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Direct Adaptive Neural Network Control for Ship Manoeuvring Modelling Group Model-Based Uncertain Nonlinear Systems in Non-Affine Pure-Feedback Form

XIN WANG [1,2] AND CARLOS GUEDES SOARES [2]
[1]College of Navigation, Dalian Maritime University, Dalian 116026, China
[2]Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisbon, Portugal

Corresponding author: Xin Wang (xin.wang@dlmu.edu.cn)

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ABSTRACT In this article, a direct neural network based adaptive backstepping control approach is proposed for a class of uncertain non-affine ship manoeuvring pure-feedback nonlinear systems. To carry out the backstepping design, the high fidelity 3 degrees of freedom Manoeuvring Modelling Group (MMG) model with external disturbances is transformed into the ship manoeuvring systems in non-affine pure-feedback form. Then, by combing the Implicit Function Theorem, Mean Value Theorem and dynamic surface control technique, the proposed approach is able to avoid completely the circularity problem and complexity growing problem exist in the adaptive neural network controller. During the controller design, the uncertain nonlinear functions are approximated by neural networks. Following this control approach, it is worth noting that the direct adaptive backstepping control for the high fidelity MMG model based ship manoeuvring nonlinear systems is achieved firstly, and the controller structure is simpler. Furthermore, it is shown via stability analysis that all signals in the closed-loop system are uniformly ultimately bounded. At last, two reference signals consist of a constant and a realistic performance requirement of ship are applied to simulation studies to illustrate the utility and merits of the proposed control scheme.

INDEX TERMS Ship manoeuvring, Manoeuvring Modelling Group (MMG) model, non-affine pure-feedback nonlinear system, adaptive neural network control, backstepping design.

I. INTRODUCTION

Since the world's first mechanical ship autopilot was constructed in 1910s, the control problem of ship manoeuvring has been an active research subject in the field of both marine engineering as well as automation and control system [1]. In practice, the properties of ship manoeuvring, which include large inertia, large time-delay, nonlinearity and uncertainty, are the major and important issue for the control of ship manoeuvring system [2]. To deal with these issues, a great number of control approaches have been studied over the past decades for control of ship manoeuvring system. Many significant results have been achieved, such as classical Proportional-Integral-Derivative (PID) control [3], [4], Linear Quadratic Gaussian (LQG) control [5], H_∞ control [6], [7], Model Reference Adaptive Control [8], Feedback Linearization Control [9], [10], Sliding Mode Control [11]–[13] and others [14]–[18]. For example, a direct feedback linearization based adaptive control was proposed for automatic steering of ships [9], in which both course-keeping and course-changing were considered. By combining active disturbance rejection control and modified predictor, an effective control approach for ship steering system with uncertainties was studied [14].

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Particularly, besides the above-mentioned control algorithms, adaptive backstepping procedure is a systematic control design technique for nonlinear system [19]. Up to now, adaptive backstepping control technique is a state-of-the-art design approaches for a large amount of nonlinear systems [20], [21]. Recently, with the rapid development of adaptive control design for nonlinear systems, several adaptive backstepping control schemes for ship steering system have been reported. As a breakthrough, a nonlinear backstepping controller was designed for ship steering system in strict-feedback form [22]. Later, to optimize ship steering controller [22], the design parameters of nonlinear backstepping controller is determined by genetic algorithm [23]. In these papers, to construct and apply the nonlinear backstepping controller, the accurate parameters and nonlinear functions of ship manoeuvring model are needed. By incorporating the Nussbaum-type gain into adaptive backstepping design, a robust controller was proposed for ship heading nonlinear system in the presence of unknown sign of uncertain control coefficients [24]. Later, this approach was extended to ship heading nonlinear system in the presence of uncertain control coefficients and time-varying characters [25], as well as input saturation [26], [27].

Meanwhile, since the outstanding universal approximation feature of neural network (NN) has been verified in the late 1990s, adaptive NN control design becomes an advanced approach in dealing with the highly uncertain, nonlinear and complex systems [28], [29]. Besides NN, fuzzy logic systems (FLSs) is another powerful tool for modeling uncertain nonlinear systems, some remarkable works have been well studied recently [30], [31]. For affine single-input single-output (SISO) strict-feedback nonlinear systems with unknown nonlinearities, a direct adaptive backstepping control scheme was developed based on NN approximation [32]. By utilizing the Takagi-Sugeno (T-S) fuzzy dynamic models, the output feedback sliding mode control was proposed for a class of uncertain nonlinear systems in continuous-time form [33] and discrete-time form [34]. Then, by integrating the control approach [32] with dynamic surface control (DSC) technique [35], the ''explosion of complexity'' problem of controller [32] was reduced obviously. Then, the minimal learning parameter (MLP) techniques was applied to control scheme [35] to reduce the number of design control parameters update online [36]. Typically, this elegant adaptive control scheme was extended to ship steering uncertain nonlinear system with rudder actuator dynamic [37], as well as input saturation [38]. Afterwards, on the back of the achieved results in [24], [25], the DSC techniques was merged with Nussbaum gain to design an adaptive controller for ship steering system with parameter uncertainties [39]. Recently, a modified DSC approach and NNs based adaptive control scheme for steering system of a robotic unmanned surface vehicle (USV) with model uncertainties and measurement noises was proposed [40]. Besides, several adaptive NN control approaches were employed to carry out the simulation studies for ship steering systems [41]–[43] recently.

A common feature of the aforementioned studies [3]–[18], [22]–[27], [37]–[43] is that the adaptive controllers are designed based on ship steering linear model of Nomoto [44], and extension nonlinear models of Norrbin [45], Bech [46] and Nomoto [47]. The main reason lies in the fact that these models are said to be in SISO strict-feedback form [48]. So far, owing to the simplicity and relative accuracy in describing the yaw dynamics, they have been widely used for controller design of ship steering system.

However, it is noticed that these models are simplified from the high fidelity 3 degrees of freedom (DOF) ship manoeuvring model, i.e. these models are obtained by eliminating the surge and sway velocity components as well as simplifying the hydrodynamic parameters and derivatives of 3 DOF ship manoeuvring model [49]. As a consequence, one limitation of these models is that they are more suitable for the description of small rudder angle yaw dynamics and low frequencies of rudder action, whereas the accuracy in describing large rudder angle yaw dynamics is insufficient [50].

Nowadays, Manoeuvring Modelling Group (MMG) model is one of the well-known and high-fidelity 6 DOF mathematical models for ship manoeuvring proposed by Japanese Towing Tank Conference (JTTC). The primary features of basic MMG model are the division of all hydrodynamic forces and moments working on the ship's hull, rudder, propeller, and their interaction [51]. Through years of progress, the studies on hydrodynamic forces acting on ships of MMG model are updated constantly, and several MMG based ship manoeuvring simulation methods have been presented [52], [53]. Recently, by taking account of accuracy and simplicity comprehensively, a proper and standard MMG methods for ship manoeuvring was derived from the existing MMG methods [54].

Nevertheless, comparing to the ship steering responsive model indicated in the aforementioned studies, it is noticed that adaptive backstepping control has not directly developed for the MMG manoeuvring model up to now. The reason lies in that the MMG manoeuvring model is not said to be in affine strict-feedback form, i.e. the MMG manoeuvring model is in non-affine form. Owing to the non-affine properties, design exact virtual controls and actual control for MMG based ship manoeuvring system becomes much more intractable in conventional adaptive backstepping design procedure. As a consequence, many ship steering responsive model based elegant backstepping control schemes maybe not suitable for MMG manoeuvring model.

In addition, in the field of automation and control system, the pure-feedback system is a generalization and extension of the strict-feedback system for describing a class of lower-triangular nonlinear systems [21], i.e. the strict-feedback system is a special case of pure-feedback system. In general, the implementation of backstepping control design for pure-feedback system is challenging since there are not affine variables which can be adopted as virtual controls and actual control. Moreover, the circularity problem will be encountered if the adaptive NN control design is applied to pure-feedback system via backstepping directly [55], that is both actual control and NN are a part of each other in the controller simultaneously. In recent years, based on backstepping design, several adaptive NN control algorithms were studied for two kind of simpler and special pure-feedback nonlinear systems, which each subsystem is affine [56], [57], as well as the last and penultimate subsystems are affine [58], [59]. Specifically, to solve circularity problem, an ISS-modular approach based adaptive backstepping control approach was presented for a class of completely non-affine uncertain pure-feedback nonlinear systems [60]. Then, the ISS-modular approach based adaptive controller [60] was further developed by using DSC technique [61]. Consequently, in [61], the circularity problem and "explosion of complexity" problem are avoided simultaneously. Essentially, it is obviously that the MMG manoeuvring model is a non-affine pure-feedback nonlinear system. Until now, there is still no report on applying the backstepping based direct adaptive NN control for MMG model based ship manoeuvring nonlinear system.

