Neurocomputing 175 (2016) 662–666

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Global finite-time heading control of surface vehicles

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ARTICLE INFO

Article history:
Received 26 September 2015
Received in revised form
19 October 2015
Accepted 28 October 2015
Communicated by M.-J. Er
Available online 4 November 2015

Keywords:
Heading control
Global finite-time stability
Surface vehicles

ABSTRACT

In this paper, a global finite-time heading control (GFHC) scheme for surface vehicles is proposed. The salient features of the GFHC scheme are triple-fold: (1) A discontinuous control law is proposed to guarantee the finite-time stability of the entire closed-loop heading control system. (2) The finite-time convergence leads to accurate heading control and remarkable disturbance rejection. (3) Furthermore, it reveals that the proposed GFHC scheme treats asymptotic heading controllers as special cases. Simulation studies and comprehensive comparisons on various scenarios demonstrate the effectiveness and superiority of the proposed GFHC scheme.

1. Introduction

In the community of ship automation, course keeping plays a significant role in the entire control system, and is directly related to the operation, economy, safety and effectiveness of the ship control system. The ship heading control problem has been attracting much attention from various researchers.

In order to realize the position and heading control of ships and oil rigs, Fossen and Perez [1] applied the Kalman filter to estimate unmeasurable states and thereby realizing output-feedback based position and heading control of ships and oil rigs. However, the foregoing approach usually requires nice compensation for low-frequency disturbances. An accurate and economic optimization method for ship heading control system was proposed in [2], whereby simulation results showed that the optimization algorithm was reliable. However, it inevitably suffers from fine tuning parameters of a PID controller. A nonlinear controller based on the backstepping technique and the sliding mode control for an air cushion vehicle was proposed in [3]. Note that the steering dynamics and/or uncertainties have not been fully addressed. Recently, intelligent approaches via fuzzy logic systems [4], neural networks [5] and fuzzy neural networks [6,7], etc. have been intensively studied and applied to tracking control of surface vehicles. Unlike traditional fuzzy/neural control approaches which require predefined structure for an approximator, these self-organizing fuzzy neural network (SOFNN) based adaptive (robust) control schemes [4–7] are able to achieve remarkable performance in terms of both tracking and approximation, since the structure of the online fuzzy/neural approximator is persistently evolving and is updated according to tracking accuracy, in addition to parameter identification. Similar idea has been applied to flight vehicles [8–10], whereby system uncertainties and disturbances can be handled. However, only asymptotic convergence can be obtained in the previous schemes.

By virtue of finite-time stability of homogeneous systems [11], non-smooth continuous control approaches have been developed rapidly and have been applied to finite-time controller synthesis. In [12], a finite-time controller for robot manipulators was designed via both state feedback and dynamic output feedback approaches. Recently, a finite-time control scheme via output feedback for tracking autonomous underwater vehicles has been proposed in [13]. The finite-time control problem of multiple manipulators [14] has also been addressed by employing the homogeneous theory which allowed unmodeled dynamics to be handled. The aforementioned finite-time control schemes achieved superior control performance in terms of both convergence rate and disturbance rejection ability.

In order to improve the maneuverability and reduce the consumption of fuel, it is desired to maintain the surface vehicle in a scheduled line course. Two important performance indexes pertaining to nonlinear control systems are the convergence rate and the robustness to disturbances, which are also crucial in the course keeping of surface vehicles. In this context, the finite-time control method with fast convergence and strong disturbance rejection ability is highly required to solve the course keeping problem of surface vehicles.

In this paper, a global finite-time heading control (GFHC) scheme is proposed for the heading control of surface vehicles. In the GFHC scheme, a discontinuous control law is employed to realize the finite-time stability of the entire closed-loop heading control system. In this context, faster convergence and stronger

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http://dx.doi.org/10.1016/j.neucom.2015.10.106
0925-2312/

disturbance rejection ability can be achieved for the ship heading control.

The rest of this paper is organized as follows. Section 2 formulates preliminaries about finite-time stability, homogeneity and the problem statement of heading control. The heading dynamics of a surface vehicle is addressed in Section 3. The GFHC scheme together with corresponding stability analysis are presented in Section 4. Simulation studies and comprehensive comparisons are conducted in Section 5. Conclusions are drawn in Section 6.

2. Preliminaries and problem statement

2.1. Preliminaries

Consider the system

$$\dot{x} = f(x), \quad x \in \mathcal{R}^n \tag{1}$$

with $x = x_e$ being the equilibrium. We recall fundamental definitions as follows:

Definition 1 (*Asymptotic Stability [Marquez, [15]]*).]The equilibrium $x_e = 0$ of system (1) is globally asymptotically stable if there exits a function $V(x)$ satisfying

(i) $V(0) = 0$.
(ii) $V(x) > 0$, $\forall x \neq 0$, and $V(x)$ is radically unbounded.
(iii) $\dot{V}(x) \leq 0$.
(iv) $\dot{V}(x)$ does not vanish identically along any trajectory in $\mathcal{R}^n$, other than the null solution $x = 0$.

