Periodica Polytechnica
Mechanical Engineering

61(2), pp. 87-93, 2017
https://doi.org/10.3311/PPme.9312

RESEARCH ARTICLE

Multivariable Robust Fault Tolerant Control For Work-Class Remotely Operated Vehicle

Zhaoqiang Wang[1*], Zhen Wang[1], Mingen Wu[1], Yiping Luo[1]

Received 08 April 2016; accepted after revision 13 October 2016

Abstract

To deal with complex disturbances and the presence of partial loss of propeller effectiveness in work-class remotely operated vehicles (ROVs), a method of robust fault tolerant control is proposed, which is based on adaptive sliding mode control. In this approach, adaptive technique is employed to estimate the bounds' information of external complex disturbances and the effectiveness loss of the propeller. And a sliding mode controller is then designed to achieve fault tolerant control and external disturbance rejection. Corresponding stability of the closed-loop control system is analyzed using Lyapunov stability theory. Apply this method to trajectory tracking control of work-class ROVs, the simulation results validate that great fault tolerant capability and a good performance of external disturbance rejection can be achieved even under partial loss of propeller effectiveness.

Keywords

work-class remotely operated vehicle, partial loss of propeller effectiveness,robust fault tolerant control, sliding mode control, multivariable control

[1] Department of Automobile Service Engineering,
School of Automotive Engineering,
Shanghai University of Engineering Science,
333 Long Teng Road, Shanghai 201620, China

[*] Corresponding author, e-mail: wangzhaoqiang_2008@126.com

1 Introduction

The work-class remotely operated vehicles (ROVs) are essential equipments which are widely used in military, commercial and scientific investigations [1]. However, the component systems of the working-class ROVs may be easy to degenerate and corrode due to the long-term and high-duty working in the harsh working condition of the deep sea. As a key system, the propulsion system is much easier to be troubled with these problems, however, which may greatly affect the control performance of the ROVs leading to the decreasing of working efficiency and increasing of working cost. Moreover, the fault of propulsion system may even lead to the loss of ROVs. Thus, the robust fault tolerant control (FTC) methods for ROVs are very necessary [2, 18-21].

Nowadays, the FTC methods mainly have two branches, the passive FTC (PFTC) and the active FTC (AFTC) [3, 4], which have been successfully adopted in the control of spacecrafts [5, 6]. Corresponding studies of FTC on ROVs are very limited, especially for the multivariable robust FTC in the deep-sea environment [7, 8].

In the Ref. [9], the neural network technology is combined with the FTC method. Corresponding controller had been verified through the simulations on the yaw control of the underwater vehicles. In the Ref. [10], an adaptive model of underwater vehicles is constructed using FIR, and LMS is used to minimize the output error between the monitored system and the FIR filter in the process. Afterwards, the sensor fault is detected and the AFTC is realized by analyzing the resulting adaptive FIR filter coefficients and error signals.

The proposed method in Ref. [10] relies on the detection of all kinds of faults to a great degree, which may lead to the out of control of the whole system due to the possibility of false detection. Moreover, there are always delayed time between the occurrence and detection of the fault, which in turn will greatly affect the control performance of the whole system [11]. Therefore, the robust FTC methods have been widely studied [12, 13].

For the dynamic positioning of ROVs under complex external disturbance and partial loss of propulsion, we propose a novel robust FTC method based on adaptive sliding mode control (SMC) inspired by the existing works concerning FTC methods. The new proposed method has good robustness against external disturbance and partial loss of propulsion. Moreover, no exact bound information of the external disturbance and partial loss of propulsion are required thanks to the adaptive technique, which leads to relative smooth control signals. *The closed-loop stability of the control system is analysed based on Lyapunov stability theory.* Finally, several simulations are conducted to verify the effectiveness of the proposed method. Corresponding simulation results show that the proposed method can provide with good robustness against both external disturbance and partial loss of propulsion.

2 System description

A reasonable dynamic model to describe ROVs' behavior must contain both the rigid-body dynamics of the vehicle's body and the representation of the surrounding fluid dynamics [14]. Thus, the dynamic model of a ROV is often described with respect to earth-fixed frame and body-fixed frame, as shown in Fig. 1.

