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Short communication

Practical proportional integral sliding mode control for underactuated surface ships in the fields of marine practice

Zhijian Sun[a], Guoqing Zhang[a,b], Bowen Yi[a], Weidong Zhang[a,*]

[a] Department of Automation, Shanghai Jiao Tong University, and Key Laboratory of System Control and Information Processing, Ministry of Education of China, Shanghai 200240, PR China
[b] Navigation College, Dalian Maritime University, Liaoning 116026, PR China

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ABSTRACT

Environmental disturbances and systematical uncertainties are the main obstacles for ship motion control. This paper devotes to enhancing the control system robustness of underactuated surface ships with model uncertainties and environmental disturbances. A novel nonlinear robust adaptive scheme with sliding mode control is proposed for underactuated ships to track the desired path generated by the logical virtual ship in the presence of unknown plant parameters and environmental disturbances. Compared with the existing results, the proposed controller is designed based on the combination of PI sliding mode control and the upper bound estimation of disturbances. With the proposed design, the control scheme could not only obtain a better performance of the control system, the continuous scheme also reduce the chattering of system by a special construction of the sliding manifolds. Numerical simulations are given to demonstrate the effectiveness of the proposed method.

1. Introduction

Underactuated surface ships have played an important role in the marine exploration and research, such as dynamic positioning for offshore oil drilling (Tannuri et al., 2010), underwater pipe-laying (Fossen, 1994) and so on. Over the last few years, ship motion control has attracted lots of attention due to its practical applications and theoretical challenges (Zhang et al., 2015). It is well known that underactuated surface ships are equipped with propellers and rudders for surge and yaw motions only, meaning that no actuator is used for the control of sway motion directly (Zhang and Zhang, 2014), and it is a challenge for the ship motion control. Control in the presence of uncertainty is one of the main topics in modern control theory (Shtessel et al., 2014), as well as in the marine control community. In the ship motion dynamics, there always exist discrepancies between the actual dynamics and its models. These discrepancies are mostly caused by the environment disturbances, unknown plant parameters and systematical uncertainties. In addition, when the number of actuators are less than the degree of freedom (Dong and Guo, 2005; Reyhanoglu, 1997; Pettersen and Egeland, 1997), it also generates the non-integral constraints in the controller design.

With the above mentioned challenges in the field of ship motion control, the so-called robust control algorithms have arose in the control system community, such as robust adaptive control (Ioannou and Sun, 2012; Lavretsky and Wise, 2013; Du and Shi, 2016), robust neural damping (Zhang et al., 2015; Zhang and Zhang, 2015, H_∞ control (Cheng et al, 2015; Zou et al., 2016; Chang et al., 2015, backstepping techniques (Li et al., 2015; Liu et al., 2016; Wang et al., 2015, Network-based technology (Wang and Han, 2016a, 2016b; Wang and Xiong, 2015), multi-time scale methods (Yi et al., 2016), and sliding mode control (Xu et al., 2015; Zhang and Chu, 2012; Fossen, 2002), probably, all those algorithms are successful to handle bounded disturbances and uncertainties.

With the consideration of robustness, sliding mode control has been widely applied in the field of ship motion control. In Xu et al. (2015), a novel adaptive dynamic sliding mode control for the trajectory tracking of underactuated unmanned underwater vehicles is proposed to handle with environmental disturbances and systematical uncertainties. However, the assumptions that the first-order derivatives of environmental disturbances and the existence of thruster are too restrictive. In addition, Li et al. (2008) develops a point-to-point navigation for underactuated ships. Although such algorithm can guarantee the closed-loop system to be uniformly ultimately bounded, that is the trajectories converge to an invariant set rather than the

* Corresponding author.
E-mail addresses: sunzhijianfuzhou@sjtu.edu.cn (Z. Sun), zgq_dlmu@163.com (G. Zhang), yibowen@sjtu.edu.cn (B. Yi), support@elsevier.com, wdzhang@sjtu.edu.cn (W. Zhang).

