A Non-Fuzzy Self-Tuning Scheme of PD-Type FLC for Overhead Crane Control

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Abstract. A non-fuzzy self-tuning scheme is proposed for Fuzzy PD controller in this paper. To eliminate the design complexity, output scaling factor (SF) of the proposed fuzzy controller is updated according to the process trend by a gain modification factor, which is determined by the normalized change of error of the system and its number of fuzzy partitions. The proposed non-fuzzy self-tuning fuzzy PD controller (NFST-FPDC) is demonstrated on a laboratory scale overhead crane. Moving a suspended load along a pre-specified path is not an easy task when strict specifications on the swing angle and transfer time need to be satisfied. In this study, twin NFST-FPDC are designed to control the trolley position of the crane and swing angle of the load. The proposed non-fuzzy gain tuning scheme guarantees a fast and precise load transfer and the swing suppression during load movement, despite of model uncertainties.

Keywords: Fuzzy control, Crane position control, Swing angle, Self-tuning.

1 Introduction

Overhead cranes are used in different industries for the loading and unloading of raw materials, freight and heavy equipments [1]. Control of overhead cranes, particularly the swing of trolley has become the requirements as a core technology for automated crane system. The purpose of crane control is to reduce the pendulum type motion of the loads while moving the trolley to the desired position as fast as possible. Thus, the need for faster cargo handling requires the precise control of crane motion so that its dynamic performance is improved [2- 3]. Various attempts have been made to solve the problem of swing of load [4- 5]. Most of them focus the control on suppression of load swing without considering the position error in crane motion. Besides, several authors have considered optimization techniques to control the cranes. They have used minimal time control technique to minimize the load swing. Since the swing of load depends on the motion and acceleration of the trolley, minimizing the cycle time and minimizing the load swing are partially conflicting requirements.

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The aim of fuzzy techniques is to get ahead of the limits of conventional techniques. A number of approaches have been proposed to implement hybrid control structures to control the nonlinear systems. Among the various types of hybrid controllers, PI-type fuzzy logic controllers (FLCs) are most common and practical [6] followed by the PD-type FLCs. But like conventional PI-controllers [7], performance of PI-type FLCs for higher order systems, systems with integrating elements or large dead time, and also for nonlinear systems may be very poor due to large overshoot and excessive oscillation. PD-type FLCs are suitable for a limited class of systems [8], like integrating, non-minimum and non-linear systems.

Practical processes are usually nonlinear in nature and associated with dead time, and their parameters may change with time and ambient conditions. Conventional FLCs with fixed values of SFs and simple MFs are not expected to provide good control performance. Mudi *et al* [9-14] proposed robust self-tuning schemes based on fuzzy rules, where the output SF of FLC is modified on-line by a gain updating factor, which is further multiplied by a fixed factor chosen empirically.

Instead of expert's defined fuzzy rules, in this paper we propose a non-fuzzy self-tuning scheme for fuzzy PD-type controller (NFST-FPDC). In the proposed NFST-FPDC, its output SF is continuously modified by a single deterministic rule defined on the normalized change of error, *i.e.*, Δe_N, and the number of its linguistic values of MFs. Observe that the proposed heuristic rule acts on the instantaneous speed of response of the process under control. Thus, the on-line adjusted output SF of the proposed NFST-FPDC is expected to improve the close-loop performance, since it incorporates the dynamics of the process.

In this study, we attempt to provide a practical solution for the anti-swing and precise position control of an overhead crane. The position of trolley, swing angle of load and their differentiations are applied to derive the proper control input of the trolley crane. Two PD-type fuzzy logic controllers are used to deal separately with the feedback signals, swing angle and trolley position, and their differentiations [15-17]. The main advantage of this separated approach is to greatly reduce the computational complexity of the crane control system. The total number of fuzzy rules for the complete control system is therefore less than the number of rules used by conventional fuzzy system. Besides, when designing the proposed fuzzy controllers, no mathematical model of the crane system is required in advance.