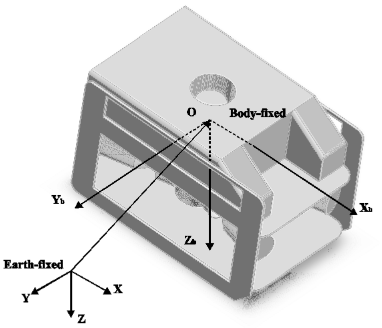

Fig. 1 Earth-fixed and Body-fixed Frame [15]

Simplified dynamic model of a ROV in 4-DOF can be represented as [15]

$$M\dot{v} + C(v)v + D(v)v + g(\eta) + \tau_d = \tau. \quad (1)$$

$$\dot{\eta} = J(\eta)v. \quad (2)$$

$$\tau = Bu \quad (3)$$

where

$M = M_{RB} + M_A, C(v) = C_{RB}(v) + C_A(v), D(v) = D_L + D_Q(v)$. $M_{RB} \in R^{4\times4}$ and $C_{RB}(v) \in R^{4\times4}$ represent the rigid body inertial matrix and the Coriolis and centripetal matrix, respectively. $M_A \in R^{4\times4}$ and $C_A(v) \in R^{4\times4}$ denote the added mass matrix and the added Coriolis and centripetal matrix, respectively. $D_L \in R^{4\times4}$ and $D_Q \in R^{4\times4}$ denote the linear and quadratic drag matrices, respectively. The vector $g(\eta) \in R^{4\times1}$ is the combined force/moment of gravity and buoyancy in the body-fixed frame. Moreover, $\eta = [x, y, z, \psi]^T$ represents the ROV's position and orientation in the earth-fixed frame, and $v = [u, v, w, r]^T$ represents the ROV's linear and angular velocity in the body-fixed frame. $\tau_d \in R^{4\times1}$ denotes the disturbance force/moment vector, and $\tau \in R^{4\times1}$ denotes the system input produced by the propellers. $J(\eta) \in R^{4\times4}$ is the kinematic transformation matrix which expresses the relationship between the body-fixed frame and the earth-fixed frame, and can be written as follows

$$J(\eta) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The dynamic distribution matrix $B \in R^{4\times5}$ is mainly determined by the arrangement of the ROV's propellers, and $u \in R^{5\times1}$ is the force vector produced by the propellers.

Furthermore, Eq. (1) can be expressed in another form for the convenience of controller design:

$$M_0\dot{v} + C_0(v)v + D_0(v)v + g_0(\eta) = \tau + F. \quad (4)$$

Where $M_0, C_0(v), D_0(v), g_0(\eta)$ are the nominal parameter matrices, and

$F = -(\tau_d + \Delta M\dot{v} + \Delta C(v)v + \Delta D(v)v + \Delta g(\eta))$ is the lumped disturbance force/moment vector including parametric uncertainties and external disturbances.

Finally, the other simplified parameter matrices can be written as:

$$M_0 = diag\{m_v - X_{\dot{u}}, m_v - Y_{\dot{v}}, m_v - Z_{\dot{w}}, I_z - N_{\dot{r}}\}. \quad (5)$$

$$C_0(v) = \begin{bmatrix} 0 & 0 & 0 & -(m_v - Y_{\dot{v}})v \\ 0 & 0 & 0 & -(m_v - X_{\dot{u}})u \\ 0 & 0 & 0 & 0 \\ (m_v - Y_{\dot{v}})v & -(m_v - X_{\dot{u}})u & 0 & 0 \end{bmatrix}. \quad (6)$$

$$D_0(v) = -diag\{X_u + X_{u|u|}u, Y_v + Y_{v|v|}v, Z_w + Z_{w|w|}w, N_r + N_{r|r|}r\}. \quad (7)$$

$$g_0(\eta) = [0, 0, W - B, 0]^T. \quad (8)$$

Where W and B represent the ROV's weight and buoyancy respectively.

3 Multivariable robust FTC design

Inspired by the results from Ref. [16], a novel multivariable robust FTC based on adaptive sliding mode is proposed and investigated for the trajectory tracking control of ROVs. The proposed method handles the external complex disturbance and partial loss of propulsion separately, and estimates corresponding bound information using two adaptive laws. This kind of designing greatly ensures the control performance and improves the working efficiency.

Generally, the goal of the robust FTC designing is to asymptotically track the desired trajectory η_d in the presence of external complex disturbance and partial loss of propulsion.

