the output language variable.

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 Table 3. 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

Table 3: The nondimensional hydrodynamic coefficients of the AUV.

U	N_{prop}												
	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
Y_{prop}													
−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
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

certain factor, and then adds to the output of sway motion and heading controller, so can form the final control quantity of the actuator.

5. Simulation

Simulation Case 1. Two simulations were carried out here to demonstrate the effect of the proposed controller. In the first one, a heading command was issued from 0 degrees to 60 degrees using the left and right thrusters, where the vehicle was initially static at the surface. For 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 set as follows: $k_1 = 3$, $k_2 = 1$, $k_3 = 0.15$, $k_4 = 0.1$, $a_1 = 1$, and $a_2 = 1$. The quantitative factor of sway thrust Y_{prop} and heading control moment N_{prop} is set as follows: $K_Y = 0.02$, $K_N = 0.05$, and the scale factor $K = 1$. Figure 14 shows the deviation of effects on sway motion before and after decoupling compensation. Two inputs and one output of compensator were shown in Figures 15 and 16. Figure 17 shows the compensation force that sways motion control obtained while adjusting heading.

From the simulation result, we can see 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 by half overall.

6. Water Tank Experiment

The preliminary verification of AUV recovery experiment based on the coordinated control strategy and fuzzy decoupling compensator design was carried out. The details are as follows.

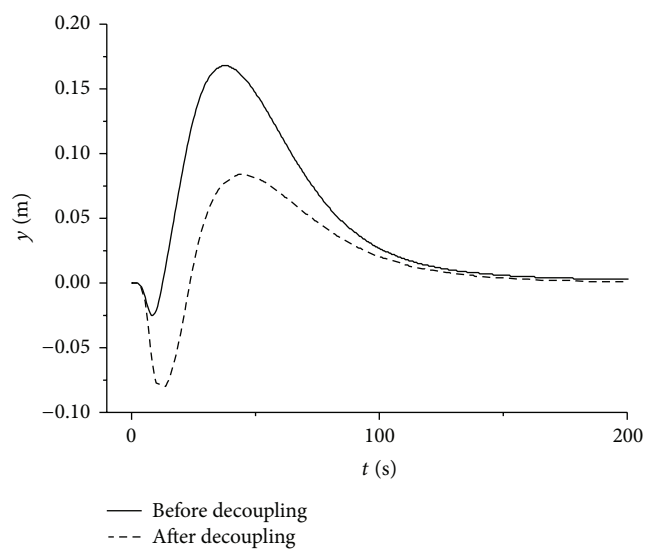


Figure 14: The comparison of transverse movement before and after decoupling compensation.

6.1. Introduction of Water Tank Experiment's Guiding Device. Guiding device for the water tank experiment is mainly composed of monocular imaging system, linear light source array, and underwater recovery guide positioning system of AUV, which is based on the short baseline.

6.1.1. Monocular Imaging System. Monocular imaging system is composed of cameras, capture cards, and processing host. The underwater experiment employs black and white camera Tornado with low illumination. Image acquisition card uses the DaHeng DH-CG320 image capture card that supports PC104-Plus bus mode, and the card can be used to collect high-quality colour/black and white video signal in real time and transfer it to the memory for real-time storage via PC104-Plus bus. Visual processing host is AUV visual

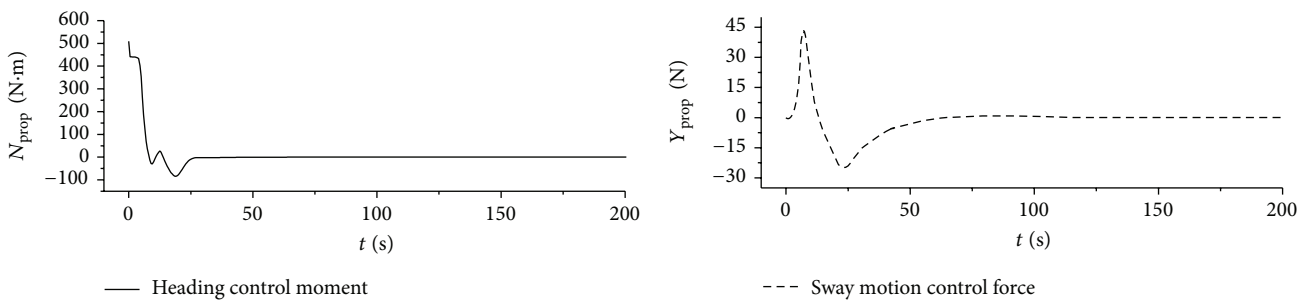


Figure 15: Two inputs of the compensator.

