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Higher-order sliding mode control for trajectory tracking of air cushion vehicle

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ABSTRACT

The air cushion vehicle (ACV) is an amphibian complex system with strong nonlinearity, internal unmodeled dynamics, and external disturbances. This article presents a new multivariable higher-order sliding mode (HOSM) control scheme on trajectory tracking of ACV. With two longitudinal thrusters, the ACV is modeled as an uncertain nonlinear system with less degree of freedom to be actuated. The control approach includes nominal continuous control law and super-twisting second-order sliding mode control part. The former is employed to stabilize nominal systems at origin in finite time and improve transient process. The latter is used to alleviate chattering of controlling force in surge and controlling torque in yaw, and overcome system uncertainties. A Lyapunov approach is used to testify finite time stability. The simulations for straight line and circular trajectories are presented to evaluate the applicability, robustness and superiority of the proposed approach.

1. Introduction

The air cushion vehicle (ACV) is a peculiar high-performance amphibious vehicle, which is nowadays being extensively applied in the fields of military and civilian [1]. Adopting a suit of flexible skirt to make the air cushion surround the hull, ACV could sail on riffle, sea surface, meadow, marsh, etc [2]. Moreover, ACV is now becoming a desirable clean form of transportation, due to rising fuel prices and energy shortages.

Unlike the regular fully actuated vessels, ACV has three degrees of freedom (sway, surge and yaw) and two independent control inputs (force in surge and torque in yaw), forming an underactuated electromechanical system described by complex nonlinear dynamic [3]. In addition, external disturbances, such as wave, current and wind, always influence the navigation performance, both for terrestrial and maritime operations. For these reasons, motion control of ACV is a hard nut to crack and becomes an active research area.

Different advanced control algorithms [2–5] have been presented to show excellent course keeping or course tracking performance. A cooperative controller for circular flocking with collision avoidance of ACVs is presented [6] as well. However, the main problems that arise in the control of ACV, are path following [1], point stabilization [7,8], and trajectory tracking [9]. For trajectory tracking purpose, it is necessary to develop control methods that impel a vessel to reach and follow a temporal reference. Considering its professional and military background, trajectory tracking control problem for ACV represents a very challenging research topic, being, thus, the problem studied in the present work.

Regarding trajectory tracking control problem of ACV, Ariaei and Jonckheere [10] achieve circular trajectory tracking based on linear dynamically varying technique. In [11], a new scheduling approach is proposed and applied for the trajectory tracking for multiple ACVs, yet, the ACV model is linear. Aiming at a nonlinear ACV model, Papers [1,12] propose the trajectory tracking control schemes. Nevertheless, the external disturbances are not considered in these schemes. Paper [13] presents a nonlinear receding horizon controller for an ACV with uncertainties. However, the asymptotic stability of closed-loop system is not guaranteed. In [14], a tracking control law for an ACV with a discrete set of inputs is designed and tested, in [15], a position tracking controller is designed by combining bioinspired neurodynamics model with backstepping algorithm, and a nonlinear Lyapunov-based tracking control scheme is also studied in [16], but for these publications [14–16], the tracking error is turned out to be exponentially convergent to a neighbourhood of the origin.

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As a consequence, a robust trajectory tracking controller has to be adopted when considering nonlinearity, external disturbances, system stability and traceability for arbitrary trajectory comprehensively. Sliding mode control (SMC) is essentially a nonlinear control means that forces the system to “slide” along a cross-section of the system’s normal behaviour by using a discontinuous control signal. As a variable structure control method, SMC is regarded as a powerful method to design robust controllers, and also find applications in vessel control [17–22]. However, the inherent chattering occurring in the control input could be harmful to the steering engine and drive mechanism [22]. In addition, the constraint of finite time stability and higher relative degree also hinder the application of the traditional SMC technique [23]. Retaining the main advantages of the standard SMC, Higher-order sliding mode (HOSM) is proposed to reduce and (or) remove the chattering effect, and achieve better accuracy [24–26]. In [27], a controller based on second-order sliding mode and differential flatness is proposed to realize trajectory tracking tasks. The robustness with respect to external disturbances is also evaluated, yet, the tracking errors are only exponentially stable. Paper [28] proposes a HOSM control scheme for MIMO uncertain nonlinear system and applies it for trajectory tracking of ACV. The finite time stability is guaranteed, but in fact, the chattering of controlling torque in yaw is not considered and the transient process could not be regulated effectively.

Motivated by these considerations, this paper proposes a new HOSM control scheme for trajectory tracking of ACV. The main characteristics of this control strategy could be summarized as: It combines HOSM, dynamic extension algorithm and finite time continuous control, and the finite time stability of closed-loop system is guaranteed.

The control objective is to track a predefined temporal trajectory in an environment characterized by the existence of current, wave, etc. The ACV model is firstly converted into input–output form via the differential of sliding variable and dynamic extension algorithm. Then the HOSM control problem is viewed as finite time stabilization of higher-order uncertain integral chain. The robust finite time controller with acceptable chattering and fast transient process is constituted by two parts: a nominal continuous controller which could be regarded as desired trajectories generator, and a robust one which is based on super-twisting second-order SMC and forces the system trajectories to track the desired trajectories. The nominal one is employed to adjust transient process while the latter is used to alleviate chattering in control input and realize robustness. The formal proof of finite time stability is based on quadratic form Lyapunov function. Finally, simulation results are provided to confirm the effectiveness of the proposed approach.