For the convenience of FTC designing, substituting Eq. (3) into Eq. (4) and taking the partial loss of propulsion into consideration, we have

$$M_0\dot{v}+C_0(v)v+D_0(v)v+g_0(\eta)=(B_0+\Delta B)u+F \quad (9)$$

Where B_0 is nominal dynamic distribution matrix when the propulsion system can work normally. And ΔB is the variation of the dynamic distribution matrix caused by the partial loss of propulsion.

Before giving the main results, following assumptions are necessary.

Assumption 1. The desired trajectory η_d is smooth, which means $\dot{\eta}_d, \ddot{\eta}_d$ existent and bounded.

Assumption 2. Following inequalities must be satisfied to realize the FTC of ROVs

$$B_0 \neq 0, B_0+\Delta B \neq 0 \quad (10)$$

Assumption 3. The dynamic distribution matrix variation and external disturbance are bounded, which means

$$0 \le |F| \le f, 0 \le |\Delta B/B_0| = L < 1 \quad (11)$$

Define the tracking error and sliding surface as

$$e=\eta_d-\eta \quad (12)$$

$$s=\dot{e}+\lambda e \quad (13)$$

Then, we have the following theorem hold.

Theorem 1. For the nonlinear model of ROVs [10], if Assumption 1-3 are satisfied, the trajectory tracking error e will asymptotically converge to zero using the following controller as

$$\begin{aligned} u &= u_0+u_d+u_f, \\ u_0 &= B_{0r}{}^{-1}\Psi, \\ u_d &= B_{0r}{}^{-1}\rho\,\mathrm{sgn}(s), \\ u_f &= B_{0r}{}^{-1}\gamma|\Psi|\mathrm{sgn}(s) \end{aligned} \quad (14)$$

And the adaptive laws are designed as

$$\dot{\rho}=\lambda_\rho|s| \quad (15)$$

$$\dot{\gamma}=\lambda_\gamma|s||\Psi| \quad (16)$$

where $B_{0r}=J(\eta)M_0^{-1}B_0$ and $\Psi=\lambda\dot{e}+\ddot{\eta}_d-J(\eta)v+J(\eta)M_0^{-1}[C_0(v)v+D_0(v)v+g_0(\eta)]$. u_0 is the nominal control signal, u_d and u_f are the control signals used to handle external disturbance and partial loss of propulsion, respectively. λ_ρ and λ_λ are constant parameters to be deigned and tuned.

Proof. Define parameter errors as

$$e_\rho=\rho_d-\rho, e_\gamma=\gamma_d-\gamma. \quad (17)$$

where

$$\rho_d=\frac{f}{1-L}, \gamma_d=\frac{L}{1-L} \quad (18)$$

It should be noted that γ_d actually cannot be obtained, meanwhile they are also not used in the proposed method. These two parameters are just defined here for the stability analysis in the following procedure.

Then, differentiating (17) with respect to time yields

$$\dot{e}_\rho=-\dot{\rho}, \dot{e}_\gamma=-\dot{\gamma}. \quad (19)$$

Choosing a Lyapunov function as

$$V=\frac{1}{2}s^2+\frac{1}{2}\frac{1-L}{\lambda_\rho}e_\rho^2+\frac{1}{2}\frac{1-L}{\lambda_\gamma}e_\gamma^2 \quad (20)$$

Differentiating (20) with respect to time and combining (15)-(19) yields

$$\begin{aligned} \dot{V} &= s\dot{s}+\frac{1-L}{\lambda_\rho}e_\rho\dot{e}_\rho+\frac{1-L}{\lambda_\gamma}e_\gamma\dot{e}_\gamma \\ &= s\left(\Psi-J(\eta)M_0^{-1}(B_0+\Delta B)u-J(\eta)M_0^{-1}F\right) \\ &\quad -(1-L)(\rho_d-\rho)|s|-(1-L)(\gamma_d-\gamma)|s||\Psi| \end{aligned} \quad (21)$$

Substituting Eq. (11) into Eq. (21) and combining Eq. (18), we have

$$\begin{aligned} \dot{V} &= -sJ(\eta)M_0^{-1}F-s\Delta BB_0^{-1}\Psi-\rho|s|-\Delta BB_0^{-1}\rho|s| \\ &\quad -\gamma|\Psi||s|-\Delta BB_0^{-1}\gamma|\Psi||s|-(1-L)(\rho_d-\rho)|s| \\ &\quad -(1-L)(\gamma_d-\gamma)|s||\Psi| \\ &< F|s|+L|s||\Psi|-(1-L)\rho|s|-(1-L)(\gamma_d-\gamma)|s||\Psi|=0 \end{aligned} \quad (22)$$

Then, we have

$$\dot{V}<0 \quad (23)$$

Thus, the closed-loop system is asymptotically stable which means the system can asymptotically track the desired trajectory η_d.