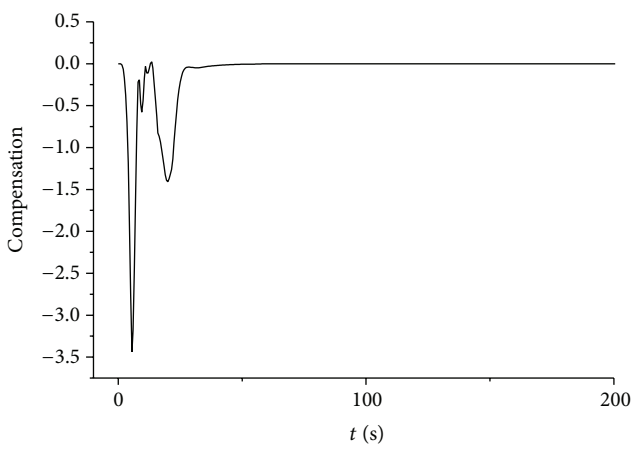


Figure 16: Output of the compensator.

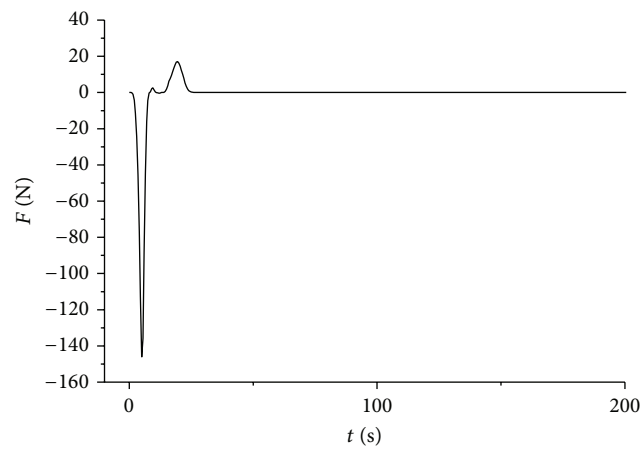


Figure 17: The compensation force of sway control.

brain responsible for image acquisition, image processing, positioning solver, and so forth, adopting PC104 + bus based on embedded systems.

6.1.2. Linear Light Source Array. A linear light source array for monocular vision on the wire position is designed in this underwater experiment. Where the reference light source is a heart-shaped light source that is made by transforming a rectangular surface light source, which uses the U.S. AI company's SL6404 (Figure 18). Other eight light sources all use blue astigmatism LED point light source assembled add waterproof cover. All light sources are arranged on the longitudinal center line at the bottom of the recovery dock tank. Heart-shaped vertex points to the heading of the dock tank, the distance between the adjacent sources is 350 mm, and the entire lighting system is 2800 mm long.

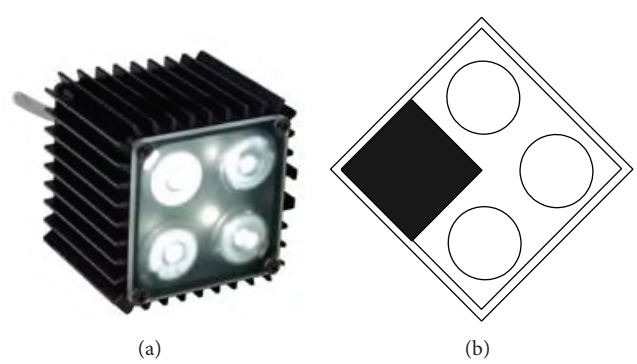
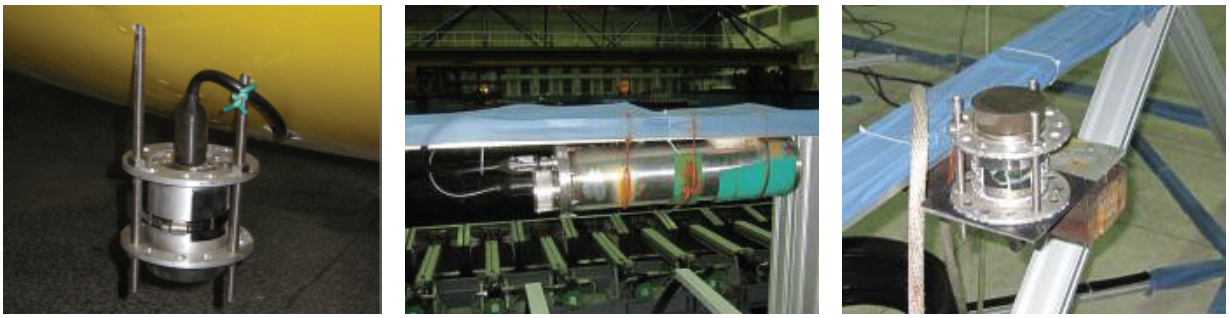


Figure 18: The reference light SL6404.

6.2. The Composition and Installation of the AUV Underwater Recovery Guide Positioning System Based on the Short Baseline. The short baseline positioning sonar system adopted by the system basically has the following several parts: short baseline sonar array (four transducers, Figure 19(a)), a beacon host, and two beacons (transducers F1, F2).

