Return to Session Directory

DYNAMIC POSITIONING CONFERENCE

October 13-14, 2009

New Applications

Dynamic Positioning System of An Underwater Vehicle for Oceanic Space-docking

Xinqian Bian, Tao Chen
Harbin Engineering University, Harbin, China

Abstract

Oceanic space-docking plays an important role in underwater vehicle technology for applications of deep submarine rescue and sub-sea space station. Reliable dynamic positioning (DP) is essential for operation of underwater vehicle docking in badly situation. In this paper, 6-DOF DP mathematic model and 6-DOF DP system addressed in low visibility, faster current and serious gradient situations for oceanic space-docking are introduced. The control equipment and control approach of 6-DOF DP system are introduced in detail. In order to realize automatic docking process, the hybrid control system based on 6-DOF DP is designed. The bottom of the hybrid control system are different control functions to control 6-DOF motions of the vehicle. The middle is conversion interface to generate events according to system states and produce control rules. The upper is operation machinery of discrete event to analyze events and guide the docking process. Successful tank experiments dealing with complex real underwater scenes are reported and validate the proposed DP system in this paper.

Introduction

Oriented to the necessities of exploitation of oceanic resource and deep submergence rescue, the shuttle underwater vehicle (SUV) or the rescuing underwater vehicle (RUV) should dock on a sub-sea space station or a disabled submarine to realize the transmission of people(survivors) or resource. Fig.1 shows a scene of DP of an underwater vehicle for submergence rescue and undersea station.

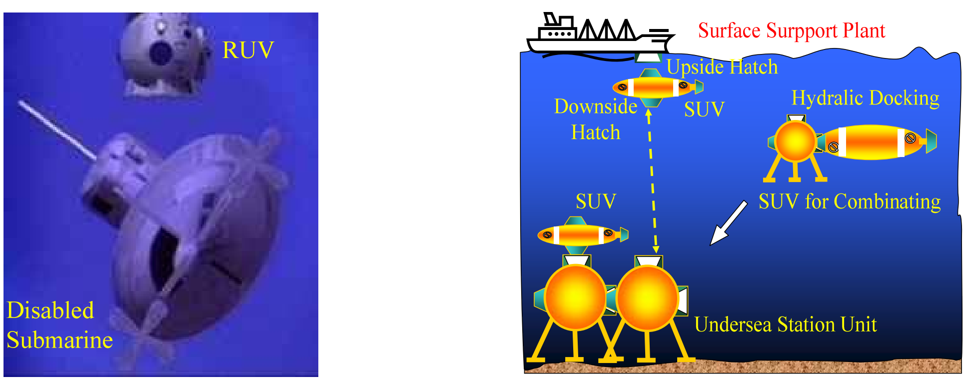


Fig. 1 DP of Underwater Vehicle for Submergence Rescue and Undersea Station

Taking notice of oceanic space-docking plays an important role in underwater vehicle technology, more and more researches are developed in the worldwide. A new DSRV (Deep Submergence Rescue Vehicle) for automatic mating simulated tester is investigated in Ref[1]. It mainly solves the automatic mating problem of wreck submarine with a large incline in a poor sea state. Ref[2] describe an automatic dynamic positioning system for ROVs (DPSROV) that is based on a mechanical passive arm (PA) measurement system. Ref[3] addresses the problem of dynamic positioning of underactuated autonomous underwater vehicles(AUVs) in the presence of constant unknown ocean currents and parametric modeling uncertainty. A model-based dynamic positioning of underwater vehicles is introduced by theory and experiment in Ref[4], the experiment results show that their method is effective. Ref[5] gives a intelligent co-ordinate control method for mating process of DSRV Based on Fuzzy Petri Net. The work of this paper is to co-ordinate the movement of the DSRV and manipulators, in order toreduce the time spent in mating process, improving the probability of success mating.

In fact, automatic docking is still a difficulty at some situations, for example as low visibility, fast current, serious gradient and so on. For many years researchs, we develops a 6-DOF automatic docking technique in the badly situations mentioned above. Our activities in oceanic space-docking of underwater vehicle is started in 1982, the development process of automatic docking for underwater vehicle is:

1982-1986: Regulating flotage and keeping depth automatically
1983-1990: 4-DOF DP
1994-1997: 4-DOF DP and compact display&control
1997-2002: 6-DOF DP and novel docking equipment with manipulators
2003-2006: 6-DOF DP and automatic docking without manipulators
2006-Now: Dynamic docking based on motion target

Automatic Docking System of Underwater Vehicle

A. Overall Design for the test system

The automatic docking system of underwater vehicle is equipped with some measure instruments, control system and actuating system, to sample the required information in real-time accurately, so that the controller can calculate the required thrust force to approach the disable submarine and realize the dynamical positioning and mating mission.