Remark 1. To ease the chatters caused by the term $\mathrm{sgn}(s)$. in the controller , the saturation function is used to replace the term $\mathrm{sgn}(s)$.

Remark 2. As shown in above rigorous theoretical derivation, our new proposed method can effectively handle the complex disturbances and partial loss of propeller thrust using the separate adaptive laws, and this is the main contribution of our work.

4 Simulation study

In order to verify the effectiveness of the algorithm, a deep-sea exercise test platform as the simulation object has been developed, as shown in Fig. 1. The main parameters of the test platform is shown in Table 1 [14].

Judging from the analysis above, the adaptive synovial multivariable robust fault-tolerant control could complete well the motion control of the ROV adopting the method. To ensure the ideal control performance, and reduce the complexity of the controller, it is necessary to simplify the model of ROV [17].

This paper adopts the nonlinear four freedom degree simplified model parameter matrix of ROV proposed in paper [17], the parameter matrix is simplified as follows [17]:

$$M = diag\left\{m_v - X_{\dot{u}}, m_v - Y_{\dot{v}}, m_v - Z_{\dot{w}}, I_z - N_{\dot{r}}\right\}. \tag{24}$$

$$c(v) = \begin{bmatrix} 0 & 0 & 0 & -(m_v - Y_{\dot{v}})v \\ 0 & 0 & 0 & -(m_v - X_{\dot{u}})u \\ 0 & 0 & 0 & 0 \\ (m_v - Y_{\dot{v}})v & -(m_v - X_{\dot{u}})u & 0 & 0 \end{bmatrix} \tag{25}$$

$$D(v) = -diag\left\{X_u + X_{u|u|}u, Y_v + Y_{v|v|}v, Z_w + Z_{w|w|}w, N_r + N_{r|r|}r\right\} \tag{26}$$

$$g(\eta) = \begin{bmatrix} 0 & 0-(W-B) & 0 \end{bmatrix}^T \tag{27}$$

$$J(\eta) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 & 0 \\ \sin\psi & \cos\psi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{28}$$

The simulation of external disturbance is set.

$$\Delta f = \begin{bmatrix} 50+100\sin(0.314t)\text{kgf} \\ 50+100\sin(0.314t)\text{kgf} \\ 50+100\sin(0.314t)\text{kgf} \\ 50+100\sin(0.314t)\text{kgf}\cdot\text{m} \end{bmatrix} \tag{29}$$

Controller parameters used in the simulations:

$\lambda = diag\{1.2, 5.2, 1.25, 2.4\}$,

$\lambda_\rho = 0.001diag\{10, 6, 15, 8\}$,

$\lambda_\gamma = diag\{0.2, 0.09, 1, 0.1\}$,

$\lambda = 0.05I_{4\times4}$.

In order to simplify the simulation process, it is assumed that all the failure degree of propeller are same,that is to say, 20% propeller thruster failure can olny output the nominal value of 80%.

Table 1 Parameters of the test platform

Parameters	Value	Parameters	Value
m_V/kg	2500	K_p/(kg·m²/(s·rad))	−9810
W/N	24525	/(kg·m²/(s·rad))	−19620
B/N	25020	N_r/(kg·m²/(s·rad))	−7848
z_B/ m	−0.493	$X_{u\|u\|}$/(kg/m)	−952
I_x/(kg·m²)	440	$Y_{v\|v\|}$/(kg/m)	−1364
I_y/(kg·m²)	1300	$Z_{w\|w\|}$/(kg/m)	−3561
I_z/(kg·m²)	1250	$K_{p\|p\|}$/(kg·m²/rad²)	−890
$X_{\dot{u}}$/kg	−2140	$M_{q\|q\|}$/(kg·m²/rad²)	−1876
$Y_{\dot{v}}$/kg	−1636	$N_{r\|r\|}$/(kg·m²/rad²)	−773
$Z_{\dot{w}}$/kg	−3000	τ_{umax}/N	7564
$K_{\dot{p}}$/(kg·m²)	−1664	τ_{vmax}/N	7564
$M_{\dot{q}}$/(kg·m²)	−4947	τ_{wmax}/N	3434
$N_{\dot{r}}$/(kg·m²)	−1524	τ_{pmax}/(N·m)	1960
X_u/(kg/s)	−3610	τ_{qmax}/(N·m)	1470
Y_v/(kg/s)	−4660	τ_{rmax}/(N·m)	9810
Z_w/(kg/s)	−11772		

