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Research article

Tracking control of nonholonomic mobile agents with external disturbances and input delay

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A R T I C L E I N F O

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A B S T R A C T

This paper investigates the tracking control problem of chained-form nonholonomic multiagent systems (MASs). In contrast to the existing works in which some algorithms have been designed for ideal conditions, the destructive factors including external disturbances and input delay are considered in the dynamics of the agents in this work. Two distributed controllers are proposed such that the states of the controlled agents can track the states of the target in the presence of external disturbances and input delay. For this purpose, a distributed controller is firstly suggested based on a switching method to solve the tracking control problem for nonholonomic MASs with external disturbances. Then, the proposed control law is extended based on a state predictor for the tracking control of agents in the presence of input delay. The stability analysis of the two distributed controllers is also provided. Simulation results show the promising performance of the proposed algorithms.

1. Introduction

The study of the tracking control problem of MASs has attracted researchers' attentions in the recent decade because of its applications in different areas such as flocking, formation control, leader-follower problem, cooperative control and so on [1–10]. In the tracking control problem, each agent utilizes a distributed estimator to estimate the states of a target and uses a distributed controller to track the estimated target. Two distributed algorithms should be designed such that each agent agrees on a common value with their neighbors in both estimation and control.

The tracking control problem of MASs can be considered in two classes: 1) agents with linear dynamics, 2) agents with nonlinear dynamics. Some algorithms have been introduced for the tracking control of agents that have linear dynamics [11–14]. In Ref. [11], a distributed control and estimation algorithm has been proposed by combining a distributed Kalman filter and a flocking algorithm. Using this algorithm, each agent estimates a linear target and tracks the target with a flocking behavior and obstacle avoidance. The proposed algorithm has also been developed for MASs with time delay [12]. In Ref. [13], authors have solved a leader-follower problem for MASs with unknown dynamics. This paper assumes that the communication graph among agents is a directed graph and a distributed tracking algorithm has been suggested to ensure that the tracking errors approximately converge to the origin. It is worth noting that in a leader-follower problem, some agents (followers) are connected to the target (leader). In Ref. [14], an observer-based distributed control law has been presented for high order MASs such that each follower can track the leader. This controller was also extended for MASs with transmission delay.

In practical tracking control applications, many MASs and targets have nonlinear dynamics with nonholonomic constraints. Thus, it is important to investigate the distributed tracking control algorithms of nonholonomic MASs. Ref. [15] has designed a cooperative control law for a nonholonomic MAS such that each agent can orbit around a target which has a time varying velocity. In Ref. [16], two discontinuous control laws have been proposed so that nonholonomic agents can track a target with unknown dynamics in a flocking manner. Suggested controllers ensure collision avoidance among agents and can be used for both fixed and switching topologies. Ref. [17] has introduced some distributed controllers for multiple nonholonomic mobile robots such that the mobile robots can move along a desired trajectory with some desired formation. In Ref. [18], the distributed formation tracking problem has been solved for

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nonholonomic multi-robot systems. In this study, multi-robot systems with some distributed event-triggered controllers produced a desired geometric configuration under fixed and switching topologies. In Ref. [19], two continuous controllers have been suggested for a nonholonomic MAS with a connected undirected communication graph. In this paper, the nonholonomic agents can achieve the desired formations. Ref. [20] has studied the distributed finite-time tracking control problem for nonholonomic mobile robots with external disturbances and unknown parameters. In this work, the distributed finite-time controllers based on finite-time disturbance observers have been suggested for each mobile robot such that each robot can converge to the desired trajectory in finite time. In Ref. [21], a sampled-data controller has been suggested for a group of nonholonomic agents to track a mobile target. In this paper, a dwell time has been assumed for the feasibility of information sensing and processing to avoid chattering caused by the abrupt changes of the neighbor relations.