The measurement system is composed of an orientation sensor, depth sensors, guiding sonar out skirt, positioning sonar in skirt, altimetry sensor, displacement measuring device and water leakage detector for the electronic cabin. Two depth sensors are used and it is redundant to the altimetry sonar, which not only increases the accuracy of the measurement system but also guaranteed the experimental security in the limited depth of the tank.

The control system includes the 6-DOF dynamic positioning control system, the submarine communication subsystem, the displacement measuring device and localization altimetry sonar measurement system. Propellers and actuators consist of five electrical propellers, frequency converter gear, and longitudinal and transverse adjusting mechanism.

B. Interior Layout of underwater vehicle

In the internal arrangement and the mechanical compatibility, the vehicle has passed through the repetitious adjustment and has overcome a series of problems caused by the space tension, including the fiberglass outer hull and skirt. The layout of the interior electrical instruments, the executors and the mechanical adjustment mechanism are shown in Fig.2.

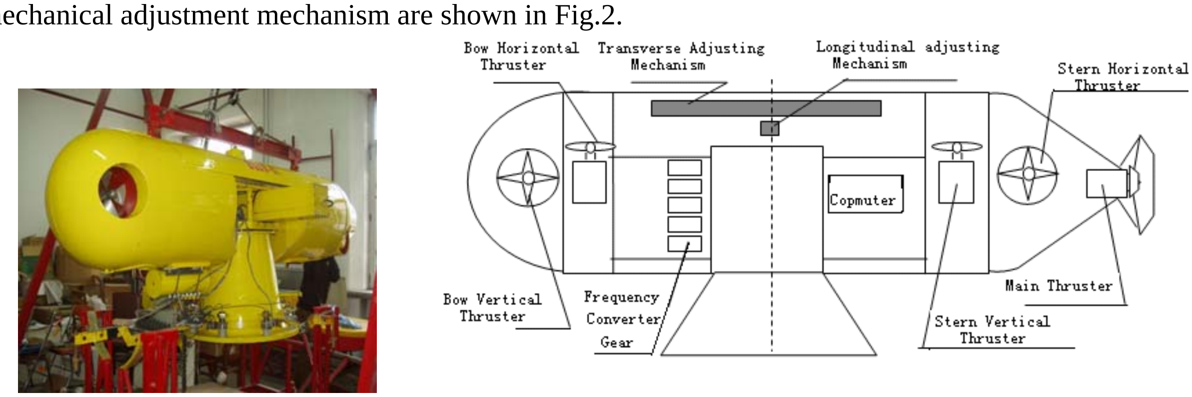


Fig. 2 Interior Layout of Underwater Vehicle

Inside the fiberglass outer hull are two electrical houses that form the pressure hull. The forward contains the thruster speed adjusting system; the rear contains the information measuring and the computer communicating system. Five electrical thrusters: one is main propeller and is arranged in the fore and aft direction; two lateral aux-thrusters which are laid in the front and the rear of the vehicle respectively are arranged horizontally; two vertical aux-thrusters which put the front and the rear respectively are arranged vertically.

The thruster in fact is an independent control subsystem, which controls the electrical machinery tracking response and drives the screw propeller beat water to produce propulsion according to the electrical machinery instruction sent by control system. Actiyator of the thruster adopts the frequency conversion gear. The longitudinal and transverse adjusting mechanism adopts the electrical machinery to drive worm wheel, which drives sliding module moving parallel, then force arm changes bringing on the change of regulation moment; ultimately the pitch and roll will be adjusted.

C. Skirt

The skirt and shock mitigation system allows the vehicle to mate with the docking seat on the submarine rescue/escape trunk). The skirt allows a watertight seal to be made between the DSRV and the submarine. After a seal is made, the submarine upper access hatch can be opened and swung up into the skirt cavity.

