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Adaptive B-spline-based fuzzy sliding-mode control for an auto-warehousing crane system

Kuo-Hsiang Cheng

Mechanical and Systems Research Laboratories, Industrial Technology Research Institute, Chutung, Hsinchu 310, Taiwan

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ABSTRACT

In this paper, an adaptive B-splined-based fuzzy sliding mode control (ABFSM) is presented to the application of auto-warehousing crane motion control. The ABFSM comprises an adaptive fuzzy identification controller (AFIC) and a B-spline-based compensation controller (BCC). The AFIC is designed to **approximate the ideal controller of a crane system**. To alleviate the **load of fuzzy rule base construction, only the information from the sliding surface is used as the input of AFIC** such that the conciseness and translucency of the control system can be upgraded. On the other hand, the BCC aims to compensate the approximation error of the AFIC. With the introduction of the B-spline function, the boundary of the approximation error can be represented **by means of** polynomial mapping. Thus, the design of the compensation controller can be **achieved** based on the characteristics of the B-spline function. In this paper, the objective of the ABFSM is to track the distance-speed reference trajectory of the **crane control system**. With the tuning law of the AFIC and the BCC, the stability can also be guaranteed by means of Lyapunov function. To validate the performance of the proposed approach, the ABFSM is applied to auto-warehousing crane motion control under various conditions for x, y, and z directions, respectively. **From the simulation the advantages of the proposed ABFSM are demonstrated, where the capability to handle the uncertainty with efficiency is verified.**

1. Introduction

Owing to its capability to transform engineering experience into applicable control strategy, extensive real-world applications of fuzzy logic have been witnessed [1,2,9,14,17,20,23,25,28]. The key element of fuzzy logic control is that the dynamics of the ill-defined controlled system can be approximated to a certain level by fuzzy reasoning. **Based on the linguistic "IF A THEN B" description, the semantic rule reasoning demonstrates a superior ability than that of the conventional control theory when inaccurate mathematical modeling is encountered.** The characteristics of soft-computation also provide the robustness to operate within a wide range of conditions **when the internal imperfection and external disturbances are considered in the applications.** For industrial approaches, fuzzy controller design is usually performed through empirical experience to define the rule base [1,12]. To attain system automation, the extensions of fuzzy controllers by introducing other techniques have aroused much interest and became the emerging topics in the field of control engineering [4,5,10,22,24,26,27,29,32,33,34].

With the advantages of great capacity, high efficiency, computerized operation, and real-time inventory, auto-warehousing crane system is widely used in industrial applications for storing and accessing heavy cargoes [3,8,12]. The auto-warehousing crane system can move in *x*, *y*, *z* directions, where the positioning accuracy has been challenging since the system is required to operate under different working conditions such as moving distance and weight of load. **Moreover, the estimation of the exact friction model along each direction is also important in order to achieve accurate positioning.** Therefore, identifying real-world auto-warehousing system is a complex task and extracting the knowledge from the real-world applications is laborious and time-consuming.

To achieve control robustness, sliding mode control has been suggested to be good approach for its advantages of uncertainty accommodation and real-time implementation [6,16,18,22,31,35]. However, the unfavorable chattering phenomenon is also introduced by the conventional sliding mode control approaches. To mitigate the adverse phenomenon, the saturation function was proposed but the stability cannot be guaranteed. An approximation error bound estimation mechanism was proposed so that the chattering phenomenon of the control effort can be improved

E-mail address: KHCheng670714@gmail.com

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Table 1
Specifications for motion control of crane in *x*, *y*, and *z* directions.

Axis	Acceleration (m/s^2)	Deceleration (m/s^2)	Maximum Speed (m/s)	Creep Speed (m/s)	Force Limitation (Newton)	Positioning Accuracy (m)
X	0.5	0.5	3	0.1	−8500 to 8500	less than 0.005
Y	0.2	0.2	2/3	0.1	0–50500	less than 0.005
Z	0.5	0.5	0.5	0.1	−1500 to 1500	less than 0.002

[10,13–15,30]. However, the adaptive law for estimating the error bound makes the bound approach infinity if the main controller is ill-designed. **Regarding the adaptive control approaches with the robust control compensation technique [13,29], the performance is subject to the predetermined attenuation level. If an inappropriate attenuation level is given, the control effort may lead to undesirable large which is difficult to implement.**

The study of B-spline functions has been an emerging topic in engineering field due to its simplicity in implementation [7,11,19]. Based on the manipulation of the control points, the B-spline function can be defined and programmed in a recurrent way, and the input space can be partitioned into sub-domains with B-spline basis functions. **With the advantage of piecewise polynomial mapping, the B-spline-based approaches were applied as an alternative design of fuzzy control systems or artificial neural networks, where the B-spline functions are used as the membership functions or hidden nodes. By incorporating with other learning algorithms, the B-spline-based concept can be used as a powerful tool for curve-fitting, system identification, and control problems** [7,19].

