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A quick position control strategy based on optimization algorithm for a class of first-order nonholonomic system

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ABSTRACT

In this paper, we develop a quick and effective position control strategy based on the differential evolution (DE) algorithm for a planar three-link passive-active-active (PAA) underactuated system with first-order nonholonomic constraint. Due to the existence of the constraint, when the angular velocities of the two active links are proportional, the planar PAA system is transformed from a first-order nonholonomic system to a holonomic system like an Acrobot. Making full use of the angular constraint of the like-Acrobot, we employ the DE algorithm to calculate the target angles of all links and the target ratio between the angular velocities of the two active links. After that, one continuous controller for one active link is designed to ensure the target ratio in the whole control process; meantime, the other continuous controller for the other active link is designed to make its angle asymptotically converge to the corresponding target value. In this way, the angles of all links can asymptotically converge to the corresponding target values according to the angular constraint, and thus the position control of the system is realized using the continuous control method. Finally, the simulation results demonstrate the quickness and effectiveness of our proposed control method.

1. Introduction

Nonholonomic systems [5,20] refer to kinds of nonlinear systems with nonholonomic constraints. In general, the nonholonomic constraints mainly include two types: the nonintegrable constraint on accelerated velocities and the nonintegrable constraint on velocities, where the former represents a class of second-order nonholonomic system and the latter represents a class of first-order nonholonomic system. Due to the numerous practical applications of nonholonomic systems, the stable control problems have been attracted considerable attention, and various control methods or techniques have been applied maturely to such systems. She et al. [25] studies the global stabilization problems of a class of second-order nonholonomic systems based on the global homeomorphic coordinate transformation and the equivalent input disturbance. Qin and Min [22] designs an adaptive state-feedback controller using the input-state-scaling technique, the backstepping recursive approach, and the parameter separation technique for a class of stochastic nonholonomic systems. Zhao et al. [30] presents a global stabilization controller using the small gain theorem, the changing supply function technique,

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and a switching control strategy for a class of uncertain nonholonomic systems. Yen et al. [29] designs an adaptive neural network-based dynamic feedback tracking controller for a class of nonholonomic systems with high-degree time-varying uncertainties.

Most of underactuated mechanical systems [6,14] belong to nonholonomic systems due to the fewer numbers of control input than that of degree of freedom. There are many practical systems with underactuated characteristic, such as wheeled mobile robots [4,8], spacecrafts [26,32], quadrotor helicopters [2,24] and so on. Moreover, the fully-actuated system will become the underactuated system when one or more actuators fail. Thus, the development of control strategies for the underactuated systems is not only able to achieve the stable control of so many practical systems and improve the fault-tolerant ability of the fully-actuated systems, it can also further perfect the control theory of nonholonomic systems.

As one class of underactuated mechanical systems, planar underactuated systems [9,23] move in the horizontal plane without affected by gravity. They have a wide application prospect in the aerospace engineering [31] and the underwater engineering [3,7] due to the lack of gravity. For the planar underactuated system, any point in the plane is the equilibrium point of the system and the linear approximate model at any equilibrium point is uncontrollable [15]. In addition, such systems can be divided into three classes according to the integral characteristic, i.e. a planar two-link Acrobot belonging to a holonomic system, a planar n-link ($n \geq 3$) system with one passive first joint belonging to a first-order nonholonomic system, and a planar system with one or more passive not-first joints belonging to a second-order nonholonomic system.

For the first class, the position control of the planar Acrobot has been achieved in [12] by using a continuous control method, where the angle of only the active link is controlled to converge to its target value based on the angular constraint of the planar Acrobot. Meantime, due to the existence of the angular constraint, some geometric reachable positions of the planar Acrobot cannot be achieved by the continuous control method.

Then, for the other two classes with nonholonomic constraints, their position control is more challenging to be realized because of both the complex nonlinear and nonholonomic characteristics. Specifically, for the third class with second-order nonholonomic constraint, scholars mainly focus on the research on the position control of such systems with a last passive joint, for instance, a planar two-link Pendubot and a planar three-link active-active-passive (AAP) underactuated system. A two-stage control method based on joint friction [18] and an open-loop control method based on nilpotent approximations and iterative steering paradigm [17] have been devised to realize the position control of the planar Pendubot. Luca et al. [16] formulates the planar AAP system as a second-order chained form, and based on the chained form, various control methods (e.g. [1,16]) have been presented to achieve its position control.

However, for the second class with first-order nonholonomic constraint, the research on the position control is relatively fewer. When $n = 3$, i.e. a planar three-link passive-active-active (PAA) underactuated system, [13] presents a two-stage control method to realize the position control of the system, where the system is reduced to two planar Acrobots and the angle of only one active link in each stage is controlled to converge to its target value. Further, this reduced-order control idea for $n = 3$ is extended to control the general system for $n > 3$. Lai et al. [11] first reduces the planar n-link($n > 3$) system to the planar PAA system and then controls this reduced system using the above two-stage control method, which is a three-stage control method. Wang et al. [28] first reduces the planar n-link($n > 3$) system to the planar Acrobot and then controls this reduced Acrobot by using the continuous control method, which is a two-stage control method. Obviously, all of the above control methods for the planar underactuated system with nonholonomic constraints are discontinuous, thus the controllers' design is complicated and the time to realize the position control of such system is long.

Motivated by the above consideration, this paper focuses on developing a simple continuous control method to realize quickly and effectively the position control of the planar PAA system with the first-order nonholonomic constraint. The position control objective is to move the end-point of the system from any initial position to any target position. First, the integral characteristics of the system are analyzed according to the dynamic equation of the passive joint. After that, we find when making the angular velocity of one active link be linearly proportional to that of the other one, there exists a constraint among the angles of all links of the system. That means the first-order nonholonomic system can be transformed into a holonomic system like an Acrobot. Based on the angular constraint of the like-Acrobot and the target position, we employ the differential evolution (DE) [21,27] algorithm to calculate the target angles of all links and the target ratio between the angular velocities of two active links. Based on these target values, one controller for one active link is designed to ensure that the ratio between the angular velocities of two active links is always kept the target value in the whole control process, and another controller for the other active link is designed to control its angle to converge asymptotically to the corresponding target value. Then, the angles of all links can asymptotically converge to the corresponding target angles according to the angular constraint. Obviously, when turning the first-order nonholonomic system into a holonomic system, we can realize the position control objective of the first-order nonholonomic system by using the continuous control strategy, which is the general control method cannot realize. Meantime, due to the adjustability of the ratio, we can overcome the control shortcoming of the Acrobot that some positions within the geometric accessible range cannot be achieved by any continuous control method. Finally, we verify the proposed control method is quick and effective by carrying out five sets of numerical simulations.

The contributions of the paper are:

1. The continuous control method for the planar PAA system with the first-order nonholonomic constraint is proposed and addressed in this paper.

2. One control strategy that reduces the first-order nonholonomic into the holonomic system by making the angular velocities of two active links be proportional is developed.