Indian Journal of Geo Marine Sciences Vol. 48 (07), July 2019, pp. 1028-1036

RBF-based supervisor path following control for ASV with time-varying ocean disturbance

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A robust model-free path following controller is developed for autonomous surface vehicle (ASV) with time-varying ocean disturbance. First, the geometrical relationship between ASV and virtual tracking point on the reference path is investigated. The differentiations of tracking errors are described with the relative motion method, which greatly simplified the direct differential of tracking errors. Furthermore, the control law for the desired angular velocity of the vehicle and virtual tracking point are built based on the Lyapunov theory. Second, the traditional proportional-integral-derivative (PID) controller is developed based on the desired velocities and state feedback. The radial basic function (RBF) neural network taking as inputs the desired surge velocity and yaw angular velocity is developed as the supervisor to PID controller. Besides, RBF controller tunes weights according to the output errors between the PID controller and supervisor controller, based on the gradient descent method. Hence, PID controller and RBF supervisor controller act as feedback and feed forward control of the system, respectively. Finally, comparative path following simulation for straight path and sine path illustrate the performance of the proposed supervisor control system. The PID controller term reports loss of control even in the unknown disturbance.

[Keywords: Autonomous surface vehicles; Path following; Radial basic function; gradient descent; Error-based line-ofsight guidance]Introduction

Marine control systems have been important topics of advanced ships, intelligent marine equipment. autonomous surface vehicles (ASVs), under water vehicles, bioinspired marine vehicles and so on^{1,2,3}. The harshness of the maritime environment poses great challenges to marine robotics. Hence, the intelligent marine systems must be reliable, robust, and highly autonomous, and it raises requirements on the hardware platform and control algorithm^{4,5,6}. Steering a vehicle along a desired reference path with assigned velocity is an important issue in many marine survey applications^{7,8}. Whether time requirements on this motion are considered would distinguish path following from trajectory tracking. The path following problem of ASVs can be degenerated into trajectory tracking by introducing the additional requirement to follow assigned time schedule, which might deteriorate the system performance^{9,10,11}. Hence, many studies are devoted to the path following problem. For instance, the motion of various types of wheeled robots, marine vehicles, and aircraft^{12,13,14,15,16}.

However, the path following control for low-speed marine vehicles is much more complicated and challenging. Especially for ASVs, with multiple unknown coupling wind, wave and current disturbances, actuator saturation and model nonlinearities^{17,18,19}. In addition, the underactuated configuration for ordinary ASVs on sway direction makes it even harder^{20,21}. A variety of path following control methods have been developed in view different on-line and off-line path planning results^{22,23,24,25,26}, such as slide mode control and its' deformation, fuzzy logical and neural network-based control, studied on 2-D and 3-D path following^{27,28,29,30,31}.

The advanced neural network control was used on general serial-link rigid robot arm³². According to the partial parameters model, the weights tuning law and stability analysis can be selected and conducted³³. Similarly, the neural net controller can be designed for the ASVs³⁴, and the neural net is used to approximate the nonlinear terms in the system and the nonlinear external disturbance. For the ASVs formation control

design³⁵, state observer and neural network are used to reduce the inexact state feedback^{36,37}. In addition, multiple neural networks are used to construct the reinforcement learning scheme, which can compensate the system inner uncertainties and estimate the evaluation function^{38,39,40}. Overall, many sorts of adaptive laws for neural weights are design based on Lyapunov function and back stepping technique.

By incorporating radial basic function neural network (RBF NN), this paper proposes a simple and practical supervisor controller for path following problem. The *materials and methods* section formulates the vehicle model and path-following problem. The control law of the virtual point and desired velocities are designed according to Lyapunov function and back-stepping method. And the kinetic controller is designed based on RBF NN. The *results and discussion* section illustrate the effectiveness of the control system with comparative numerical simulation about straight-line and sine-line path following. The *conclusion* section systematically elaborates the results and some issues for further study.