The skirt looks like a frustum of a cone, as shown in Fig.3; it is reduced to the scale of 1:2 compared to the actual docking skirt. There are three inner positioning sonars on the wall of the lower cavity room, which are well distributed over the skirt as 120 degrees array. Four pairs of depth sonar are well distributed and stagger the inner positioning sonar shifts. There are brackets in the outer side of the skirt wall, which used for the installment of the outer positioning sonar. In the hemline of the mating skirt, eight touched sensors are installed, which used to measure the contract situation between the skirt department and docking seat in real-time, as shown in Fig. 3.

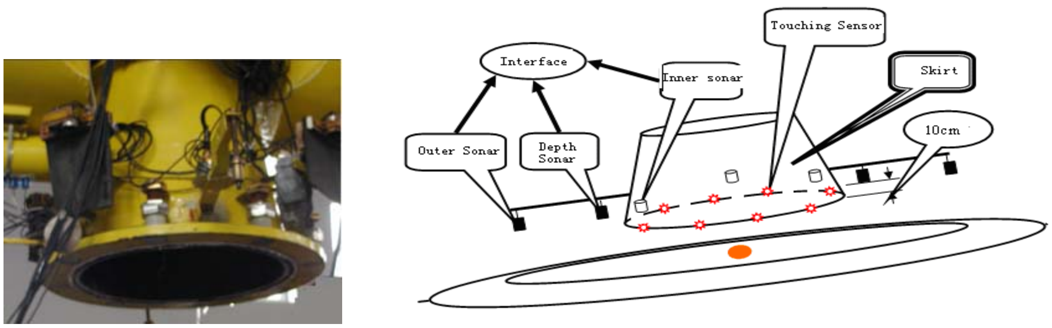


Fig. 3 Skirt of Vehicle

6-DOF Mathematic Model of Underwater Vehicle

The 6 DOF components of the vehicle rigid body dynamic equations of motion can be written incomponents form as in [6]. The form of equation of motion is obtained with body axes coincidentwith the principles axes of inertia, and the origin not at the center of mass center of gravity (CG). For this case the equation in the dimensionless form are:

$$
\begin{aligned}
X &= m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] \\
Y &= m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(pq + \dot{r})] \\
Z &= m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(pr - \dot{q}) + y_G(rq + \dot{p})] \\
K &= I_x\dot{p} + I_{xy}\dot{q} + I_{xz}\dot{r} + (I_{zx}p + I_{zy}q + I_z r)q - (I_{yx}p + I_y q + I_{yz}r)r + m\left[y_G(\dot{w} + vp - uq) - z_G(\dot{v} + ur - wp)\right] \\
M &= I_{yx}\dot{p} + I_y\dot{q} + I_{yz}\dot{r} + (I_x p + I_{xy}q + I_{xz}r)r - (I_{zx}p + I_{zy}q + I_z r)p + m\left[z_G(\dot{u} + wq - vr) - x_G(\dot{w} + vp - uq)\right] \\
N &= I_{zx}\dot{p} + I_{zy}\dot{q} + I_z\dot{r} + (I_{yx}p + I_y q + I_{yz}r)p - (I_x p + I_{xy}q + I_{xz}r)q + m\left[x_G(\dot{v} + ur - wp) - y_G(\dot{u} + wp - vr)\right]
\end{aligned}
\tag{1}
$$

Where, X is surge force, Y is sway force, Z is heave force. K is roll moment, M is pitch moment, N is yaw moment, p is roll rate, q is pitch rate, r is yaw rate, u is surge velocity, v is sway velocity, w is heave velocity, x is body fixed axes in positive forward, y is body fixed axes in positive starboard, z is body fixed axes in positive down, I_x, I_y , I_z are vehicle mass moment of inertia around the x-axis, the y-axis, the z-axis respectively, x_G is longitudinal position of center of gravity, y_G is athwart location of center gravity, z_G is vertical position of center of gravity, m is the mass of the AUV.

The attitude equations are:

$$\begin{aligned}\dot{\varphi} &= p + q\sin\varphi\tan\theta + r\cos\varphi\tan\theta \\ \dot{\theta} &= q\cos\varphi - r\sin\varphi \\ \dot{\psi} &= q\sin\varphi/\cos\theta + r\cos\varphi/\cos\theta\end{aligned} \tag{2}$$

Where, φ is roll angle, θ is pitch angle, and ψ is yaw angle.

