Adaptive Neural Path Following Control of Underactuated Surface Vessels With Input Saturation

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ABSTRACT In this paper, considering the input saturation, off-diagonal mass matrix, model uncertainties and time-varying environment disturbances, an adaptive neural path following control strategy, which is based on the surge-heading line-of-sight guidance law, is presented for underactuated surface vessels. In view of the practical situation, we consider that the mass and damping matrices are off-diagonal. For the sake of better path following performance, a surge-heading line-of-sight guidance law is established, where the surge-heading line-of-sight guidance law not only generates the desired heading angle, but also designs the desired surge speed for the control system. Then, adaptive neural path following controllers are designed to track the referenced signals, where the input saturation nonlinearity is handled by a hyperbolic tangent function, and the lumped disturbances including external environment disturbances, approximation errors and model uncertainties are approximated by adaptive radial basis function neural network. On the basis of the proposed control scheme, all error signals of the whole system are proven to be uniformly ultimately bounded, so that the target of path following problem is realized. At last, simulation results are applied to indicate that the presented approach is effective.

INDEX TERMS Input saturation, neural networks, path following, surge-heading line-of-sight.

I. INTRODUCTION

In recent years, with the requirement of developing marine resources, motion control of underactuated surface vessels (USVs) has gained great attention [1]–[6]. The purpose of path following control problem, which is an important part of motion control, is to design a control strategy for an USV to arrive and sail on a predefined path [7]. In order to obtain better path following performance, numerous control schemes, which are made up of guidance system and control system, have been applied widely.

Based on the path information, the guidance system is developed to generate the desired signals for control system to accomplish the path following task. In the past years, the line-of-sight (LOS) guidance law, which is a simple and convenient method, has been researched extensively. In [8], a proportional LOS (PLOS) guidance law was designed and the uniform semiglobal exponential stability was guaranteed. However, the PLOS guidance law did not consider the environment disturbances, which can create the sideslip angle and damage the path following performance. In order to deal with the sideslip angle, some improved LOS guidance laws were developed, such as integral LOS (ILOS) [9], [10], adaptive LOS (ALOS) [11], extended state observer based-LOS (ELOS) [12], and sideslip-tangent LOS (SLOS) [13], [14]. In addition, the above guidance laws only concluded the desired heading angle signals, and the referenced surge speeds were predefined as constants, so that the maneuverabilities of USVs were decreased. For improving the path following performance, the surge-varying LOS guidance law was developed to generate the desired surge speed and heading angle simultaneously in [15].

It should be noted that the aforementioned methods did not consider the input saturation. In practice, actuator saturation...
nonlinearity exists. The control performance will be degraded and instability may occur, while the input saturation is not handled. In this situation, the input saturation should be considered in the control design to obtain better performance [16]. In [17], an auxiliary design system in the form of anti-windup compensator was applied to deal with actuator saturation. In [18], an auxiliary system was employed to compensate for the effect of actuator saturation. Then, the auxiliary system method was applied in the fullactuated vessels [19]. Moreover, this method was combined with path following control law to deal with the input saturation for underactuated surface vessels [20]. In [21], a hyperbolic tangent function was applied to approximate the effect of input saturation nonlinearity, so that the backstepping technique was used in the control design.

Besides input saturation, another challenge of path following problem is the model uncertainties, which is a common problem in engineering application [22], [23]. In order to deal with the model uncertainties, the neural network (NN) was used to approximate a nonlinear function based on the universal approximation property in [24]. In [25], a multilayer neural-networks (MLPNN) was employed to compensate the model uncertainties. However, the structure of MLPNN is complicated, so that the design parameters are difficult to choose and the learning speed is slow. In [26], the radial basis function neural network (RBFNN) was applied to estimate the unknown model dynamics of fullactuated vessels for dynamic position. For path following problem of USVs, the RBFNN was used to compensate the model uncertainties and environment disturbances in [27] and [28]. In addition, most path following studies assumed that the mass matrices of USVs were diagonal, which was a simplification of the practical condition. In practice, the assumption is not reasonable and causes a problem that the sway and yaw dynamics are coupled, which means that the yaw moment can also control the sway dynamic. In this case, the path following control designs become difficult. In order to solve the problem, the coordinate transformation method was applied in [29], [30].

Motivated by the aforementioned considerations, we consider the path following problem of USVs with off-diagonal mass matrix in the presence of model uncertainties, input saturation and time-varying environment disturbances. An adaptive neural path following control (ANPFC) scheme, which is based on the surge-heading line-of-sight (SHLOS) guidance law, is proposed in this paper. The main contributions of this paper are summarized as follows.

1) Different from the conventional LOS guidance law, a SHLOS guidance law is presented for the path following problem of USVs, while the SHLOS guidance law can generate desired surge speed and heading angle simultaneously. Compared with the designed guidance law in [15], the condition of off-diagonal mass matrix is considered in the SHLOS guidance law.

2) The input saturation is handled by a hyperbolic tangent function, so that the dynamic surface control (DSC) technique can be used in the control design. Then the adaptive neural path following control laws are designed with the lumped disturbances approximated by a RBFNN.

3) It is proven that all states of closed-loop control system are uniformly bounded by using the proposed control scheme.

The paper is organized as follows. The preliminaries and problem formation are stated in Section II. The designs of guidance system and control system are given in Section III and Section IV, respectively. Then, Section V formulates the stability analysis. In addition, Section VI shows the simulation results. At last, Section VII concludes the paper.