Motivated by above observation, in this article, a direct adaptive NN control scheme is developed for non-affine MMG model based ship manoeuvring nonlinear systems via backstepping firstly. Moreover, two reference signals consist of a constant and a realistic performance requirement of ship are applied to simulation studies to illustrate the effectiveness and merits of the proposed control scheme.

The rest of the paper is organized as follows. The high fidelity 3 DOF ship manoeuvring model, i.e. the MMG model, is introduced in Section 2 in detail. Section 3 describes the MMG model based ship manoeuvring system is described, and some preliminaries are provided. In Section 4, the adaptive NN control design procedure and stability analysis for non-affine MMG model based ship manoeuvring nonlinear system are carried out. Then, simulation studies via two reference signals are presented to demonstrate the effectiveness of the proposed control scheme in Section 5. This paper ends with conclusion in Section 6.

II. MANOEUVRING MODELLING GROUP (MMG) MODEL (3 DOF)

Nowadays, the MMG model is one of the well-known and high-fidelity 6 DOF mathematical models for ship manoeuvring motion proposed by JTTC. Overall, the primary features of basic MMG are the division of all hydrodynamic forces and moments working on the ship's hull, rudder, propeller, and their interaction. In this section, the state-of-the-art and standard 3 DOF MMG simulation model for single propeller single rudder ship in still water is introduced as follows [54].

Figure 1 shows the space-fixed coordinate system o_0-$x_0y_0z_0$ and the body-fixed coordinate system o-xyz, it is worth noting that the center of body-fixed coordinate system o is fixed to the mid-ship of ship. As shown in Figure 1, ψ, r, δ, u, v_m, U and β are heading angle, yaw rate, rudder angle,

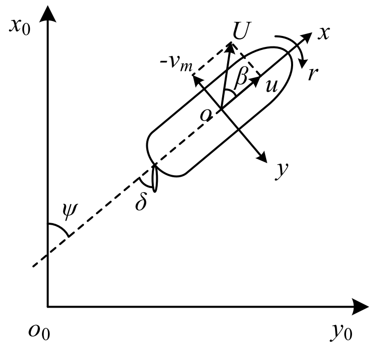

FIGURE 1. Coordinate systems.

surge velocity, sway velocity, total velocity and drift angle of ship, respectively. Then,

$$v = v_m + x_G r \tag{1}$$

$$\beta = \tan^{-1}\left(-v_m/u\right) \tag{2}$$

$$U = \sqrt{u^2 + v_m^2} \tag{3}$$

where v means the sway velocity at the centre of gravity, x_G is the distance from centre of gravity to mid-ship.

In general, the standard 3 DOF MMG manoeuvring equations are expressed as [54]

$$\begin{cases} (m+m_x)\dot{u} - (m+m_y)v_m r - x_G m r^2 = X \\ (m+m_y)\dot{v}_m + (m+m_x)ur + x_G m\dot{r} = Y \\ (I_{zG} + x_G^2 m + J_z)\dot{r} + x_G m(\dot{v}_m + ur) = N_m \end{cases} \tag{4}$$

where m is ship's mass, m_x is ship's added mass in o-x axis direction, m_y is ship's added mass in o-y axis direction, J_z is ship's added moment of inertia around mid-ship. X, Y, N_m denote the surge force, lateral force, yaw moment around mid-ship, which are expressed as follows

$$\begin{cases} X = X_H + X_R + X_P + X_A + X_W + X_E \\ Y = Y_H + Y_R + Y_A + Y_W + Y_E \\ N_m = N_H + N_R + N_A + N_W + N_E \end{cases} \tag{5}$$

where subscripts H, R, P,A,W and E denote the hydrodynamic forces or moment induced by ship hull, rudder, propeller, wind, wave and external forces, respectively.

In the first place, the influence of current is considered as a coordinate system that moves with the current [62], then ship hull's hydrodynamic forces X_H, X_R and X_P are expressed as follows

$$\begin{cases} X_H = (1/2)\rho L_{pp} d U^2 X'_H(v'_m, r') \\ Y_H = (1/2)\rho L_{pp} d U^2 Y'_H(v'_m, r') \\ N_H = (1/2)\rho L_{pp}^2 d U^2 N'_H(v'_m, r') \end{cases} \tag{6}$$

where ρ denote water density, L_{pp} denote ship length between perpendiculars, d is ship draft. v'_m is non-dimensionalised by v_m/U, r' is non-dimensionalised by rL_{pp}/U, as well as $X'_H(v'_m, r')$, $Y'_H(v'_m, r')$ and $N'_H(v'_m, r')$ are non-dimensionalised values, which are expressed as

$$\begin{cases} X'_H(v'_m, r') = -R'_0 + X'_{vv}v'^2_m + X'_{vr}v'_m r' + X'_{rr}r'^2 + X'_{vvvv}v'^4_m \\ Y'_H(v'_m, r') = Y'_v v'_m + Y'_R r' + Y'_{vvv}v'^3_m + Y'_{vvr}v'^2_m r' + Y'_{vrr}v'_m r'^2 \\ \qquad + Y'_{rrr}r'^3 \\ N'_H(v'_m, r') = N'_v v'_m + N'_R r' + N'_{vvv}v'^3_m + N'_{vvr}v'^2_m r' \\ \qquad + N'_{vrr}v'_m r'^2 + N'_{rrr}r'^3 \end{cases} \tag{7}$$

where R'_0 is non-dimensionalised resistance coefficient of ship, the remaining parameters, e.g. X'_{vv}, X'_{vr}, X'_{rr}, etc. are non-dimensionalised hydrodynamic derivatives.

Secondly, ship propeller's surge force X_P is expressed as

$$X_P = (1 - t_p)T \tag{8}$$

where t_p is thrust deduction coefficient, T is propeller thrust and expressed as

$$T = \rho n_p^2 D_p^4 K_T(J_P) \tag{9}$$

where n_p is propeller revolution, D_p is propeller diameter, $K_T(J_P)$ is propeller thrust open water characteristic which can be approximated by following equation

$$K_T(J_P) = k_{t2}J_P^2 + k_{t1}J_P + k_{t0} \tag{10}$$

where k_{t0}, k_{t1}, k_{t2} are coefficients of propeller thrust open water characteristic, and J_P is propeller advanced ratio and expressed as

$$J_P = \frac{u(1 - w_p)}{n_p D_p} \tag{11}$$

where w_p is wake coefficient of propeller and expressed as

$$w_p = w_{p0}\exp(C_0\beta_p^2) \tag{12}$$

where w_{p0} is wake coefficient of propeller in straight moving, C_0 is experimental constant, β_p denote propeller's inflow angle when ship is manoeuvring and expressed as

$$\beta_p = \beta - x'_p r' \tag{13}$$

where x_p is longitudinal coordinate of propeller position.

Thirdly, rudder's hydrodynamic forces X_R, Y_R, N_R by steering are expressed as

$$\begin{cases} X_R = -(1 - t_R)F_N \sin\delta \\ Y_R = -(1 + a_H)F_N \cos\delta \\ N_R = -(x_R + a_H x_H)F_N \cos\delta \end{cases} \tag{14}$$

where t_R is steering resistance deduction factor, a_H is increase factor of rudder force, x_H is the distance from additional lateral force component to mid-ship, and x_R is the distance from rudder to mid-ship ($= -0.5L_{pp}$). F_N is the rudder normal force and expressed as

$$F_N = (1/2)\rho A_R U_R^2 f_\alpha \sin\alpha_R \tag{15}$$

where A_R is profile area of rudder, f_α denote the rudder lift gradient coefficient. α_R and U_R are angle and resultant velocity of rudder inflow, which are expressed as

$$\begin{cases} U_R = \sqrt{u_R^2 + v_R^2} \\ \alpha_R = \delta - \tan^{-1}(v_R/u_R) \approx \delta - v_R/u_R \end{cases} \tag{16}$$

where u_R, v_R are rudder's longitudinal and lateral inflow velocity, which are expressed as

$$\begin{cases} v_R = U\gamma_R\beta_R \\ u_R = \varepsilon u(1 - w_p) \\ \quad \times\sqrt{\varsigma\left\{1 + \kappa\left(\sqrt{1 + 8K_T/\pi J_P^2} - 1\right)\right\}^2 + (1 - \varsigma)} \end{cases} \tag{17}$$

where γ_R is flow straightening coefficient, ζ is equal to D_p/H_R, H_R is rudder span length, ε is equal to (1-w_R)/(1-w_P), κ is an experimental constant, and β_R is rudder's effective inflow angle and expressed as

$$\beta_R = \beta - l'_R r' \tag{18}$$

where l_R is effective distance from rudder position to mid-ship, and treated as an experimental constant. Specifically, the rudder's hydrodynamic forces X_R, Y_R, and N_R are mainly varying with surge velocity u, sway velocity v_m and rudder angle δ, respectively.