The rest of the paper is organized as follows. In Section 2, the ACV model is stated. Section 3 shows the controller design including control problem formulation and HOSM control strategy, and the tracking simulations are carried out in Section 4. Section 5 concludes the work.

2. ACV model

In contrast with a general two wheel mobile robot, ACV could move freely sideways in spite of this degree of freedom is not actuated. The general kinematics and dynamic equations of the ACV could be developed based on an earth-fixed coordinate frame and a body-fixed coordinate frame as shown in Fig. 1.

The dynamic of a general surface vessel [29] is depicted as

$$\begin{cases} \mathrm{P}\dot{\nu}+\mathrm{C}(\boldsymbol{\nu})\boldsymbol{\nu}+\mathrm{D}\boldsymbol{\nu}=\tau \\ \dot{\gamma}=\mathrm{J}(\boldsymbol{\gamma})\boldsymbol{\nu} \end{cases} \tag{1}$$

with the inertia matrix $\mathbf{P}=\mathrm{diag}\left\{p_{11}\quad p_{22}\quad p_{33}\right\}$, $\mathrm{C}(\boldsymbol{\nu})=\begin{bmatrix} 0 & 0 & -p_{22}v \\ 0 & 0 & p_{11}u \\ p_{22}v & -p_{11}u & 0 \end{bmatrix}$, $\mathbf{D}=\mathrm{diag}\left\{d_{11}\quad d_{22}\quad d_{33}\right\}$, $\mathrm{J}(\boldsymbol{\gamma})=\begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$.

The $\mathrm{C}(\boldsymbol{\nu})$ is the matrices of Coriolis and centripetal forces. $\mathbf{D}$ represents the hydrodynamic damping. $J(\boldsymbol{\gamma})$ is the transformational matrix between body-fixed and earth-fixed coordinates. The vector $\boldsymbol{\gamma}=\begin{bmatrix} x & y & \theta \end{bmatrix}^T$ denote the position and the orientation of ACV in the earth-fixed frame. $\boldsymbol{\nu}=\begin{bmatrix} u & v & r \end{bmatrix}^T$ are the linear velocities in surge, sway, and angular velocity in yaw. The vector $\boldsymbol{\tau}=\begin{bmatrix} \tau_a & \tau_b & \tau_c \end{bmatrix}^T$ represent the controlling forces in surge and sway, and the controlling torque in yaw.

In consideration of the simplification of ACV [27] as depicted in Fig. 1, the simplifying conditions could be employed as

$$\begin{aligned} &p_{11}=p_{22}, \qquad \tau_a=p_{11}\tau_u, \quad \tau_b=0, \quad \tau_c=p_{33}\tau_r, \\ &d_{11}=d_{33}=0, \qquad \alpha=\frac{d_{22}}{p_{22}} \end{aligned} \tag{2}$$

A model for such symmetric ACV could be directly deduced as

$$\begin{cases} \dot{x}=u\cos\theta-v\sin\theta \\ \dot{y}=u\sin\theta+v\cos\theta \\ \dot{\theta}=r \\ \dot{u}=vr+\tau_u \\ \dot{v}=-ur-\alpha v \\ \dot{r}=\tau_r \end{cases} \tag{3}$$

In fact, external disturbances such as wave, current and wind always influence navigation performance of ACV. Some additive perturbations are introduced in the surge velocity equation and the sway dynamics. Eq. (3) becomes

$$\begin{cases} \dot{x}=u\cos\theta-v\sin\theta \\ \dot{y}=u\sin\theta+v\cos\theta \\ \dot{\theta}=r \\ \dot{u}=vr+\tau_u \\ \dot{v}=-ur-\alpha v+\Delta_v \\ \dot{r}=\tau_r+\Delta_r \end{cases} \tag{4}$$

3. Controller design

3.1. Problem formulation

The control objective is to achieve trajectory tracking of the perturbed ACV in finite time. The ACV model (4) is a MIMO nonlinear system, with two control inputs (τ_u and τ_r). Since the ACV is underactuated, exact linearization could not be attained directly via a static state feedback. It could be checked that the model does not have a well-defined vector relative degree with respect to the position outputs x and y. Indeed, $\ddot{x}$ and $\ddot{y}$ depend on τ_u rather than on τ_r. It is therefore necessary to constitute a second-order dynamic extension of τ_u for the exact linearization of model (4). Detailed description about Dynamic Extension Algorithm is referred to [30].

Let $\boldsymbol{Ex}$ denote the extended states and $\boldsymbol{\tau}$ the new control input, expressed as

$$\boldsymbol{Ex}=[x_1,x_2,x_3,x_4,x_5,x_6,x_7,x_8]^T=\left[x,y,\theta,u,v,r,\tau_u,\dot{\tau}_u\right]^T \tag{5}$$

$$\boldsymbol{\tau}=[\tau_1,\tau_2]^T=[\ddot{\tau}_u,\tau_r]^T \tag{6}$$