2 Laboratory Based Overhead Crane Set-up

A laboratory scale crane setup (FEEDBACK, UK) shown in Fig. 1 and Fig. 3 consists of a cart moving along the 1m length track and a load is attached with the cart through shaft. The cart can move back and forth causing the load to swing. The movement of the cart is caused by pulling the belt in two directions by the DC motor attached at the end of the rail. By applying a voltage to the motor we control the force with which the cart is pulled. The value of the force depends on the value of the control voltage. Two variables that are read using optical encoders, installed on the cart, are the load angle and the cart position on the rail. The controller's task will be to change the DC motor voltage depending on these two variables, in such a way that the desired crane control task is fulfilled. Initially the control signal is set to -2.5v to 2.5v and the generated force is of around -20N to +20N. The cart position is physically bounded by the rail length and is equal to -0.5m to +0.5m.

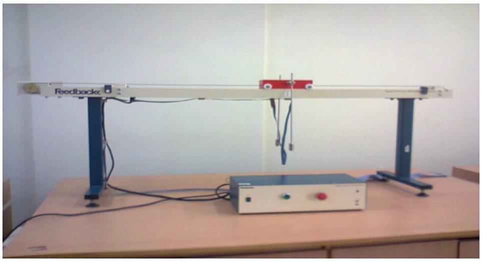

Fig. 1. Overhead crane set-up

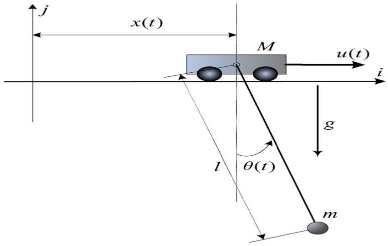

Fig. 2. Model of the overhead crane

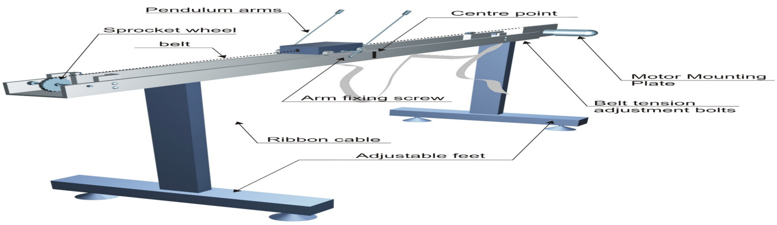

Fig. 3. Mechanical unit of the overhead crane system

Fig. 2 shows the schematic of overhead crane traveling on a rail, where *x(t), θ(t)*, and *u(t)* are the cart position, load swing angle, and cart driving force respectively. The cart mass, load mass, load arm length, and gravity are represented by *M, m, l*, and *g* respectively. In this paper, the stiffness and mass of the rope are neglected and the load is considered as a point mass. The proposed scheme is focused on anti sway tracking control of an indoor overhead crane; therefore, the hoisting motion and the effects of wind disturbance are not considered. Then, the equations of motion of the overhead crane system without uncertainty [4] are obtained through the following equations:

$$(M+m)x'' + (ml\cos\theta)\theta'' - (ml\sin\theta)\theta'^2 = u \quad (1)$$

$$ml^2\theta'' + (ml\cos\theta)x'' - mgl\sin\theta = 0 \quad (2)$$

The main difficulty in controlling the overhead crane system basically lies in the handling of the coupled nature between the sway angle and trolley movement. The dynamic model obtained is nonlinear in nature, that means the cart position and its derivative or swing angle and its derivative is a nonlinear function.

3 Proposed Controller Design

The output scaling factor should be considered a very important parameter of the FLC since its function is similar to that of the controller gain. Moreover, it is directly related to the stability of the control system. So the output SF should be determined very carefully for the successful implementation of a FLC. Depending on the error (e) and change of error (Δe) of the controlled variable, an expert operator always tries to modify the controller gain, i.e., output SF, to enhance the system performance [9-14].