4.1 No outside interference and propeller thruster failure

The simulation results are shown in Fig. 2 and Fig. 3. Seen from them, the system can reach quickly a steady state in x, y, z directions, and steady-state error becomes smaller, while yawing after about 40s gradually stabilized, the steady-state error becomes very small. It can be seen from the results above, that the algorithm can still track very well the desired signal without the precise information about foreign interference. At the same time, the algorithm to foreign interference has a good robustness judging from small tracking error.

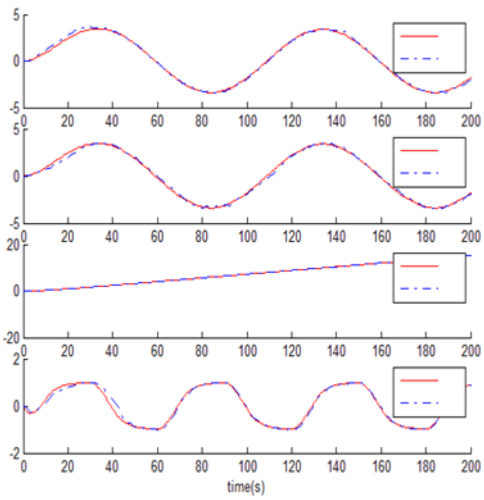

Fig. 2 Simulation Results of $\boldsymbol{\eta}$ (Blue) Tracking $\boldsymbol{\eta}_d$ (Red)

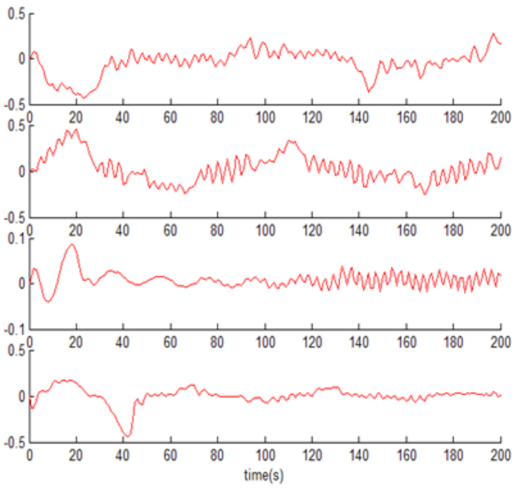

Fig. 3 Simulation Results of Position Tracking Errors

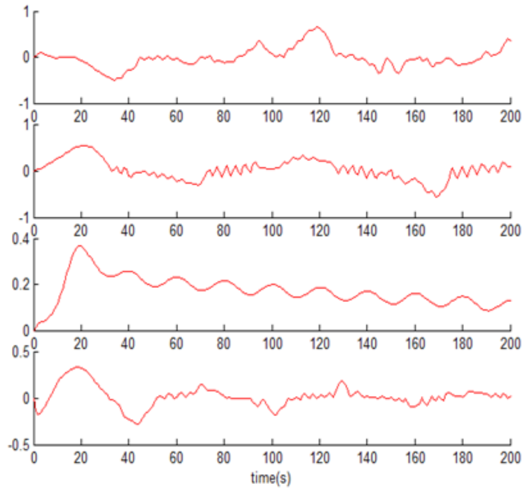

Fig. 5 Simulation Results of Position Tracking Errors

4.2 Foreign interference and 35% propeller thruster failure

The simulation results are shown in Fig. 4, shown in Fig. 5. Seen from them, under the condition of the 35% propeller thruster failure, the performance of dynamic tracking is still more ideal, steady-state error increases compared to no failure. in x direction it has about 15% error when the time is approximately 120 seconds, and the steady-state error of the other time is less than 10%. the steady-state error in y direction is better than x direction,locating in less than 10%. The steady-state error in z direction has good dynamic performance and the steady-state error decreases with the increase of time. The control performance of bowing is still very good. It is basically same to the condition above.

That is to say that this algorithm is still applicable under the condition of the 35% propeller thruster failure.

