ISA Transactions xxx (2018) 1–11

Contents lists available at ScienceDirect

ISA Transactions

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

Research article

Adaptive fixed-time trajectory tracking control of a stratospheric airship

Zewei Zheng [a], Mir Feroskhan [b,*], Liang Sun [c]

[a] The Seventh Research Division, School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798, Singapore
[c] School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China

ARTICLE INFO

Article history:
Received 4 November 2017
Revised 13 March 2018
Accepted 23 March 2018
Available online XXX

Keywords:
Adaptive control
Fixed-time control
Stratospheric airship
Trajectory tracking

ABSTRACT

This paper addresses the fixed-time trajectory tracking control problem of a stratospheric airship. By extending the method of adding a power integrator to a novel adaptive fixed-time control method, the convergence of a stratospheric airship to its reference trajectory is guaranteed to be achieved within a fixed time. The control algorithm is firstly formulated without the consideration of external disturbances to establish the stability of the closed-loop system in fixed-time and demonstrate that the convergence time of the airship is essentially independent of its initial conditions. Subsequently, a smooth adaptive law is incorporated into the proposed fixed-time control framework to provide the system with robustness to external disturbances. Theoretical analyses demonstrate that under the adaptive fixed-time controller, the tracking errors will converge towards a residual set in fixed-time. The results of a comparative simulation study with other recent methods illustrate the remarkable performance and superiority of the proposed control method.

1. Introduction

The stratosphere has promptly garnered special attention from the aviation research industry that aims to capitalize on its stable meteorological conditions. This serves as motivation to develop long endurance stratospheric aircrafts that possess the capacity to play a significant role in surveillance and intelligence, earth observation, telecommunications and environmental monitoring, similar to satellites. As such, the design of the stratospheric aircraft takes the form of lighter-than-air aerostats such as balloons [1] and airships [2–5], unlike the conventional aeroplane, as aerostats generally rely on buoyancy rather than aerodynamic lift for flight. The stratospheric airship is more advantageous operationally than satellites because it can be launched at a much lower cost, is reusable and can be conveniently maintained. Unlike the balloon, the stratospheric airship is also able to fly precisely along a scheduled route, also known as trajectory tracking, to cater to a wider range of mission objectives [6–10]. However, the tracking control design poses challenges since the airship is an inherently nonlinear and highly coupled multi-input multi-output (MIMO) system with unknown external disturbances.

There are several control methods for the trajectory tracking of the stratospheric airship that have been covered in the following literature. Based on an active disturbance rejection method to handle the external disturbances, a robust nonlinear controller was proposed for the trajectory tracking of an airship [11]. However, the controller was developed based on a simplified airship dynamic model where the airship's motion is limited to yawing and translation along the horizontal plane. The authors in Ref. [12] utilized a non-certainty equivalence adaptive approach to develop a trajectory tracking controller that accommodates the uncertain mass and inertia parameters of a fully-actuated stratospheric airship. Together with neural network approximation, another control approach that involves a terminal sliding mode surface is adopted for a robotic airship in Ref. [13]. The case of an under-actuated airship control problem was studied in Ref. [14], where an integrator backstepping controller based on the Lyapunov theory was shown to provide stability in its ascent and descent maneuvers. In Ref. [15], a rigorous multi-loop control structure for the trajectory tracking of the airship was formulated based on trajectory linearization control technique. A path tracking gain-scheduling controller that caters to controlling both the lateral and longitudinal motions simultaneously, was designed in Ref. [16] for an airship subjected to wind disturbances. In addition to the trajectory tracking control, many other control schemes were also widely researched for airships, such as attitude control [17], hovering control [18], path following control [19–21], and specific configuration airship control [22,23].

---

* Corresponding author.
E-mail addresses: zeweizheng@buaa.edu.cn (Z. Zheng), mir.alikhan@ntu.edu.sg (M. Feroskhan), liangsun@ustb.edu.cn (L. Sun).

https://doi.org/10.1016/j.isatra.2018.03.016
0019-0578/© 2018 ISA. Published by Elsevier Ltd. All rights reserved.