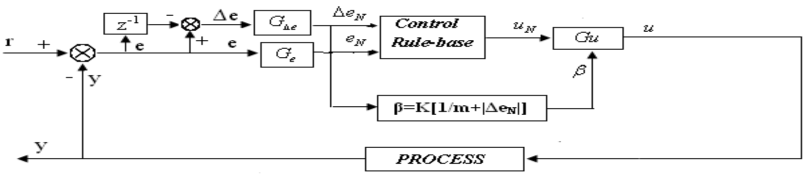

Fig. 4. Diagram of NFST-FPDC

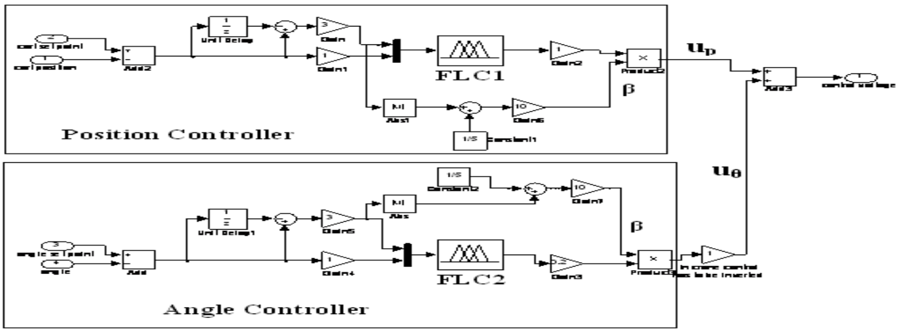

Fig. 5. Diagram of twin NFST-FPDC for overhead crane control

Following such an operator's policy, here, we suggest a simple self-tuning scheme of Fuzzy PD Controller (FPDC), where an online gain modifier (β) is determined from the relation, $\beta = K[1/m + |\Delta e_N|]$ as shown in Fig. 4. Here, β is the on-line adjustable parameter for the output SF G_u, m is the number of fuzzy partitions of Δe_N (*i.e., m*= 5), and K is a positive constant that will bring appropriate variation in β. The difference between conventional (FPDC) and proposed (NFST-FPDC) controllers is that the FPDC uses only G_u to generate its output (*i.e.*, $u = G_u u_N$), whereas the output of NFST-FPDC is obtained by using the effective SF, *i.e.*, βG_u, as shown in Fig. 4. Unlike fuzzy based self-tuning scheme, which requires expert's defined fuzzy self-tuning rules, here β is computed on-line by a single model independent non-fuzzy relation.

In place of single controller as shown in Fig. 4, in crane control we use dual controllers, one for position and another for angle control. The feedback signals from the crane act as the input variables of FPDC and NFST-FPDC as shown in the Fig. 5.

The same NFST-FPDC shown in Fig. 5 can be used as FPDC by eliminating the gain modifier β. There are two similar fuzzy logic controllers, which work separately with cart position and sway angle. The position controller and angle controller, which deal separately with the cart position and swing angle, drive the overhead crane. In this design, the position error (e) and change of position error (Δe) are selected as the input linguistic variables of fuzzy position controller. The input linguistic variables of fuzzy angle controller are selected as the swing angle error (e_θ) and its derivative Δe_θ.

Control surfaces (e and Δe versus u) of FPDC and NFST-FPDC are depicted in Fig. 6 and Fig. 7 respectively. After a careful inspection of the two surfaces it can be realized that the control surface of the proposed NFST-FPDC is more non-linear in nature but smooth than that of FPDC. In practical implementation the smoothness of the control surface is highly desirable for the limited speed of the actuator and to avoid the chattering problem.