II. PRELIMINARIES AND PROBLEM FORMATION

A. NOTATION

The following notations will be used throughout this paper. $|·|$ represents the absolute value of a scalar. $∥·∥$ represents

| Notations | Descriptions |
|-----------|--------------|
| $(x, y)$  | position in the north-east reference frame |
| $\psi$    | heading angle |
| $u, v$    | surge and sway speed |
| $r$       | yaw rate |
| $m_{ij}$  | ship inertia including added mass, $i = 1, 2, 3, j = 1, 2, 3$ |
| $d_{ij}$  | hydrodynamic damping term, $i = 1, 2, 3, j = 1, 2, 3$ |
| $\tau_1$  | surge force |
| $\tau_2$  | yaw moment |
| $\sigma_1$ | control command by surge speed controller |
| $\sigma_2$ | control command by heading controller |
| $\delta_i$ | unknown time-varying environment disturbances on surge, sway, and yaw, $i = u, v, r$ |
| $D_i$     | unknown lumped disturbances on surge, sway, and yaw, $i = u, v, r$ |
| $\theta$  | path variable |
| $x_e, y_e$ | path following along-track error and cross-track error |
| $\gamma_p$ | path-tangential angle |
| $\Delta$  | look-ahead distance |
| $U$       | speed of underactuated surface vessel |
| $\beta$   | sideslip angle |
| $u_d, \psi_d$ | desired surge speed and desired heading angle |
| $u_e$     | first error surface of surge speed controller |
| $\psi_e$  | heading tracking error |
| $r_d$     | virtual input to stabilize $\psi_e$ |
| $r_s$     | second error surface of heading controller |
| $\bar{\theta}_i$ | estimation of the optimal weight value, $i = 1, 2$ |
| $\xi_i$   | auxiliary design signal, $i = 1, 2$ |
| $\gamma_i$ | adaption gain, $i = u, r$ |
| $k_i$     | design parameter, $i = 1, 2, 3, 4, 5, 6$ |
| $k_u$     | control parameter of surge speed controller |
| $k_{wr}$  | control parameters of heading controller |
the Euclidean norm. \( || \cdot ||_F \) represents Frobenius norm. \( \mathbb{R}^n \) represents the n-dimensional Euclidean Space. \( (\cdot)^T \) denotes the transpose of a matrix. \( \text{tr}(\cdot) \) denotes the trace of the respective matrix. \( \text{sign}(\cdot) \) and \( \tanh(\cdot) \) denote the sign function and hyperbolic tangent function, respectively. \( \cdot \) denotes the estimation value of \( (\cdot), \) and \( \hat{(\cdot)} - (\cdot) \) implies the estimating error.

\section{B. RBFFN}

On the basis of the universal approximation property, unknown continuous function can be approximated by the RBFFN, which is a popular method. For any nonlinear continuous function \( f(x) : \mathbb{R}^m \rightarrow \mathbb{R} \) over a compact set \( \Omega_x \subset \mathbb{R}^m, \) it can be approximated by the RBFFN, which is described as [31]:

\[
    f(x) = W^T \Phi(x) + \chi,
\]

where \( x \in \Omega_x \) is the input vector, \( \chi \) is the approximation error, which is a bound parameter, i.e. there exist an unknown positive constant \( \chi^* \), such that \( |\chi| \leq \chi^* \). In addition, \( W^* = [w_1, w_2, \ldots, w_m] \in \mathbb{R}^m \) denotes the optimal weight vector, and \( m \) is the node number of the hidden neurons. The optimal weight vector is unknown in practice, and can be given as:

\[
    W^* = \arg \min_{\hat{W}} \left\{ \sup_{x \in \Omega_x} \left| f(x) - \hat{W}^T \Phi(x) \right| \right\},
\]

where \( \hat{W} \) is the estimation value of \( W^* \), and can be applied to estimate unknown function. Then, we can get the estimation of \( f(x) \) with the estimation value \( \hat{W} \):

\[
    \hat{f}(x) = \hat{W}^T \Phi(x),
\]

where \( \Phi(x) = [\phi_1(x), \phi_2(x), \ldots, \phi_m(x)] \) is the basis function, and can be chosen as Gaussian function with the form as:

\[
    \phi_i(x) = \exp \left( -\frac{||x - c_i||^2}{2b_i^2} \right), \quad i = 1, 2, \ldots, m
\]

where \( c_i \) is the center vector and \( b_i \) is the width of the Gaussian function.

\section{C. MODEL OF UNDERACTUATED SURFACE VESSEL}

Based on [32], only consider the motion on the horizontal plane, and the mathematic model of the USV is expressed by:

\[
    \dot{\eta} = R(\psi) \upsilon,
\]

\[
    M \ddot{\upsilon} + C(\upsilon) \upsilon + D \upsilon = \tau + \delta,
\]

where \( \eta = [x, y, \psi]^T \) stands for the position and heading angle of the USV in the north-east-down (NED) reference frame; \( \upsilon = [u, v, r]^T \) stands for velocities in the body-fixed frame; \( R(\psi) \) is a state dependent rotation matrix and given as:

\[
    R(\psi) = \begin{bmatrix}
    \cos \psi & -\sin \psi & 0 \\
    \sin \psi & \cos \psi & 0 \\
    0 & 0 & 1
    \end{bmatrix}.
\]

In addition, \( \delta(t) = [\delta_x, \delta_y, \delta_z]^T \) denotes the unknown time-varying environment disturbances produced by wind, waves and ocean current. \( M \) represents the ship inertia matrix including added mass; \( C(\upsilon) \) represents the Coriolis and centripetal matrix; and \( D \) is the hydrodynamic damping matrix. The \( M, C(\upsilon) \) and \( D \) are given as:

\[
    M = \begin{bmatrix}
    m_{11} & 0 & 0 \\
    0 & m_{22} & m_{23} \\
    0 & m_{23} & m_{33}
    \end{bmatrix},
\]

\[
    C(\upsilon) = \begin{bmatrix}
    0 & 0 & -m_{22}v - m_{23}r \\
    0 & 0 & m_{11}u \\
    m_{22}v + m_{23}r & -m_{11}u & 0
    \end{bmatrix},
\]

\[
    D = \begin{bmatrix}
    d_{11} & 0 & 0 \\
    0 & d_{22} & d_{23} \\
    0 & d_{32} & d_{33}
    \end{bmatrix}.
\]

