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A Novel System for Underwater Docking in Difficult Situations

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Abstract

In order to carry out tasks such as the rescue of disabled submarine when the state of the sea is unfavorable and the direct docking is impossible, a novel automatic underwater docking system has been developed in laboratory fo r experiment and further research. The system has four manipulators, each is controlled by a single chip microcomputer in order to realize some low level local intelligence. These four single chip microcomputers operate in coordination under the supervision of another single chip microcomputer which also serves for the communication with the computer of the Integrated Control And Display system(ICAD). The overall description, docking strategy, fuzzy method which was applied in docking procedure and made the cheap electromagnet valve controlled manipulators suitable for application, some features in program design for realizing system function, and some preliminary experiments are presented in this paper.

1. Introduction

Underwater docking is the technology used to connect two chambers in underwater environment, the task includes the mechanical connection and sealing. This technology originated from and mainly used in the rescue of submarines in the past and recent years, and will find more and more application potentials in the near future in supporting underwater activities of human being, such as personnel transfer and materials transportation between the underwater living chambers or from the outside above the water.

The Sealing in underwater docking depends on the design of the two parts to be docked, and there is technology ready to be used. The problem which remains unsolved is to realize mechanical connection under very difficult situations, such as in the state of the sea with strong current and very poor visibility. In the 70s and 80s last century, many countries developed DSRV(Deep Submergence Rescue Vehicle)"[21] which depended upon manoeuver-ability to undertake the docking task, and naturally the demand of a better state of the sea needed to be satisfied for the rescue task. The state of the art technology is not yet enough for emergent work.

In order to obtain the technology and finally to develop an equipment which can fulfill underwater docking tasks under bad conditions, with different design concept, a novel automatic docking system with manipulators was put forward, see Fig. 1. The docking procedure constitutes the following steps: searching for the assistant ring by the manipulators; guided centering after the preliminary connection by the manipulators grasping the assistant ring; and pulling the system down to finish connecting the two parts mechanically.

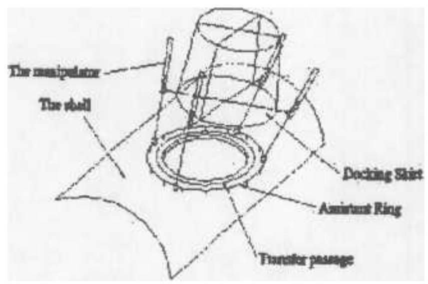

Fig.1 The **design concept of the automatic underwater docking system**

The manipulators are each assigned a single chip microcomputer to control their movement. The automatic search for the assistant ring by these manipulators is quite important for docking. The manipulators strentch out and are ideal to be kept contact with the shell while moving inwards to the ring. A fizzy method has been adopted in the control algorithm, which makes the low cost system functioning well.

The development of the system was finished last year, and in water pool inside laboratory some preliminary experiments have been carried out by mounting the equipment under a underwater robot.

2. System Overall Description and Docking Strategy

2.1 The Underwater Docking System

As shown in Fig.2, the underwater docking system was mounted under an underwater robot before experiments, with four manipulators equationally around the skirt of the docking system, two in one side can be seen in the photograph, the other two are in the other side. Each of the manipulators has two degrees of freedom and one grasping function, one freedom is the rotation around horizontal axis

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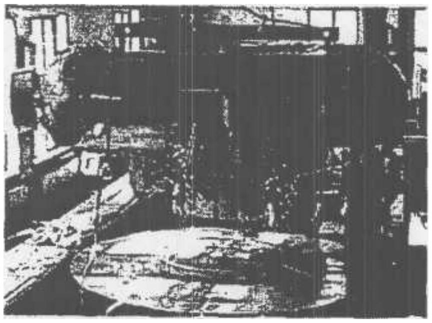


Fig.2 The underwater docking system mounted under underwater robot
One ᴜnderwater **robot; (gl** he underwater docking **system; (MI7te manipulator, Qfhe shell of the part to be docked; @f**he assistant ring

inside vertical plane and the other one is the line movement of the cylinder. Meanwhile there are compliant functions along the axis of the piston rod of the cylinder and around the same axis. The manipulators are actuated by hydraulic power and the movements are controlled by eletromagnet valves. The joints' position are measured by potentiometer. There are also three on-off signals which can provide information of the contact of the endeffector of the manipulator with the shell, the overload of the contacting force, and the rod of assistant ring is grasped by the gripper.