Materials and Methods

Model description for the underactuated ASV

In addition to the assumption on the symmetry about xz-plane of the underactuated ASV, we assume that the motion on heave, roll and pitch direction are negligible. Hence, the mathematical model of the underactuated ASV moving on the horizontal surface can be described as⁴¹:

$$\begin{cases} \dot{\eta} = J(\psi)\upsilon\\ M\dot{\upsilon} = -C\upsilon - (D+D_n)\upsilon + \tau + J^T(\psi)\tau_c + \tau_w \end{cases}$$
(1)

where the matrix $J(\psi)$, the mass matrix M, hydrodynamic Coriolis and centripetal matrix C(v), the linear and nonlinear damping matrix $D + D_n(v)$ are given as:

$$J(\psi) = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$
$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix}$$
$$C(\psi) = \begin{bmatrix} 0 & 0 & C_{13} \\ 0 & 0 & C_{23} \\ C_{31} & C_{32} & 0 \end{bmatrix}$$

$$D + D_n(v) = \begin{bmatrix} D_{11} & 0 & 0\\ 0 & D_{22} & D_{23}\\ 0 & D_{32} & D_{33} \end{bmatrix}$$

with vector $\eta = [x, y, \psi]^T$ represent the position and orientation of the vehicle in the north-east-down (NED) reference frame; the surge velocity, sway velocity and yaw angular velocity in the body-fixed reference frame are represented with $v = [u, v, r]^T$; and $\tau = [\tau_u, 0, \tau_r]^T$ denotes the thrust force and the turning ship moment that act on the underactuated vehicle in surge and yaw direction respectively.

In addition, the vector $\tau_c = [\tau_{cu}, \tau_{cv}, \tau_{cr}]$ represents the external time-varying current in the earth-based frame, and $\tau_w = [\tau_{wu}, \tau_{wv}, \tau_{wr}]$ represents wave induced disturbance in the body-fixed frame.

Control objectives

A geometrical illustration for the line-of-sight (LOS) guidance law and tracking errors is detailed in Fig. 1. For a vehicle located at $O_h(x, y)$ and a given reference path in NED frame, the along tracking error, cross tracking error and heading errors between the O_b and $O_p(x_r, y_r)$ are represented with x_e , y_e and ψ_e in the Serret-Frenet frame respectively, which is pathtangential moving on the given reference path, and the origin of the frame is the virtual tracking point O_p . The reference path parameters given are by $\Theta_r = (x_r, y_r, \psi_r).$

The velocities of the vehicle are defined in the bodyfixed frame, and $U = \sqrt{u^2 + v^2}$ is the resultant speed, $\beta = atan^2(v, u)$ is the sideslip angle of the vehicle, and $\psi_w = \psi + \beta$ is the course angle. The tracking control objectives are listed as follows:



Fig. 1-Interpretation of LOS guidance law and path following errors

A. Denote the tracking error vector as $\Theta_e = (x_e, y_e, \psi_e)$, and the desired tracking velocity as U_d . Under bounded time-varying external wave and current disturbance, the control objectives yield:

$$\begin{cases} \lim_{t \to \infty} \Theta_e \to 0\\ \lim_{t \to \infty} U \to U_d \end{cases}$$
(2)

B. Design a dynamic controller without accurate model support to simplify the process for control parameters adjustment.

Kinematic control design

In the Serret-Frenet reference frame, denote the tracking errors as:

$$\begin{bmatrix} x_e \\ y_e \\ \psi_e \end{bmatrix} = \begin{bmatrix} \cos\psi_r & \sin\psi_r & 0 \\ -\sin\psi_r & \cos\psi_r & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x - x_r \\ y - y_r \\ \psi_w - \psi_r \end{bmatrix}$$
(3)