The vector \( \tau = [\tau_1, \tau_2]^T \) represents the surge force and yaw moment, which are the inputs of the USV and outputs of actuators, so that the vessel is underactuated. Due to the saturation nonlinearities of actuators, the inputs of the USV can be described as follows:

\[
    \tau_i = \text{sat}(\sigma_i) = \begin{cases}
    \text{sign}(\sigma_i) \tau_{Mi}, & |\sigma_i| \geq \tau_{Mi} \\
    \sigma_i, & |\sigma_i| < \tau_{Mi}
    \end{cases}
\]

where \( \sigma_i, i = 1, 2 \) are the control commands; \( \tau_{Mi}, i = 1, 2 \) are the bounds of the \( \tau_i \).

\textbf{Remark 1:} In general, the conformation of the bow of vessels is different from that of the stern. The mass matrix \( M \) is off-diagonal in this context, which is different from the most studies. The sway and yaw dynamics are coupled, so that the yaw moment can control the sway dynamics, which makes the control design become difficult.

\textbf{Remark 2:} Sharp corners exist when \( |\sigma_i| = \tau_{Mi} \), so that backstepping technique cannot be applied directly.

In order to deal with the problem that saturation control law cannot be applied directly in the DSC design, a smooth function is employed to approximate the saturation characteristic, which is described as follows [16]:

\[
    h_i(\sigma_i) = \tau_{Mi} \tanh(\frac{\sigma_i}{\tau_{Mi}}), \quad i = 1, 2
\]

Then \( \tau_i \) can be expressed as:

\[
    \tau_i = h_i(\sigma_i) + \rho_i(\sigma_i)
\]

where \( \rho_i(\sigma_i) = \tau_i - h_i(\sigma_i), i = 1, 2 \), which are the approximate errors between \( \tau_i \) and \( h_i(\sigma_i) \), are bounded.

\[
    |\rho_i(\sigma_i)| = |\tau_i - h_i(\sigma_i)| \leq \tau_{Mi}(1 - \tanh(1)) = \gamma_i
\]

where \( \gamma_i, i = 1, 2 \) are positive constants.

In order to facilitate the following written, we omit \( \sigma_i \) without confusion, such as \( \rho_i(\sigma_i) = \rho_i, h_i(\sigma_i) = h_i \).

For the sake of handling the situation that sway dynamics and yaw dynamics are controlled by the yaw moment concurrently, a coordinate transformation is applied. The coordinate transformation is described as: \( \bar{x} = x + \epsilon \cos \psi, \epsilon \in 

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Rotated with an angle as \((\text{SF})\) frame at the point parameterized by a path variable described as the USV follows a predefined path, which is 

\[
x = x_e \quad \text{and} \quad y = y_e,
\]

where \(x_e\) and \(y_e\) are designed in this paper. The mathematic model of the USV is rewritten as:

\[
\begin{align*}
\dot{x} &= u \cos \psi - \bar{v} \sin \psi \\
\dot{y} &= u \sin \psi + \bar{v} \cos \psi \\
\dot{\psi} &= r \\
\dot{u} &= D_u + \frac{h_1}{m_1} \\
\dot{\bar{v}} &= -\frac{d_2 \bar{v}}{m_2} + D_v \\
\dot{r} &= D_r + \frac{m_2 h_2}{\Gamma}.
\end{align*}
\]

where

\[
\begin{align*}
D_u &= \frac{1}{m_1} \left( m_{12} v r - d_{11} u + m_{23} r^2 + \delta_u + \rho_1 \right), \\
D_v &= \frac{1}{m_2} \left( m_{11} u r + d_{22} \dot{r} - d_{23} r + \delta_r \right), \\
D_r &= \frac{1}{\Gamma} \left\{ \left( m_{11} m_{22} - m_2^2 \right) \dot{u} v + \left( m_{11} m_{23} - m_{23} m_{22} \right) u r \\
& \quad - m_{22} (d_{23} r + d_{22} v) + m_{23} (d_{23} r + d_{22} v) \\
& \quad + m_{22} \delta_r - m_{23} \delta_v + m_{22} \rho_2 \right\}, \\
\Gamma &= m_{22} m_{33} - m_{23}^2.
\end{align*}
\]

D. PATH FOLLOWING ERROR DYNAMIC

As shown in Figure 1, the path following problem can be described as the USV follows a predefined path, which is parameterized by a path variable \(\theta\). Denote a Serret-Frenet (SF) frame at the point \((x_p(\theta), y_p(\theta))\) along the desired path. To arrive at the SF frame, the NED frame should be rotated with an angle as:

\[
\gamma_p = \text{atan2} \left( y_p'(\theta), x_p'(\theta) \right),
\]

where \(x_p'(\theta) = \partial x_p/\partial \theta\) and \(y_p'(\theta) = \partial y_p/\partial \theta\).