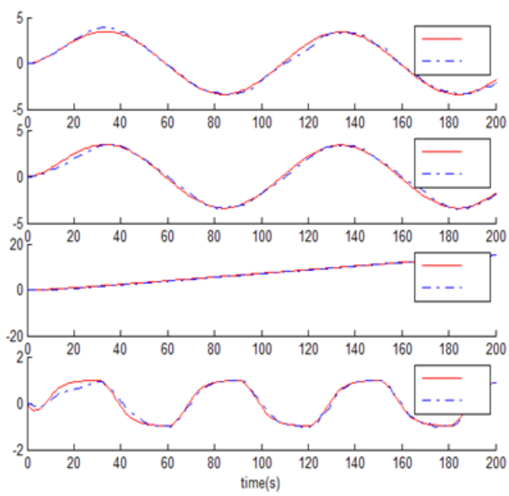

Fig. 4 Simulation Results of $\boldsymbol{\eta}$ (Blue) Tracking $\boldsymbol{\eta}_d$ (Red)

4.3 Foreign interference and 60% propeller thruster failure

Judging from the simulation results shown in Fig. 6 and Fig. 7, a marked deterioration will become under the condition of the propeller thruster failure 60%, in the tracking performance of the controller compared to the thruster failure 35%, and the error increases nearly doubled in x, y direction. On the other hand the z direction error reaches a maximum near to 50%. However, the control performance of bowing is still good, indicating that this algorithm in yawing control [23] has a good control performance.

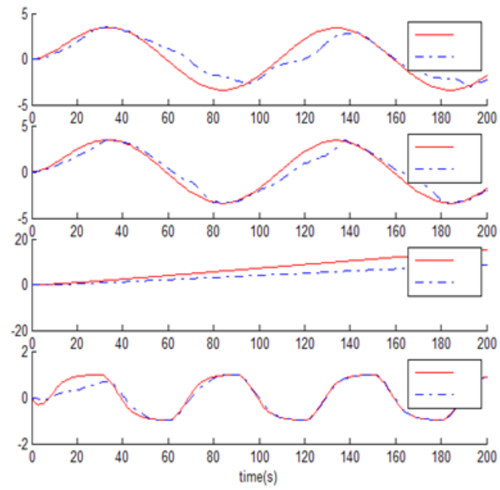

Fig. 6 Simulation Results of $\boldsymbol{\eta}$ (Blue) Tracking $\boldsymbol{\eta}_d$ (Red)

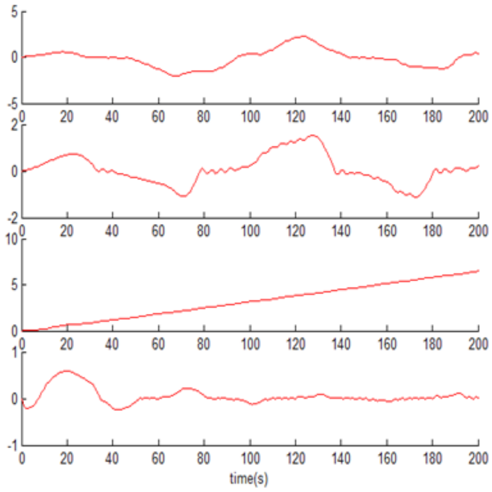

Fig. 7 Simulation Results of Position Tracking Errors

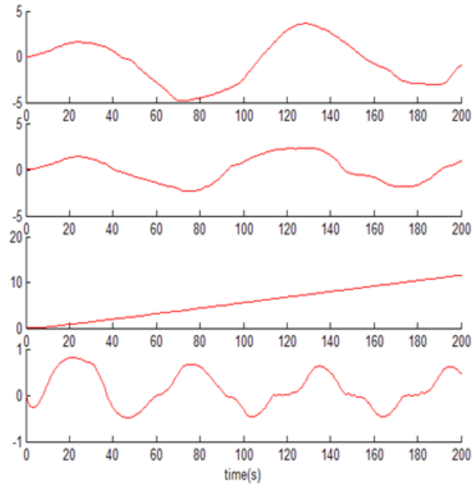

Fig. 9 Simulation Results of Position Tracking Errors

4.4 Foreign interference and 80% propeller thruster failure

Judging from the simulation results shown in Fig. 8 and Fig. 9. The control performance is worse under the condition of the 80% thruster failure, even the yawing control [23] also appears more than 50% of the error, so the algorithm is not applicable to the 80% propeller thruster failure. Based on the four simulation study above under different degree of failure, it can be seen that this algorithm has very good robustness to external complex disturbance, while the tracking performance in four directions (x, y, z and Ψ are very good, and the fault-tolerant ability even more than 60% for yawing control. So it can be said that the use of the algorithm on the ROV model not only has good robustness to foreign interference but also has strong fault tolerance for the part of the propeller thruster failure.