In the recent decades, the study of nonholonomic systems in chained-form has received great attentions because this form includes any kinematic model of mechanical nonholonomic systems. Actually, Ref. [22] proved that nonholonomic systems can be converted into chained-form by state and input transformation. For example, cars with trailers and unicycles which have two inputs and three states can be converted into the first order chained-form nonholonomic system. There are some works which have considered the tracking control problem of chained-form nonholonomic systems [23–25]. In Ref. [23], a recursive fast terminal sliding mode strategy has been presented to solve the finite time tracking control problem for chained-form nonholonomic system. Ref. [24] has studied the leader-follower problem of high order nonholonomic MASs. In this work, a finite time observer and observer-based controller have been employed to guarantee the finite time convergence of the agents to the target. In Ref. [25], some controllers have been suggested for chained-form nonholonomic MASs such that agents can reach to a reference target with chained-form nonholonomic dynamics under a directed graph. It should be mentioned that the tracking control algorithm of [23] has been suggested for a single nonholonomic system and cannot be applied for chained-form nonholonomic MASs. Furthermore, it is assumed that at least one of the agents is connected with the targets in Refs. [24,25]. This assumption does not hold in the tracking control problem and therefore the presented algorithms in Refs. [24,25] cannot be used for the tracking control of chained-form nonholonomic MASs.

In practical environments, some factors affect the system performance and may lead to instability. One of the factors is external disturbance which is a source of poor performance and instability of systems and is inevitable in MASs. Another factor is time delay which exists in practical MASs and degrades the performance of the system. One type of time delay in MASs is input delay that is made due to processing and connecting time for the packets arriving at every agent. Refs. [26–28] have considered the finite-time tracking control problem of chained-form nonholonomic systems with external disturbances. These controllers have been expended for chained-form nonholonomic systems with uncertain parameters and time-varying external disturbance in the chattering-free case [29]. In Ref. [30], the stabilization problem of chained-form nonholonomic systems with input delay has been studied. In this paper, a control law has been presented based on the backstepping approach and input-state-scaling technique to guarantee global asymptotically stability of the closed-loop system. It should be noted that although the suggested controllers in Refs. [26–30] have been proposed for chained-form nonholonomic systems with external disturbances and input delay, they are not distributed control laws and cannot be used for the tracking control of chained-form nonholonomic MASs. Based on these explanations, it is necessary to propose some algorithms to solve the tracking control problem of chained-form nonholonomic MASs in the presence of external disturbances and input delay. To the best of the authors' knowledge, this problem has not been considered in the literature. This motivates us for this study.

This paper will focus on solving the tracking control problem for chained-form nonholonomic MASs with external disturbances and input delay. In the first step, it is assumed that each agent is subject to external disturbances and a finite time control law is suggested, based on switching method, for every agent to track a target. In the second step, a new controller is developed using a state predictor (SP), for each agent to deal with the tracking control of nonholonomic MASs in the presence of input delay. The Dynamics of target and agents is described by a third-order nonholonomic model in the chained-form.

Compared with the previous works in nonholonomic MASs [15–30], the contributions of this paper is at least fourfold. First, in contrast to the works of [15–21], which proposed some controllers for the dynamic form of nonholonomic MASs and cannot be applied for chained form nonholonomic MASs, this paper suggests some control laws for chain-form nonholonomic MASs and can be used for any nonholonomic MASs with three states and two inputs. Second, it is assumed in this paper that the target is not connected with any agent in the design of the distributed controller for tracking control, whereas the previous results in Refs. [24,25] have assumed that at least one of the agents is connected with the target. Third, in contrast to the works of [23,26–30], in which the suggested controllers are not distributed and cannot be used for MASs, in this paper some distributed control laws are presented to solve the tracking control of chained form nonholonomic MASs. Fourth, in Refs. [15–19,23–25] some controllers have been designed for nonholonomic systems in the ideal conditions, whereas the proposed controllers in this paper are obtained for nonholonomic MASs with input delay and external disturbances that mean these algorithms can be used in practical environments and work appropriately in the presence of destructive factors including input delay and disturbances.

The rest of this paper is organized as follows: the preliminaries and problem definition are presented in Section 2. Section 3 proposes distributed control laws for nonholonomic MASs with external disturbances and input delay. The effectiveness of the suggested algorithms is studied with simulations in Section 4. Finally, the conclusions are drawn in Section 5.

Notation: $\mathbb{R}^z$ expresses the z dimensional Euclidean space. $\mathbb{R}^{z\times m}$ denotes the set of all $z\times m$ real matrices. I_M presents an $M\times M$ identity matrix. $\lambda_{\min}(.)$ is the smallest eigenvalue.

2. Preliminaries and problem formulation

2.1. Preliminaries

Graph Theory. To model MASs, an undirected graph $G=(\psi,\varepsilon,A)$ is used in which $\psi=\{1,2,\ldots,N\}$,$\varepsilon\in\psi\times\psi=\{(i,j):i,j\in\psi\}$ and $A=$

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