Fourthly, the wind force and moment acting on the ship are expressed as

$$\begin{cases} X_A = (1/2)\rho_A A_T V_A^2 C_{XA}(\theta_A) \\ Y_A = (1/2)\rho_A A_L V_A^2 C_{YA}(\theta_A) \\ N_A = (1/2)\rho_A A_T L_{pp} V_A^2 C_{NA}(\theta_A) \end{cases} \tag{19}$$

where ρ_A is air density, V_A is the relative wind velocity, A_T and A_L are the frontal projected area and the lateral projected area, respectively, as well as C_{XA}, C_{YA} and C_{NA} are the coefficients as functions of relative wind direction θ_A.

In addition, the wave-induced steady forces and moment in regular waves are expressed as [63]

$$\begin{cases} X_W = \rho g H_W^2 (B^2/L) C_{XW}(U, T_v, \chi_0) \\ Y_W = \rho g H_W^2 (B^2/L) C_{YW}(T_v, \chi_0) \\ N_W = \rho g H_W^2 B^2 C_{NW}(T_v, \chi_0) \end{cases} \tag{20}$$

where g is the gravity acceleration, B is the breadth, H_W is the amplitude of wave height, T_v is the wave period, χ_0 is the relative wave direction, C_{XW}, C_{YW}, C_{NW} are steady force coefficients in regular waves.

It is notable that several aforementioned hydrodynamic force coefficients, such as hydrodynamic derivatives, are usually unknown and estimated from empirical formulae, captive model tests, numerical computations, or system identifications. Thereby, the existing mathematical model of ship maneuvering motion, including MMG model, are typical physical model with uncertainties in nature.

III. MMG MODEL BASED SHIP MANOEUVRING SYSTEM AND PRELIMINARIES

A. MMG MODEL BASED SHIP MANOEUVRING SYSTEM

Consider the MMG model described from Eq. (4) to Eq. (20), the rudder angle δ is model input, the surge velocity u, sway velocity v_m, and yaw rate r are model output. In general, the rudder angle δ is mainly applied to control ship heading angle ψ when ship is manoeuvring, while surge velocity u and sway velocity v_m are varied accordingly.

Hence, the relationship between rudder angle δ and ship heading angle ψ is usually used to design the controller of ship manoeuvring. By integrating the second and third formulation of Eq. (4), the derivative of r becomes

$$\dot{r} = f_r(r)/\sigma_r + (g_r/\sigma_r)\sin(\delta - v_R/u_R)\cos\delta + \xi \quad (21)$$

where $f_r(r) = (m+m_y)N_H + x_G m u r(m_x - m_y) - x_G m Y_H$ is a highly nonlinear uncertain function of r, $g_r = 0.5\rho A_R U_R^2 f_\alpha \times [(1+a_H)x_G m - (m+m_y)(x_R + a_H x_H)]$ and $\sigma_r = x_G^2 m m_y + (m+m_y)(I_{zG} + J_z)$ are uncertain parameters, ξ donates bounded uncertain external disturbance, include wind, wave and external forces.

Meanwhile, in view of the actual practice, the first order rudder actuator dynamics model is expressed as follows

$$\dot{\delta} = -(1/T_E)\delta + (K_E/T_E)\delta_E \quad (22)$$

where T_E is time constant of a steering gear, K_E is the steering quality index, δ_E is the order angle of the steering gear.

Then the control system regarding the ordered rudder angle δ_E and ship heading angle ψ is expressed as follows

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = f_r(r)/\sigma_r + (g_r/\sigma_r)\sin(\delta - v_R/u_R)\cos\delta + \xi \\ \dot{\delta} = -(1/T_E)\delta + (K_E/T_E)\delta_E \end{cases} \quad (23)$$

Consider the control system (23), it can be observed that it is entirely different from affine strict-feedback nonlinear system, which is shown in [32]. Hence, control system (23) is not said to be considered as a class of affine strict-feedback nonlinear systems. Furthermore, owing to the non-affine properties, it is extremely difficult to design exact virtual controls and actual control for MMG based ship manoeuvring system (23) in conventional adaptive backstepping design procedure.

Essentially, it is easy to find out that the control system (23) could be viewed as a class of uncertain nonlinear systems in non-affine pure-feedback form, as shown in [60]. Thereby, to carry out the adaptive backstepping design for ship manoeuvring system, the control system (23) is considered to be a class of non-affine pure-feedback nonlinear system with uncertainties in this section.

For convenience, define $x_1 = \psi$, $x_2 = r$, $x_3 = \delta$, and $u = \delta_E$, the control system (23) is transformed to the following form:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = f_2(\bar{x}_3) \\ \dot{x}_3 = f_3(\bar{x}_3, u) \\ y = x_1 \end{cases} \quad (24)$$

where $\bar{x}_3 = [x_1, x_2, x_3]^T \in R^3$ is system state variables, $u \in R$ is system input, $y \in R$ is the system output, and $f_i(\cdot)$, $i = 2, 3$, are uncertain smooth nonlinear functions with external disturbances.

For the control design of system (24), define

$$g_2(\bar{x}_3) = \partial f_2(\bar{x}_3)/\partial x_3,\ g_3(\bar{x}_4) = \partial f_3(\bar{x}_4)/\partial x_4 \quad (25)$$

where $x_4 = u$. Owing to the external disturbances is bounded in practice, it is easy to see that the signs of $g_2(\cdot)$ and $g_3(\cdot)$ are positive, and exist constants $g_{i1} \geq g_i(\cdot) \geq g_{i0} > 0$, $i = 2, 3$.

In the meanwhile, for system output y, the reference trajectory $y_r(t)$ is a sufficiently smooth function of t and $y_r(t)$, $\dot{y}_r(t)$, $\ddot{y}_r(t)$ are bounded for $t \geq 0$.

B. RADIAL BASIS FUNCTION (RBF) NEURAL NETWORK

Owing to the universal approximation ability, neural network (NN) has become one of the most frequently tools in control domain. Owing to the simple structure and good approximation capability, the radial basis function (RBF) NN is exploited to approximate the continuous function $h(Z)$: $R^q \rightarrow R$ in this paper as follows

$$h_{nn}(Z) = W^T S(Z) \quad (26)$$

where $Z \in \Omega_Z \subset R^q$ is input vector, $W = [w_1, w_2, \ldots, w_l]^T \in R^l$ is weight vector, l is RBF NN node number, and $S(Z) = [s_1(Z), s_2(Z), \ldots, s_l(Z)]^T$ with $s_i(Z)$ is expressed as the following Gaussian function

$$s_i(Z) = \exp\left[-(Z-\mu_i)^T(Z-\mu_i)/\sigma_i^2\right], \quad i = 1, 2, \ldots, l \quad (27)$$

where the centre of receptive field $\mu_i = [\mu_{i1}, \mu_{i2}, \ldots, \mu_{iq}]^T$, and σ_i is the width of the Gaussian function.

Furthermore, for each continuous function over a compact set $\Omega_Z \subset R^q$, arbitrary approximate accuracy could have achieved by RBF NN in following form

$$h(Z) = W^{*T} S(Z) + \xi, \forall Z \in \Omega_Z \quad (28)$$

where weight vector W^* is an ideal constant and needs to be estimated by $\hat{W}$, ξ means the approximation error.

IV. MMG MODEL BASED ADAPTIVE BACKSTEPPING CONTROL DESIGN

A. ADAPTIVE BACKSTEPPING CONTROL DESIGN

In this section, based on NN approximation and DSC technique, the direct adaptive backstepping control design procedure for non-affine ship manoeuvring nonlinear system (24) is described in detail. The control design procedure contains 3 steps, as follows:

Step 1: Defining $s_1 = x_1 - y_r$, then the derivative of s_1 is

$$\dot{s}_1 = x_2 - \dot{y}_r \tag{29}$$

Considering x_2 as a virtual control input, and choosing the ideal control input α_2 as follow

$$\alpha_2 = -k_1 s_1 + \dot{y}_r \tag{30}$$

where k_1 is a design positive constant.