When the position of the USV is denoted as \((x, y)\), and define the path following along-track error and cross-track error built in the SF frame as \(x_e\) and \(y_e\), then the error vector is represented by:

\[
\begin{bmatrix}
x_e \\
y_e
\end{bmatrix} =
\begin{bmatrix}
\cos \gamma_p & -\sin \gamma_p \\
\sin \gamma_p & \cos \gamma_p
\end{bmatrix}^T
\begin{bmatrix}
x - x_p(\theta) \\
y - y_p(\theta)
\end{bmatrix}.
\]

Differentiating (19), the path following error dynamics model in the SF frame is written as follows:

\[
\begin{align*}
\dot{x}_e &= u \cos \left( \psi - \gamma_p \right) - \bar{v} \sin \left( \psi - \gamma_p \right) + \bar{v}_p y_e - u_x, \\
\dot{y}_e &= u \sin \left( \psi - \gamma_p \right) + \bar{v} \cos \left( \psi - \gamma_p \right) - \bar{v}_p x_e,
\end{align*}
\]

where \(u_x\) is the speed of virtual target along the desired path and is expressed by:

\[
u_x = \dot{\theta} \sqrt{\bar{v}_x^2(\theta) + \bar{v}_y^2(\theta)}.
\]

Considering the sideslip angle \(\beta = \text{atan2}(\bar{v}, u)\), the path following error dynamics are rewritten as:

\[
\begin{align*}
\dot{x}_e &= u \cos \left( \psi - \gamma_p - \beta \right) - \bar{v} \sin \left( \psi - \gamma_p \right) + \bar{v}_p y_e - u_x, \\
\dot{y}_e &= u \sin \left( \psi - \gamma_p + \beta \right) + \bar{v}_p x_e - u_x,
\end{align*}
\]

where \(U = \sqrt{u^2 + v^2}\) is the speed of the USV.

In the presence of off-diagonal mass matrix, model uncertainties, unknown external disturbances and input saturation, the path following objective of this study is to ensure that the USV arrives and follows the predefined path. In this situation, a SHLOS guidance law, which is used to generate the desired surge speed and heading angle, and a control system, which is applied to produce the suitable surge force and yaw moment are designed in this paper.

In order to accomplish the design of guidance and control laws for the USV, the following assumptions are made.

**Assumption 1**: All states are available for measuring.

**Assumption 2**: The damping matrix is unknown.

**Assumption 3**: The environment disturbances \(\delta_i\) are bounded, i.e., there exist unknown positive constants \(\delta_i\) such that \(|\delta_i| \leq \delta_i\).

**Remark 3**: Assumption 1 is a common precondition in the field of control design of vessels \([4], [5], [19], [28]\). In Assumption 2, the damping terms are difficult to obtain \([29]\). The energy of environment disturbances is limited, so that Assumption 3 is reasonable. In practice, the velocities of USV are bounded. In addition, the approximation errors \(\rho_1\) and \(\rho_2\) are bounded, so that the unknown nonlinear terms \(D_u\) and \(D_r\) are bounded, and can be approximated by RBFNN.

III. GUIDANCE SYSTEM

From the previous studies, it is known that most guidance laws only generate desired heading angles for control systems and referenced surge speed signals are predefined. In this situation, the cross-track error is only influenced by the yaw...
dynamics, which will lead to more wear and tear on the rudder. For obtaining more prefect path following performance, not only the desired heading angle but also referenced surge speed are produced by the SHLOS guidance law in this section.

In order to deal with the singularity of sideslip angle when surge and sway speeds are zero simultaneously, the desired sideslip angle is defined as:

$$\beta_d = \tan(2\tilde{v}, u_d)$$

where $u_d$ is the desired surge speed, which is generated by the SHLOS guidance law and always greater than zero.

Define the surge speed tracking error and the heading angle tracking error as:

$$\tilde{u} = u - u_d$$
$$\psi_e = \psi - \psi_d$$

where $\psi_d$ is the desired heading angle.

Substitute (23), (24) and (25) into (22), and we obtain:

$$\dot{x}_e = u \cos(\psi - \psi_p) - u_d \sin(\psi - \psi_p) \tan(\beta_d + \gamma_p y_e - \xi_x),$$
$$\dot{y}_e = U_d \cos(\psi + \beta_d - \gamma_p) + \gamma_p y_e - \xi_x + \dot{u} \cos(\psi - \psi_p),$$
$$\dot{\tilde{v}} = U_d \sin(\psi - \psi_p) + u_d \sin(\psi - \psi_p) \tan(\beta_d - \gamma_p x_e),$$
$$\dot{\psi}_e = \dot{u} \sin(\psi - \psi_p) + U \omega \psi_e,$$

$$\dot{u}_e = u \sin^2 \psi + \sin \psi \psi_e - \psi_d + \bar{d}_1.$$ 

In this section, the tracking control laws, which are made up of the surge control force and yaw control moment, are designed under the lumped disturbances and input saturation. The unknown nonlinear terms $D_p$ and $D_t$ contain the environment disturbances, model uncertainties and approximation errors, which are compensated by RBFNN.

### IV. CONTROL SYSTEM

In this section, the tracking control laws, which are made up of the surge control force and yaw control moment, are designed under the lumped disturbances and input saturation. The unknown nonlinear terms $D_p$ and $D_t$ contain the environment disturbances, model uncertainties and approximation errors, which are compensated by RBFNN.

### A. SURGE SPEED CONTROL

On the basis of the SHLOS guidance law, the surge speed control force is designed for tracking the desired surge speed. Define the first error surface as:

$$u_e = u - u_d - \xi_1 = \tilde{u} - \xi_1$$

where

$$\xi_1 = \frac{1}{m_1}(h_1 - \xi_1)$$

where $k_3 > 0$ is the design constant.

**Remark 4:** As (17) shown, we can not get the control input $\sigma_1$ directly, so that we introduce an auxiliary signal to handle the problem.