There is another characteristics of the manipulators which is important for docking operation. When the joints of the manipulator stop to be active actuated, they can be switched between two states: the locking state and the floating state, they are determined by the special design of the hydraulic system. The floating state means that in this state the joint can be moved by extern force, because the cavities of the cylinder have been connected together with the oil tank.

The system configuration diagram is shown in Fig.3. There is only a pair of RS485 signal wires from the main single chip microcomputer of the underwater docking system connected with the ICAD computer. The main single chip microcomputer is through dual-port RAMs connected with the four low level single chip microcomputers, each of which directly control a manipulator to realize some local intelligence, such as automatic searching of the assistant ring. The hydraulic power is directly controlled by the main single chip microcomputer. Commands come from the ICAD through main single chip microcomputer down to the four low level ones, and the information comes back in the opposite direction up to the ICAD computer.

2.2 the Docking Strategyhl

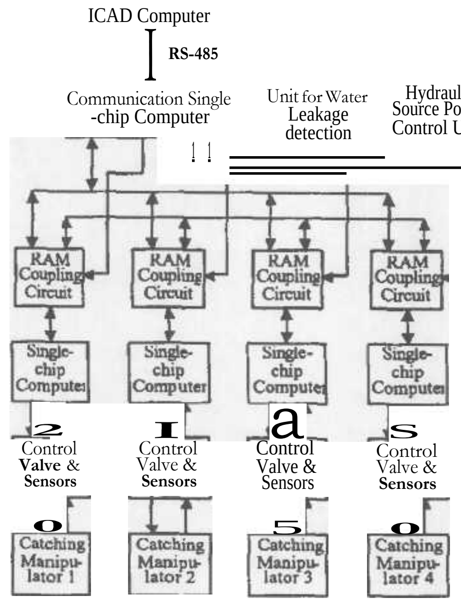


Fig.3 **The system configuration diagram**

When the underwater robot is rovering within a certain range above the docking target, then begin the docking procedure which can be divided into the following steps:

(I)Automatic searching: The manipulators automatically search for the assistant ring to fulfill preliminary connection. This is the most important step in the docking operation. Receiving commands from the main single chip microcomputer, the low level computers control the correspondent manipulators to begin the searching tasks. First the manipulator rotates out to the maximum angle and then stretched out until it touches the shell or reaches its maximum position, second the manipulator rotate towards inside to the minimal angle position, while try to keep the end effector contact with the shell, which will be discussed in more detail in 3.1. If the assistant ring is in the searching range of the manipulator, the gripper of the manipulator will touch the rod of the ring, one of the three on-off switches will give the signal which tells the control system that the rod is inside the gripper, and the gripper will be controlled to close to finish the automatic search. The two joints will be switched to floating state after the automatic search has been fulfilled.

(2)Gu ided Centering: This step is supervised by the main single chip microcomputer. The manipulators are controlled to move in coordination. When two opposite manipulators have grasping the assistant ring, begin the centering procedure, refer to Fig.4(b), the end points of the manipulators are noted as A and A' . The two opoosite manipulators take the other two manipulators(their end points are B and B') into the centering position and then switch into locking state, Fig.4(c). The other two then search and grasp the assistant ring, Fig.4(d). The first two open their grippers, Fig.4(e), and the second two will be controlled to position the first two into centering position, and then the first two grasp the rod of the ring, Fig.4(f). By the end of the centering step all of the joints of the manipulator will be in locking state.

(3)Pulling Down: In this step, the rotation joints of the four manipulators are in lock state. By making use of the information from the linear potentiometers, the docking system together with the underwater robot is controlled to slowly move down towards the docking position.