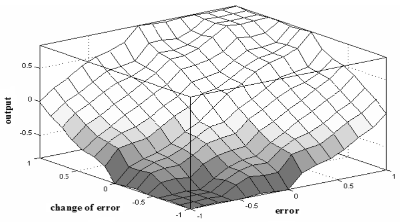

Fig. 6. Control surface of FPDC

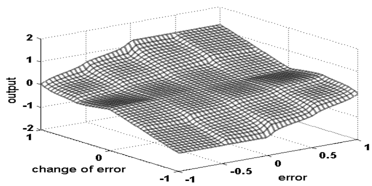

Fig. 7. Control surface of NFST-FPDC

In our design for crane swing control, the left swing of the load is considered as positive swing, while the right swing of the load is negative swing. The output of the FPDC for position and swing angle control are u_P and u_θ respectively. Thus, the actual control action to drive the cart is defined as: $u=u_P+u_\theta$. For the overhead crane control using NFST-FPDC, we incorporate a self-tuning scheme through an online gain modifier β determined by the relation $\beta = K[1/m + |\Delta e_N|]$ as shown in Fig. 5. The controller output u of FPDC and NFST-FPDC is used to drive the DC motor of the overhead crane system. Fig. 8 shows the MFs of e, Δe and u_P, whereas the MFs of e_θ, Δe_θ and u_θ are represented by Fig. 9. Error (e) due to position and error (e_θ) due to angle are obtained respectively from the cart position encoder and swing angle encoder. The ranges of input-output variables for position controller are [-1, +1] and [-20°, +20°] for angle controller.

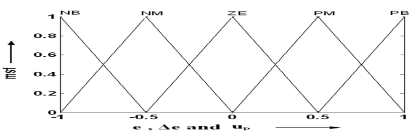

Fig. 8. MFs of e, Δe and u_p

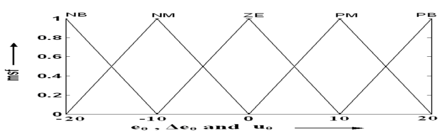

Fig. 9. MFs of e_θ, Δe_θ and u_θ

Table 1. Fuzzy rules for computation of position controller output

Δe \ e	NB	NM	ZE	PM	PB
NB	NB	NB	NB	NM	ZE
NM	NB	NB	NM	ZE	PM
ZE	NB	NM	ZE	PM	PB
PM	NM	ZE	PM	PB	PB
PB	ZE	PM	PB	PB	PB

Table 2. Fuzzy rules for computation of angle controller output

Δe_θ / e_θ	NB	NM	ZE	PM	PB
NB	PB	PB	PB	PM	ZE
NM	PB	PB	PM	ZE	NM
ZE	PB	PM	ZE	NM	NB
PM	PM	ZE	NM	NB	NB
PB	ZE	NM	NB	NB	NB

Each of the position and angle controllers consists of only 25 fuzzy rules as shown in Table 1 and Table 2 respectively. The proposed dual controller structure for crane control divides the input antecedents of fuzzy rules into two parts. Hence, both position controller and angle controller have only $i/2$ fuzzy antecedents, where 'i' is the number of input linguistic variables, here $i=4$. If each input variable has 'n' linguistic terms, here $n=5$, then the possible control rules required for our scheme is $2*n^{i/2}$ =50. Thus the total number of rules for FPDC and NFST-FPDC in the crane control scheme are greatly reduced compared to traditional fuzzy control schemes, which may need n^i, *i.e.,* $5^4=625$ rules.

4 Results

The proposed self-tuning scheme is tested on an overhead crane (Fig. 1) with sinusoidal and step input with amplitude of 0.3m. The controller output u of FPDC and NFST-FPDC separately applied to the overhead crane to control the crane position as well as swing angle of the load attached. The NFST-FPDC outperforms the FPDC as shown in Fig. 10 to Fig. 17 under various inputs. Real-time experiments on the overhead crane illustrate the advantages of proposed non-fuzzy self-tuning scheme. From Fig. 11 and Fig. 15, we observed negligible deviation in trolley position from the set point value. From Table 3, we find that the different performance parameters such as IAE, ITAE, and ISE are reduced by a large percentage when controlled by NFST-FPDC compared to FPDC. Figs. 13 and 17 shows that the load swing is minimum, especially in case of step input the swing angle approaches to almost zero for our proposed scheme. We also study the system with conventional controller and found that the load sway is not smooth for different inputs, which is one of the most desirable parameters for overhead crane control in industry. Thus, the above study reveals that the proposed self-tuning scheme for fuzzy controller can fix the over-head crane in its desired position with negligible sway angle.

