Research on adaptive AUV tracking control system based on least squares support vector machine

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Received 1 February 2014, www.tsi.lv

Abstract

Aimed at the nonlinear, uncertainties and impreciseness in AUV tracking control, an adaptive LSSVM control is highlighted. It is including the approximate dynamic inversion control law, linear controller and the robust adaptive LSSVM controller. The key is designed that adaptive LSSVM controller, which is to decrease or offset the uncertain dynamic inverse model errors. The online adjustment LSSVM parameters rules are deduced by the Lyapunov stability theorem. So the closed-loop tracking control system's stability and asymptotical convergence of tracking error can be guaranteed. It can be seen that the tracking errors converge and stay at a small neighbourhood of zero. At last taken a certain real AUV as an example, the numerical simulation results are given in the presence of the ocean current wave interference. They show the proposed method has good tracking performance and a certain robustness against modelling errors.

Keywords: AUV, LSSVM, tracking control, adaptive controller

1 Introduction

Since last decade AUV (Autonomous Underwater Vehicle, AUV) has gradually developed a new type of underwater vehicle with some type of autonomous navigational capability. It can be replaced manned vehicle, especially in dangerous tasks or difficult to reach the sea field. Thus, it is necessary to design an autonomous and precise guidance control system. The tracking control is essentially complete AUV motion control. The main task is accurately tracking a given path considering the AUV actual position and the state of motion. It is a very important link for AUV navigation. But the AUV has strong nonlinear uncertain parameters. And it is difficult to establish precise mathematical model. It is a more difficult problem to robust adaptive control.

Considered the relative merits of previous models, an adaptive LSSVM tracking control model for AUV is key put forward in the study. There is no dimension disaster and local minimum problems based on empirical risk minimization. It can solve the nonlinear uncertainty of error approximation problem during the AUV tracking control. And it has the high learning speed, good generalization and fine robustness. It can effectively prevent the over fitting phenomenon. The LSSVM provides a good effective means for nonlinear system identification and modelling. Therefore, the AUV tracking control is designed by the adaptive LSSVM controller in the study.

The rest of the paper is organized as follows. The problem formulation of the AUV tracking control system is presented in the section 2. It is including the velocity and the heading subsystem. The next section is the key. The section 3 shows the robust adaptive controller based on the LSSVM. It consists of the approximate dynamic inversion control law, linear controller and the robust adaptive LSSVM controller. The simulation study of the adaptive LSSVM tracking controller is in the section 4. Firstly the AUV tracking control simulation model is given. Then the simulation results of the AUV tracking control are provided to demonstrate the robust adaptive LSSVM controller. At last, conclusions are drawn.

2 Problem Formulation of the AUV Tracking Control System

A complete six degree-of-freedom mathematical model for AUV can be found in reference [5]. Assume that the coupling was neglected the coupling between longitudinal and lateral movement. The uncertain AUV tracking equations can be simplified as described below.

$$\begin{cases} \dot{x}_v = x_a \\ \dot{x}_a = \overline{f}(x_v, x_a, u_1) + \tilde{f}(x_v, x_a, u_1), \\ y_1 = Cx = x_v \end{cases} \quad (1)$$

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$$\begin{cases} \dot{x}_\psi = x_r \\ \dot{x}_r = \bar{f}(x_\psi, x_r, u_2) + \tilde{f}(x_\psi, x_r, u_2). \\ y_2 = Cx = x_\psi \end{cases} \quad (2)$$

$x_1 = (x_v, x_\psi)^T$, $x_2 = (x_a, x_r)^T$, $u = (u_1, u_2)^T$, $y = (y_1, y_2)^T$, where $x_1, x_2 \in R^n$, x_1 is the control output. x_v and x_ψ is the AUV velocity and the yaw output, respectively. x_2 is the derivative of the AUV speed and yaw. Namely, they are acceleration and angular rate. The control put is $u \in R^m$. The u_1 and u_2 are the rudder control input. The output is $y \in R^n$. C is the appropriate dimensional matrix. $\bar{f}$ is the nominal value. $\tilde{f}$ is uncertainties.

Note $x = (x_1^T, x_2^T)$, $f = \bar{f} + \tilde{f}$.