Then, a first-order filter with time constant τ_2 is employed to turn α_2 into a new state variable z_2

$$\tau_2 \dot{z}_2 + z_2 = \alpha_2, z_2(0) = \alpha_2(0) \tag{31}$$

Step 2: Defining $s_2 = x_2 - z_2$, then the derivative of s_2 is

$$\dot{s}_2 = f_2(\bar{x}_3) - \dot{z}_2 \tag{32}$$

since $\partial f_2(\bar{x}_3)/\partial x_3 \geq g_{20} > 0$, then $\partial [f_1(\bar{x}_2) - \dot{y}_r]/\partial x_2 \geq g_{20} > 0$.

Considering x_3 as a virtual control input, on the basis of Implicit Function Theorem, there is a continuous smooth function $x_3 = \alpha_3^*(\bar{x}_2, \dot{z}_2)$ satisfy

$$f_2(\bar{x}_2, \alpha_3^*) - \dot{z}_2 = 0 \tag{33}$$

At the same time, in accordance with the Mean Value Theorem, there is a λ_2 $(0 < \lambda_2 < 1)$ t satisfies

$$f_2(\bar{x}_3) = f_2(\bar{x}_2, \alpha_3^*) + g_{\lambda_2}(x_3 - \alpha_3^*) \tag{34}$$

where $g_{\lambda_2} = g_2(\bar{x}_2, x_{\lambda_2})$ with $x_{\lambda_2} = \lambda_2 x_3 + (1 - \lambda_2)\alpha_{i+1}^*$.

Combining (32) - (34) yields

$$\dot{s}_2 = g_{\lambda_2}(x_3 - \alpha_3^*) \tag{35}$$

Here, $\alpha_3^*(\bar{x}_2, \dot{z}_2)$ can be approximated by RBF NN $W_2^T S_2(Z_2)$ as follow

$$\alpha_3^*(\bar{x}_2, \dot{z}_2) = W_2^T S_2(Z_2) + \xi_2 \tag{36}$$

where $Z_2 = [\bar{x}_2, \ \dot{z}_2]^T \in \Omega_2 \subset R^3$, and approximation error $|\xi_2| \leq \xi_2^*$ with constant $\xi_2^* > 0$.

The virtual control input α_3 is chosen as

$$\alpha_3 = -k_2 s_2 + \hat{W}_2^T S_2(Z_2) \tag{37}$$

where k_2 is a design positive constant, and consider the following adaptation law

$$\dot{\hat{W}}_2 = \Gamma_2 \left[-S_2(Z_2) s_2 - \eta_2 \hat{W}_2 \right] \tag{38}$$

with any constant matrix $\Gamma_2 = \Gamma_2^T > 0$, and a real scalar $\eta_2 > 0$.

Then, a first-order filter with time constant τ_3 is employed to turn α_3 into a new state variable z_3

$$\tau_3 \dot{z}_3 + z_3 = \alpha_3, z_3(0) = \alpha_3(0) \tag{39}$$

Step 3: Defining $s_3 = x_3 - z_3$, then the derivative of s_3 is

$$\dot{s}_3 = f_3(\bar{x}_3, u) - \dot{z}_3 \tag{40}$$

since $\partial f_3(\bar{x}_3, u)/\partial u \geq g_{30} > 0$,then $\partial [f_3(\bar{x}_3, u) - \dot{z}_3]/\partial u \geq g_{30} > 0$.

Similarly with Step 2, there is a continuous smooth function $u = u^*(\bar{x}_3, \dot{z}_3)$ satisfy

$$f_3(\bar{x}_3, u^*) - \dot{z}_3 = 0 \tag{41}$$

and there is a λ_3 $(0 < \lambda_3 < 1)$ satisfy

$$f_3(\bar{x}_3, u) = f_3(\bar{x}_3, u^*) + g_{\lambda_3}(u - u^*) \tag{42}$$

where $g_{\lambda_3} = g_3(\bar{x}_3, x_{\lambda_3})$ with $x_{\lambda_3} = \lambda_3 u + (1 - \lambda_3)u^*$.

Combining (40) - (42) yields

$$\dot{s}_3 = g_{\lambda_3}(u - u^*) \tag{43}$$

Here, $u^*(\bar{x}_3, \dot{z}_3)$ can be approximated by RBF NN $W_3^T S_3(Z_3)$ as follow

$$u^*(\bar{x}_3, \dot{z}_3) = W_3^T S_3(Z_3) + \xi_3 \tag{44}$$

where $Z_3 = [\bar{x}_3, \ \dot{z}_3]^T \in \Omega_3 \subset R^4$, and approximation error $|\xi_3| \leq \xi_3^*$ with constant $\xi_3^* > 0$.

Then, choose the actual control input u as

$$u = -k_3 s_3 + \hat{W}_3^T S_3(Z_3) \tag{45}$$

where k_3 is a design positive constant, and consider the following adaptation law

$$\dot{\hat{W}}_3 = \Gamma_3 \left[-S_3(Z_3) s_3 - \eta_3 \hat{W}_3 \right] \tag{46}$$

with any constant matrix $\Gamma_3 = \Gamma_3^T > 0$, and a real scalar $\eta_2 > 0$.

Remark 1: It is worth noting that if the NNs are employed to approximate the desired virtual control (36) and desired actual control (44) in adaptive NN (or FLS) control as [28]–[43], the circular construction of the actual controller for non-affine ship manoeuvring nonlinear pure-feedback system (24) will appear since the NN approximation is one part of control u. To overcome this difficulty, in this article, the Implicit Function Theorem [58] and Mean Value Theorem are used to show the existence of desired feedback control α_3^* and u^*, as well as design the stabilizing function, which the RBF NN is employed to approximate the desired feedback control α_3^* and u^*. Following this approach, the circularity problem during adaptive backstepping design for system (24) is avoided with less restrictive assumptions.

Remark 2: In addition, to design a practicable adaptive controller, the complexity growing problem is another difficulty in the conventional backstepping design procedure due to the repeated differentiations of certain nonlinear functions [35], e.g. for system (24), the derivatives of α_2 and α_3 would have to appear in α_3 and u respectively, lead to a complex expression of u. Specifically, in this article, by incorporating the DSC technique, the quantity $\dot{\alpha}_i$ is replaced by $\dot{z}_i$ in defining the virtual control α_{i+1}, and z_i is defined by a first-order filter with α_i as input. Obviously, simpler algebraic operations replace the operation of differentiation. As a result, the complexity growing problem is avoided and a much simpler adaptive NN controller is achieved.

Remark 3: It is well known that the backstepping design method is a major and elegant control design technique for lower-triangular systems with nonlinearities, uncertainties, time-varying, time-delay. Besides the ship manoeuvring nonlinear system (24), the backstepping design has been well developed for a great deal of mechatronic systems nowadays, e.g. to deal with the various nonlinearities and uncertainties in teleoperation system, an adaptive fuzzy backstepping control design is proposed for bilateral teleoperation manipulators [64].

B. STABILITY ANALYSIS

This section gives the stability analysis of ship manoeuvring closed-loop system (24). To this end, define the NN weight estimation error as

$$\tilde{W}_i = \hat{W}_i - W_i^*, i = 2, 3 \tag{47}$$

According to Eqs. (36), (37), (44) and (45), then the error surface s_i, $i = 1, 2, 3$ becomes

$$\begin{cases} \dot{s}_1 = s_2 + z_2 - \dot{y}_r \\ \dot{s}_2 = g_{\lambda_2}\left[s_3 + z_3 - W_2^T S_2(Z_2) - \xi_2\right] \\ \dot{s}_3 = g_{\lambda_3}\left[-k_3 s_3 + \tilde{W}_3^T S_3(Z_3) - \xi_3\right] \end{cases} \tag{48}$$

Define

$$\begin{cases} y_2 = z_2 - \alpha_2 = z_2 + k_1 s_1 - \dot{y}_r \\ y_3 = z_3 - \alpha_3 = z_3 + k_2 s_2 - \hat{W}_2^T S_2(Z_2) \end{cases} \tag{49}$$

then

$$\begin{cases} \dot{s}_1 = -k_1 s_1 + s_2 + y_2 \\ \dot{s}_2 = g_{\lambda_2}\left[-k_2 s_2 + s_3 + y_3 + \tilde{W}_2^T S_2(Z_2) - \xi_2\right] \\ \dot{s}_3 = g_{\lambda_3}\left[-k_3 s_3 + \tilde{W}_3^T S_3(Z_3) - \xi_3\right] \end{cases} \tag{50}$$