In the dynamic system which consists of moving vehicle and moving virtual tracking point on the reference path, the relative moving velocity in the Serret-Frenet reference frame is the first order derivative of Θ_e , which can be expressed as:

$$\begin{cases} \dot{x}_e = U \cos \psi_e + y_e r_p - u_p \\ \dot{y}_e = U \sin \psi_e - x_e r_p \\ \dot{\psi}_e = r + \dot{\beta} - \dot{\psi}_r \end{cases}$$
(4)

with

$$\begin{cases} u_p = \dot{s} \sqrt{\dot{x}_p^2 + \dot{y}_p^2} \\ r_p = \arctan(\dot{y}_p, \dot{x}_p) = \kappa u_p \end{cases}$$

where u_p is the linear velocity of the tracking point O_p along the path-tangential direction, r_p is the angular velocity of the moving tracking point, and κ is the curvature of the reference path at the present moment. The reference path propagates according to u_p and r_p .

Next, defining the cross-tracking error-based LOS guidance law as:

$$\psi_{LOS} = \arctan\left(\frac{y_e}{\Delta}\right) \tag{5}$$

where Δ is the lookahead distance. As shown in Fig. 1, a big Δ is expected when y_e is small, and vice versa. Hence, the variable Δ is design as:

$$\Delta = \Delta_{min} + (\Delta_{max} - \Delta_{min}) \cdot e^{-k_{\Delta} y_e^2}$$
(6)

where Δ_{min} and Δ_{max} denote the minimum and maximum allowed values, respectively. Hence, the

variable Δ is bounded in $(\Delta_{min}, \Delta_{max}]$. Fig. 2 compares the cross-tracking error-based look ahead distance Δ in different constant convergence rate k_{Δ} .

The desired yaw rate control law is designed as:

$$r_{d} = \psi_{r} + \psi_{LOS} - \beta - k_{1}(\psi_{e} - \psi_{LOS})$$
(7)
with
$$\begin{cases} \dot{\psi}_{r} = r_{p} \\ \dot{\psi}_{LOS} = -2y_{e}\dot{y}_{e}k_{\Delta}(\Delta_{max} - \Delta_{min})e^{-k_{\Delta}y_{e}^{2}} \end{cases}$$

For the heading tracking error ψ_e and line-of-sight guidance angle ψ_{LOS} , construct the following Lyapunov candidate function:

$$V_{kin,1} = \frac{1}{2} (\psi_e - \psi_{LOS})^2 \ge 0$$
(8)

The fist-order derivative of $V_{kin,1}$ can be expressed as:

$$\begin{split} \dot{V}_{kin,1} &= (\psi_e - \psi_{LOS}) \cdot \left(\dot{\psi}_e - \dot{\psi}_{LOS}\right) \\ &= (\psi_e - \psi_{LOS}) \\ &\cdot \left(r + \dot{\beta} - \dot{\psi}_r - \dot{\psi}_{LOS}\right) \\ &= -k_1 (\psi_e - \psi_{LOS})^2 \leq 0 \end{split}$$

Design the reference path variable as:

$$\dot{s} = \frac{U\cos\psi_e + k_2 x_e}{\sqrt{\dot{x}_p^2 + \dot{y}_p^2}}$$
(9)

Construct the tracking error Lyapunov candidate function as:

$$V_{kin,2} = \frac{1}{2}(x_e^2 + y_e^2 + (\psi_e - \psi_{LOS})^2) > 0$$
(10)

Consequently, the fist order derivate of $V_{kin,2}$ can be expressed as:

$$\begin{split} \dot{V}_{kin,2} &= \dot{V}_{kin,1} + x_e \dot{x}_e + y_e \dot{y}_e \\ &= \dot{V}_{kin,1} + x_e \big[U \cos \psi_e + y_e r_p - u_p \big] \\ &+ y_e \big[U \sin \psi_e - x_e r_p \big] \end{split}$$



Fig. 2—Error-based look ahead distance in different convergence rate k_{Λ}

$$= -k_1(\psi_e - \psi_{LOS})^2 - k_2 x_e^2 - U \frac{{y_e}^2}{\sqrt{\dot{x_p}^2 + \dot{y_p}^2}} \le 0$$

Thus, $V_{kin,2}$ is nonpositive outside a compact set, $V_{kin,2} = 0$ if and only if $\Theta_e = (0,0,0)$, which reveals that the kinematic tracking system is globally uniformly asymptotically stable under the tracking error-based LOS guidance law and visual tracking point control law.