The time derivative of $u_e$ is given as:

$$\dot{u}_e = D_u + \frac{h_1}{m_1} - \dot{u}_d + \frac{\sigma_1 - h_1 + k_3 \xi_1}{m_1}$$

Then the desired surge control $\sigma^*_1$ is designed as:

$$\sigma^*_1 = -m_1 (k_u u_e + D_u - \dot{u}_d) - k_3 \xi_1$$

where $k_u > 0$, and $D_u$ is the unknown lumped disturbance in surge, which can be approximated by RBFNN:

$$D_u = W_1^T \Phi(u) + \chi_1$$

where $W_1^*$ is the optimal weight value and $\chi_1$ is the approximation error. Therefore, the desired surge control law $\sigma^*_1$ is designed as:

$$\sigma^*_1 = -m_1 (k_u u_e + W_1^T \Phi(u) + \chi_1 - \dot{u}_d) - k_3 \xi_1$$
Since the $W^*$ and $\chi_1$ are unknown, the control law $\sigma_1$ can be expressed as:

$$\sigma_1 = -m_{11}(k_u u_e + \hat{W}_1^T \Phi(u) - \hat{u}_d) - k_3 \xi_1$$  \hspace{1cm} (40)$$

where $\hat{W}_1$ is the estimation of $W^*_1$.

Consider the Lyapunov function as:

$$V_2 = \frac{1}{2} u_e^2 + \frac{1}{2} \gamma_u \text{tr}(\hat{W}_1^T \hat{W}_1) + m_{11} \xi_1^2$$  \hspace{1cm} (41)$$

where $\hat{W}_1 = \hat{W}_1 - W^*$ is the estimation error of the weight value, and $\gamma_u$ is the design parameter.

Taking the time derivative of $V_2$, we obtain

$$\dot{V}_2 = u_e \dot{u}_e + \frac{1}{2} \gamma_u \text{tr}(\hat{W}_1^T \dot{\hat{W}}_1) + m_{11} \dot{\xi}_1^2$$

$$= -k_u u_e^2 - \dot{\hat{W}}_1^T u_e \Phi(u) + \frac{1}{2} \gamma_u \text{tr}(\hat{W}_1^T \dot{\hat{W}}_1)$$

$$- \rho_1 \dot{\xi}_1 - k_3 \xi_1^2$$  \hspace{1cm} (42)$$

Design the update law of $\hat{W}_1$ as:

$$\dot{\hat{W}}_1 = \gamma_u (u_e \Phi(u) - k_4 \hat{W}_1)$$  \hspace{1cm} (43)$$

where $k_4 > 0$ is the design constant.

Then, (42) is rewritten as:

$$\dot{V}_2 = -k_u u_e^2 + \chi_1 u_e - k_4 \text{tr}(\hat{W}_1^T \dot{\hat{W}}_1) - \rho_1 \dot{\xi}_1 - k_3 \xi_1^2$$  \hspace{1cm} (44)$$

The result in (44) will be used for the stability analysis of the whole control system in Section V.

**B. HEADING CONTROL**

In this subsection, the yaw control moment is designed to track the desired heading angle, which is generated by SHLOS guidance law.

Step 1: Consider the heading tracking error $\psi_e$ and take the time derivative, then we have

$$\dot{\psi}_e = r - \dot{\psi}_d$$  \hspace{1cm} (45)$$

To stabilize the dynamic surface $\psi_e$, a virtual input $r_d$ is chosen as:

$$r_d = -k_\psi \psi_e + \dot{\psi}_d$$  \hspace{1cm} (46)$$

where $k_\psi > 0$ is a design parameter.

In order to avoid the complexity explosion problem induced by the repeated differentiations of the virtual control law, the DSC technology is applied. Let the virtual control input $r_d$ pass through a first-order filter

$$t_1 \dot{\alpha}_r + \alpha_r = r_d, \alpha_r(0) = r_d(0)$$  \hspace{1cm} (47)$$

where $t_1$ is the design time constant, and $\alpha_r$ is the output of the first-order filter.

Define the output error of the filter as $z_1 = \alpha_r - r_d$, and take the derivative respect with time

$$\dot{z}_1 = -\frac{z_1}{t_1} - \dot{r}_d$$  \hspace{1cm} (48)$$

where $\dot{r}_d = -k_\psi (r - \dot{\psi}_d) + \dot{\psi}_d$ is a bounded nonlinear term, where the maximum value denotes $d_3$.

Step 2: Define the second error surface $r_e$

$$r_e = r - \alpha_r - \dot{\xi}_2$$  \hspace{1cm} (49)$$

where

$$\dot{\xi}_2 = \frac{m_{22}}{\Gamma} (h_2 - \sigma_2 - k_5 \xi_2)$$  \hspace{1cm} (50)$$

where $k_5 > 0$ is the design constant.

Then the derivative of (49) is given as follows:

$$\dot{r}_e = D_r + \frac{m_{22} h_2}{\Gamma} - \alpha_r - \frac{m_{22}}{\Gamma} (h_2 - \sigma_2 - k_5 \xi_2)$$

$$= D_r + \frac{m_{22}(\sigma_2 + k_5 \xi_2)}{\Gamma} - \alpha_r$$  \hspace{1cm} (51)$$

Then the desired yaw control $\sigma_2^*$ is designed as:

$$\sigma_2^* = -\frac{\Gamma}{m_{22}} (k_r r_e + \psi_e + W^*_2 \Phi(u) + \chi_2 - \dot{\alpha}_r) - k_5 \xi_2$$  \hspace{1cm} (52)$$

where $W^*_2$ is the optimal weight value and $\chi_2$ is the approximation error. Then the desired yaw control law $\sigma_2^*$ is designed as:

$$\sigma_2^* = -\frac{\Gamma}{m_{22}} (k_r r_e + \psi_e + W^*_2 \Phi(u) + \chi_2 - \dot{\alpha}_r) - k_5 \xi_2$$  \hspace{1cm} (53)$$

where $W^*_2$ and $\chi_2$ are unknown, the control law $\sigma_2$ can be expressed as:

$$\sigma_2 = -\frac{\Gamma}{m_{22}} (k_r r_e + \psi_e + \hat{W}_2 \Phi(u) - \dot{\alpha}_r) - k_5 \xi_2$$  \hspace{1cm} (55)$$

where $\hat{W}_2$ is the estimation of $W^*_2$.