The asymptotic stability reference model is:

$$\begin{cases} \dot{x}_{m1} = x_{m2} \\ \dot{x}_{m2} = -K_{m1}x_{m1} - K_{m2}x_{m2} + K_{m1}r , \\ y = C_m x_m = x_{m1} \end{cases} \quad (3)$$

where $x_{m1}, x_{m2} \in R^n$, $x_m = (x_{m1}^T, x_{m2}^T)^T$, $r \in R^n$ is the input of the reference model. $y_m \in R^n$ is the output of the reference model. C_m and $K_{mi}(i-1,2)$ are the optimal dimensional matrixes. The control goal is to design robust adaptive control law u makes the closed loop system stable. And the output y can track the any given reference signal y_m.

3 Design of Robust Adaptive Controller

The robust adaptive controller is including the approximate dynamic inversion control law, linear controller and the robust adaptive LSSVM. The first one is approximate dynamic inversion control law. It is to decrease or offset the nonlinear and time-variant characteristic. The online LSSVM is to minish or counteract uncertain dynamic inverse model errors, which caused by model inaccuracy and uncertainty. Linear control law makes the system response has the desired quality. The principle block diagram of robust adaptive controller is as the following Figure.1.

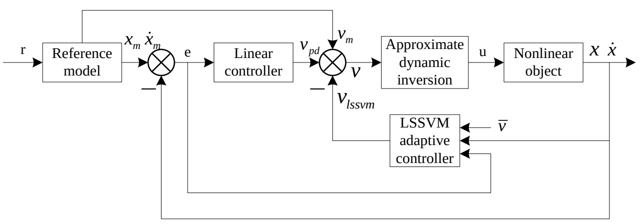

FIGURE 1 The principle diagram of robust adaptive controller

3.1 APPROXIMATE DYNAMIC INVERSE CONTROL

Suppose

$$\bar{f}(x,u) = v , \quad (4)$$

where v is the pseudo-control quantity. The approximate dynamic inverse control law of system (1) are obtained by the Formula (4) of inverse.

$$u = \bar{f}^{-1}(x,v). \quad (5)$$

It must be pointed out that appropriate modify $\bar{f}(x,u)$ to $\hat{f}(x,u)$ to ensure the existence of approximate dynamic inversion control law when there nonexistence the inverse of $\bar{f}^{-1}(x,u)$. Such the introduction of the model inversion errors are compensated by the LSSVM. The approximate dynamic inversion errors often cannot be completely offset the nonlinear because of inaccurate, uncertain factors, interference and even system failure. Therefore, there exists dynamic inversion error.

Note the inverse error is

$$\tilde{f} = f(x,u) - \bar{f}(x,u), \quad (6)$$

$$\ddot{x}_1 = v + \tilde{f} . \quad (7)$$

3.2 DESIGN OF LINEAR PD CONTROLLER

Set pseudo-control quantity

$$v = v_{pd} + v_m + v_{lssvm} , \quad (8)$$

where

$$\begin{cases} v_{pd} = K_p(x_{m1} - x_1) + K_D(\dot{x}_{m1} - \dot{x}_1) \\ v_m = \ddot{x}_{m1} \end{cases} , \quad (9)$$

where, K_P and K_D are the appropriate dimensional proportional and differential parameters matrix. v_{pd} is the output of the linear controller. It is the proportional derivative control. v_m is the signal from the reference model. v_{lssvm} is the LSSVM adaptive output signal. It is used to offset the inverse error $\tilde{f}$. x_{m1} is the status signals of the reference model.

The Eq. (8) and Eq. (9) are substituted into the formula (7). After the compilation, it can be tracking error dynamic characteristics. It is as follows.

$$\dot{e} = Ae + B(v_{lssvm} - \tilde{f}). \quad (10)$$

The system matrix A can be a Hurwitz matrix by selecting reasonable parameters K_P and K_D. If the K_P and K_D are diagonal matrix the Lyapunov equation is constructed as follows.

$$PA + A^T P = -I . \quad (11)$$

Positive definite symmetric solution is

$$P = \begin{bmatrix} \frac{K_D K_P^{-1}}{2} + \frac{K_P K_D^{-1}}{2} & \frac{K_P^{-1}}{2} \\ \frac{K_P^{-1}}{2} & \frac{K_D^{-1}}{2}\left(1 + K_P^{-1}\right) \end{bmatrix} . \quad (12)$$

Theorem 1: To the given asymptotically stable reference model (3), the state of the system can be completely track the reference model output when $K_P = K_{m1}$, $K_D = K_{m2}$ and there is no inverse error or the inverse error completely offset by using LSSVM.