In this paper, an adaptive B-splined-based fuzzy sliding mode control (ABFSM) is presented for auto-warehousing crane motion control**. The proposed approach aims to free the burden of model-based design by introducing fuzzy-logic-based control and a novel control compensater.** The proposed ABFSM comprises an adaptive fuzzy identification controller (AFIC) and a B-spline-based compensation controller (BCC). The AFIC is exploited to approximate the ideal controller for the crane system. **To alleviate the requirement of fuzzy rule construction, in this paper, only the information from the sliding surface is exploited as the input signal of AFIC such that the conciseness and translucency of the control system can be upgraded.** On the other hand, to avoid the shortcoming of the chattering of the sliding mode control, the BCC is exploited to compensate the approximation error of the AFIC. **With the introduction of the B-spline function, the boundary of approximation error can be represented by means of polynomial mapping. The proposed BCC provides a moderate way to compensate the performance of the AFIC when the boundary of approximation error is unavailable in advance.** Moreover, with the adoption of B-spline concept, the function of the compensation controller can be easily undertaken by a microprocessor, **where the function can be defined in a recurrent way based on the given knot vector. Thus, the design of the compensation controller can be easily implemented.** In this paper, with the tuning law of the AFIC and the BCC, the objective of the ABFSM is to track the distance-speed reference trajectory of the warehousing crane system while the stability of closed-loop control system can also be guaranteed by the means of Lyapunov function. To validate the performance of the proposed approach, the ABFSM is applied to the auto-warehousing crane motion control under various loading conditions in *x*, *y*, and *z* direction, respectively. Simulation is conducted to demonstrate the advantages of the proposed ABFSM, where the capability to handle the uncertainty with efficiency is verified. This paper is organized as follows. In section 2, the dynamics of the auto-warehousing crane system and the design of distance-speed reference curve are given. In section 3, the designs of the AFIC and BCC are given. In section 4, the design of the ABFSM and the stability analysis are represented. In section 5, to investigate the capabilities of the proposed approach, the ABFSM is applied to the crane system control with different working conditions. Finally, the conclusion is given in section 6.

Table 2
Parameters of reference curve.

Axis	Minimum $S_{\text{max-speed}}$ (m)	Deceleration (m)	Maximum Speed (m/s)	
x	0.3	0.2	0.013	
y	0.2	0.2	upward 0.002	downward 0.005
z	0.2	0.2	0.002	

Table 3
Parameters for the crane motion equations in *x*, *y*, and *z* directions.

Axis		x	y	z
Crane mass	loaded	1.5×10^4 kg	5×10^3 kg	2×10^3 kg
	unloaded	1.35×10^4 kg	3.5×10^3 kg	5×10^2 kg
Friction Coefficient	α_s	0.03	none	0.03
	α_d	0.001	none	0.001
Time constantτ_k		0.1 s	0.07 s	0.05 s
Braking constant$C_{brake,k}$		5×10^5	3.5×10^5	2×10^5

2. Design of the auto-warehousing crane system

2.1. Motion equations of the crane system

In this subsection, the dynamics of the auto-warehousing crane system of the *x*, *y* and *z* directions, and the specifications are given in Tables 1–3, are discussed [12]. The motion equations of the crane system of the *x*, *y*, and *z* directions are described below.

1) For the *x* and *z* directions, the motion equations are given as follows:

$$m_k\ddot{S}_k(t) = F_{input,k}(t) - \alpha_k N_k \tag{1}$$

$$m_k\ddot{S}_k(t) = F_{brake,k} \tag{2}$$

where $k = x$ and z. The parameter m_k is the mass of crane, $S_k(t)$is the distance of crane to the start position at time *t*, $F_{input,k}(t)$ is the control input to the crane system with the consideration of delay of mechanical transmission, α_k is the coefficient of friction, which can be given with the coefficient of static friction $a_{s,k}$ when $\dot{S}_k(t) = 0$ or with the coefficient of dynamic friction $a_{d,k}$ when $\dot{S}_k(t) > 0$. $N_k = gm_k = 9.81m_k$ is the normal force. $F_{brake,k}$is the braking force when the brake is activated. In this paper, the time delay of mechanical transmission is assumed as a time constant and the control inputs are regulated as

$$F_{input,k}(t) = \left[F_{input,k}(t-1) - u_k(t)\right]\exp\left(\frac{-T_k}{\tau_k}\right) + u_k(t) \tag{3}$$

where $T_k = 0.025\ \ s$ is the sampling time, τ_k is the time constant of delay, and $u_k(t)$ is the control input of the controller. In (3), the