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equilibrium. Furthermore, in Li and Sun (2009), an adaptive sliding mode control law combined with backstepping technique is proposed to solve the trajectory tracking problem, but a simplified simple system model is investigated. Under the design with rudder angle, it makes tracking insensitive, especially for small-scale change yaw angle.

Motivated by the above research line, due to the high performance of sliding mode control in dealing with parameter perturbations and dynamic uncertainties (Zhang et al., 2014, 2013), a novel design is developed to solve the problem of the trajectory tracking for under-actuated surface ships based on the combination of sliding mode control and backstepping technique. Unlike Li et al. (2008), a continuous adaptive sliding mode surface term is derived to reduce the chatting of the closed-loop system. With this proposed design, the controller can not only guarantee the convergence of states to equilibrium, but also reduce the chatting of the system. Furthermore, the algorithm also enhances the robustness to the system uncertainty, such as systematic uncertainties and unknown parameters. The main contributions of this paper are twofold.

1). By combination of a novel nonlinear robust adaptive PI sliding mode scheme and the upper bound estimation of the disturbances, the proposed algorithm is developed to implement the trajectory tracking task of underactuated vehicles.

2). An adaptive continuous PI sliding mode scheme is constructed to stabilize the control system. By using this special property and structure, the control method could not only eliminate the chattering of the closed-loop system, but also relax some assumptions in Xu et al. (2015) (Table 1).

2. Problem formulation

According to Fossen (2002); Li et al. (2008), the kinematic and dynamical equations of underactuated surface ship can be described as Eq. (1). It has two control inputs: the force in surge degree and the control torque in the yaw degree (Jiang, 2002).

$$\begin{cases} \dot{x} = cos(\psi)u - sin(\psi)v \\ \dot{y} = sin(\psi)u + cos(\psi)v \\ \dot{\psi} = r \\ \dot{u} = \Theta_u^T f_u(\dot{\eta}, \eta) + \zeta_u \tau_u + \tau_{w1} \\ \dot{v} = \Theta_v^T f_v(\dot{\eta}, \eta) + \tau_{w2} \\ \dot{r} = \Theta_r^T f_r(\dot{\eta}, \eta) + \zeta_r \tau_r + \tau_{w3} \end{cases} \tag{1}$$

where (x,y) denotes the position coordinates of the underactuated surface vessel model in the earth-fixed frame and ψ is the yaw angle. $\dot{\eta} = R(\psi)(u, v, r)^{\mathrm{T}}$ and (u, v, r) are the velocities in surge, sway and yaw directions. The surge force τ_u and the yaw moment τ_r are considered as two available control inputs with the known nonzero constant control coefficients ζ_u and ζ_r. $\Theta_u \in \Re^{n_u}$, $\Theta_v \in \Re^{n_v}$ and $\Theta_r \in \Re^{n_r}$ are unknown constant vectors with known dimensions n_u,n_v and n_r. $f_u(\dot{\eta}, \eta) \in \Re^{n_u}$, $f_v(\dot{\eta}, \eta) \in \Re^{n_v}$ and $f_r(\dot{\eta}, \eta) \in \Re^{n_r}$ are all known smooth vector fields. τ_{w1}, τ_{w2} and τ_{w3} are the environmental disturbance acting on the surge, sway and yaw axes, respectively.

For path-following control of underactuated surface ships, we define the control objectives in Fig. 1. The error variables have been define as follows (Zhang et al., 2015):

Table 1
Notations.