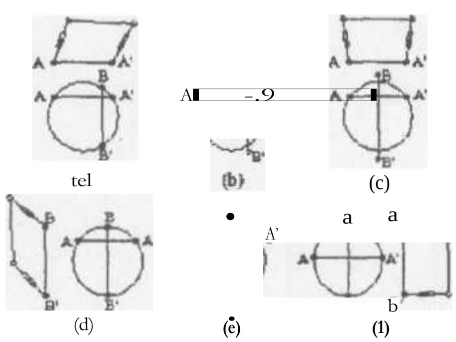


Fig.4 The centering step
• -The gripper is closed; o -The gripper is open

3. Realization of Automatic Searching

3.1 **The Driving Mechanism** of the **Manipulators**

As mentioned above, the manipulators are actuated by hydraulic cylinders which are controlled by electromagnet valves. The moving speed of this kind of driving mechanism can not be controlled, it will change when the load has been changed. The relationship of the speed and the load is easily to be described by fuzzy terms.

The cylinder which actuates the rotating joint is arranged quite near the rotation center, so the amt of force is very short. The force imposed on the end-effector has the overwhelming influence on the rotation speed when compared to the pressure flunctuation and other factors.

As to the cylinder for actuating the linear movement, the speed will not change too much when it contacts the shell, it will continue to push the unterwater robot up. But when it is in floating state, the moving speed will also reflect the force along its axis. As there are the contact and overload switch signals, this characteristic is not so important in our system.

The driving mechanism does not have good performance as it is controlled by eletromagnet valves, but the system is very easy to maintain and very cheap, for the price of a electromagnet valve is less than 1% of that of hydraulic servo valve. It is desireful to use this low price simple element to realize our purpose, so in the first prototype system, electromagnet valves are applied.

3.2 General Idea for Applying Fuzzy Method

As to the control to realize the goal of automatic searching, traditional control technique does not function, for it is difficult to express the goal in mathematics, and there are two main factors which hinder us to get the model for control, the first is that the underwater robot covering about in water, it is moving all the time, the moving range and the cycle are all changing; the second is that the contact force of the end-effector with the shell will disturb the underwater robot, and this disturbance will influence other manipulators. We do not know when and how these disturbance or uncertainties happens.

It is naturally to remind of fuzzy control, which by trying to integrate some human sense into the controller may be a way leading to solution. In automatic searching, our goal is to control the end-effector of the manipulator contact the shell while moving towards the assistant ring. The following two general fuzzy rules are applied:

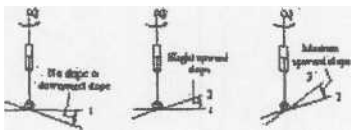
(1)When the end ofmaniputor contacts the shell and then it loses contact, it should stop rotate inside, and should wait a period of time to let the underwater robot rover back, stretch out f it has not reach its maximum length. To do this the manipulator can avoid missing the assistant ring by moving over it;

(2)While the end of the manipulator contacts the shell, according to the fuzzy input of the change of the speed of the rotation cylinder, the cylinder for linear movement stretch back and forth a correspondent distance within certain rotating angle of the rotation cylinder.

3.3 Fuzzy Method for Dealing with the **Contact of the Endeffector and Shell in Automatic Searching**

In automatic searching, the end-effector needs to be controlled in contact with the shell. The force generated by the contact of the manipulators and the shell disturb the robot by pushing it away from its formerly position. A fuzzy method was adopted to alleviate the disturbance in order to realize our control goal.

As it is not possible to obtain the contact force information directly, the speed of rotation has been considered in order to have some knowledge about the contact force. The contact force will cause the load to change, and the contact force also change according to the relative position between the manipulator and the shell in the automatic searching step, as shown in Fig.S. When the rotation speed change significantly, the end-effector should better move back a small distance while the rotation joint rotates. The control value of the linear cylinder in automatic searching is summarized in Table.l. The speed of rotation is calculated with the angle values at certain time interval. One point should be metioned that membership functions are not used for extropolation for saving computing time and the subprogram may be interrupt before it finishes.