Prove: it is gained between the Eq. (7) and Eq. (8).

$$\ddot{x}_1 = K_P x_{m1} - K_P x_1 + K_D \dot{x}_{m1} - K_D \dot{x}_1 + \ddot{x}_{m1} . \quad (13)$$

Let Eq. (3) into equation (13). It can be gained when $K_P = K_{m1}$ and $K_D = K_{m2}$.

$$\dot{x}_1 = x_2, \dot{x}_2 = -K_{m1} x_1 - K_{m2} x_2 + K_{m1} r .$$

Thus, it can be seen the state of the system response is the reference model state response.

3.3 THE DESIGN OF THE ADAPTIVE LSSVM CONTROLLER

3.3.1 LSSVM Model

The LSSVM is proposed by Suykens. It is used to solve classification and function estimation problems. The function estimation algorithm of LSSVM is deduced briefly as follows. Suppose the training sample is a n-dimensional vector, and N samples form the sample set D, $D = \{(x_i, y_i) | i = 1,2,\ldots,N\}$, $x_i \in R^n$, $y_i \in R$, where x_i is an input data, and y_i the corresponding output value. LSSVM can map the data to a high-dimensional feature space by using a nonlinear mapping ϕ. Then, the equation of linear regression is

$$y(x) = w^T \phi(x) + b , \quad (14)$$

where $w \in R^{n_h}$ is a weight vector, b is a constant bias.

The learning process can be translated into an optimization problem according to the principle of structural risk minimization.

$$\min J(w,e) = \frac{1}{2} w^T w + \frac{1}{2} C \sum_{i=1}^{N} e_i^2 \text{ , s.t.}$$

$$y_i = w^T \varphi(x_i) + b + e_i \text{, i=1, 2,…,N.} \quad (15)$$

$\varphi(x): R^n \ to\ R^{n_h}$ is a mapping function in the kernel space, $e_i \in R$ is the error variance, J is the loss function, C is the adjustable regularized parameter.

A Lagrangian function can be introduced to solve the above optimization problem, which can transform the optimization with constraint to the optimization without constraint.

$$L(w, b, \dot{e}, a) = J(w, e) - \sum_{i=1}^{N} \alpha_i \left(w^T \varphi(x_i) + b + e_i - y_i \right), \quad (16)$$

where $\alpha_i \in R$ is a Lagrangian multiplier. The partial derivatives of L with respect to w, b, e_i and α_i are found out according to Karush-Kuhn-Tucker (KKT condition. The middle variables w and e_i are eliminated, and the solution of α_i and b can be obtained

$$\begin{bmatrix} 0 & \eta \\ s & \Omega + \gamma^{-1} I \end{bmatrix} \begin{bmatrix} \alpha \\ b \end{bmatrix} = \begin{bmatrix} 0 \\ Y \end{bmatrix}, \quad (17)$$

where $\Omega \in R^{N \times N}$, $\Omega_{km} = \phi^T(x_k)\phi(x_m)$, $Y = [y_1, \ldots, y_N]^T$, η is a N-dimensional column vector, namely, $\eta = [1..N]$, $\alpha = [\alpha_1, \ldots, \alpha_N]$, I is a confirmed matrix, S is a N dimensional row vector, namely, $s = [1..N]^T$.

So the function estimation can be expressed as

$$y(x) = \sum_{i=1}^{N} \alpha_i K(x_i, x_j) + b , \quad (18)$$

where $K(x_i, x_j)$ is the kernel function that meets Mercer requirements [9]. Gaussian radial basis function (RBF) is selected as the kernel function in this paper.

$$K(x_i, x_j) = \exp\left(- \|x_i - x_j\|^2 / 2\delta^2 \right), \quad (19)$$

where $K(x_i, x_j)$ is the kernel function that meets Mercer requirements [9]. δ is the kernel factor, i.e. the width of the kernel function.

3.3.2 The structure of the adaptive LSSVM controller

The dynamic inversion error signal is approached by the LSSVM. The outputs of support vector machine are the pseudo-linear system control inputs. The errors are online eliminated. The structure drawing of the adaptive LSSVM is as followings figure. 2.