Kinetic controller

There are so many neural network-based control techniques about marine vehicles, robot manipulator and so on. For model-free controller design methods, always depend on complicated updating process for weights, which will consume more computer resources. For the model-depend and partial-model-depend control method, CFD and towing model test should be conducted to access the model parameters. This paper develops a model-free supervisor controller based on single hidden layer (SHL) RBF neural network (Fig. 3).

The output of the SHL RBF neural network are given by:

$$y = W \cdot H \tag{11}$$

where $W \in \mathbf{R}^{j \times m}$ denote the real $j \times m$ weights matrices, and $H \in \mathbf{R}^m$ denote the SHL output vectors, which are given by:

$$h_r = exp\left(-\frac{\|x - c_r\|^2}{2b_r^2}\right) \tag{12}$$

where $c_r = [c_{r,1}, c_{r,2} \cdots c_{r,n}]$ is the center vector for neuron r, and $b = [b_1, b_2 \cdots b_m]$ is the width vector.

The supervisory learning mechanism is shown in Fig. 4, wherein the feed forward supervisor controller establishes the inverse model of the vehicle by

learning the traditional propositional derivative (PD) controller online in the initial state. And the feedback controller is recalled when the system is disturbed severely, which guarantee the stability and the robustness of the system.

With the desired surge velocity and yaw angular velocity, the input vector of the network is given by:

$$\rho = \begin{bmatrix} U_d & r_d \end{bmatrix} \tag{13}$$

Thus, the direct dynamic error vector is given as:

$$e_{\rho}^{T} = \begin{bmatrix} U_d - U & r_d - R \end{bmatrix}$$
(14)

Let the velocity error vector pass through a firstorder filter with time constant vector $\gamma = [\gamma_u, \gamma_r]$:

$$e_{f,n} = \gamma e_{\rho} + (1 - \gamma) e_{f,n-1}$$
 (15)

where the constant vector $\gamma \in [0,1]$, $e_{f,n}$ represents the filtered sample dynamic error vector at *n*th sample point.

In addition, the RBF supervisor controller term $\tau_{RBF} = [\tau_{RBF,u}, \tau_{RBF,r}]$, and the PID controller term $\tau_{PID} = [\tau_{PID,u}, \tau_{PID,r}]$. And the traditional PID control output term is given by:



Fig. 3—Straight-line path following with unknown time-varying disturbance



Fig. 4-Model-free supervisor control diagram for under actuated ASV

$$\begin{cases} \tau_{PID,u} = k_{p,u} e_{f,u} + k_{i,u} \int e_{f,u} dt + k_{d,u} \dot{e}_{f,u} \\ \tau_{PID,r} = k_{p,r} e_{f,r} + k_{i,r} \int e_{f,r} dt + k_{d,r} \dot{e}_{f,r} \end{cases}$$
(16)

The supervisor controller is pretty relaxed about the PID controller output, hence, $k_{i,u}$ and $k_{i,r}$ is useless in the supervised mode. However, $k_{i,u}$ and $k_{i,r}$ should be adjusted to appropriate sections, such that the dynamic system can be stabilized, and the static deviation can be eliminated with external disturbance. With the back propagation of evaluated error, the gradient descent-based weight-tuning algorithm for RBF network is designed as:

$$V_{dyn,1} = \frac{1}{2} (\tau_{PID} - \tau_{RBF})^2$$
(17)

According to the gradient descent method for NN weights:

$$\Delta w_{j} = -\sigma \frac{\partial V_{dyn,1}}{\partial w_{j}} = -\sigma \frac{\partial V_{dyn,1}}{\partial \tau_{RBF}} \frac{\partial \tau_{RBF}}{\partial w_{j}} = \sigma (\tau_{RBF} - \tau_{hj})$$

$$(18)$$

where σ is the learning rate.

