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Anti-sway tracking control of tower cranes with delayed uncertainty using a robust adaptive fuzzy control

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Abstract

Tower cranes are very complex mechanical systems and have been the subject of research investigations to reduce the swaying of the payload for several decades. Inherently, the dynamical model of the tower cranes is highly nonlinear and classified as underactuated. Also, the actuators are far from the payload which makes the system non-colocated. It is proposed here to use an H_∞ based adaptive fuzzy control technique to control the swaying motion of a tower crane. The advantage of employing an adaptive fuzzy system is the use of linear analytical results instead of estimating the dynamics of the tower crane with an online update law. The proposed robust control law for payload positioning is based on a variable structure (VS) adaptive fuzzy control scheme. The adaptive fuzzy control technique fuses a VS scheme and it is derived based on a Lyapunov criterion and the Riccati-inequality. The control design overcomes modeling inaccuracies, such as drag and friction losses, effect of time delays from backlash, as well as parameter uncertainties and compensate for the effect of the external disturbances on tracking error such that all the states of the system are uniformly ultimately bounded (UUB). Therefore, the H_∞ tracking performance can be achieved such that the payload swing is reduced to as small as possible when the payload is moved from point to point. Simulations show that the proposed control scheme is effective in reducing payload swing in the presence of uncertainties, time delays, and external disturbances.

Keywords: Tower crane systems; Adaptive fuzzy control; H_∞ control; Variable structure scheme; Time delays

1. Introduction

Tower cranes are common industrial structures that are used to lift and move heavy payloads during the construction of high-rise buildings, factories, and harbors. Moving the payload from point to point is time consuming and

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tends to disturb the crane operations causing swaying of the payload and vibration of the crane which may lead to inaccurate positioning and reduce safety and efficacy of the overall system. Moreover, a crane system has potentially six degrees of freedom but only three actuators, and, to date, they are operated manually. It is difficult to manually control the cranes when large and fast maneuvering is required. Such problems decrease the work efficiency and, in some cases, cause damage to the payload and constitutes a safety hazard. Consequently, many researchers have proposed automatic control schemes to minimize the swaying of the payload and eliminate its effects on the performance of the system (see for example [1–5] and the references therein). In [1,2], the authors proposed gain-scheduling feedback control methods for tower crane enabling the controller feedback gains to be calculated for varying loads and cable lengths. Input shaping control method is adopted in [4,5] to reduce the vibratory response of overhead crane systems substantially. However, most of these methods need accurate system models and complex matrix computation greatly affected by system linearization and parameter uncertainties. Time-delays phenomena also affects the behavior of such systems.

Backlash is a phenomenon which can severely limit the control system performance. Typically backlash appears in mechanical couplings because of the gap between the motor-side and the load-side contact points. As backlash increases (gap increases) the time-delay due to backlash increases and achieving stability and tracking performance is more difficult [6–8]. In [6], the authors proposed a backlash compensator to reduce the delay introduced by backlash. A backlash controller is designed to shorten the period of gear disengagement by varying the damping ratio of the dominant closed-loop poles [7]. An adaptive fuzzy output-feedback control is investigated for a class of uncertain nonlinear systems with unknown backlash-like hysteresis and unmeasured states such that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded (SUUB) [8]. Inherently, the dynamical model of tower cranes with time-delays is highly nonlinear and also classified as underactuated. Thus, it is not justifiable to use a linear controller to deal with the control problem of the tower crane with time-delays. Several control schemes have surfaced over the years to deal with time delayed systems, e.g., sliding-mode control [9], adaptive neural network control [10,11], and adaptive fuzzy control [12,13]. Each method has its own advantages and disadvantages. The major advantage of adaptive fuzzy control is that a mathematical model for the true plant is not required. Therefore, the controller is constructed assuming that the fuzzy logic system approximately represents the true plant. An adaptive law plays an important role in estimating the parameters in the fuzzy model representing the plant since its parameters are unknown or varying due to external disturbances and parameter perturbation. The problem of robust tracking control of MIMO nonlinear systems has drawn a lot of attention in recent years. Many approaches have been used to solve this control problem; see for example [12,14]. In general, adaptive fuzzy controllers involve two main components; The first component is a fuzzy logic system and the second is some robust compensator such as H_∞ control [12,13,15–18], sliding-mode control [19–24] or a combination of both [14] for rough and fine-tuning, respectively.

A variable structure (VS) scheme is a robust design methodology to compensate for the effects of external disturbance combined with parameter variations of the crane systems [25,26]. Recently, adaptive fuzzy control with VS schemes has been proven to be a robust strategy to compensate for the effects of nonlinearities, external disturbance, and deal with parameter variation and unmodeled dynamics of uncertain systems [27,28]. It is worth mentioning that a conservative design may result from the application of the aforementioned scheme. Since the VS scheme control algorithm is designed to deal with the worst case scenarios of uncertainties, external disturbances may be of finite-energy only, but not bounded. Thus, the proposed design method attempts to incorporate an attenuation technique via an H_∞ tracking design approach as described in [29–32].

Robust adaptive fuzzy tracking control has proven to be a viable tool in the control of nonlinear MIMO systems. Motivated by these latest developments, this control technique is applied here to a tower crane system. The type of nonlinearities, uncertainties, and time delays in the system make it a very good candidate for the aforementioned control technique. Backlash of the tower, jib and payload motors is usually represented by nonlinear functions (dead-zone) of the backlash width Δ. As Δ increases, the time delay due to backlash increases which increases the difficulty level of achieving stability and tracking performance [6–8]. Therefore, adaptive fuzzy tracking control may lead to more robustness in the closed-loop system. Motivated by the above observations, an adaptive fuzzy tracking control approach is presented in this paper for a tower crane system with plant uncertainties, external disturbances, and time delayed states. Due to the underactuated feature of tower crane systems, the controller is designed using all state feedback such that the uncontrolled states are simultaneously included into the control mode. Hence, these uncontrolled states can be indirectly manipulated by the proposed controller. Each delayed state associated with a time-varying uncertainty is assumed to be bounded by an unknown gain. A VS scheme combined with H_∞ schemes is capable