In figure 2 $\bar{x}=\left[x^T,\dot{x}^T,e^T,\dot{e}^T,\bar{v}^T\right]^T$ is the input vector. $\bar{v}$ is a signal after the pseudo control amount V saturated nonlinear processed. The hidden layer nodes is $N+1$. Where, the first node is defined as the deviation of the hidden layer. Its value is 1 from the formula (18). $w_j(1,2,\ldots,N,N+1)$ are the weights of the hidden layer and the output one, where $w_1=b$, $w_j=a_{j-1}(j=2,3,..N,N+1)$.

The input-output relation of LSSVM is

$$v_{lssvm}=W^T\beta, \tag{20}$$

where $W=[w_1,w_2,\ldots,w_{N+1}]^T$, $\beta[1,K(x_1,\bar{x}),..K(x_N,\bar{x})]$.

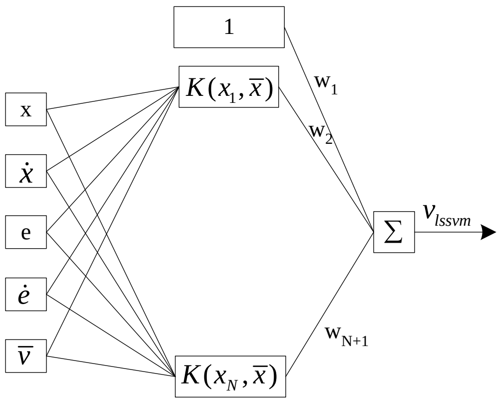

FIGURE 2 The structure drawings of the adaptive LSSVM

There exists the optimal weight vector W^* when reconstruction error $\varepsilon<0$ for the continuous uncertain nonlinear inverse error function $\tilde{f}$ and any given inverse error because LSSVM algorithm can be approached the continuous nonlinear function in arbitrary precision. It makes the following equation is established.

$$\left|W^{*T}\beta-\tilde{f}\right|\le\varepsilon,\ \varepsilon>0. \tag{21}$$

The system tracking error dynamic equation (10) is re-writing the following formula:

$$\dot{e}=Ae+B\tilde{W}^T\beta+B\left(W^{*T}\beta-\tilde{f}\right), \tag{22}$$

where $\tilde{W}=W-W^*$. W^* is the optimal weight vector.

Theorem 1: For the AUV velocity formula (1) and heading (2) system, Least squares support vector machine dynamic inversion error compensated control structure is as Fig.1. The analytical expression of the control structure is the formula (8). The adaptive compensation term is the equation (20). The all signals in the closed-loop tracking control system remain bounded when the law of weight adjustment is the formula (23). Where $\gamma>0$ is the adaptive gain. P is the equation (12).

$$\begin{cases}\dot{W}=\dot{\tilde{W}}=-\gamma e^T PB\beta, & \|e\|\ge e_0\\ 0, & \|e\|\le e_0\end{cases}. \tag{23}$$

Prove: the following Lyapunov function is selected.

$$V=\begin{cases}\frac{1}{2}e^T Pe+\frac{1}{2\gamma}\tilde{W}^T\tilde{W} & \|e\|\ge e_0\\ E_0+\frac{1}{2\gamma}\tilde{W}^T\tilde{W} & \|e\|\le e_0\end{cases}. \tag{24}$$

The E_0 in the equation (24) is satisfied

$$E_0=\frac{1}{2}e^T Pe,\ \|e\|=e_0. \tag{25}$$

It can be ensure that V is continuous when the error is at the boundary of the dead zone.

There is equation (26) outside the dead zone $\|e\|\ge e_0$.

$$\dot{V}=\frac{1}{2}\dot{e}^T Pe+\frac{1}{2}e^T P\dot{e}+\frac{1}{\gamma}\tilde{W}^T\dot{\tilde{W}}. \tag{26}$$

It can be gained by the formula (22) and (23).

$$\dot{V}=-\frac{1}{2}e^T Ie+e^T PB\left[W^{*T}\beta+\left(W^{*T}\beta-\tilde{f}\right)\right]+\frac{1}{\gamma}\tilde{W}^T\dot{\tilde{W}}. \tag{27}$$

By the formula (21)

$$\dot{V}\le-\frac{1}{2}e^T Ie+\varepsilon\left|e^T PB\right|+\tilde{W}^T\left(e^T PB\beta+\frac{1}{\gamma}\dot{\tilde{W}}\right). \tag{28}$$

The adaptive law can be got by using the formula (23).

$$\begin{aligned}\dot{V}&\le\left(-\frac{1}{2}e^T Ie+\varepsilon\left|e^T PB\right|\right)\\ &\le\left(-\frac{1}{2}\|e\|\lambda_{\min}(I)\|e\|-2\varepsilon\lambda_{\max}(P)\right)\end{aligned}, \tag{29}$$

$$\because\ \|B\|=1$$
$$\therefore\ \dot{V}<0,$$

when

$$\|e\|>\frac{2\varepsilon\lambda_{\max}(P)}{\lambda_{\min}(I)}>2\varepsilon\lambda_{\max}(P). \tag{30}$$

So if $\|e\| > e_0$, then $\dot{V} < 0$. If $\|e\| \le e_0$, then $\dot{V} = 0$.

