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Indirect adaptive fuzzy control for a nonholonomic/underactuated wheeled inverted pendulum vehicle based on a data-driven trajectory planner

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Abstract

In this study, we investigate an error data-based trajectory planner and indirect adaptive fuzzy control for a class of wheeled inverted pendulum vehicle systems. Based on the error dynamics, the closed-loop trajectory planner can generate the desired velocity values. Using the virtual acceleration input for the tilt angle subsystem, composite control for the rotational and longitudinal subsystems can be constructed via indirect adaptive fuzzy and sliding mode control approaches to achieve simultaneous velocity tracking and tilt angle stabilization. We rigorously prove the system stability and convergence of the tracking error signals using the Lyapunov theory and LaSalle's invariance theorem. The results of our numerical simulations demonstrated the efficiency of the proposed control strategies and the implementations of the algorithms.

Keywords: Adaptive mechanism; Data-driven; Indirect fuzzy control; Nonholonomic/underactuated; Wheeled inverted pendulum

1. Introduction

A wheeled inverted pendulum (WIP) vehicle possesses only two active driving wheels but it can implement nearly every mode of motion, such as advancing, steering, and stopping. Over the past few years, there has been extensive interest in the development of these types of vehicles (e.g., [1–4]). Due to their advantageous features, such as compact construction, convenient operation, high maneuverability, and low fuel consumption, WIP vehicles can be employed in emerging applications in commercial, civilian, and military areas. However, the efficient control of the WIP platform is a challenging problem, mainly because: (*i*) it is difficult to use current modeling techniques to obtain an accurate vehicle dynamic model, which is generally highly nonlinear, time-varying, and coupled in nature; (*ii*) the system

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suffers from a nonholonomic constraint on the kinematic level, which traditional control methods are unable to use directly; and (*iii*) the dynamics of the suspension possess obvious underactuated characteristics, which means that the number of control inputs is less than the number of degrees of freedom. All of these difficult issues are hindrances to the control community [5–7].

Many previous studies have focused on control methods to implement trajectory tracking for WIP vehicles, such as conventional proportional-integral-derivative (PID) control, feedback stabilization, sliding mode schemes, and intelligent control. It is well known that PID control is a simple and easy approach but due to the complexities of WIP vehicles, it is a difficult to select three appropriate gains [8,9]. Thus, to improve the system control performance, feedback stabilization based on an approximate linear model is widely employed. For example, in [10], a two-level controller was proposed for tracking and stabilizing the vehicle's posture based on a partial linear model where the internal dynamics were isolated. Similar methods were also employed by [11,12]. In addition, the variable structure method is another powerful approach for controlling WIP vehicles. For instance, Yue et al. employed a sliding mode scheme to effectively control a two-wheeled vehicle with a dropping pendulum-like suspension, where the mobile platform was fairly similar to that in a WIP vehicle [13]. However, most of these controllers rely on the system model information, which can rarely be obtained in practice. It should also be mentioned that many advanced modeling and identification techniques can be used for model-based control design (e.g., [14–16]), but it is still difficult to obtain an explicit description of the vehicle in real time. Intelligent control, including the use of fuzzy control and neural networks (NNs), has been shown to be a powerful technique for control design when dealing with complex dynamical systems (e.g., [17–20]). In particular, Li et al. developed an output feedback adaptive NN controller with a linear dynamic compensator to achieve stable dynamic balance of the vehicle body, while tracking of the desired trajectories could also be achieved at the same time [21,22]. Moreover, in [23], an adaptive fuzzy logic control system was explored based on updated laws for a WIP vehicle and the control performance was improved. Based on these studies, it is clear that intelligent control is an effective tool for controlling WIP vehicles, which have complex dynamics and nonholonomic/underactuated behaviors.

Furthermore, compared with the aforementioned control approaches, fuzzy control can usually achieve better control performance because it does not depend on an exact mathematical model and it can effectively synthesize the successful experiences of operators using linguistic instructions [24–28]. In general, fuzzy control comprises indirect fuzzy control and direct fuzzy control. In contrast to direct fuzzy control, which is based on the difference between the performance of the actual system and the ideal performance level, indirect fuzzy control applies the universal approximation theorem to obtain system models of the controlled object, which is appropriate for merging the other control techniques that comprise a composite controller in an entire underactuated system [29,30]. Surprisingly, direct fuzzy control has been used widely to control WIP vehicles (e.g., [31–33]), but few studies have employed the indirect fuzzy scheme to control this type of wheeled mobile platform.

In addition to the underactuated behaviors of WIP vehicles, the nonholonomic constraint is another unavoidable problem when a vehicle tracks the reference trajectories. If the wheeled mobile platform moves while the wheel-terrain satisfies the pure rolling condition, then the constraint cannot be integrated into a linear form [34,35]. According to Brockett's necessary condition for asymptotic stabilization, no continuous time-invariant state-feedback controller exists that can asymptotically stabilize the mobile platform [36]. For a WIP vehicle, the combination of underactuated suspension and the nonholonomic constraint represent a challenging task during control system synthesis. With the exception of a few previous studies, the tracking objective has focused on tracking the longitudinal and rotational velocities, whereas tracking of the position trajectory was described in the Cartesian frame. Therefore, simultaneously addressing the underactuated and nonholonomic problems for WIP vehicles is still an open problem, and thus the motivation of the present study.

In the present study, we propose a novel data-driven closed-loop trajectory planner that differs from the traditional path planning, which solves the nonholonomic constraint and underactuated control issues on kinematic and dynamic levels, respectively. With respect to the trajectory planner, we conceive a hypothesized vehicle with the desired posture values and we then establish the error dynamics based on the posture tracking error data so we can apply Lyapunov stability theory to guarantee the stability of the closed-loop planner. It should be noted that the closed-loop trajectory planner is similar to a close-loop system based on the vehicle kinematics, where the planner's outputs are regarded as the desired longitudinal and rotational velocities for the vehicle's dynamic system. This treatment allows the data-driven trajectory planner to generate the desired values in real time, where the closed-loop feedback characteristics can enhance the robustness of the planner system against unavoidable parameter variation and unpredictable external