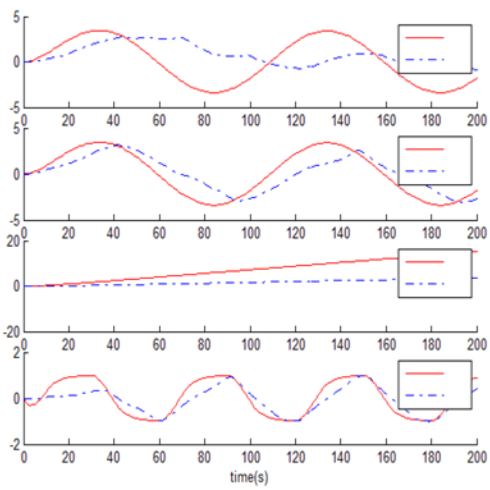

Fig. 8 Simulation Results of $\boldsymbol{\eta}$ (Blue) Tracking $\boldsymbol{\eta}_d$ (Red)

5 Conclusion

Aimed to complex interference and part failure of propeller thruster for the control problem of the operation type ROV, the paper has proposed a multivariable robust fault-tolerant control algorithm based on adaptive synovial. While the algorithm does not need to know the external interference and the failure degree of accurate information, but by an adaptive algorithm to estimate, which greatly improved the practical value of the algorithm. In order to simplify the simulation process, a kind of four degrees of freedom model is used instead of the more complex six degree of freedom model. And the simulation results show that the algorithm not only has good robustness to foreign complex interference, but also has strong ability of fault tolerance for the propeller thruster.

For the future research, the total loss of propeller thrust will be taken into consideration, and corresponding improved FTC method will be given for this situation.

Acknowledgments

This study was funded by the Project (No.51505272) supported by National Science Foundation of China and the Shanghai Funded Training Plan of Young Teachers in Colleges and Universities (No.ZZGCD15043). The authors would like to thank all the anonymous reviewers for their detailed and valuable comments which strengthened this manuscript.

References

[1] Dawe, C. T., Stakes, D. S., McGill, P. R., Barry, J., Etchemendy, S. "Subsea instrument deployments: methodology and techniques using a work class remotely operated vehicle (ROV)." *Oceans '98 Conference Proceedings*. Nice, France, Sep. 28-Oct. 1, 1998. pp. 1589-1593. https://doi.org/10.1109/OCEANS.1998.726340

[2] Xu, Y., Pang, Y., Gan, Y., Sun, Y. "AUV-state-of-the-art and prospect." *CAAI Transactions on Intelligent Systems*. 1, 2006.

[3] Blanke, M., Zamanabadi, R. I., Bogh, S. A., Lunau, C. P. "Fault-tolerant control systems – a holistic view." In: Tutorial Workshop on Supervision, Fault Detection and Diagnosis of Technical Systems, 13th IFAC World Congress, San Francisco, CA, Jun. 30–Jul. 5., 1996. pp. 693-702.

[4] Zhang, Y., Jiang, J. "Bibliographical review on reconfigurable fault-tolerant control systems." *Annual Reviews in Control*. 32(2), pp. 229-252. 2008. https://doi.org/10.1016/j.arcontrol.2008.03.008

[5] Kobayahi, Y., Ikeda, M., Fujisaki, Y. "Stability of large space structures preserved under failures of local controllers." *IEEE Transactions on Automatic Control.* 52(2), pp. 318-322. 2007. https://doi.org/10.1109/TAC.2006.887897

[6] Alwi, H., Edwards, C. "Fault tolerant control using sliding modes with on-line control allocation." *Automatica*. 44(7), pp. 1859-1866. 2008. https://doi.org/10.1016/j.automatica.2007.10.034

[7] Soylu, S., Buckham, B. J., Podhorodeski, R. P. "A chattering-free sliding-mode controller for underwater vehicles with fault-tolerant infinity-norm thrust allocation." *Ocean Engineering.* 35(16), pp. 1647-1659. 2008. https://doi.org/10.1016/j.oceaneng.2008.07.013

