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H_∞ tracking adaptive fuzzy integral sliding mode control for parallel manipulators

Wen-Shyong Yu *, Chien-Chih Weng

Department of Electrical Engineering, Tatung University, 40 Chung-Shan North Rd. 3rd. Sec., Taipei 10451, Taiwan

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Abstract

Highly nonlinear coupling phenomenon is an inherently inevitable in parallel manipulators in which limbs/links undergo rotating and sliding with/without fixed base. In this paper, an H_∞ tracking adaptive fuzzy integral sliding mode control scheme is proposed for controlling parallel manipulators with nonlinear unmodeled dynamics, external disturbances, and limb-to-limb couples in which each coupled uncertainty is assumed to be bounded by an unknown gain. The dynamics of the parallel manipulator is formulated as an error dynamics according to a specified reference model; then, a fuzzy model is used to approximate the uncertainties. Two on-line estimation schemes are developed to overcome the uncertainties and identify the gains of the unknown coupled uncertainty bounds from limb-to-limb couples, simultaneously. The advantage of employing an adaptive fuzzy system is the use of linear analytical results instead of estimating nonlinear uncertain functions with an on-line update law. By the concept of parallel distributed compensation (PDC), the adaptive fuzzy scheme uses an integral sliding mode control scheme to resolve the system uncertainties, unknown limb-to-limb coupled uncertainties, and the external disturbances such that H_∞ tracking performance is achieved. The control laws are derived based on a Lyapunov criterion and the Riccati-inequality such that all states of the system are uniformly ultimately bounded (UUB) and the effect on the tracking error can be attenuated to any prescribed level to achieve H_∞ tracking performance. Finally, a numerical example of a planar 2-dof parallel robot system is given to verify the effectiveness of the proposed control scheme.

Keywords: Integral sliding mode; Adaptive fuzzy control; H_∞ tracking performance; Lyapunov stability theorem; Riccati-like equation; Planar 2-dof parallel robot system

1. Introduction

Over the last decades, parallel manipulators have been studied by many researchers and are employed in various applications [1–3], because they possess advantages of low inertia, high stiffness, and large payload driven capability as compared with the serial manipulators. However, according to mechanical geometry and motion dynamics, they suffer from inherently nonlinear phenomena with couples caused by mechanical limits for joints and links, which result in control design difficulty and/or complex computations in control design even if their dynamics are simplified

* Corresponding author. Tel.: +886 2 25925252x3470x103; fax: +886 2 25925252x3470x0.
E-mail address: wsyu@ttu.edu.tw (W.-S. Yu).

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greatly. Hence, control design with full dynamic model including nonlinear couples is needed such that the stability as well as the performance of the system can be improved. Traditionally, dynamic control design for parallel manipulators generally includes the augmented PD (APD) controller and computed-torque (CT) controller [4,5]. However, the closed-loop system stability at high-speed motions can not be guaranteed and the performance of the system using these controllers will be degenerated.

Recently, some novel control design schemes for dynamic controllers with performance indicators were presented for parallel manipulators to improve the performances of the system [6–8]. In order to reduce the effect of nonlinear uncertainties, many researchers proposed neural networks and fuzzy systems for function approximation capability with some advanced robust control theories to guarantee tracking performance and stability of the system [9–11]. Since the mechanic structure characteristics of the parallel manipulator may contain a number of interconnected branch chains, the designed controllers for joints in each branch should consider the interconnections from other branch chains. Fuzzy control with adaptation, on the other hand, have been utilized to learn unknown dynamics of nonlinear systems while relaxing the linear under the assumption of unknown control parameters. Compared to the traditional control scheme, the fuzzy control scheme has two practical advantages: First, a mathematical model of the system to be controlled is not required, and second, a suitable nonlinear controller can often be developed empirically in practice without complicated mathematics. Fuzzy control schemes with various adaptation strategies [12] or supervisor-based fuzzy control [13] can efficiently eliminate or minimize both external disturbances and approximation errors with many applications [14–16].

Sliding-mode control (SMC) has various attractive features such as fast response, good transient performance, and order-reduction, and has been successfully applied to a wide variety of practical engineering systems [17], robot manipulators [18], DC–DC converters [19], underwater vehicles [20], and automotive engines [21]. The major advantages of SMC guarantee system stability and robustness against bounded parameter variations, uncertainties, and external disturbances [22–24]. SMC consists of two components: a reaching mode control that forces the error state to reach a stable hyperplane or manifold, and an equivalent control that assures the error state following the sliding surface and approaching zero. Linear sliding hyperplanes or manifolds guarantee asymptotic stability of the system in the sliding mode, but the system states will converge to the equilibrium point at an infinite time. To assure finite time convergence, two control schemes, integral sliding mode (ISM) [25,26] and terminal sliding mode (TSM) [27,28], were proposed to provide faster convergence than that by linear hyperplane-based sliding mode. The merits of the ISM control scheme have no reaching phase and insensitivity of the uncertainties for trajectory tracking from the initial time instant. Furthermore, since the ISM control includes an integral term in the sliding surface, the trajectories of the system states can start on the sliding surface from the initial time instant [29]. In [25], the robustness properties of the ISM control are extended to control systems with unmatched vanishing uncertainties, while an off-line initialization is given in [30]. Since the system using ISM technique is constrained to evolve on the integral sliding surface from the initial time instant, the possible singularities in the matrix of the input channel during the transient are avoided provided the sliding surface is suitably chosen. Consequently, the ISM design principle can be based on the first-order sliding mode control to reject the effect of matched uncertainties, while the second-order integral sliding mode control is to reject the effect of a larger class of uncertainties.

Besides, adaptive feedback linearization control design for various nonlinear systems with or without modeling errors or parameterized uncertainties has been proposed to solve the tracking problem of nonholonomic mobile robots [31]. They assumed that the uncertain quantities in dynamic systems can be expressed linearly with respect to unknown parameters. Traditionally, nonlinear adaptive control designs can guarantee convergence of the tracking error to a residual set, whose size depends on the designed parameters or some unknown but bounded terms. However, no systematic procedure exists to accurately compute the required upper bounds, thus making the a priori selection of the aforementioned controller parameters to satisfy certain steady state behavior is practically difficult.

The proposed control scheme assumes that the limb-to-limb couple is a function of state which increase the complexity of nonlinear parallel manipulator systems. Therefore, the control design technique becomes more challenging. Moreover, the proposed scheme uses an adaptive law to estimate the couple gain and views it as uncertainty. To achieve good tracking performance at a finite time and to attenuate efficiently the effects of both external disturbances and coupled uncertainties to a prescribed level, we adopt H_∞ tracking adaptive fuzzy integral sliding mode (ISM) control scheme (HTAFIS–MCS) in the control design for parallel manipulators with plant uncertainties. The adaptive fuzzy scheme uses two on-line estimations, which allow for the inclusion of estimation coupled uncertain gains and training of the weights of the fuzzy system, simultaneously. The integral sliding mode control is used not only to