Consider the Lyapunov function as:

$$V_3 = \frac{1}{2} \psi_e^2 + \frac{1}{2} r_e^2 + \frac{1}{2} \gamma_r \text{tr}(\hat{W}_2^T \hat{W}_2) + \frac{1}{2} \xi_2^2 + \frac{m_{22}}{2\Gamma} \xi_2^2$$  \hspace{1cm} (56)$$

where $\hat{W}_2 = \hat{W}_2 - W^*_2$ is the estimation error of the weight value, and $\gamma_r$ is the design parameter.

The time derivative of $V_3$ is given by:

$$\dot{V}_3 = \psi_e \dot{\psi}_e + \dot{r}_e \dot{r}_e + \frac{1}{\gamma_r} \text{tr}(\hat{W}_2^T \dot{\hat{W}}_2) + z_1 \dot{z}_1 + \frac{m_{22}}{\Gamma} \xi_2$$

$$= \psi_e (r_e + \dot{z}_1 + \dot{\xi}_2 - k_\psi \psi_e + z_1) - \frac{1}{t_1} \dot{r}_d$$

$$+ r_e (k_r \dot{r}_e - \psi_e - \dot{\psi}_d + \dot{\chi}_2)$$

$$+ \frac{1}{\gamma_r} \text{tr}(\hat{W}_2^T \dot{\hat{W}}_2) + \xi_2 (-\dot{\rho}_2 - k_3 \xi_2)$$

$$= -k_\psi \psi_e^2 - k_r \dot{r}_e^2 - \frac{1}{t_1} \dot{z}_1 - k_5 \xi_2^2 + \psi_e z_1 + \psi_e \dot{z}_1$$

$$+ r_e \chi_2 - z_1 \dot{r}_d - r_e \hat{W}_2^T \Phi(u) + \frac{1}{\gamma_r} \text{tr}(\hat{W}_2^T \dot{\hat{W}}_2)$$

$$- \rho_2 \xi_2$$  \hspace{1cm} (57)$$
Design the update law of $\hat{W}_2$ as:
\[
\dot{\hat{W}}_2 = \gamma_e (r_e \Phi(u) - k_6 \hat{W}_2)
\]
(58)
where $k_6 > 0$ is the design constant.

Then, (57) is rewritten as:
\[
\dot{V}_3 = -k_\psi \psi e^2 - k_r r_e^2 - \frac{1}{\eta_1} z_1^2 - k_3 \bar{x}_2^2 + \psi_e z_1 + \psi_e \xi_2 + r_e \bar{x}_2 - z_1 \bar{r}_d - k_6 \text{tr}(\hat{W}_2^T \hat{W}_2) - \rho_2 \xi_2
\]
(59)

The result in (59) will be used for the stability analysis of the whole control system in Section V.

V. STABILITY ANALYSIS

In the presence of the off-diagonal mass matrix, environment disturbances, model uncertainties and input saturation, the SHLOS guidance law and tracking control laws are applied to obtain prefact path following performance for an USV. As the result, the stability analysis is presented as following.

**Theorem 1:** Considering the USV model (2), (3) with the off-diagonal mass matrix, environment disturbances, model uncertainties and input saturation, and supposing that Assumptions 1–3 are satisfied, the SHLOS guidance law (27)–(29), the tracking control laws (40), (55), the RBFNN update laws (43), (58), the first-order filter (48) and the auxiliary signal dynamics (35), (50) are applied to accomplish the path following objective, such that all error signals of the closed-loop system are uniformly ultimately bounded.

**proof:** Choose the following Lyapunov function:
\[
V = V_1 + V_2 + V_3
\]
\[
\leq \frac{1}{2} \psi e^2 + \frac{1}{2} r e^2 + \frac{1}{2} u e^2 + \frac{1}{2} \text{tr}(\hat{W}_2^T \hat{W}_2) + \frac{m_{11}}{2} z_1^2
\]
\[
+ \frac{1}{2} \psi e^2 + \frac{1}{2} r e^2 + \frac{1}{2} \text{tr}(\hat{W}_2^T \hat{W}_2) + \frac{m_{22}}{2} \xi_2^2
\]
(60)

Based on (33), (44) and (59), the time derivative of $V$ is derived as:
\[
\dot{V} \leq -k_1 x_e^2 - k_2 y_e^2 - k_3 \bar{x}_2^2 - k_4 \psi_e^2 - k_r r_e^2
\]
\[
- \frac{1}{\eta_1} z_1^2 - k_5 \bar{x}_2^2 + \bar{u}_e \bar{x}_1 + r_e \bar{x}_2 + x_e \bar{u} \cos(\psi - \gamma)
\]
\[
+ \gamma_e \bar{u} \sin(\psi - \gamma) + U \omega y_e \psi_e - k_4 \text{tr}(\hat{W}_2^T \hat{W}_2) - \rho_1 \xi_1
\]
\[
+ \psi e z_1 + \psi e \xi_2 - z_1 \bar{r}_d - k_6 \text{tr}(\hat{W}_2^T \hat{W}_2) - \rho_2 \xi_2
\]
(61)

