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Research article

Trajectory exponential tracking control of unmanned surface ships with external disturbance and system uncertainties

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ABSTRACT

Any unmanned surface ship is subject to system uncertainty, unknown parameters, and external disturbance induced by the wind, the wave loads, and the ocean currents. They may deteriorate ship's control accuracy. This paper aims to solve the trajectory tracking control problem of unmanned surface ships with disturbance and system uncertainty accommodated simultaneously. An estimator-based backstepping controller is presented with an estimator designed to provide a precise estimation of the disturbance and uncertainties. The proposed controller ensures the closed-loop tracking system to be globally exponentially stable. The trajectory tracking error and the estimation error of disturbance and uncertainties are globally exponentially stable. The key feature of the developed control scheme is that it is more robust to disturbances and system uncertainties. Simulation results are further presented to validate the effectiveness of the approach.

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1. Introduction

Unmanned surface ships have currently played a major role in exploring marine resources. With application of these unmanned ships, many marine activities, such as ocean exploration, oil harvesting, and transportations, can be conducted autonomously. To guarantee that the unmanned surfaces ships can operate autonomously, an autonomous control system should be designed for them with many related problems addressed. For example, mathematical modeling and system identification were carried out in Ref. [1]. Damping control design for ships was discussed in Ref. [2]. The path tracking control problem was investigated in Refs. [3,4]. It should be stressed that the path tracking control problem is a fundamental issue that needs to be solved for autonomous control of unmanned surface ships. At present, more and more attention has been paid to address this problem, as suggested in Refs. [5–11]. For the controllers presented in Refs. [5–11], an assumption that the dynamics of the surface ships is known was made. However, this assumption would be not satisfied in practice. Hence, the application of these controllers was limited.

The results in the above-cited references can only solve trajectory tracking problem without considering other challenges such as actuator saturation and state constraint, etc. In practical engineering, any surface ship is subject to these negative effects. To solve these issues, many advanced tracking controllers were developed for surface ships by using sliding mode control (SMC) technique [12–14], while the SMC's superior advantages including robustness to system perturbations are taken [15–18]. In Refs. [19–21], a more practical issue, *i.e.*, state constraint including the limited ships' velocity and the constrained ships' attitude, was solved in tracking controller design. The solution of this practical issue is very important for unmanned surface ships engineering because all the states of surface ships are constrained in practice. If this issue can not be addressed appropriately, it will deteriorate the tracking control performance. In addition, the tracking control problem was further investigated in Refs. [22–25] with actuator saturation considered. In Refs. [26–28], tracking control design with output feedback only was extensively solved.

It is worth mentioning that although several challenges as stated above have been addressed, external disturbance and system uncertainties are another two issues that need to be solved in tracking controller design for surface ships. These two issues will always act on the ship. They will directly deteriorate ships' tracking control performance. Up to now, there are many investigations on handling these two problems [29]. Taking system uncertainties and actuator saturation into consideration, a backstepping-based tracking control scheme was presented in Ref. [30]. Although the

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system uncertainties were approximated and compensated by using the neural network, the tracking error was guaranteed to be ultimately bounded only, while an asymptotic convergence can not be achieved. An alternative solution to tracking control problem in the presence of disturbance and system uncertainties is the robust design framework. In this framework, a tracking controller is designed to ensure that the control performance is robust to disturbances and uncertainties [31,32].

In except to the above solutions to achieve trajectory tracking for surface ships/vessels, many other nonlinear control theory-based design approaches are also available in the literature. Among these approaches, adaptive control is one of the widely applied techniques. For this design method, the upper bound on disturbance and system uncertainties is adaptively learned [33,34]. In Ref. [35], the ships' uncertainties were approximated by using a neural network, and then an adaptive law was developed to update the weight of the network. However, the proposed tracking controller can only govern the tracking error reaching into a neighborhood around zero. In Ref. [36], a global robust adaptive tracking controller was developed for underactuated ships. Stochastic disturbances acting on the ship were accommodated. However, the path tracking error was governed to be ultimately bounded. Another solution to handle disturbance and uncertainties is observer-based control design [37–41]. An observer is proposed to estimate or reconstruct system uncertainties or disturbances, and a compensation control law is then developed by using the estimated values to achieve tracking control objectives with the disturbances and uncertainties compensated. For instance, a disturbance estimation law was presented in Ref. [42] for multiple surface vessels. The disturbance was successfully estimated with the tracking error ensured to be finite-time stable.

Although a number of control solutions are available to achieve desirable tracking performance for unmanned surface ships in the presence of external disturbances and system uncertainties, most of them can only guarantee that the closed-loop tracking system is globally asymptotically stable or uniformly ultimately bounded. It is well known that exponential stability can ensure the system to be more robust to system perturbations including uncertain parameters and external disturbance. Although exponential tracking control was achieved in Ref. [43], the ships considered were free of disturbance and uncertainties. Motivated by this, this paper aims to present an exponential tracking control design framework for unmanned surface ships subject to disturbances and uncertainties. In this framework, an observer-based estimation will be preliminarily designed to estimate the disturbance and system uncertainties. Then, a backstepping controller will be synthesized with a compensation control effort incorporated for accommodating the disturbance and uncertainties, while this compensation law is developed by using the estimation knowledge provided by the estimation law. The main contribution of this work can be summarized as follows:

1) In comparison with the tracking control approaches to achieve asymptotic stability [10] or ultimately bounded stability [30] for surface ships, exponentially stability of the closed-loop tracking system resulted from the proposed control solution can be achieved. This guarantees the proposed approach is more robust to system uncertainties and disturbances than the results in Refs. [10,30].
2) Comparing with the controller in Ref. [29], although both schemes are able to achieve globally exponential stability, the proposed control approach can handle all types of disturbances and system uncertainties, while the controller in Ref. [29] is capable of handling constant disturbance only.