Noting that

$$\dot{z}_i = (\alpha_i - z_i)/\tau_i, i = 2, 3 \tag{51}$$

gives

$$\begin{cases} \dot{y}_2 = \dot{z}_2 + k_1\dot{s}_1 - \ddot{y}_r = -y_2/\tau_2 + B_2(s_1, s_2, y_2, y_r, \dot{y}_r, \ddot{y}_r) \\ \dot{y}_3 = \dot{z}_3 + k_2\dot{s}_2 - \dot{\hat{W}}_2^T S_2(Z_2) - \hat{W}_2^T \dfrac{\partial S_2}{\partial \bar{x}_2}\dot{\bar{x}}_2 - \hat{W}_2^T \dfrac{\partial S_2}{\partial \dot{z}_2}\ddot{z}_2 \\ = -y_3/\tau_3 + B_3(s_1, s_2, s_3, y_2, y_3, \hat{W}_2, \hat{W}_3, y_r, \dot{y}_r, \ddot{y}_r) \end{cases} \tag{52}$$

where $B_2(s_1, s_2, y_2, y_r, \dot{y}_r, \ddot{y}_r) = k_1\dot{s}_1 - \ddot{y}_r$, $B_3(s_1, s_2, s_3, y_2, y_3, \hat{W}_2, \hat{W}_3, y_r, \dot{y}_r, \ddot{y}_r) = k_2\dot{s}_2 - \dot{\hat{W}}_2^T S_2(Z_2) - \hat{W}_2^T \frac{\partial S_2}{\partial \bar{x}_2}\dot{\bar{x}}_2 - \hat{W}_2^T \frac{\partial S_2}{\partial \dot{z}_2}\ddot{z}_2$ are continuous functions and satisfies $|B_2| \le M_2$, $|B_3| \le M_3$.

1) INPUT-TO STATE PRACTICALLY STABLE (ISPS) OF SY-SUBSYSTEM

In this subsection, the stability analysis of sy-subsystem is carried out, and the result shows that the sy-subsystem is input-to state practically stable (ISpS) [65]–[67].

Lemma 1: Considering y and $\tilde{W}$ are input, s is state, the sy-subsystem composed by Eqs. (50) and (52) is ISpS.

Proof: Choose the ISpS-Lyapunov function candidate of sy-subsystem as follow

$$V_{Sy} = \frac{1}{2}\sum_{i=1}^{3} s_i^2 + \frac{1}{2}\sum_{i=1}^{2} y_{i+1}^2 \tag{53}$$

The derivative of V_{Sy} is

$$\begin{aligned} \dot{V}_{Sy} &= s_1\dot{s}_1 + s_2\dot{s}_2 + s_3\dot{s}_3 + \sum\nolimits_{i=1}^{2}\left(-y_{i+1}^2/\tau_{i+1} + y_{i+1}B_{i+1}\right) \\ &= -k_1 s_1^2 + s_1 s_2 + s_1 y_2 + g_{\lambda_2}[-k_2 s_2^2 + s_2 s_3 + s_2 y_3 \\ &\quad + s_2\tilde{W}_2^T S_2(Z_2) - s_2\xi_2] + g_{\lambda_3}[-k_3 s_3^2 + s_3\tilde{W}_3^T S_3(Z_3) \\ &\quad - s_3\xi_3] + \sum\nolimits_{i=1}^{2}\left(-y_{i+1}^2/\tau_{i+1} + y_{i+1}B_{i+1}\right) \end{aligned} \tag{54}$$

using the fact that

$$\begin{cases} s_i s_{i+1} \le s_i^2 + (1/4)\, s_{i+1}^2, \\ s_i y_{i+1} \le s_i^2 + (1/4)\, y_{i+1}^2, \\ s_i\tilde{W}_i^T S_i(Z_i) \le s_i^2 + (1/4)\, \chi_i^2 \left\|\tilde{W}_i\right\|^2, \\ -s_i\xi_i \le s_i^2 + (1/4)\, \xi_i^2, \\ y_{i+1}B_{i+1} \le (1/\upsilon)\, y_{i+1}^2 B_{i+1}^2 + \upsilon/4, \end{cases} \tag{55}$$

where χ_i satisfies $|S_i(Z_i)| \le \chi_i$ (According to Lemma 1 of [58]), then

$$\begin{aligned} \dot{V}_{Sy} &\le \left[(-k_1+2)s_1^2 + \frac{1}{4}s_2^2\right] + g_{\lambda_2}\left[(-k_2+4)s_2^2 + \frac{1}{4}s_3^2\right] \\ &\quad + g_{\lambda_3}(-k_3+2)\, s_3^2 + \frac{1}{4}\sum_{i=2}^{3} g_{\lambda_i}\chi_i^2\left\|\tilde{W}_i\right\|^2 + \frac{1}{4}\sum_{i=2}^{3} g_{\lambda_i}\xi_i^2 \\ &\quad + \frac{1}{2}\upsilon + \left(\frac{1}{4} - \frac{1}{\tau_2} + \frac{B_2^2}{\upsilon}\right) y_2^2 + \left(\frac{g_{\lambda_2}}{4} - \frac{1}{\tau_3} + \frac{B_3^2}{\upsilon}\right) y_3^2 \end{aligned} \tag{56}$$

From Assumption 1, $|B_2| \le M_2$ and $|B_3| \le M_3$, we have

$$\begin{aligned} \dot{V}_{Sy} &\le \left[(2-k_1)s_1^2 + \frac{1}{4}s_2^2\right] + \left[(4\bar{g}_2 - k_2 g_2)s_2^2 + \frac{1}{4}\bar{g}_2 s_3^2\right] \\ &\quad + (-k_3 g_3 + 2\bar{g}_3)\, s_3^2 + \frac{1}{4}\sum_{i=2}^{3}\bar{g}_i\chi_i^2\left\|\tilde{W}_i\right\|^2 + \frac{1}{4}\sum_{i=2}^{3}\bar{g}_i\xi_i^2 \\ &\quad + \frac{1}{2}\upsilon + \left(\frac{1}{4} - \frac{1}{\tau_2} + \frac{M_2^2}{\upsilon}\right) y_2^2 + \left(\frac{\bar{g}_2}{4} - \frac{1}{\tau_3} + \frac{M_3^2}{\upsilon}\right) y_3^2 \end{aligned} \tag{57}$$

choose

$$\begin{cases} k_1 \ge 2 + \frac{1}{2}a_1, \\ k_2 g_2 \ge 4\bar{g}_2 + \frac{1}{4} + \frac{1}{2}a_1, \\ k_3 g_3 \ge 2\bar{g}_3 + \frac{1}{4}\bar{g}_2 + \frac{1}{2}a_1, \end{cases} \tag{58}$$

where $a_1 > 0$, and let

$$\frac{1}{\tau_2} \geq \frac{1}{4} + \frac{M_2^2}{\upsilon} + \frac{1}{2}a_1, \frac{1}{\tau_3} \geq \frac{\bar{g}_2}{4} + \frac{M_3^2}{\upsilon} + \frac{1}{2}a_1,$$
$$b_1 = \frac{1}{4}\max\left\{\bar{g}_i\chi_i^2 \,|i = 2, 3\right\}, c_1 = \frac{1}{4}\sum_{i=2}^{3}\bar{g}_i\xi^{*2} + \frac{1}{2}\upsilon \quad (59)$$

then, we obtain

$$\dot{V}_{Sy} \leq -a_1 V_{Sy} + b_1 \left\|\tilde{W}\right\|^2 + c_1 \quad (60)$$

According to the Definition 2 of [32], if we choose a class K-functions $\theta_1(s) = \theta_2(s) = (1/2)\, s^2$, $\theta_3(s) = (1/2)\, a_1 s^2$ and $\theta_4(s) = bs^2$, then the ISpS of sy-subsystem is achieved and sy-subsystem's nonlinear L∞ gain function is expressed as

$$\varphi_1(s) = \theta_1^{-1} \circ \theta_2 \circ \theta_3^{-1} \circ \theta_4(s) = \sqrt{\frac{2b_1}{a_1}}s \quad (61)$$

2) ISPS OF $\tilde{W}$-SUBSYSTEM

In this subsection, the stability analysis of $\tilde{W}$-subsystem is carried out, and the result shows that the sy-subsystem is ISpS. For this purpose, the $\tilde{W}$-subsystem is rewritten as

$$\dot{\tilde{W}}_i = \Gamma_i \left[-S_i (Z_i)\, s_i - \eta_i \tilde{W}_i - \eta_i W_i\right], i = 2, 3 \quad (62)$$

Lemma 2: Considering s is input, $\tilde{W}$ is state, the $\tilde{W}$-subsystem (62) is ISpS.