In virtue of Young’s inequality, we obtain:
\[
x_e \bar{u} \cos(\psi - \gamma) \leq \bar{u}_e \bar{u}_e + \xi_1
\]
\[
\leq \frac{\xi_1 + \xi_2}{2} \bar{u}_e^2 + \frac{1}{2} \bar{u}_e^2 + \frac{1}{2} \xi_2^2
\]
(62)
\[
y_e \bar{u} \sin(\psi - \gamma) \leq \bar{u}_e \bar{u}_e + \xi_1
\]
\[
\leq \frac{\xi_1 + \xi_2}{2} \bar{u}_e^2 + \frac{1}{2} \bar{u}_e^2 + \frac{1}{2} \xi_2^2
\]
(63)

\[
U \omega y_e \psi_e \leq U \omega \xi_1 \psi_e + U \omega \psi_e^2
\]
\[
\leq \frac{1}{2} u_e^2 + \frac{1}{2} \bar{x}_1^2 + \rho_1 \xi_1
\]
(64)
\[
- \rho_1 \xi_1 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \bar{x}_2^2 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \bar{x}_2^2
\]
(65)
\[
- \rho_1 \xi_1 \leq \frac{1}{2} \psi e^2 + \frac{1}{2} \xi_2^2 \leq \frac{1}{2} \psi e^2 + \frac{1}{2} \xi_2^2
\]
(66)
\[
- \rho_1 \xi_1 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2
\]
(67)
\[
U \omega \xi_1 \psi_e \leq \frac{1}{2} \bar{x}_1^2 + \frac{1}{2} \bar{r}_d^2 \leq \frac{1}{2} \bar{x}_1^2 + \frac{1}{2} \bar{r}_d^2
\]
(68)
\[
U \omega \xi_1 \psi_e \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2
\]
(69)
\[
U \omega \xi_1 \psi_e \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2
\]
(70)
\[
U \omega \xi_1 \psi_e \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2 \leq \frac{1}{2} \bar{r}_d^2 + \frac{1}{2} \xi_2^2
\]
(71)

where $\xi_i > 0$, $i = 1 \sim 5$.

In addition, consider the fact as follows:
\[
-k_4 \text{tr}(\hat{W}_2^T \hat{W}_1) \leq \frac{k_4}{2} \left\| \hat{W}_1 \right\|_F^2 + k_4 \left\| W_1^* \right\|_F^2
\]
(72)
\[
-k_6 \text{tr}(\hat{W}_2^T \hat{W}_2) \leq \frac{k_6}{2} \left\| \hat{W}_2 \right\|_F^2 + k_6 \left\| W_2^* \right\|_F^2
\]
(73)

Substituting (62)–(73) into (61), we get:
\[
\dot{V} \leq -k_1 x_e^2 - k_2 y_e^2 - k_3 \bar{x}_2^2 - k_4 \psi_e^2 - k_r r_e^2
\]
\[
- \frac{1}{\eta_1} z_1^2 - k_5 \bar{x}_2^2 + \bar{u}_e \bar{x}_1 + r_e \bar{x}_2 + x_e \bar{u} \cos(\psi - \gamma)
\]
\[
+ \gamma_e \bar{u} \sin(\psi - \gamma) + U \omega y_e \psi_e - k_4 \text{tr}(\hat{W}_2^T \hat{W}_2) - \rho_1 \xi_1
\]
\[
+ \psi e z_1 + \psi e \xi_2 - z_1 \bar{r}_d - k_6 \text{tr}(\hat{W}_2^T \hat{W}_2) - \rho_2 \xi_2
\]
\[
\leq \frac{k_4}{2} \left\| \hat{W}_1 \right\|_F^2 + \frac{k_4}{2} \left\| W_1^* \right\|_F^2 - \frac{k_6}{2} \left\| \hat{W}_2 \right\|_F^2 - \frac{k_6}{2} \left\| W_2^* \right\|_F^2
\]
\[
\leq -2\psi + C
\]
(74)
where $K = \min \left\{ \left( k_1 - \frac{\xi_1 + \xi_2}{2} \right), \left( k_2 - \frac{\xi_1 + \xi_4 - Ud_4 \xi_5}{2} \right), \left( k_u - \frac{1}{2 \xi_1} - \frac{1}{2 \xi_2} - \frac{1}{2} \right), \left( k_\psi - 1 - \frac{Ud_4 \xi_5}{2 \xi_1} \right), \left( k_r - \frac{1}{2} \right), \left( k_3 - \frac{1}{2} - \frac{1}{2 \xi_1} - \frac{1}{2 \xi_2} \right), \frac{1}{\xi_1} - \frac{1}{2} \right\}$, $(k_5 - 1), k_4^2 \gamma_u, k_6^2 \gamma_r$, and $C = \frac{1}{2} \gamma_1^2 + \frac{1}{2} d^2 + \frac{1}{2} \gamma_2^2 + \frac{1}{2} \gamma_3^2 + \frac{1}{2} \gamma_4^2 + \frac{k_2}{2} \| W^* \|_2 + \frac{k_2}{2} \| W^*_2 \|_2^2$.

Then, choose the suitable design parameters satisfy $K > 0$, such that $k_1 - \frac{\xi_1 + \xi_2}{2} > 0, k_2 - \frac{\xi_1 + \xi_4 - Ud_4 \xi_5}{2} > 0, k_u - \frac{1}{2 \xi_1} - \frac{1}{2 \xi_2} - \frac{1}{2} > 0, k_\psi - 1 - \frac{Ud_4 \xi_5}{2 \xi_1} > 0, k_r - \frac{1}{2} > 0, k_3 - \frac{1}{2} - \frac{1}{2 \xi_1} - \frac{1}{2 \xi_2} > 0, \frac{1}{\xi_1} - \frac{1}{2} > 0, k_5 - 1 > 0, k_4 \gamma_u > 0, k_6 \gamma_r > 0$.

We can obtain the solution of (74)

$$V \leq e^{-2K(t)} V(0) + \frac{C}{2K} .$$

It is concluded that $V$ is bounded, which means that the error signals are uniformly ultimately bounded.

As a result, the proof is concluded.