Because of $\dot{\tilde{W}} = 0$ in the formula (23).

In short V has the following properties.

(1) The V is a continuous when $V \ge E_0 > 0$ and $\|e\| = e_0$;

(2) $\dot{V} < 0$ when $\|e\| > e_0$; $\dot{V} = 0$ when $\|e\| \le e_0$;

(3) Assume $\|e(t_0)\|$ and $\|\tilde{W}(t_0)\|$ are bounded, then $V \ge \lambda_{\min}(P)\|e\|^2/2 + \|\tilde{W}\|^2/2$.

The properties (1)~(3) mean that $\|et\|$ and $\|\tilde{W}t\|$ are uniformly bounded

When the $\varepsilon = 0$ the dead zone definition in the equation (30) is zero. The formula (22) and (23) can be changed into the followings.

$$\dot{e} = Ae + B\tilde{W}^T\beta, \tag{31}$$

$$\dot{\tilde{W}} = -\gamma e^T PB\beta. \tag{32}$$

The above two equation equilibrium point is the origin $(e = 0, \tilde{W} = 0)$. The corresponding Lyapunov functions are taken as.

$$V = \frac{1}{2}e^T e + \frac{1}{2\gamma}\tilde{W}^T\tilde{W}, \tag{33}$$

$$\dot{V} = -\frac{1}{2}e^T e. \tag{34}$$

The equation state is consistent with stable is described between the equation (31) and (32) from the equation (33) and (34).

The $\dot{e}$ is bounded from the equation (31). Because

$$\frac{1}{2}\int_{t_0}^{\infty} e^T e d\tau = -\int_{t_0}^{\infty} \dot{V} d\tau = V(t_0) - V(\infty) < \infty. \tag{35}$$

So the e is the square integrable. Because $\dot{e}$ and e are bounded, and e square integrable the formula (36) is gained by the Barbalat theorem.

$$\lim_{t\to\infty} e(t) \to 0. \tag{36}$$

So the equation (22) is asymptotically stable by $\varepsilon = 0$.

4 Simulation Study of the Adaptive LSSVM Tracking Controller

To verify the robust adaptive controller's effectiveness, taking a real certain vehicle as objective, the tracking control simulations are conducted. Assume there are 60^o ocean current direction and two sea state wave forces in the simulation environment. The AUV tracks the circle path under the specified speed. Suppose the AUV track along a radius of 4.8m, and the track centre at (0,4.8) circular path. The middle uniform tracking speed is 1.4m/s. the acceleration is the 0.2m/s^2 in the initial and end times. Select 300 data as the training samples, the other 200 data as the test samples. The simulation results are described as follows.

The numerical results are shown in figures. 3-9. the many AUV curves are given. Such as the displacement and velocity, the displacement and heading, the changes sailing speed and heading, the tracking error in the x-direction and y-direction. At last the AUV tracking the circle path by the adaptive LSSVM controller. It can be seen that the tracking errors converge and stay at a small neighbourhood of zero.