$\lvert\cdot\rvert$ is the norm of a scalar
$\lVert\cdot\rVert$ is the norm of a vector
$\lVert\cdot\rVert^2 = \Sigma_{i,j}(\cdot)_{i,j}^2 \cdot (\cdot)_{i,j}$ the element of $(\cdot)$ in row i and column j
$\widetilde{(\cdot)} = \widehat{(\cdot)} - (\cdot)$; $\widehat{(\cdot)}$ is the estimate of $(\cdot)$; $\widetilde{(\cdot)}$ is the estimation error

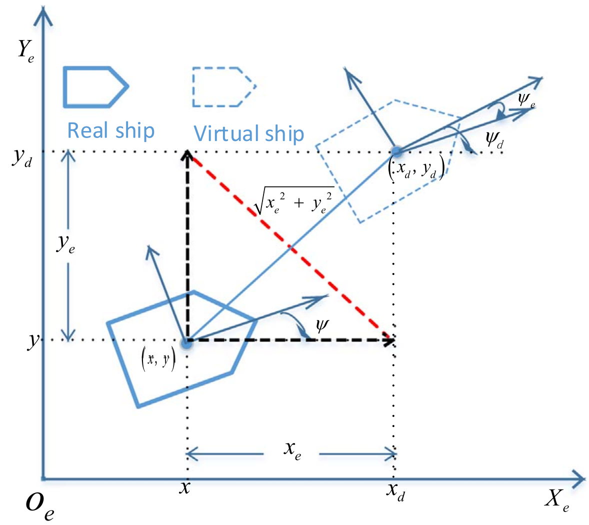

Fig. 1. General framework for path-following control of underactuated surface ship.

$$\begin{aligned} & x_e = x_d - x, \quad y_e = y_d - y \\ & z_e = \sqrt{x_e^2 + y_e^2}, \quad \psi_e = \psi_r - \psi \end{aligned} \tag{2}$$

where (x_d, y_d, ψ_d) denotes the desired position and orientation of an underactuated surface vessel model in earth-fixed frame, z_e denotes the position error. ψ_d is the ships's azimuth angle, which is defined as follows (Li et al., 2008):

$$\psi_r = \begin{cases} 0.5[1 - \mathrm{sign}(x_e)]\mathrm{sign}(y_e)\pi + \arctan(y_e/x_e), & \text{when } z_e \neq 0 \\ \psi_d, \text{ when } z_e = 0 \end{cases} \tag{3}$$

where $sign(\cdot)$ is a sign function, which is defined as follows:

$$\begin{cases} \mathrm{sign}(x) = -1, & x < 0 \\ \mathrm{sign}(x) = 0, & x = 0 \\ \mathrm{sign}(x) = 1, & x > 0 \end{cases} \tag{4}$$

Assumption 1.

1) The environmental disturbances are bounded satisfying $|\tau_{w1}| \leq \tau_{w1max}$, $|\tau_{w2}| \leq \tau_{w2max}$, $|\tau_{w3}| \leq \tau_{w3max}$.
2) The states of the reference model x_d, $\dot{x}_d$, $\ddot{x}_d$, y_d, $\dot{y}_d$, $\ddot{y}_d$ and $\dot{\psi}_d$ are all bounded.

Assumption 2. From the Fig. 1, it can be seen that the control objective is to develop a sliding mode control scheme to let the underactuated ship track the reference path, which is generated by a virtual ship as (5): Zhang et al. (2015)

$$\begin{cases} \dot{x}_d = u_d cos(\psi_d) \\ \dot{y}_d = u_d sin(\psi_d) \\ \dot{\psi}_d = r_d \end{cases} \tag{5}$$

Remark 1. Assumption 2 is introduced in the existing reference (Zhang et al., 2015), different from given the reference path by x_d and y_d. The advantage of this design not only satisfies the condition 2 of Assumption 1, but also obtains the reference path just by the variables u_d and r_d of the virtual ship, as Fig. 1.

3. Controller design

In this section, a practical integral sliding mode controller for path-following control of underactuated surface ships is proposed. Through the description of kinematic and dynamic expressed as (1) with Assumptions 1–2, all the states are guaranteed to be uniformly ultimately bounded in the closed-loop system. In order to prove the