Proof: Choose the ISpS-Lyapunov function candidate of $\tilde{W}$-subsystem as follow

$$V_{\tilde{W}} = \frac{1}{2}\sum_{i=2}^{3}\tilde{W}_i^T \tilde{W}_i \quad (63)$$

The derivative of $V_{\tilde{W}}$ is

$$\dot{V}_{\tilde{W}} = \sum_{i=2}^{3}\left[-\tilde{W}_i^T \Gamma_i S_i (Z_i)\, s_i - \eta_i \tilde{W}_i^T \Gamma_i \tilde{W}_i - \eta_i \tilde{W}_i^T \Gamma_i W_i\right] \quad (64)$$

using the fact that

$$\begin{cases} -\tilde{W}_i^T \Gamma_i S_i (Z_i)\, s_i \leq \dfrac{\lambda_{\min}(\Gamma_i)\, \eta_i}{4}\tilde{W}_i^T \tilde{W}_i + \dfrac{\|\Gamma_i\|^2 \chi_i^2}{\lambda_{\min}(\Gamma_i)\, \eta_i} s_i^2, \\ -\eta_i \tilde{W}_i^T \Gamma_i \tilde{W} \leq -\lambda_{\min}(\Gamma_i)\, \eta_i \tilde{W}_i^T \tilde{W}_i, \\ -\eta_i \tilde{W}_i^T \Gamma_i W \leq \dfrac{\lambda_{\min}(\Gamma_i)\, \eta_i}{4}\tilde{W}_i^T \tilde{W} + \dfrac{\eta_i \|\Gamma_i\|^2 \|W_i\|^2}{\lambda_{\min}(\Gamma_i)}, \end{cases} \quad (65)$$

Then we obtain

$$\dot{V}_{\tilde{W}} \leq \sum_{i=2}^{3}\frac{\lambda_{\min}(\Gamma_i)\eta_i}{2}\tilde{W}_i^T \tilde{W}_i + \sum_{i=2}^{3}\frac{\|\Gamma_i\|^2 \chi_i^2}{\lambda_{\min}(\Gamma_i)\eta_i}s_i^2 + \sum_{i=2}^{3}\frac{\eta_i \|\Gamma_i\|^2 \|W_i\|^2}{\lambda_{\min}(\Gamma_i)} \quad (66)$$

choose

$$\min\{\lambda_{\min}(\Gamma_i)\eta_i \,|i = 2, 3\} \geq a_2 \quad (67)$$

where $a_2 > 0$, and let

$$b_2 = \frac{1}{4}\max\left\{\frac{\|\Gamma_i\|^2 \chi_i^2}{\lambda_{\min}(\Gamma_i)\eta_i} \,|i = 2, 3\right\},$$
$$c_2 = \sum_{i=2}^{3}\frac{\eta_i \|\Gamma_i\|^2 \|W_i\|^2}{\lambda_{\min}(\Gamma_i)} \quad (68)$$

Then we obtain

$$\dot{V}_{\tilde{W}} \leq -a_2 V_{\tilde{W}} + b_2 \|s\|^2 + c_2 \quad (69)$$

Similar with the sy-subsystem, if we choose a class K-functions $\theta_1(s) = \theta_2(s) = (1/2)\, s^2$, $\theta_3(s) = (1/2)\, a_1 s^2$ and $\theta_4(s) = bs^2$, then the ISpS of $\tilde{W}$-subsystem is achieved and nonlinear L_∞ gain function of $\tilde{W}$-subsystem is expressed as

$$\varphi_2(s) = \theta_1^{-1} \circ \theta_2 \circ \theta_3^{-1} \circ \theta_4(s) = \sqrt{\frac{2b_2}{a_2}}s \quad (70)$$

3) ISPS OF THE COMPOSITE SYSTEM

In this subsection, based on small gain theorem [68], the stability analysis of composite system is described as follows.

Theorem 1: In view of the closed-loop system which is composed of sy-subsystem and $\tilde{W}$ subsystem. Then, for any bounded initial conditions, all the closed-loop system signals remain uniformly ultimately bounded, and the steady state tracking error converges to a neighbourhood around zero by appropriately choosing control parameters.

Proof: Choose the function

$$\varphi_1 \circ \varphi_2(s) = \sqrt{\frac{4b_1 b_2}{a_1 a_2}}s \quad (71)$$

From the expressions of a_1, a_2, b_1 and b_2, we can choose k_i, Γ_i and η_i approximately to make $\sqrt{4b_1 b_2/(a_1 a_2)} < 1$, i.e., the composite system consisting of Eqs. (50), (52) and (62) satisfies Theorem 1, then the closed-loop system is ISpS.

According to the Definition 1 of [36], then

$$\left\|\left[s^T, y^T, \tilde{W}^T\right]_t\right\| \leq \omega\left(\left\|\left[s^T, y^T, \tilde{W}^T\right]_0\right\|, t\right) + e \quad (72)$$

where $\omega(\cdot, \cdot)$ denote a class KL-function, and $e > 0$. Then, the uniformly ultimately bounded for the states of composite system is achieved for $\omega(\cdot, t) \to 0$ when $t \to \infty$. In addition, the Eq. (60) is rewritten as

$$\dot{V}_{Sy} \leq -a_1 V_{Sy} + c_1^* \quad (73)$$

where $b_1 \left\|\tilde{W}\right\|^2 + c_1 \leq c_1^*$.

Solving the inequality (73) gives

$$V_{Sy} \leq \frac{c_1^*}{a_1} + \left[V_{Sy}(0) - \frac{c_1^*}{a_1}\right]e^{-a_1 t}, \quad \forall t \geq 0 \quad (74)$$

It can be seen from Eq. (74) that V_{Sy} is bounded by c_1^* / a_1 in the end. As a result, the semi-globally uniformly ultimately bounded for all signals s_i, $i = 1, 2, 3$, and y_i, $i = 2, 3$, are achieved.

Remark 4: According to the proof, it is obvious that if the positive constants k_1, k_2, k_3 are increasing, as well as the time constants τ_1, τ_2, τ_3 are reducing, that is means the positive constant a_1 is increasing, then the quantity of c_1^* / a_1 will approach to arbitrary small. Consequently, the tracking error will approach to arbitrary small.

V. SIMULATION STUDIES

To illustrate the effectiveness and merits of the proposed control scheme, two simulation examples for MMG based ship manoeuvring nonlinear system are studied in this section.

In the simulation, sample ship is the VLCC tanker named as "KVLCC2". Table 1 and 2 gives the principal particulars and the main experimental hydrodynamics force coefficients of sample ship [54], respectively.

Based on the adaptive control design of this paper, the virtual control input and the actual control input for ship manoeuvring nonlinear systems (24) are given as

$$\begin{cases} \alpha_2 = -k_1 s_1 + \dot{y}_r \\ \alpha_3 = -k_2 s_2 + \hat{W}_2^T S_2(Z_2) \\ u = -k_3 s_3 + \hat{W}_3^T S_3(Z_3) \end{cases} \tag{75}$$

TABLE 1. Principal particulars of KVLCC2 tanker.

Symbol	Quantity	Symbol	Quantity
L_{pp}	320.0 m	*Cb*	0.81
B	58.0 m	*Dp*	9.86 m
d	20.8 m	*Hr*	15.8 m
Displacement	312,600 m^3	*Ar*	112.5 m^2
x_G	11.2 m		

TABLE 2. Main hydrodynamics force coefficients of KVLCC2 tanker.