The motion relation formulas are:

$$\begin{aligned}\dot{\xi} &= u\cos\psi\cos\theta + v(\cos\psi\sin\theta\sin\varphi - \sin\psi\cos\varphi) + w(\cos\psi\sin\theta\cos\varphi + \sin\psi\sin\varphi) \\ \dot{\eta} &= u\sin\psi\cos\theta + v(\sin\psi\sin\theta\sin\varphi + \cos\psi\cos\varphi) + w(\sin\psi\sin\theta\cos\varphi - \cos\psi\sin\varphi) \\ \dot{\varsigma} &= -u\sin\theta + v\cos\theta\sin\varphi + w\cos\theta\cos\varphi\end{aligned} \tag{3}$$

Where, ξ , η , ς are displacements in inertial coordinate system.

There is always ocean current in the sea area where the vehicle navigates. So, it is necessary to research ocean current interference model. The velocity of ocean current is usually low, and much lower in deep ocean. But the velocity of ocean current is variational in different area, depth and seasons. So, the velocity of ocean current is a complex function anent space and time. Usually, the sea area where the vehicle navigates and navigational time are restricted. So, it is supposed that the ocean current is horizontal and its velocity is fixed.

Let $U(u_\xi, v_\eta, w_\zeta)$ is the velocity of ocean current in inertial frame, $U(u_c, v_c, w_c)$ is the velocity in frame, then:

$$\begin{bmatrix} u_c \\ v_c \\ w_c \end{bmatrix} = S^{-1} \begin{bmatrix} u_\xi \\ v_\eta \\ w_\zeta \end{bmatrix} \tag{4}$$

Where, S is coordinate transform matrix from kinetic coordinate system to inertial coordinate system. S can be calculated as belows:

$$S = \begin{bmatrix} \cos\psi\cos\theta & \sin\psi\sin\theta\sin\varphi - \sin\psi\cos\varphi & \cos\psi\sin\theta\cos\varphi + \sin\psi\sin\varphi \\ \sin\psi\cos\theta & \sin\psi\sin\theta\sin\varphi + \cos\psi\cos\varphi & \sin\psi\sin\theta\cos\varphi - \sin\psi\sin\varphi \\ -\sin\theta & \cos\theta\sin\varphi & \cos\theta\cos\varphi \end{bmatrix} \tag{5}$$

Let $V_R(V_{Rx}, V_{Ry}, V_{Rz})$ is the velocity of the vehicle relative to ocean current, then:

$$V_{Rx} = u - u_c, \quad V_{Ry} = v - v_c, \quad V_{Rz} = w - w_c \tag{6}$$

Let (V_{Rx}, V_{Ry}, V_{Rz}) replaces (u, v, w) in (1), then obtain the ocean current interferential model of the vehicle.

Control Strategy Based on Hybrid Control System

A. Hybrid control system

Hybrid control system (HS) is a uniform dynamic system combined with Continuous Variable Dynamic System (CVDS) and Discrete Event System (DES). Vehicle movement is continuous, 6 DOF complicated, strong coupling and non-linear. Object model in RW theory is a stochastic automata, the operation process should be abstracted an automation model while applied the RW theory to it. Stochastic automata model based discrete event dispose the observation value (data sampled from sensor) and actions with symmetrical manner and event method. In the mating process, events correspond to the state and the discrete transitional phase. While continuous variable dynamic system control is designed to get the control ratio to make the performance specification minimize under given control region. There are three layers in the hybrid control system[7][8].

1) Bottom

The bottom is composed of two parts: real vehicle and controller. For automatic docking of the vehicle, controller include roll adjustor, pitch adjustor, vertical controller, horizontal controller and heading controller. In the vehicle, it is equipped with extractors and measurement system introduced above.

2) Middle

The middle is conversion interface; it is composed of event generator and extractor. Event generator is mainly used to judge the system state based on signal which measured from bottom. Extractor produces control rule to decide which controller should work and how to work.

3) Upper

The upper is the operation machinery of discrete event; it is composed of event analysis and control decision. Event analysis is used to judge whether the vehicle can meet with the mating conditions or not, namely whether every state error exceed usual data or not. If exceeding, control decision will decide correlative mode and send control signal.