The remainder of this paper is organized as follows: The mathematical model for describing the kinematics and the dynamics of an unmanned surface ship is introduced in Section 2, where the control problem will also be stated. The main solution to the exponential tracking problem with external disturbance and system uncertainty considered is presented in Section 3. Numerical validation of the proposed control approach is carried out in Section 4. Conclusions and future work are given in Section 5.

2. System model and problem statement

For any unmanned surface ship, translation motion in the surge, sway, and heave axes and rotation motion in roll, pitch, and yaw axes are involved. However, the translation motion in heave axes and the rotation motion in roll and pitch axes are open-loop stable for most unmanned surface ships. These motions can be not considered when designing control law. Only the motion in the surge, sway, and yaw axes should be investigated. Consequently, a six degree-of-freedom (6DOF) control problem of surface ships can be reduced to a 3DOF control. In accordance, the kinematics and the dynamics of an unmanned surface ship can be established as [14,31]:

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{1}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{D}(\boldsymbol{\nu})\boldsymbol{\nu} = \boldsymbol{\tau} + \boldsymbol{\tau}_d \tag{2}$$

where $\boldsymbol{\eta} = [x \quad y \quad \psi]^{\mathrm{T}} \in \Re^3$ and $\boldsymbol{\nu} = [u \quad \upsilon \quad \omega]^{\mathrm{T}} \in \Re^3$ are the system states. The vector $[x \quad y]^{\mathrm{T}} \in \Re^2$ denotes the position of the unmanned surface ship. $\psi \in \Re$ is the yaw angle of the ship in the earth-fixed inertial frame. $u \in \Re$ and $\upsilon \in \Re$ are the translation velocities in the surge and the sway axes, respectively. $\omega \in \Re$ is the rotation angular velocity in the yaw axes. $\boldsymbol{\tau} \in \Re^3$ is the total control power. $\boldsymbol{\tau}_d \in \Re^3$ is the unknown external disturbance forces induced by the wind, the wave loads, and the ocean currents. $\boldsymbol{M} \in \Re^{3\times3}$ is the positive-definite inertia matrix. $\boldsymbol{C}(\boldsymbol{\nu}) \in \Re^{3\times3}$ is the Coriolis matrix. $\boldsymbol{D}(\boldsymbol{\nu}) \in \Re^{3\times3}$ is the damping matrix. $\boldsymbol{J}(\boldsymbol{\eta}) \in \Re^{3\times3}$ denotes the rotation matrix, which is given by

$$\boldsymbol{J}(\boldsymbol{\eta}) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

In practice, the system parameters $\boldsymbol{C}(\boldsymbol{\nu})$ and $\boldsymbol{D}(\boldsymbol{\nu})$ would not be precisely established. They may be uncertain. Hence, let $\boldsymbol{C}_0(\boldsymbol{\nu})$ and $\boldsymbol{D}_0(\boldsymbol{\nu})$ denote their nominal dynamics, and $\Delta\boldsymbol{C}(\boldsymbol{\nu}) \in \Re^{3\times3}$ and $\Delta\boldsymbol{D}(\boldsymbol{\nu}) \in \Re^{3\times3}$ represent their uncertain dynamics, respectively. Then, $\boldsymbol{C}(\boldsymbol{\nu})$ and $\boldsymbol{D}(\boldsymbol{\nu})$ can be represented as

$$\boldsymbol{C}(\boldsymbol{\nu}) = \boldsymbol{C}_0(\boldsymbol{\nu}) + \Delta\boldsymbol{C}(\boldsymbol{\nu}), \boldsymbol{D}(\boldsymbol{\nu}) = \boldsymbol{D}_0(\boldsymbol{\nu}) + \Delta\boldsymbol{D}(\boldsymbol{\nu}) \tag{4}$$

Moreover, due to fuel consumption and payload motion, the inertia matrix $\boldsymbol{M} \in \Re^{3\times3}$ will also be uncertain and even time-varying. Let its nominal part and its uncertain part be denoted as $\boldsymbol{M}_0 \in \Re^{3\times3}$ and $\Delta\boldsymbol{M} \in \Re^{3\times3}$, respectively. It follows that $\boldsymbol{M} = \boldsymbol{M}_0 + \Delta\boldsymbol{M}$. Moreover, the nominal inertia $\boldsymbol{M}_0$ is also positive-definite and symmetric. Although the ship is subject to uncertainties, these uncertainties should be bounded. More specifically, these uncertainties should be constrained by their nominal values, *i.e.*, $||\Delta\boldsymbol{M}|| \le ||\boldsymbol{M}_0||$, $||\Delta\boldsymbol{C}(\boldsymbol{\nu})|| \le ||\boldsymbol{C}_0(\boldsymbol{\nu})||$, and $||\Delta\boldsymbol{D}(\boldsymbol{\nu})|| \le ||\boldsymbol{D}_0(\boldsymbol{\nu})||$.

Let the desired trajectory of the unmanned surface ship be denoted as $\boldsymbol{\eta}_d \in \Re^3$. Given any initial states $\boldsymbol{\eta}(0)$ and $\boldsymbol{\nu}(0)$, then the control objective of this paper can be stated as: Design a finite-time control law for the system (1) and (2) to guarantee that the desired trajectory $\boldsymbol{\eta}_d$ can be followed. More specifically, the tracking error

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