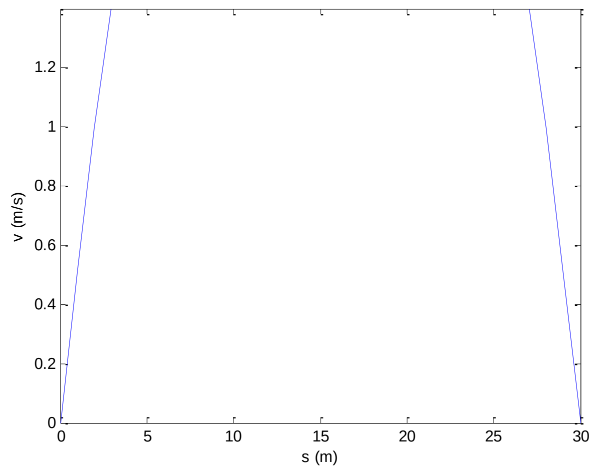

FIGURE 3 The change curve between the displacement and velocity

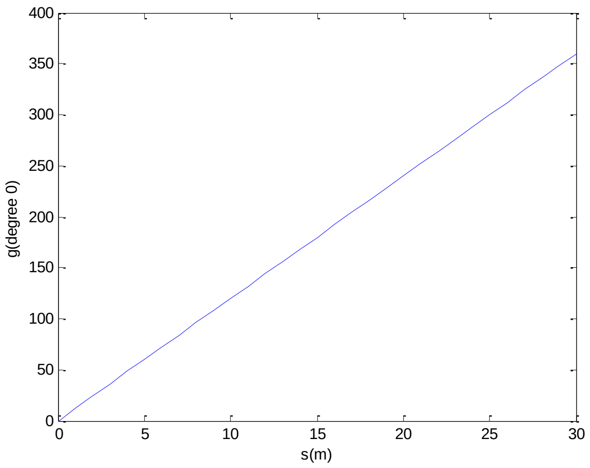

FIGURE 4 The change curve between the displacement and heading

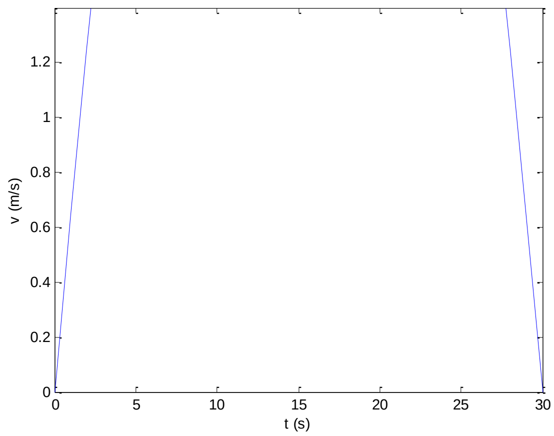

FIGURE5 The changes sailing speed curve

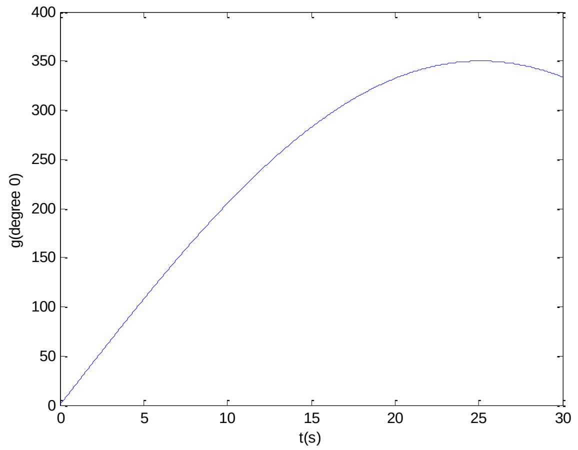

FIGURE 6 The AUV changes heading curve

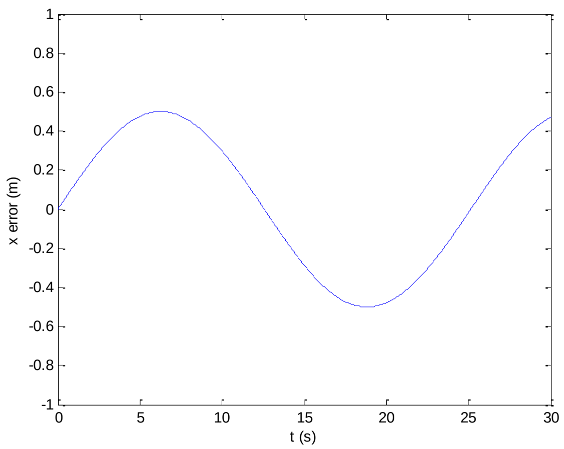

FIGURE 7 The AUV tracking error in the x-direction

The figure 3 shows the AUV has been achieved a desired speed 1.4m/s about less than 5 meters. And it meets the requirements before less than 5 meters distance to the end. The good effect is obvious. The change curve between the displacement and heading is showed in the figure 6. Generally, the yaw angle was linearly increasing trend with the voyage increase. The yaw angle of 360 degrees has been gained when the AUV about runs the full circle, namely the sail distance is about 30 meters. The preferably expectations are reached.