B. Model and Structure Design of DEDS

The vehicle movement in sea is continuous which state space is divided into limited regions, every region is the relative position and posture between mating skirt and docking seat. When coordinating with skirt and seat, the region may be entered easily for vehicle. The movement of vehicle is driven by thrusters and longitudinal and transverse adjusting mechanism, while their control actions become events, as well as failure actions coursed by disturber. vehicle hangs over the disable submarine, if it enters a region which planning in advance, a signal will generate. DES controller receives this signal and sends the control instruction. Every control module will translate the continuous action and adjust its movement. After successful mating, DES controller generates signal to seal between the vehicle and the docking plane. Mating model is shown as Fig.4.

States were defined as follows:

1) Whether sensors were touched with plane or not

1) Whether sensors were touched with plane or not

2) Whether DSRV has finished its actions or not.

$x(t) \in X_C$ is DSRV vector state.

$u(t) = \alpha(X_D)$ are the control parameters coming from discrete event controller to vehicle.

$\Sigma = \Sigma_u \bigcup \Sigma_c$, where $\Sigma_u = \{\sigma_i, \beta_i, \pi,\}$; $\Sigma_c = \{\eta_i, \lambda, \tau, \omega\}$ 。

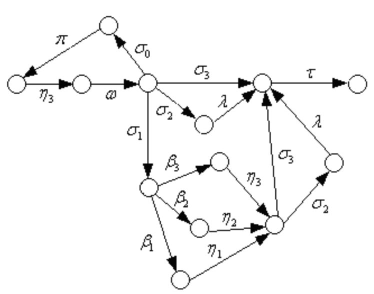


Fig.4 Model of Mating Process

σ_0: Inclined degree between skirt with plane exceeds the scope of measurement of sensors.

σ_1: Skirt is parallel, touched and un-sit with docking plane.

σ_2: Skirt is unparallel but touched with docking plane.

σ_3: Skirt is parallel, touched and middle-sit with docking plane completely.

b_1: Skirt is parallel with docking plane while vehicle has pitch.

b_1: Skirt is parallel with docking plane while vehicle has roll.

b_3: Skirt is parallel with docking plane while vehicle has roll and pitch simultaneity

η_1: Adjustment with Longitudinal adjusting mechanism

η_2: Adjustment with transverse adjusting mechanism.

η_3: Adjustment with longitudinal and transverse adjusting mechanism simultaneity.

λ: Middle sit adjusted.

ω: Vehicle is close to the docking.

τ: Mating and sealed.

π: Failure events.

Tank Experiments

In order to validate the validity and feasibility of the automatic docking control system, we design tank experiments dealing with complex real underwater scenes. Fig.5 shows the tank test system. The system includes: the vehicle, docking seat, acoustic positioning system, control mainframe, traveling crane and so on. Docking seat is to simulate the posture of the disable submergence by adjusting different heading, roll and pitch. There is a responder of the acoustic positioning system on the docking seat. Traveling crane is to simulate the ocean current. The ocean current we simulated is constant, traveling crane move the docking seat forward in a definite speed. For the vehicle, to achieve dynamic position such as hanging, approaching and mating, it must move in the same speed to conquer the water resistance, which is equal to produce such a speedy flow. Acoustic positioning system is to measure the distance and phase from the responder to the skirt by three outer and three inner position sonars arrayed in the vehicle. The position information can sent to control mainframe real-timely by serial port 485. Control computer is an ordinary PC, which configured with multi-serial board to complete the communication with other systems. It is used to sample measurement data and sent the control instruction.

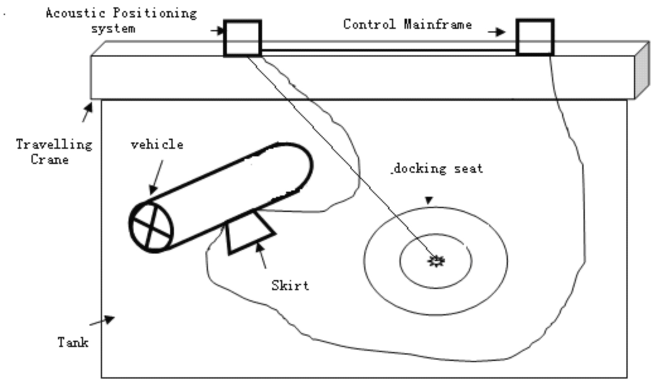
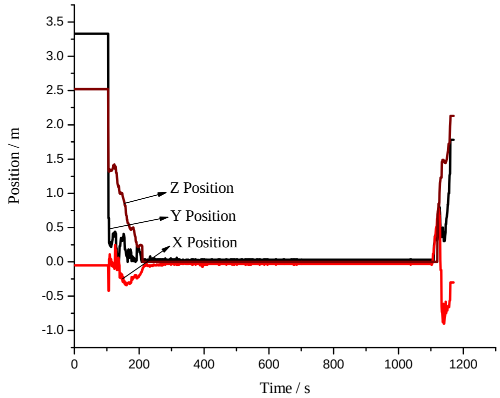