Please cite this article in press as: Zheng Z, et al. Adaptive fixed-time trajectory tracking control of a stratospheric airship, ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.03.016

The aforementioned control approaches can only guarantee asymptotical convergence, which means that the setting time is infinite. However, in the airship design, the convergence time is an important design index that needs to be set explicitly. Alternatively, the finite-time control schemes [3,24–26] can provide a faster convergence rate and the system states will reach equilibrium within a finite time. However, the setting time for the finite-time methods depends on the initial states of the system. This prohibits the application of finite-time methods in the scenario where information on the initial states are unavailable or inaccurate. In contrast, the fixed-time stability concept [27] was proposed to acquire a fixed maximum settling time that can be estimated and is independent of the initial states. Moreover, it performs uniformly for the fixed-time control under different initial conditions and its control parameters are not required to be re-tuned to sustain the convergence time [28–30].

Research in fixed-time control methods is rather recent and not yet exhaustive. In Refs. [29,30], by extending the method of adding a power integrator, the fixed-time control solutions for nonlinear systems and Euler-Lagrange systems are presented. However, these methods are theoretical results and cannot be applied directly to actual aircraft objects. In Ref. [31], a fixed-time nonrecursive differentiator algorithm was implemented in a hypersonic missile simulation. Based on the nonsingular terminal sliding mode protocol developed by Ref. [32], a leader-following fixed-time consensus controller was successfully employed for multi-agent systems that contain input delay [33]. On the other hand, for the multi-agent systems in the presence of external disturbance, a cascade structure [34] that integrate a fixed-time consensus protocol with a fixed-time observer [35] was presented to ensure the fixed-time consensus tracking. In Refs. [36,37], fixed-time fault-tolerant controllers that incorporated a sliding mode surface were developed for the spacecraft that is being subjected to thruster faults and actuator saturation. Although several literature regarding the fixed-time control for different systems have been documented, the fixed-time tracking design for nonlinear systems in the presence of unknown external disturbances is still an open issue.

Motivated by the aforementioned analyses and inspired by Refs. [29,30], this paper presents an adaptive fixed-time trajectory tracking control scheme for a stratospheric airship under external disturbances. The main contributions and the key features of the proposed method are summarized as follows.

1) A new globally fixed-time tracking control method is designed using the method of adding a power integrator. If the disturbances are not considered, the method ensures that the tracking errors converge to zero within a fixed time.
2) An adaptive algorithm that estimates the bound of unknown disturbances is incorporated into the proposed controller to alleviate the effects of disturbances that results in better system robustness. The tracking errors will converge towards a residual set in fixed-time.
3) Unlike the fixed-time methods in Refs. [31–37], the control signals of the proposed method that lead to the fixed-time convergence of the tracking errors are smooth and the method does not contain any signum operator.

This paper is organized as follows. The preliminaries and the problem formulation are described in Section 2. Section 3 is devoted to formulating the fixed-time controllers for the stratospheric airship with external disturbances. Results of simulation are shown in Section 4. Section 5 concludes the paper.

2. Preliminaries and problem formulation

2.1. Preliminaries

Throughout this paper, $|\cdot|$ represents the absolute value of a scalar while $\|\cdot\|$ represents the Euclidean norm of a vector. For $\boldsymbol{a} \in \mathbb{R}^n$, $a_i, i = 1, 2, \dots, n$ represents the ith component of $\boldsymbol{a}$, $\boldsymbol{a}^k = [a_1^k, a_2^k, \dots, a_n^k]^T$, and $\lceil \boldsymbol{a}^k \rfloor = \mathrm{diag}\{a_1^k, a_2^k, \dots, a_n^k\}$. Consider the system

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t)),\ \boldsymbol{f}(\boldsymbol{0}) = \boldsymbol{0},\ \boldsymbol{x} \in \mathbb{R}^n \tag{1}$$

where $\boldsymbol{f} : D_0 \to \mathbb{R}^n$ is continuous on an open neighborhood D_0 of the origin. The definitions and lemmas that are required for the control design are delineated as follows.

Definition 1. [27] The equilibrium $\boldsymbol{x} = \boldsymbol{0}$ of (1) is fixed-time stable if it is globally finite-time stable and the settling-time function $T(\boldsymbol{x})$ is bounded, i.e. there is an existing positive constant $T_{\max}$ such that $T(\boldsymbol{x}) \le T_{\max}$ for any $\boldsymbol{x} \in \mathbb{R}^n$.