Definition 2 (*Homogeneity [Rosier, [16]]*).]Let $f(x) = (f_1(x), \dots, f_n(x))^T$ be a continuous vector field. $f(x)$ is homogeneous of degree $k \in \mathcal{R}$ with respect to the dilation $(r_1, \dots, r_n)$, if, for any given $(r_1, \dots, r_n) \in \mathcal{R}^n$ as well as $\varepsilon > 0$,

$$f_i(\varepsilon^{r_1} x_1, \dots, \varepsilon^{r_n} x_n) = \varepsilon^{k + r_i} f_i(x), \quad i = 1, \dots, n, \forall x \in \mathcal{R}^n. \tag{2}$$

Let $V(x) : \mathcal{R}^n \to \mathcal{R}$ be a continuous scalar function, if $\forall \varepsilon > 0$, $\exists \delta > 0$ and dilation $(r_1, \dots, r_n) \in \mathcal{R}^n$, $r_i > 0, i = 1, \dots, n$, thus

$$V(\varepsilon^{r_1} x_1, \dots, \varepsilon^{x_n} x_n) = \varepsilon^{\sigma} V(x), \quad i = 1, \dots, n, \forall x \in \mathcal{R}^n. \tag{3}$$

$V(x)$ is a homogeneous function of degree σ with respect to dilation $(r_1 ,\dots, r_n)$.

An important lemma about finite-time stability is ready to be given here.

Lemma 1 (*Finite-time Stability [Hong et al., [12]]*). *]System (1) is global finite-time stable if it is globally asymptotically stable and is homogeneous with a negative degree $k < 0$.*

Throughout this paper, the foregoing definitions and Lemma 1 help to derive the main result.

2.2. Problem statement

The main task during the automatic navigation in the sea is to provide crews a safe working environment, comfortable living environment as well as to short the voyage cycle, reduce fuel consumption and save voyage. In this context, a precise and stable course keeping and changing plays an important role in this process. Hence, our objective is to design a heading controller such that the actual heading ψ can converge to the desired heading ψ_d with fast convergence and little overshoot which are actually trapped into a dilemma in traditional asymptotic control methods.

Moreover, due to model uncertainties and unknown disturbances imposed on a surface vehicle, a finite-time control method is highly desired to realize remarkable performance of disturbance rejection pertaining to the complex heading dynamics of a surface vehicle.

3. Heading dynamics

Consider the Nomoto equation for steering dynamics of a surface vehicle as follows [17]:

$$\frac{\psi(s)}{\delta(s)} = \frac{K(1 + T_3 s)}{s(1 + T_1 s)(1 + T_2 s)} \tag{4}$$

where T_1, T_2, and T_3 are time constants, and K is the system gain. It can further be written as the first-order Nomoto model at low frequency given by

$$T\ddot{\psi} + \dot{\psi} = K\delta \tag{5}$$

where $T = T_1 + T_2 - T_3$.

Remark 1. System (5) is the linear model for heading dynamics of a surface vehicle. For most ships, system (5) properly describes the dynamic behavior for the case where only little rudder angle and low rudder operating frequency are considered.

However, the linear dynamics in system (5) cannot address well the heading behavior when the surface vehicle changes its course with large rudder angle. Actually, system (5) is only the linearization of the ship heading dynamics. However, such a linear model can only be valid for the case where both little rudder angle and low rudder frequency are considered. In this context, a nonlinear term $H(\dot{\psi})$ is usually employed to address the complex heading dynamics with large maneuvers. Hence, the nonlinear heading model can be written as follows:

$$T\ddot{\psi} + H(\dot{\psi}) = K\delta \tag{6}$$

where

$$H(\dot{\psi}) = \alpha_0 + \alpha_1 \dot{\psi} + \alpha_2 \dot{\psi}^2 + \alpha_3 \dot{\psi}^3 \tag{7}$$

with Norrbin coefficients $\alpha_i > 0 (i = 0, 1, 2, 3)$ and rudder reflection angle δ.

4. Controller design and stability analysis

In this section, the GFHC scheme via state feedback for surface vehicles is proposed by employing the homogeneous theory. Moreover, the finite-time stability of the entire closed-loop heading control system can be guaranteed by using the Lyapunov approach.

4.1. Controller design

The heading dynamics in (6) can be rewritten as follows:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \dfrac{1}{T}(K\delta - \alpha_0 - \alpha_1 x_2 - \alpha_2 x_2^2 - \alpha_3 x_2^3) \end{cases} \tag{8}$$

where $x_1 = \psi$ and $x_2 = \dot{\psi}$ are measurable states.

The desired heading is denoted as ψ_d. Incorporating the feedback linearization into the finite-time controller design, we design the GFHC scheme as follows:

$$u = -\frac{Tk_1}{K} |x_1 - \psi_d|^{\beta_1} \operatorname{sgn}(x_1 - \psi_d) - \frac{Tk_2}{K} |x_2|^{\beta_2} \operatorname{sgn}(x_2) + \phi(x_2) \tag{9}$$

where

$$\phi(x_2) = \frac{\alpha_0}{K} + \frac{\alpha_1}{K} x_2 + \frac{\alpha_2}{K} x_2^2 + \frac{\alpha_3}{K} x_2^3 \tag{10}$$

with positive constants $k_1 > 0$, $k_2 > 0$, $0 < \beta_1 < 1$, and $\beta_2 = 2\beta_1 / 1 + \beta_1$. It should be noted that the term $\phi(x_2)$ is used to