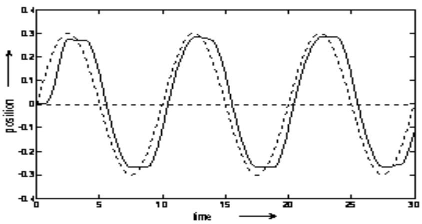

Fig. 10. Crane position control for sine input using FPDC (dotted lines – reference crane position and solid lines – actual crane position)

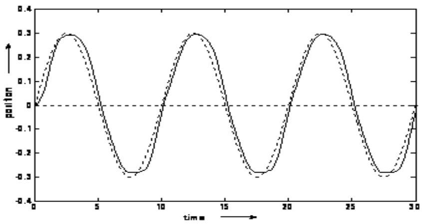

Fig. 11. Crane position control for sine input using NFST-FPDC (dotted lines – reference crane position and solid lines – actual crane position)

Table 3. Performance analysis for the overhead crane control

Reference Input	FLC	IAE	ITAE	ISE
Sine (amplitude 0.3)	FPDC	32.6416	799.2207	2.8917
	NFST-FPDC	9.8239	147.4995	0.4209
Step (amplitude 0.3)	FPDC	7.5129	75.5667	0.6952
	NFST-FPDC	2.1929	3.9660	0.3458

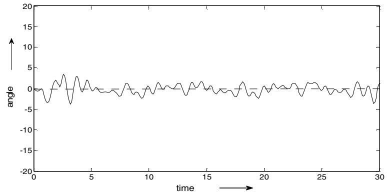

Fig. 12. Overhead crane swing angle control for sine input with FPDC

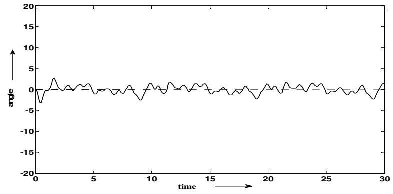

Fig. 13. Overhead crane swing angle control for sine input with NFST-FPDC

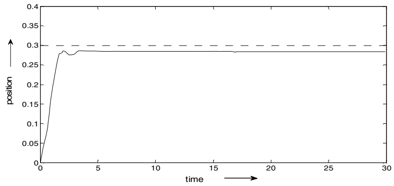

Fig. 14. Overhead crane position control for step input with FPDC (dotted lines – reference crane position and solid lines – actual crane position)

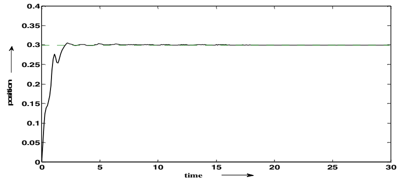

Fig. 15. Overhead crane position control for step input with NFST-FPDC (dotted lines – reference crane position and solid lines – actual position)

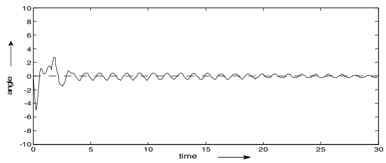

Fig. 16. Overhead crane swing angle control for step input with FPDC

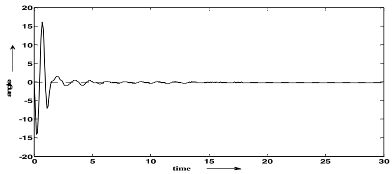

Fig. 17. Overhead crane swing angle control for step input with NFST-FPDC

5 Conclusion

In this paper, we proposed a simple self-tuning scheme for PD-type FLCs. Here, the controller gain (output SF) has been updated on-line through a gain modifying parameter β defined on the change of error (Δe) and its number of fuzzy partitions. Our proposed NFST-FPDC exhibited effective and improved performance compared to its conventional fuzzy counterpart. The proposed twin control scheme for overhead crane reduces the computational complexity and is very easy to understand. By applying the proposed self-tuning method and dual control scheme the load swing angle of the crane comes to a minimum. Experimental results verified that the proposed NFST-FPDC not only positioned the trolley in the desired location, it also significantly reduced the load swing during movement.

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