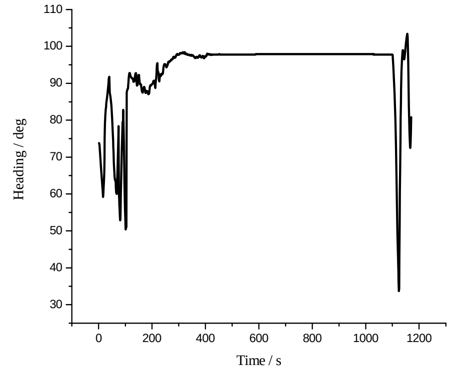
Fig.5 Tank test system for DSRV

The device vehicle tested in Tank (120m Length ×7m Width ×4m Depth) on the basis of software design and implementation. After fulfilled initial real docking conditions, vehicle stopped near the docking seat, 6-DOF dynamic position system (DPS) carried out position control; the vehicle suspended above docking seat, depth control was used to approach it while stern vertical thrusts went all out. 8 touching sensors data were detected real-timely. After skirt and docking seat touched completely, electromagnetic valve were opened, pressure difference between skirt and seat were detected by sensors, mating completed.

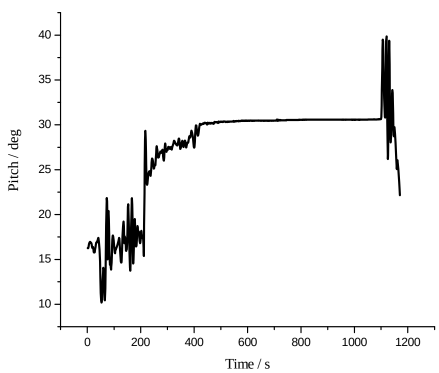
Begin, vehicle stopped in water away from docking seat; at time 104, 6-DOF DPS was operated (X:0m,Y:0m; Z: 2.35m; Heading:80°; Pitch:16.2°; Roll:5.3°), this process was corresponded with discrete event η_3; at time 191, depth changed 0.25m; at time 214, skirt began to mate with plane, this process was corresponded with discrete event ω; at time 229 skirt touched plane(No.1 approaching sensor value is 0), this process was corresponded with discrete event σ_1 and β_3, at the same time, longitudinal and transverse adjusting mechanism were operated automatically based on touching sensor value.(the vehicle has roll and pitch degree with plane), this process was corresponded with discrete event η_3; at time 619, longitudinal and transverse adjusting process was over. Skirt was nearly parallel to plane, this process was corresponded with σ_2;The bailing valve was opened automatically(because of the difference pressure, the value of touching sensors were declined to 0 gradually) this process was corresponded with τ; at time 969, vehicle was free with the bailing state and departed from skirt (Value of touching sensors were big gradually); at time 1170, test was over. It took 192m to mate from beginning the dynamic positioning control to finishing mating process on condition of the simulative sea current speed as 0.2kn. This test process validated the vehicle was completely mating as the planning sequence $\eta_3\omega\sigma_1\beta_3\eta_3\sigma_2\tau$. The control computer recorded the test data. The response curves show as fig.6.