Ultimately, the tuning algorithm process for weight matrix is given by:

$$W(k) = W(k-1) + \Delta W(k) + \epsilon (W(k-1) - Wk-2)$$
(19)

where ϵ is the momentum factor.

Results and Discussion

Numerical simulation environment

A 17.5 kg-weight, 1.2 m-long mono-hull ship model is used for numerical simulation³⁸. The parameters of the ship model are given in Table 1.

The slowly time-varying, unknown external wave and current disturbances are given as^{10,41}

$$\begin{cases} \tau_{wu} = 0.2m_{11}(1+0.1\sin(0.2t)) \\ \tau_{wv} = 0.2m_{22}(1+0.1\sin(0.2t)) \\ \tau_{wr} = 0.2m_{33}(1+0.1\sin(0.2t)) \end{cases}$$

and

$$\begin{cases} \tau_{cu} = 1 \sin(0.05t) \\ \tau_{cv} = 1 \sin(0.05t) \\ \tau_{cr} = 0.5 \sin(0.05t) \end{cases}$$

Due to the saturation characteristics of the propellers and control surface, the control force and moments are limited by:

$$\tau_{u} = \begin{cases} \tau_{u,max} & \\ \tau_{u} & \\ \tau_{u,min} & \end{cases} \quad if \quad \begin{cases} \tau_{u} > \tau_{u,max} \\ |\tau_{u}| \le \tau_{u,max} \\ \tau_{u} < -\tau_{u,max} \end{cases}$$

and

$$\tau_{u} = \begin{cases} \tau_{r,max} & \\ \tau_{r} & if \\ \tau_{r,min} & \\ \end{cases} \begin{cases} \tau_{r} > \tau_{r,max} \\ |\tau_{u}| \le \tau_{r,max} \\ \tau_{u} < -\tau_{r,max} \end{cases}$$

with

$$\tau_{u,max} = 20N$$
 $\tau_{r,max} = 4Nm$

Based on the off-line test on the output control force and moment, the center matrix of the RBF NN supervisor is given as:

$$c = \begin{bmatrix} -1.5 & -1 & -0.5 & 0 & 0.5 & 1 & 1.5 \\ -30 & -20 & -10 & 0 & 10 & 20 & 30 \end{bmatrix}$$

In addition, the width matrix is chosen as:

<i>b</i> =	[0.5	0.5	0.5	0.5	0.5	0.5	0.5]
	l 1	1	1	1	1	1	1

Case 1: Path following for straight line

To compare the performance of the tracking-error based PID controller and the RBF NN-based supervisor controller, and to demonstrate the supervised learning performance of the RBF NN control with the combination of PD control method, we first consider straight-line path following in the same simulation environment. The reference path is set as $x_r(s) = y_r(s) = s$. The initial position and posture of the vehicle are set as: $[x_0, y_0, \psi_0] =$ $[0 \text{ m}, 20 \text{ m}, \pi/2 \text{ rad}]$. The desired tracking velocity is chosen as 1 m/s. The tracking results are shown in Fig 5. The vehicle can converge to the desired reference path in the guidance of PID controller and

Table 1—ASV model coefficients						
Coefficients	Value	Unit				
m_{11}	25.8	kg				
m_{22}	33.8	kg				
m_{33}	2.76	kg m ²				
m_{23}	6.2	kgm				
m_{32}	6.2	kgm				
D_{11}	12+2.5 u	$kg s^{-1}$				
D ₂₂	17+4.5 v	$\rm kg~s^{-1}$				
D ₃₃	0.5+0.1 r	$kg m^2 s^{-1}$				
D ₂₃	0.2	$kg m^{-1}$				
D ₃₂	0.5	kg m ²				

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RBF supervisor controller under time-varying unknow disturbance. However, the vehicle can navigate farther with RBF supervisor controller in the same simulation period.