The change sailing speed curve is showed in the Figure 5. The specified speed 1.4m/s is reached with the 0.2m^2/s acceleration in several seconds. And the velocity is reached zero within the a few seconds at the end of the voyage. The system has good rapidity and high accuracy. The Figure6 showed the AUV changes heading curve. The yaw angle is to the 360 degree at about 25s. Namely, the AUV can fully reach tracking the whole circle path. In ideal the all round is about 21s. The heading angle control effect is good considering the rise and fall time.

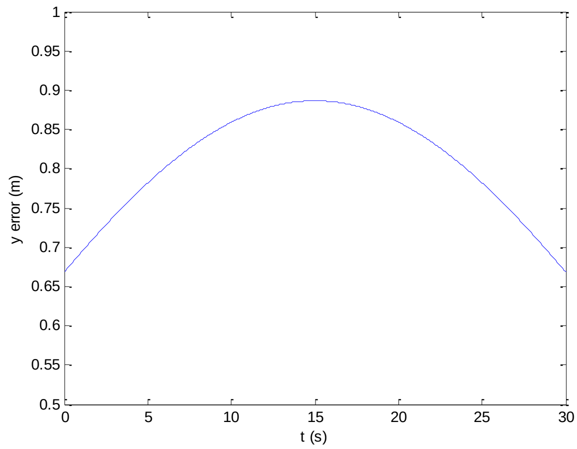

FIGURE 8 The tracking error in the y-direction

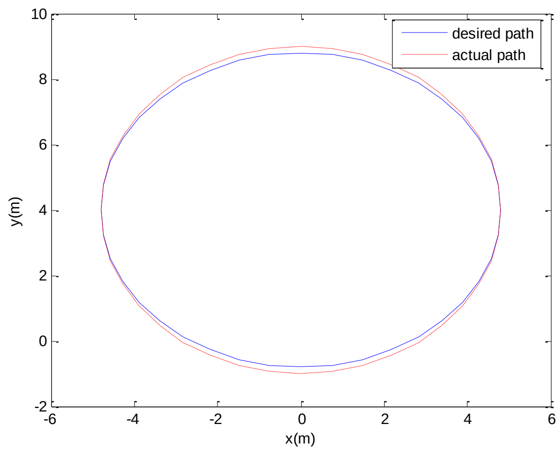

FIGURE 9 Tracking the circle path by the adaptive LSSVM controller

The AUV tracking error is displayed in the x-direction and y-direction from the figure 8 and 9, respectively. The errors do not exceed 1m. The error is very small. The control accuracy is quite satisfactory. At last, the AUV circular path tracking in the horizontal plane in the figure 10. The blue solid line is the ideal path. And the red dotted line is the corresponding actual path. It can be seen there is a certain degree of error between the two situations. However, the error is still in the relatively small area. The overall tracking performance is quite satisfied.

5 Conclusions

In this study the problem of AUV trajectory-tracking has been investigated by the robust adaptive LSSVM controller. The design of robust adaptive controller is focused on. It is including the approximate dynamic inversion control law, linear controller and the robust adaptive LSSVM controller. The third part the robust adaptive LSSVM controller is the key built and designed. The LSSVM model can be approached a continuous nonlinear function in arbitrary precision by the adjusting the weight matrix. The online LSSVM is to minish or counteract the uncertain dynamic inverse model errors, which caused by model inaccuracy and uncertainty. It make the system output can be tracked the output of the reference model as small as possible errors. The online adjustment LSSVM parameters rules are deduced by the Lyapunov stability theorem. So the closed-loop tracking control system's stability and asymptotical convergence of tracking error can be guaranteed. It can be seen that the tracking errors converge and stay at a small neighbourhood of zero. At last taken a certain real AUV as an example, the numerical circle path simulation results are given in the presence of the ocean current wave interference. The numerical results have been showed that the proposed method has good tracking performance and certain robustness against modelling errors. The method have been improved the model's accuracy, reliability and strong anti-interfere capability.

Acknowledgments

The project is financially supported the Education Department of Shaanxi Provincial Government Research Project and the Xi'an Science and Technology Bureau Project. The authors would like to thank the underwater vehicle Institute of Marine Engineering, Northwestern Polytechnical University. The parts of experiment have been done by their help and support. And the authors would like to express my gratitude to my friends who had helped me!

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