W tb) (at

Fig. 5 The fuzzy method for the determination of the shell **slope**

Table I The control of the line movement cylinder

Overload signal	Contact signal	compared with on load	co 0 of the linear movement cylinder
	0		
0	on		n eating state
off	on	>S,% bit c62%	I a rotating a , draw back Ah
off	on	>62% but <6%	r e rotating a , draw back Ah
off	on	>4%	i e rotating a , draw back Ab
on	on		21002MM

4. Some Considerations and Features in Design of the Single Chip Micro Computer Program

The following are some considerations in the design of the programs in the single chip microcomputers, and by the realization of these considerations the system has the desired functions.

(1)The ICAD computer sends commands through RS485 to the main single chip microcomputer, and the later answers at once by sending information about the state of the docking system. If the single chip microcomputer receives incorrect data by sum check, it sends back information to notice the 1CAD computer that the command has not been carried out.

(2)The computers inside the docking system use interrupt mode to receive commands, so the commands can be dealt with at once.

(3)From the ICAD computer, operator can switch the docking system between automatic mode and manual mode. The manual mode means that the operator can control every joints of the manipulators by klick the buttons on the screen, and this is useful for test and in some cases in real operation.

(4)The main single chip microcomputer send warning to the ICAD when unusual situations happen, such as water leakage, and over time error, that means it has not received commands for too long time, the interval between two commands from ICAD computer will not be longer than a time limit

(S)The ICAD computer can modify some of the programs in the single chip microcomputers trough RS485 lines. This function is really good for test, it makes it possible that the docking system and the underwater robot need not to be taken out of water in experiment for some modification of the software in the local microcomputers.

5. Wormation Displayed in]CAD Computer

The information displayed in ICAD computer about the docking procedure makes it possible that the docking task is being carried out automatically while operator can monitor before the screen of the ICAD computer. The operator can interrupt the automatic operation at anytime when he judges that some abnormal things happens. The information displayed in ICAD computer includes:

(1)The signals from the manipulators
The low level for single chip microcomputers timerly collect the reformation about the joints position through A/D converters, and the contact, the overload, and the grasping on-off switch signals, and also the joint state, i.e. floating, locking or in movement.

(2)The relative position and attitude of the docking system and the assistant ring or the shell
When the docking system is far from the target, the information is provide by sonar system installed in the underwater robot. When the docking system approach the target, the sonar systems functions not good.

When the automatic searching begin, the position and relative attitude information is from the processing of the information from the state information of the manipulators. From the joints information and the contact signal, the position of the shell can be approximately determined before the preliminary connection is finished. After preliminary connection, the position and attitude of the assistant ring can be calculated with the joints information from the manipulators, the method will be presented in Appendix.

6. Experiment and Conclusion

Some preliminary experiments have been carried out in water pool in laboratory. Experiments includes docking in still water and in water with current of 0.2m/s. The current was generated by dragging the assistant ring in the water pool_ The docking time is about 5-6 minutes.

The docking procedure in experiment is shown in Fig.6, in the following description, manipulators 1,2,3,4 stand for the manipulators of left front, right front, left behind, right behind.

ŋ Above the assistant ring, the underwater robot is approaching the object

Manipulators 1 and 4 have grasped the ring and began centering procedure.

® The state after manipulators I and 4 have finish centering.

@After the centering of manipulators I and 4, manipulator 2,3 have grasped the rod of the assistant ring.

@Manipulators 1, 4 released the rod of the ring, and began the centering of 2,3.

() Again the manipulator 1,4 grasped the ring, the centering step finishes.

(}The pulling down step has been finished, the docking task has been successfully finished.