Lemma 1. [27] Suppose there is a Lyapunov function $V(\boldsymbol{x})$ defined on a neighborhood D of the origin and $\dot{V}(\boldsymbol{x}) \le -(\alpha V(\boldsymbol{x})^p + \beta V(\boldsymbol{x})^g)^k$, where $\{\alpha, \beta, p, g, k\} \in \mathbb{R}^+$, $pk < 1$ and $gk > 1$, then the origin of (1) is fixed-time stable. As such, $V(\boldsymbol{x})$ from any initial position within the region D is able to converge to $V(\boldsymbol{x}) \equiv 0$ within a fixed time where the setting time T is bounded by $T \le \frac{1}{\alpha^k(1-pk)} + \frac{1}{\beta(gk-1)}$.

Lemma 2. [36] Suppose the Lyapunov function $V(\boldsymbol{x})$ in Lemma 1 satisfies $\dot{V}(\boldsymbol{x}) \le -(\alpha V(\boldsymbol{x})^p + \beta V(\boldsymbol{x})^g)^k + \vartheta$, where $\vartheta > 0$, then the origin of (1) is practical fixed-time stable, and the residual set is given by

$$\left\{ \lim_{t \to T} \boldsymbol{x} \mid V(\boldsymbol{x}) \le \min \left\{ \alpha^{-\frac{1}{p}} \left(\frac{\vartheta}{1-\theta^k} \right)^{\frac{1}{kp}}, \beta^{-\frac{1}{p}} \left(\frac{\vartheta}{1-\theta^k} \right)^{\frac{1}{kg}} \right\} \right\}$$

where $\theta \in (0, 1]$. The setting time T required to attain the residual set is bounded by $T \le \frac{1}{\alpha^k \theta^k (1-pk)} + \frac{1}{\beta \theta^k (gk-1)}$.

Lemma 3. [38]. The inequality $0 \le |x| - x \tanh(x/\eta) \le \kappa \eta$ holds for any $\eta \in \mathbb{R}^+$ where $x \in \mathbb{R}$ and $\kappa = \mathrm{e}^{-(\kappa+1)}$.

Definition 2. Matrix $\mathrm{Tanh}(\boldsymbol{x}) : \mathbb{R}^n \to \mathbb{R}^{n\times n}$ is defined as $\mathrm{Tanh}(\boldsymbol{x}) = \mathrm{diag}\{\tanh(x_1), \tanh(x_2), \dots, \tanh(x_n)\}$.

Lemma 4. [24]. For $\{m, n\} > 0$ and a positive function $a(x, y)$, there exists a positive function $c(x, y)$ such that $|a(x, y)x^m y^n| \le c(x, y)|x|^{m+n} + \frac{n}{m+n} \left(\frac{m}{(m+n)c(x,y)} \right)^{\frac{m}{n}} |a(x, y)|^{\frac{m+n}{n}} |y|^{m+n}$.

Lemma 5. [30,32] Let x_i, $i = 1, 2, \dots, n$ be real numbers. In the case where $p > 0$, $(|x_1| + |x_2| + \cdots + |x_n|)^p \le \max(n^{p-1}, 1)(|x_1|^p + |x_2|^p + \cdots + |x_n|^p)$. If $p = m/n \le 1$, in which $\{m, n\} > 0$ are odd integers, $|x_1^p - x_2^p| \le 2^{1-p}|x_1 - x_2|^p$.

2.2. Model of airship

Fig. 1 shows the stratospheric airship with a typical ellipsoidal ballonet. The ballonet that comprises of the helium gas generates the buoyancy force for lift. A gondola that is situated under the ballonet provides space for mounting the flight control, power and payload systems. The elevator and rudder that are located on the empennage of the airship provide the aerodynamic control deflections for yawing and pitching motions respectively. A propeller with vectored thrust capability is mounted on each side of the gondola to generate the thrust input for flight.

Please cite this article in press as: Zheng Z, et al. Adaptive fixed-time trajectory tracking control of a stratospheric airship, ISA Transactions (2018), https://doi.org/10.1016/j.isatra.2018.03.016