[8] Corradini, M. L., Monteriu, A., Orlando, G. "An Actuator Failure Tolerant Control Scheme for an Underwater Remotely Operated Vehicle." *IEEE Transactions on Control Systems Technology.* 19(5), pp. 1036-1046. https://doi.org/10.1109/TCST.2010.2060199

[9] Yan, M.-Z., Liu, Q., Zhu, D.-Q. "Fault tolerant control and experimental study for underwater vehicles based on neural network." *Ship & Ocean Engineering*. 38(5), pp. 138-141. 2009.

[10] Zhu, D.-Q., Chen, L., Liu, Q. "Sensor fault diagnosis and fault-tolerant control method of underwater vehicles." *Control and Decision*. 24(9), pp. 1335-1339. 2009.

[11] Hu, C.-H., Xu H.-L. "Design and Analysis of Fault-tolerant Control and Fault Diagnosis for Control System." National Defence Industry Press, 2000.

[12] Chen X.-Q., Geng, Y.-H., Zhang, Y.-C., Wang, F. "Robust fault-tolerant H-infinity control based on LMI approach and application in satellite attitude control system." *Control Theory & Applications*. 25(1), pp. 95-99. 2008.

[13] Jiang, Y., Hu, Q., Ma, G. "Adaptive backstepping fault-tolerant control for flexible spacecraft with unknown bounded disturbances and actuator failures." *ISA Transactions.* 49(1), pp. 57-69. 2010. https://doi.org/10.1016/j.isatra.2009.08.003

[14] Zhu, K., Gu, L. "A MIMO Nonlinear Robust Controller for Work-Class ROVs Positioning and Trajectory Tracking Control." In: Control and Decision Conference (CCDC), May 23-25, 2011, pp. 2565-2570. https://doi.org/10.1109/CCDC.2011.5968643

[15] Wang, Y., Chen, J., Gu, L. "Output Feedback Fractional-Order Nonsingular Terminal Sliding Mode Control of Underwater Remotely Operated Vehicles." *The Scientific World Journal.* 3, p. 19. https://doi.org/10.1155/2014/838019

[16] Wang, T., Xie, W., Zhang, Y. "Sliding mode fault tolerant control dealing with modeling uncertainties and actuator faults." *ISA Transactions.* 51(3), pp. 386-392. 2012. https://doi.org/10.1016/j.isatra.2012.02.003

[17] Zhu, K-W., Gu, L. "Multivariable back stepping robust control for work-class remotely operated vehicle." *Control Theory & Applications*. 28(10), pp. 1441-1446. 2011.

[18] Wang, Y., Gu, L., Gao, M., Zhu, K. "Multivariable output feedback adaptive terminal sliding mode control for underwater vehicles." *Asian Journal of Control.* 18(1), pp. 247-265. https://doi.org/10.1002/asjc.1013

[19] Kamarlouei, M., Ghassemi, H. "Robust control for horizontal plane motions of autonomous underwater vehicles." *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. 38(7), pp. 1921-1934. 2016. https://doi.org/10.1007/s40430-015-0403-8

[20] Kaviarasan, B., Sakthivel, R., Kwon, O. M. "Robust fault-tolerant control for power systems against mixed actuator failures." *Nonlinear Analysis: Hybrid Systems*. 22, pp. 249-261. 2016. https://doi.org/10.1016/j.nahs.2016.05.003

[21] Sakthivel, R., Santra, S., Mathiyalagan, K., Su, H. "Robust reliable control design for networked control system with sampling communication." *International Journal of Control*. 88(12), pp. 2510-2522. 2015. https://doi.org/10.1080/00207179.2015.1048294

[22] Sakthivel, R., Selvaraj, P., Mathiyalagan, K., Park, J. H. "Robust fault-tolerant control for offshore steel jacket platforms via sampled-data approach." *Journal of the Franklin Institute.* 352(6), pp. 2259-2279. https://doi.org/10.1016/j.jfranklin.2015.03.016

[23] Peng, Z., Wang, D., Wang, H., Wang, W. "Distributed coordinated tracking of multiple autonomous underwater vehicles." *Nonlinear Dynamics*. 78(2), pp. 1261-1276. 2014. https://doi.org/10.1007/s11071-014-1513-z