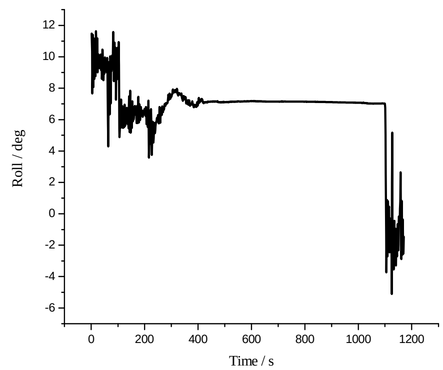
(a) Position in X, Y ,Z



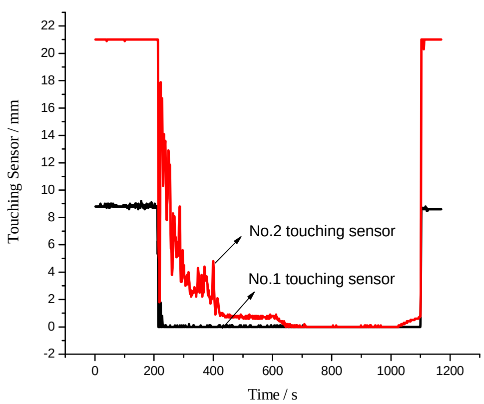
(b) Direction of Heading



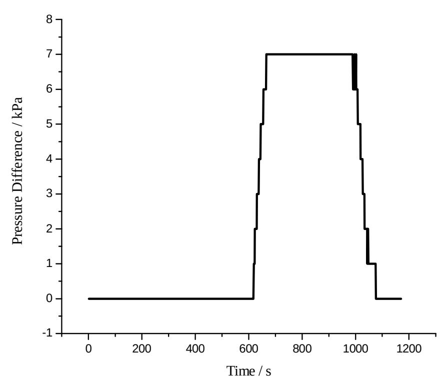
(c) Direction of Pitch



(d) Direction of roll



(e) Touching sensor Measurement



(f) Pressure Difference

Fig.6 Tank Test Response Curves

The result show that the vehicle can succeed in automatic mating in poor visibility underwater condition with heavy ocean current, and that the docking seat has a large inclined angle .Fig.8 are real frames of the automatic mating process in tank test. From these, we can see that the vehicle can locate the submarine docking seat in several minutes.

Fig.8 Process of tank tests for underwater automating

Conclusion

6-DOF DP system addressed in low visibility, faster current and serious gradient situations for oceanic space-docking is addressed in this paper. The vehicle, the docking devices and the 6-DOF model considered current are introduced in detail. In order to realize automatic docking process, the hybrid control system based on 6-DOF DP is designed. Model and structure of DEDS is designed to guide the vehicle for automatic docking. Tank experiments dealing with complex real underwater scenes are carried out, The result show that the vehicle can succeed in automatic mating in poor visibility underwater condition with heavy ocean current, and that the docking seat has a large inclined angle.

References

[1] Hou Shuping and Yan Zheping, "State-of-Art and Development Trend of Deep Submarine Rescue Vehicle(DSRV),"in *Ship Engineering*.*China*, Vol.26, No.4, pp.1-5,2004

[2] Liu Hsu and Ramon R. Costa, "Underwater Vehicle Dynamic Positioning Based on a Passive Arm Measurement System,"in *2nd Workshop on Mobile Robots for Subsea Environment. Monterey CA*, pp.1-10,1994

[3] A. PEDRO AGUIAR and ANT´ ONIO M. PASCOAL, "Dynamic Positioning and Way-Point Tracking of Underactuated AUVs in the Presence of Ocean Currents,"in *International Journal of Control*, pp.1-26,2007

[4] David A. Smallwood and Louis L. Whitcomb, "Model-Based Dynamic Positioning of Underwater Robotic Vehicles: Theory and Experiment,"in *IEEE JOURNAL OF OCEANIC ENGINEERING, VOL. 29, NO. 1, JANUARY 2004*, pp.1-10,2004

[5] Zheping Yan and Xiaocheng Shi, "Intelligent Co-ordinate Control for Mating Process of DSRV Based on Fuzzy Petri Net,"in *Journal of Marine Science and Application. Harbin China, VOL. 1, NO. 2, December* 2002 pp.23-27,2002

[6] Nanang Syahroni, Young Bong Seo, Jae Weon Choi, "Open control platform implementation for autonomous underwater vehicle," SICE Annual Conference, 2007, pp. 2042-2047

[7] Stiver J,Antsaklis P. "Modelling and analysis of hybrid control systems,".*Proceedings of the 31st Conference on Decision and Control. Tucson,Arizona*,1992.

[8] Stiver J,Antsaklis P. "On the control ability of hybrid control systems,".*Proceedings of the IEEE Int Confon Decision and Control,32nd CDC. SanAntonio,Texas*,1993.