**Remark 5:** Considering the sway dynamics, choose the Lyapunov function

$$V_v = \frac{1}{2} \tilde{v}^2$$

The time derivative can obtain as:

$$\dot{V}_v = \tilde{v} \ddot{v} = -\frac{d^2 v^2}{\xi_v} + \tilde{v} D_v$$

$$\leq -\frac{d^2 v^2}{\xi_v} + | \tilde{v} | | D_v |$$

Since $D_v$ is bounded, so $\tilde{v}$ is uniformly ultimately bounded [28]. Consider the coordinate transformation $\tilde{v} = v + \epsilon$, and $r$ is bounded, then we can get the sway velocity $v$ is bounded.

**Remark 6:** A parameter selection guide is provided as follows. First, the parameter $\Delta$ determines the convergence speed of cross-path error. The convergence speed can be fast by increasing $\Delta$. Second, the parameter $k_1$ influences the convergence speed of along-path error. Third, the parameters $\gamma_u, \gamma_r$ determine the learning rate of RBFNNs. Forth, the parameters $k_u, k_\psi$ and $k_r$ influence the output response, and a tradeoff should be made between response speed and stability margin. Finally, optimal parameters can be obtained with running simulation.

### VI. SIMULATION

In this section, the simulation results and comparison are provided to confirm the validity and merits of the proposed method. The simulation is tested in the Cybership II [33], which is considered as an underactuated surface ship with input saturation. The surge control force and yaw control moment are limited as 2N and 1.5Nm, respectively [33]. The parameters of the ship are given as:

$$M = \begin{bmatrix} 25.8 & 0 & 0 \\ 0 & 33.8 & 1.01 \\ 0 & 1.01 & 2.76 \end{bmatrix} ,$$

The desired path to be followed is defined as:

$$x_p (t) = \begin{cases} 2 \theta, & 0 \leq \theta < 5 \\ 2 \sin (0.5 \theta - 2.5) + \theta + 5, & \theta \geq 5 \\ \theta \end{cases}$$

In addition, the unknown environment disturbances are set as:

$$\delta (t) = \begin{bmatrix} \sin (0.3 \theta + 0.3 \pi) \\ 0.5 \cos (0.3 \theta + 0.1 \pi) + 0.7 \\ \cos (0.3 \theta + 0.2 \pi) \end{bmatrix} .$$

The initial states of the USV are considered as $[x, y, \psi]^T = [4, 0, 0]^T$ and $[u, v, r]^T = [0, 0, 0]^T$. In order to test the proposed adaptive neural path following control laws, the design parameters are chosen as $k_1 = 1, k_2 = 0.25, \Delta = 1, k_3 = 30, k_4 = 0.005, k_u = 5, k_\psi = 2, k_r = 5, t_1 = 0.1, k_5 = 3, k_6 = 0.005, \gamma_u = 2, \gamma_r = 2$. In addition, the node number of RBFNN $m = 9$, and the initial value of the weights of RBFNN are set as $W_{10} = [0, 0, 0, 0, 0, 0, 0, 0, 0]^T$, $W_{20} = [0, 0, 0, 0, 0, 0, 0, 0, 0]^T$.

In order to show the advantages of the proposed strategy, a comparison between the ANPFC with the ANPFC/SA, which is defined as the ANPFC method without considering the input saturation is applied. In addition, we also conduct a comparison between ANPFC based on the SHLOS guidance with the ELOS guidance law [12], while the desired surge speed of the ELOS law is defined as 0.25m/s, and the observer gain $K_o = 10$.

### A. COMPARISON WITH ANPFC/SA

In this subsection, the importance of the method with considering input saturation is revealed by the comparison analysis between ANPFC with ANPFC/SA. The simulation results of the different methods are shown in Figure 2–Figure 6. As we can see that, the ANPFC/SA method with the unconstrained
controller has a better path following performance. Due to the input saturation, the surge speed based ANPFC is smaller than ANPFC/SA, then the convergence time of ANPFC is more than ANPFC/SA. However, the control inputs break through the limitations of actuators, so that this situation is not practical. In addition, the ANPFC can force the USV to arrive and follow the desired path, and the desired heading angle and surge speed can be tracked accurately, while the control inputs via ANPFC method stay in the limitations, as shown in Figure 2–Figure 6. Based on the simulation results, we can conclude that the presented ANPFC method is more efficient and operable.
In this subsection, a comparison between the proposed SHLOS guidance law with ELOS is applied. The results of simulation are shown in Figure 7–Figure 12. From Figure 7–Figure 8, we can see that the SHLOS performs better than ELOS, while the USV based on SHLOS guidance law arrive the desired path faster than ELOS. In addition, the steady-state path tracking errors of ELOS are larger than SHLOS. The heading angle and surge speed tracking performance are shown in Figure 9–Figure 10, and illustrate that the two methods can track the desired values. In addition, the surge speed based on SHLOS guidance law is bigger than ELOS, so that the convergence time of SHLOS is less than ELOS. In addition, from Figure 11–Figure 12, we can conclude that the lumped disturbances can be estimated with RBFNN accurately, and the control inputs are smooth and keep in the limits. The simulation results demonstrate the efficiency of the designed control strategy.

VII. CONCLUSION

In this paper, an adaptive neural path following control scheme based on the SHLOS guidance law has been proposed for path following problem of an USV in the presence of off-diagonal mass matrix, unknown time-varying environment disturbances, model uncertainties and input saturation. The SHLOS guidance law can generate the reference surge speed and heading angle simultaneously. The effect of input saturation is handled by the hyperbolic tangent function, and the lumped disturbances are compensated by the RBFNN. Then, the proposed ANPFC scheme has been designed via DSC technique, so that the USV can arrive and follow the desired path. It has been proven that all error signals of the whole system are uniformly ultimately bounded. In addition, the simulation results confirm the effectiveness of the proposed control method. In the future, the path following tracking errors constraint problem will be considered in path following control design.

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