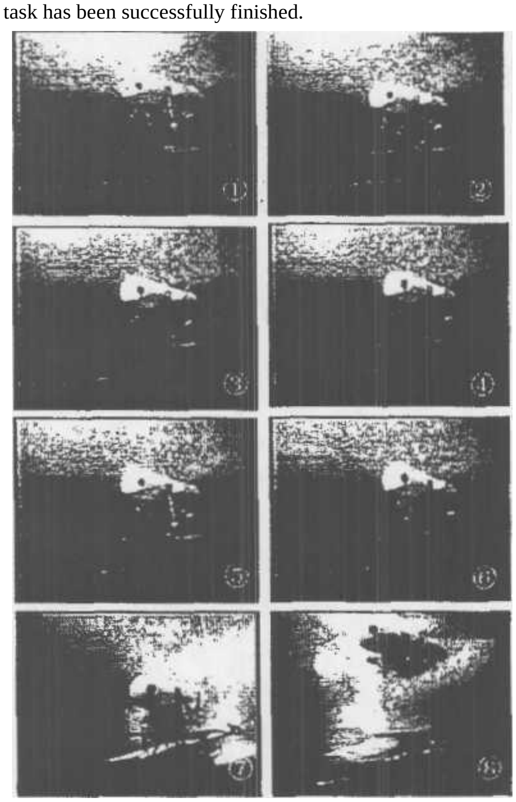


FIg.6 Docking Procedure

IThe docking system released the ring.

In experiment, no significant disturbance caused by the contact of the end-cffector and the shell has been observed, which indicated that the fuzzy mothod has really functioned

In underwater applications, the reliability is much more important than the advancement of technology. The effectiveness of the simple electromagnet value controlled hydraulic actuating system and the simple computer control technique has been demonstrated by the successful experiments. These preliminary experiment also demonstrate the feasibility of the novel underwater docking system for farther development and application

7. References

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Appendix Calculation Of The Assistant Ring's Spatial Position and Attitude

The relative position and attitude of the two docking parts can be calculated when the positions of the manipulators' joints are known. It is common sense that not all of the joints' information are needed.

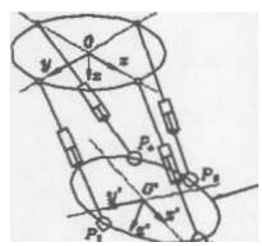

Figure Al The Coordinate System on Docking System and Assistant Ring

Set up the coordinate systems $Oxyz$ on the docking system and $O'x'y'z'$ on the assistant ring, as are shown in figure Al. Two manipulators are in Oxz plane, the other two in Oyz Plane, the coordinates of the end-effectors of four catching manipulators are: P,(O,y,,z,) , P,(O,y,,z,) ,

$P_2(x_2,0,z_2)$, $P_3(x_3,0,z_3)$. Assume that the transfer matrix of coordinate system $O'x'y'z'$ from $Oxyz$ is $[T]$, thus:

$$\begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

in [T], n_x, n_y, n_z are the directional cosines of axis x, in coordinate system Oxys, o_x, o_y, o_z are the directional cosine of axis y_1, and a_x, a_y, a_z are the directional cosine of axis z, in coordinate system Oxyz, (p_x, p_y, p_z) is the coordinate of the original point of $O'x'y'z'$ in Oxyl.

(1) Calculation of Directional Cosines of Axes of 0' x' y' z' in Oxyz.

Because axis z' is perpendicular to the plane of the catching ring, we have

$$a_x \cdot 0 + a_y \cdot (y_1 - Y_2) + a_z \cdot (z_1 - z_2) = 0 \quad (2)$$

$$a_x x_3 + a_y \cdot (0 - y_2) + a_z (z_3 - z_2) = 0 \quad (3)$$

And: $a_x^2 + a_y^2 + a_z^2 = 1$ (4)

From (2)(3)(4):

$$\begin{cases} a_x = \dfrac{K_1}{\sqrt{K_1^2 + K_2^2 + 1}} \\ a_y = \dfrac{K_2}{\sqrt{K_1^2 + K_2^2 + 1}} \\ a_z = \dfrac{1}{\sqrt{K_1^2 + K_2^2 + 1}} \end{cases} \quad (5)$$

in (5): $K = \frac{-z_3 - 1}{x_3} - \frac{Y_2(z_1 - z_2)}{x_3(Y_1 - Y_2)}$, $K \quad \frac{z_2 - z_1}{Y_1 - Y_2}$