Symbol	Quantity	Symbol	Quantity	Symbol	Quantity
R'_0	0.022	Y'_{vrr}	-0.391	m'_y	0.223
X'_{vv}	-0.040	Y'_{rrr}	0.008	J'_z	0.011
X'_{vr}	0.002	N'_v	-0.137	t_p	0.220
X'_{rr}	0.011	N'_R	-0.049	k_{t0}	0.2931
X'_{vvvv}	0.771	N'_{vvv}	-0.030	k_{t1}	-0.2753
Y'_v	-0.315	N'_{vvr}	-0.294	k_{t2}	-0.1385
Y'_R	0.083	N'_{vrr}	0.055	w_{p0}	0.35
Y'_{vvv}	-1.607	N'_{rrr}	-0.013	C_0	-2.1
Y'_{vvr}	0.379	m'_x	0.022		

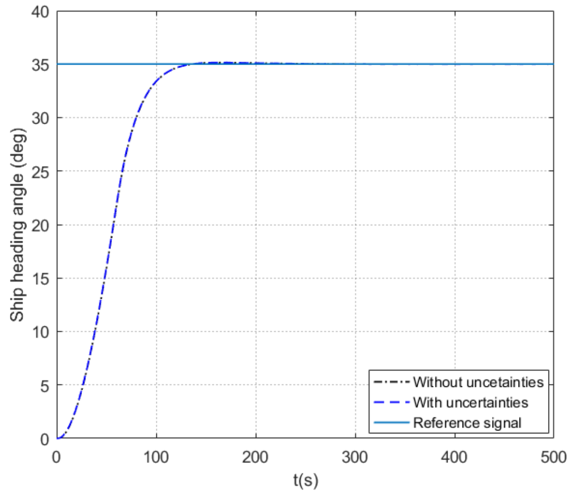

FIGURE 2. Ship heading angle of Example 1.

and the adaptive laws are

$$\begin{cases} \dot{\hat{W}}_2 = \Gamma_2 \left[-S_2(Z_2)s_2 - \eta_2 \hat{W}_2 \right] \\ \dot{\hat{W}}_3 = \Gamma_3 \left[-S_3(Z_3)s_3 - \eta_3 \hat{W}_3 \right] \end{cases} \tag{76}$$

In the initial status of simulation, the heading angle ψ, yaw rate r, surge velocity u and sway velocity v_m and rudder angle δ of sample ship are 0°, 0°/s, 15.5 kn, 0 kn and 0°, respectively, as well as the initial weight of RBF NN are $\hat{W}_2(0) = 0$, $\hat{W}_3(0) = 0$. Moreover, another design controller parameters $k_1 = 0.05$, $k_2 = 600$, $k_3 = 10$, $\Gamma_1 = \Gamma_2 = \text{diag}\{10\}$, and $\eta_1 = \eta_2 = 0.1$. Both RBF NN $\hat{W}_2^T S_2(Z_2)$ and $\hat{W}_3^T S_3(Z_3)$ contains 25 nodes ($l = 25$), with centre μ_i ($i = 1,\ldots,l$) evenly spaced in $[-4, 4] \times [-4, 4]$, and widths $\eta_i = 2 (i = 1,\ldots,l)$.

In this article, two reference signals are studied.

Example 1. The reference signal is assumed as a constant, e.g.

$$y_r = 35° \tag{77}$$

To validate the utility of the proposed method for ship manoeuvring systems with and without model uncertainties, an external disturbance $\xi = 0.00004 \times \sin(0.5t)$ is employed and regarded as uncertainties in control system. The simulation results, including with and without uncertainties, are presented in Figures 2-5. Figure 2 shows the heading angle ψ of sample ship and the reference signal y_r. From Figure 2, it can be seen that the good tracking performance is achieved for ship manoeuvring system with and without model uncertainties. The curves of surge, sway and resultant velocity of sample ship are given in Figure 3, and it is obvious that the surge, sway and resulting velocity of the sample ship vary with the changes of heading angle, which is steered by the rudder. Figure 4 shows the curve of yaw rate of the sample ship, and the curves of order rudder angle (control input) and actual rudder angle of sample ship is given in Figure 5. It can be observed from Figure 5 that the actual rudder angle turns

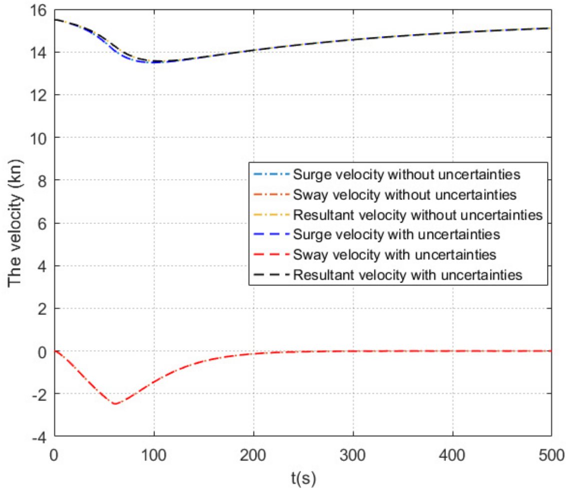

FIGURE 3. Surge, sway and resultant velocity of Example 1.

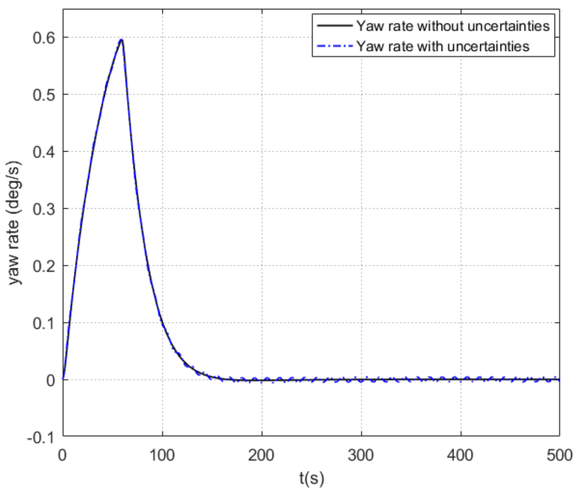

FIGURE 4. Yaw rate of Example 1.

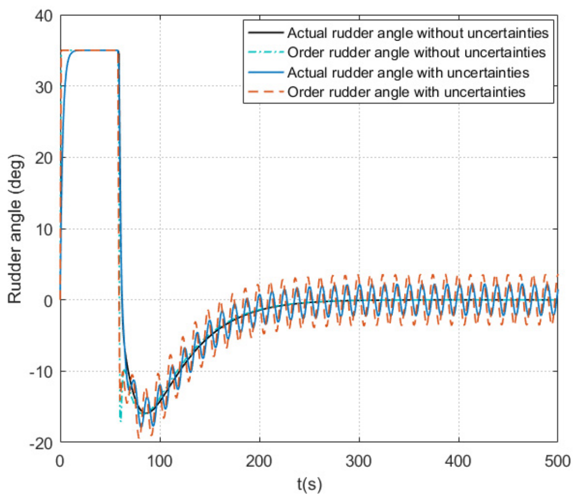

FIGURE 5. Rudder angle of Example 1.

from 0 degree to 35 degrees in about 20 seconds, hence the practical rudder dynamics is considered sufficiently in this paper. Figure 6 shows the boundedness of norms of RBF NN

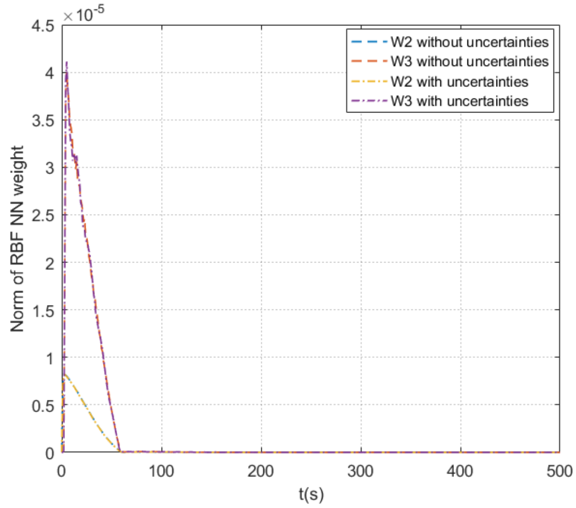

FIGURE 6. Norms of NN weight $\hat{W}_2$ and $\hat{W}_3$ of Example 1.

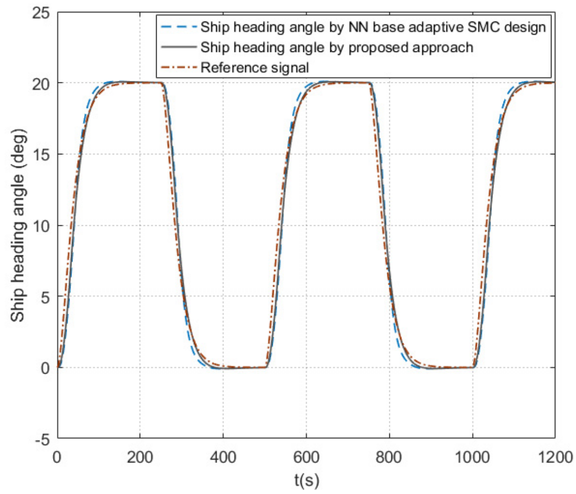

FIGURE 7. Ship heading angle of Example 2.

weights for example 1. Based on the above observation, it is obvious that for the proposed approach is a viable control scheme for ship manoeuvring nonlinear system with uncertainties.