The different crussing range can be revealed from Fig. 6 and 7. The along-tracking errors x_e are almost the same in different controllers. Never the less, the



Fig. 5—Straight-line path following with unknown time-varying disturbance



Fig. 7-Surge velocity and Yaw rotation velocity

external disturbances have a significant effect on the cross-tracking errors y_e with PID controller guidance.

In addition, there is 0.2 m/s static deviation by using PD controller, and which can be eliminated by using PID controller. The surge velocity will gradually converge to the desired value after about 150 s. Large or small integration coefficients have great impact on tracking performance.

In the tracking process, the saturated control thrust force and moment are shown in Fig. 8 and 9. The partial enlarged views reveal that the supervisor controller term plays a dominate role in dynamic control output. Especially for the saturated control moment, the PID term tends to 0 Nm, and the RBF supervisor output is the main part to balance the wave and current disturbances. Hence, the RBF supervisor controller can guarantee the robustness of the system for straight-line path following with unknown disturbance.



Fig. 8-Saturated control thrust force and partial detail view



Fig. 9-Saturated control moment and partial detail view







Fig. 11—A cross-and along-tracking errors y_e , x_e



Fig. 12-Surge velocity and yaw rotation velocity

Case 2: Time-varying path parameters with slowly varying disturbances

In addition, for the path with time-varying curvature, we choose the reference path as $x_r(s) = s$, $y_r(s) = 20 + 20 \sin(0.05s)$. The initial states of the vehicle are set as: $[x_0, y_0, \psi_0] = [0 \text{ m}, 10 \text{ m}, 0 \text{ rad}]$. The desired tracking velocity is set as 1 m/s. The racking results are shown in

Fig. 10. There will be a little bit difference in the path segments with big curvature, where around x=80 m, x=160 m, and x=225 m, which can be revealed from Fig. 11. In the time buckets around 140 s and



Fig. 13-Saturated control thrust force and partial details



Fig. 14-Saturated control moment and partial details

220 s, the along-tracking error will deviate from 0 m slightly.

The RBF supervisor controller performs well in anting external unknown disturbance for curve-path tracking, which can be revealed from the crosstracking error in Fig. 11.

The presentation of surge and yaw velocity is similar with straight-line tracking process.

For the reference path with time-varying curvature, the RBF supervisor controller output time-varying control thrust force and rotation moment, which guarantees the robustness of the tracking system. And the PID controller term maintained 0 except for the initial stage (Figs 12 to 14).

Conclusion

This paper proposes a model-free RBF NN-based supervisor controller for ASV. The cross-tracking-errorbased LOS guidance and relative motion method are used to establish the relationship between and the virtual tracking point on the reference path. Based on the design of desired velocity state feedback, a composite feed forward and feedback control framework is established by using RBF NN controller and PD controller, respectively. Numerical simulations for straight-line and sine-line path following demonstrate the effectiveness and robustness of the RBF supervisor controller. In the steady control stage, the control term of supervisor controller plays a dominate roll in control output, even for the curve path having time-varying curvature in external unknown time-varying ocean disturbance. For the future work, the performance of the proposed controller can be demonstrated with field experiment.

Acknowledgment

This work was supported in part by the National Natural Science Foundation of China under Grant 51579111, in part by the Shenzhen Science and Technology Plan Project under Grant JCYJ201704I311305468, in part by the National Key Research and Development Program of China (Grant 2017YFB1302302) and in part by the Research Fund from Science and Technology on Underwater Vehicle Technology under Grant SXJQR2017KFJJ06.

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