Axes x' and y' are assigned in the plane of the catching ring. Because the rotation around axis z' does not affect interfacing, axes x' and y' should be assigned to satisfy the condition that there is no rotation around axis z'. In order to keep the course of the submarine in interfacing process the elements in matrix [T] then should be determined according to the assigned axes. After the rotation of Oxyz around axes x, y in proper angles, axis z' and axis z share the same direction. When axes x1, y, are in parallel to axes x, y, there is no rotation around axis z'. The axis $k(k_x, k_y, k_z)$ of the equilibrium rotation around axis x, y, is perpendicular to axes z and z', and the angle of the equilibrium rotation is the included angle of axis z and axis z_1. So we have:

$$\begin{aligned} k_x \cdot a_x + k_y \cdot a_y + k_z \cdot a_z &= 0 \\ k_x \cdot 0 + k_y \cdot 0 + k_z \cdot 1 &= 0 \\ k_x^2 + k_y^2 + k_z^2 &= 1 \end{aligned} \quad (6)$$

$$\theta = \cos^{-1} a_z \quad (7)$$

From (6), O(O> O, k, 2: 0)can be solved for

$$\begin{aligned} k_x &= \frac{a_y}{\sqrt{a_x^2 + a_y^2}} \\ k_y &= -\frac{a_x}{\sqrt{a_x^2 + a_y^2}} \\ k_z &= 0 \end{aligned} \quad (8)$$

From (7): $\sin\theta = \sqrt{1 - a_z^2} = \sqrt{a_x^2 + a_y^2}$ (9)

According to the equation of rotation around random axis, we get:

$$Rot(k,\theta) = \begin{bmatrix} k_x k_x \operatorname{vers}\theta + \cos\theta & k_y k_x \operatorname{vers}\theta - k_z \sin\theta & k_z k_x \operatorname{vers}\theta + k_y \sin\theta & 0 \\ k_x k_y \operatorname{vers}\theta + k_z \sin\theta & k_y k_y \operatorname{vers}\theta + \cos\theta & k_z k_y \operatorname{vers}\theta - k_x \sin\theta & 0 \\ k_x k_z \operatorname{vers}\theta - k_y \sin\theta & k_y k_z \operatorname{vers}\theta + k_x \sin\theta & k_z k_z \operatorname{vers}\theta + \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 + a & 1 - a' & & 0 \\ - & 1 + a & + a_z & a \quad 0 \\ a_x & n & a_y & 0 \\ a & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

The former 3 columns in the matrix in (10) are the same as the ones in matrix[T] .

(2) Calculation of Coordinate of the Original of O' x' y' z' in OxxZ

In the forth column of [T] , fhe former three elements are three components of coordinate of $O'x'y'z'$ system's original point 0' .

Point O' (p_x, p_y, p_z) is the intersection of three planes:

1DThe plane cross the midpoint of line segment P_1P_2 and perpendicular to P_1P_2

$$(Y_1 - Y_2)\left(y - \frac{Y_1 + Y_2}{2}\right) + (z_1 - z_2)\left(z - \frac{z_1 + z_2}{2}\right) = 0 \quad (11)$$

©The plane cross the mid point of line segment PP_3 and perpendicular to PP_3:

$$\ldots = 0 \quad (12)$$

© The plane of the catching ring:

$$a_x \cdot (x - x_2) + a_y y + a_z (z - z_2) = 0 \quad (13)$$

The coordinate (p_x, p_y, p_z) can be easily solved for through (11)(12)(13). In above calculating process, the coordinates of three points P_1, P_2, P_3 are used. In fact, if 5 joint positions, the dimensions of the docking system, the radius of the catching ring are known, the coordinates of P_1, P_2, P_3, P_4 can be calculated.