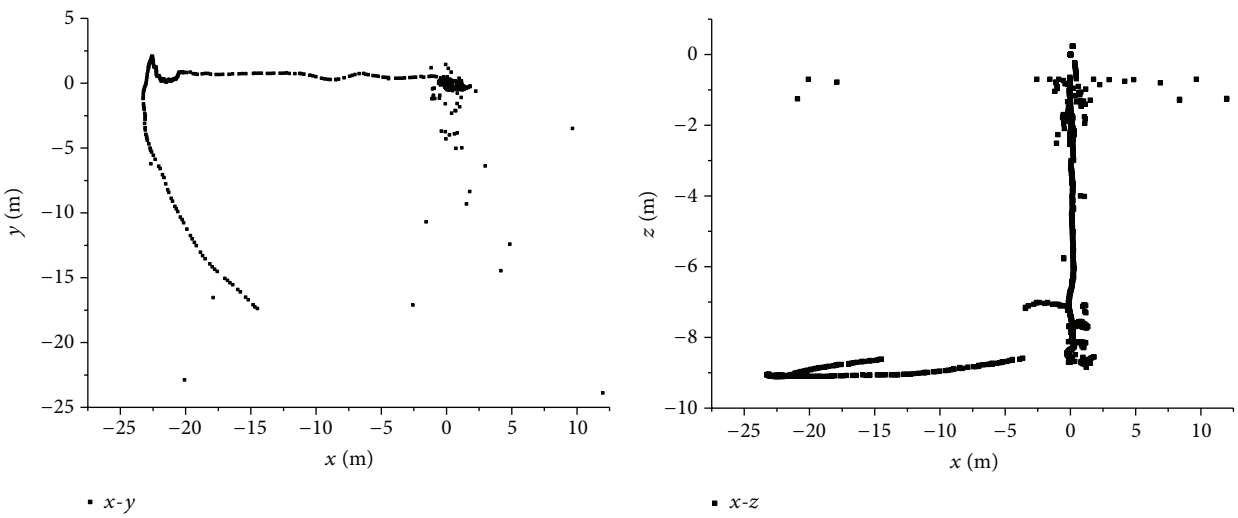
Transponder beacon consists of beacon host and F1, F2. F1 is hairstyle and F2 is emission type, radiating device faces to the surface of the water when used. The beacon host is installed as shown in Figure 19(b), and transducers F1 are instillated as shown in Figure 19(c).

6.3. The Analysis of Water Tank Experimental Data. The trajectory of the recovery process AUV obtained from each projection plane, such as the x-y, x-z, and three-dimensional trajectories, is shown as follows in Figure 20.

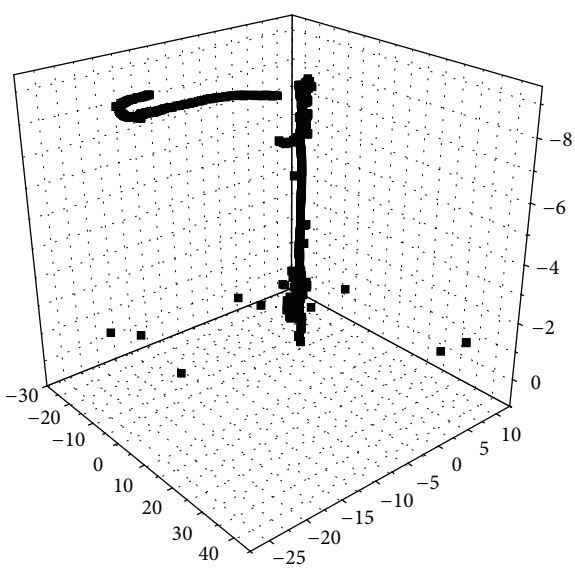


(a) (b) (c)

Figure 19: Short baseline physical installation diagram.



(a) (b)



(c)

Figure 20: The track graph of water tank experiment.

As to the analysis of experimental data obtained by water tank, since this type of AUV has better suppression and self-recovery performance to roll, shielding the x-axis torque output of the controller did not take the initiative to suppress the roll. Since the data is based on body-fixed frame, the starting point of y is small only means that heading direction is almost aligned with the recovery platform at this moment. Also in the height of the curve, jump section shows that depth sonar's surveying sound waves hit the recovery platform frame.

Since the data is based on body-fixed frame, this is rather distinct with the actual trajectory in the water tank, which only is used to verify the effectiveness of the controller here. In addition, according to the entire recovery process which is divided into several stages, it needs to analyze actions according to the characteristics of the various stages. In the vertical plane, although the height value of space has more jump error, due to the fact that the speed is faster, there are only a few points that have the jump error and do not use the height value in the process. Until the coordinate stabilizes, it has no jump error during the whole process. Therefore, it did not affect the control process.

Through the water tank experiments and analysis of experimental data, the effectiveness and feasibility of AUV recovery movement coordinated control based on fuzzy decoupling method are validated successfully. However, further trials need to be carried out in order to achieve the parameter optimization.

7. Conclusion

In this paper the coupling relationship between sway movement and heading control in AUV recovery process was studied. Based on BSAV- AUV platform, this paper proposed an 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 which is insufficient thrust compared with the actuator (main thruster) of surge motion controller. Therefore, this paper mainly focuses on the influence that the heading control acts on sway motion. And according to the coupling mechanism formulate fuzzy decoupling rules and design fuzzy decoupling compensator. The results of simulation and water tank experiments 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 effective in the AUV recovery motion control. However, other aspects of tuning parameters need to be further improved and optimized and still need further experimental verification.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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