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Mapping filtered forwarding-based trajectory tracking control ☆

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Abstract

Forwading-based immersion and invariance approaches have been applied to control the high-order nonlinear systems, whereas it is an off-line algorithm and needs to directly compute analytic derivatives of the mappings. In our study, a new tracking control algorithm is developed by introducing a second-order filter at each step of the design. This recursive algorithm does not only overcome the problem of "explosion of complexity" to improve computational efficiency, but also suppresses the high-frequency noise arising from time derivatives of states and virtual controls. Unlike other existing control methodologies, it does not require the knowledge of a Lyapunov function in principle. The boundedness of all mappings and their analytic derivatives can be ultimately guaranteed by using the internal stability of filters. Also, this bottom-up algorithm is able to provide the modularized design of the controller, where real-time applications can be to some extent realized. In this work, a quadrotor helicopter is used to demonstrate the controller performances via various simulations.

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1. Introduction

Trajectory tracking control of high-order nonlinear systems has played an important role in the control field. Indeed, there are only a few methods for controlling the n-dimensional nonlinear systems. Saberi et al. presented a well-known method, backstepping, for partially linear composite systems in strict feedback form in 1990 [1]. Sepulcher et al. proposed an integrator forwarding method for nonlinear systems in strict feedforward form in 1997 [2]. In [3], a practical design method was developed for cooperative tracking control of higher-order nonlinear systems with a dynamic leader, and an adaptive neural network technique was used. In [4], a recursive design procedure was provided by using the method of the so-called adding a power integrator merging with adaptive technique. In recent years, many results based on backstepping technique have been provided to control high-order nonlinear systems [5–7]. In order to implement these control algorithms, the desired output and its first n derivatives must be available and bounded. A Lyapunov function also is needed at each step of the design.

However, as the degree of freedom (DOF) increases, backstepping implementation becomes increasingly complex. This inherent complexity is caused mainly by the need to compute the command derivatives at each step of the design. There are several approaches to overcome the problem of "explosion of complexity". Dynamic surface control (DSC) was proposed for designing controllers, where low pass filters were included to end the complexity arising from the "explosion of terms" [8]. Subsequently DSC methods combined with other control techniques such as fuzzy control and neural network control were successfully presented [9–11]. Farrell et al. presented command filtered backstepping (CFBS) approaches in 2009, and by introducing command filters into the backstepping design, a modification was specified to obviate the need for analytic computation of command signal derivatives [12,13]. Zuo designed a trajectory tracking controller with command-filtered compensation for a quadrotor, but did not conduct a stability analysis [14]. Hu and Zhang proposed a guidance law based on a nested saturation function and I&I theorem for controlling VTOL vehicles, and analyzed the influence of the command filter's frequency on the closed-loop system [15]. Overall, the soul of all these methods is the backstepping technique. So finding a new method which is not needed for Lyapunov function to control the high-order nonlinear systems deserves our attention.

Immersion and invariance (I&I) theorem, proposed by Astolfi and Ortega in 2003, is one of the promising and effective approaches [16]. I&I theorem does not need the Lyapunov candidate function in the controller design phase. Another advantage is the perfect decoupling calculation between manifold attractivity and invariance [17–26]. To the end, we have developed a recursive algorithm, from design direction point of view, called forwarding-based immersion and invariance control. Note that for a class of n-dimensional nonlinear systems in strict-feedback form, the required mapping in controller expression can be transformed into a virtual input of the target system by selecting a suitable and lower-order target system at each step of the design; then the order of the nonlinear systems can be reduced step-by-step by implementing the I&I theorem repetitively. However, it is an off-line algorithm. The direct computations of the mappings and their analytic derivatives would increase the computation cost. The time derivatives of states and virtual controls would make the closed-loop system prone to noise amplification. Furthermore, the boundedness of all trajectories could not be easily ensured unless certain assumptions are satisfied. All these issues severely restricted the physical implementation of forwarding-based control algorithm.

This study focuses on a bottom-up procedure for designing trajectories tracking control laws for a class of n-dimensional nonlinear systems in strict-feedback form. At each step of the design,