Example 2. The reference signal is assumed as a realistic performance requirement of ship, i.e.

$$\ddot{\phi}_m(t) + 0.1\dot{\phi}_m(t) + 0.0025\phi_m(t) = 0.0025\phi_r(t) \quad (78)$$

where $\phi_m(t)$ means the desired ship heading signal, $\phi_r(t)$ is an order input signal with period in 500s and values from 0° to 20°, i.e.,

$$\phi_r(t) = \left[20\left(\text{sign}\left(\sin\left(2\pi t/1000\right)\right) + 1\right)/2\right]\pi/180 \quad (79)$$

The simulation results are presented in Figures 7-11. From Figure 7, it is obvious that the good tracking performance is achieved for heading angle ψ of sample ship to the reference signal y_r. Figure 8 and 9 gives the curves of surge, sway and resultant velocity as well as yaw rate of sample ship, respectively. The curves of order rudder angle (control input)

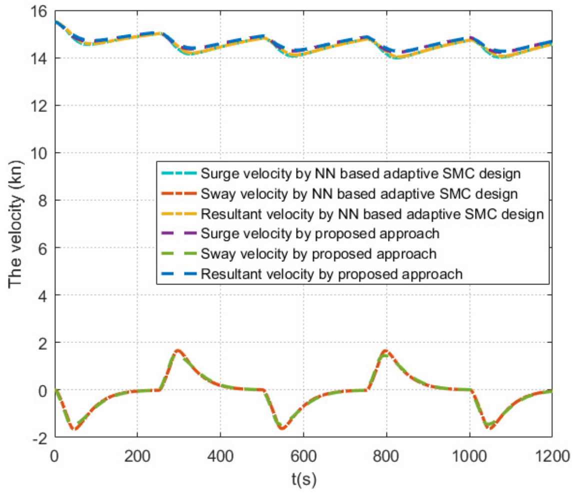

FIGURE 8. Surge, sway and resultant velocity of Example 2.

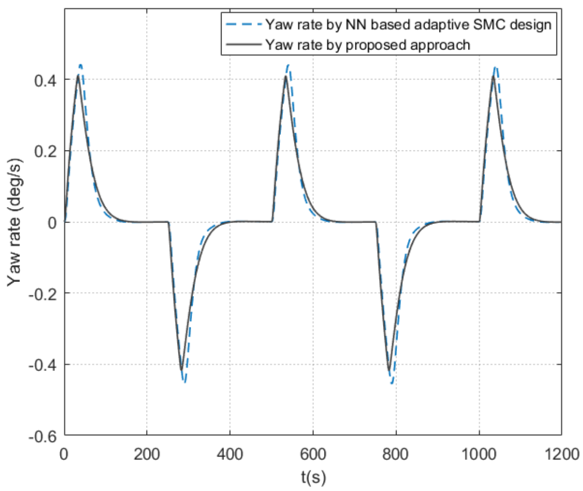

FIGURE 9. Yaw rate of Example 2.

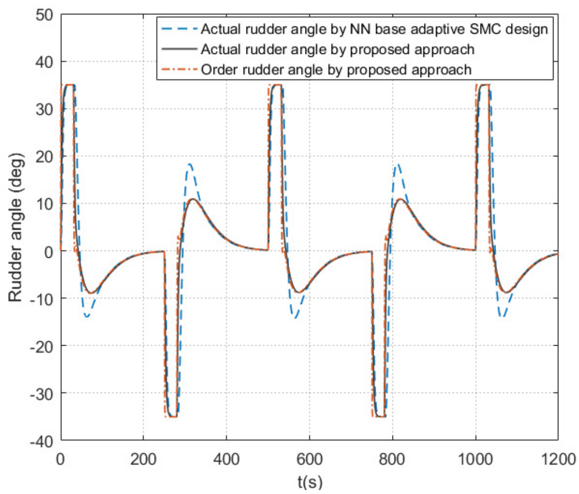

FIGURE 10. Rudder angle of Example 2.

and actual rudder angle of sample ship is given in Figure 10, and Figure 11 shows the boundedness of norms of RBF NN weights for example 2.

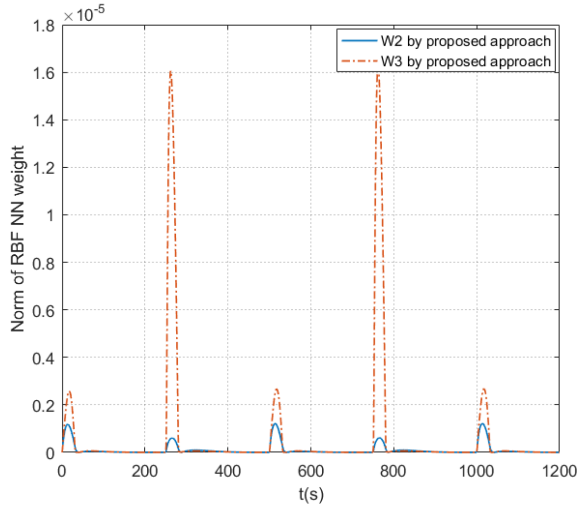

FIGURE 11. Norms of NN weight $\hat{W}_2$ and $\hat{W}_3$ of Example 2.

Remark 5: It is worth noting that the simulation results of Example 2 are carried out by using the proposed approach and the RBFNN based adaptive sliding mode control (SMC) design scheme [69] simultaneously. From Figures 7-10, it is easily observed that there are slight differences in the tracking performance, yaw rate and actual rudder angle of sample ship by using two control approaches. Since the RBFNN based adaptive SMC design scheme have been applied to many industrial systems and achieved many remarkable results in practice, e.g. multilateral tele-robotic system [69], based on the above observations, it can be certified that the performance of proposed approach is effective and practicable.

VI. CONCLUSION

The simulation results are encouraging, and indicate that the control performance of the proposed adaptive NN control scheme for 3 DOF MMG manoeuvring system is excellent, which means that the direct backstepping control design for high fidelity non-affine ship manoeuvring system is feasible and successful via the proposed adaptive NN control scheme. Thereby, comparing with the controller designed based on the simplified ship manoeuvring system, the proposed adaptive NN control scheme is able to realize good control performance for most of ship manoeuvres. Moreover, the complexity of the proposed adaptive NN control scheme is reduced significantly based on DSC technique, which means that it is easy to achievable in practice. As a result, both theoretical analysis and case studies have demonstrated that the proposed adaptive NN controller is a workable and advanced control scheme for high fidelity non-affine ship manoeuvring system in this article.

Furthermore, the proposed direct adaptive NN control scheme will be introduced to study and improve the tracking performance of high fidelity 3 DOF MMG manoeuvring model in regular or irregular waves in future work.

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XIN WANG received the B.Sc. degree in marine technology from Dalian Maritime University, China, in 2012, and the Ph.D. degree in traffic information engineering and control from the Dalian Maritime University, in 2017.

In 2018, he worked as a Postdoctoral Researcher at the Centre for Marine Technology and Ocean Engineering (CENTEC), University of Lisbon. He is currently a Lecturer with the College of Navigation, Dalian Maritime University. His research interests include marine safety, maritime autonomous surface ships, ship maneuverability, ship motion and control, and adaptive neural network control for marine vehicles.

CARLOS GUEDES SOARES received the M.Sc. degree in ocean engineering from the Massachusetts Institute of Technology, Cambridge, MA, USA, in 1976, the Ph.D. degree from the Norwegian Institute of Technology, University of Trondheim, in 1984, and the D.Sc. degree from the Technical University of Lisbon, Portugal, in 1991.

He is currently a member of the Portuguese Academy of Engineering, and is a Distinguished Professor of the Engineering Faculty (Instituto Superior Técnico), University of Lisbon, and the Head of the Centre for Marine Technology and Ocean Engineering (CENTEC), University of Lisbon. His research interests include marine environment, marine dynamics and hydrodynamics, marine structures, as well as safety and logistics of maritime transportation. He is a Fellow of the ASME, SNAME, RINA, IMarEST, and Ordem dos Engenheiros, as well as a member of the ASCE, AGU, and SRA.