Design of a Fuzzy Controller: Some Experience

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Abstract**—**This paper describes the design and implementation of the fuzzy controller for an overhead crane model. A model used in this project was a laboratory model of the gantry cranes commonly seen in dockyards and factories. The fuzzy controller is used for suppressing load swing while positioning the trolley of an overhead crane. Simulation and experimental results are included to verify the validity of the controller developed. Further discussions on the utilisation of this laboratory model is provided.

Keywords—Fuzzy controller; overhead crane; laboratory model.

I. Introduction

Fuzzy logic, first introduced by Lotfi A. Zadeh in 1965 [1], is a form of logic which is much closer to human thinking and a natural language than traditional binary logic. Fuzzy logic provides an effective means of capturing the approximate, inexact nature of the real world. Since the late 1980s, control has become the area to which fuzzy systems are most widely applied today. This wide and diverse range of successful applications of fuzzy technologies has been responsible for the increasing interest in the subject area [2]. In the 1090s, fuzzy logic issues have been introduced to the electrical engineering curriculum in tertiary institutions [3], [4]. This paper presents some experience obtained through the introduction of fuzzy logic control in the final year Honours projects at the University of Tasmania, Australia. An overhead crane laboratory model is used as an example.

The problem with the overhead crane system is moving a load from an initial position to a specified final one with minimal pendulum-like swing of a load with uncertainty in mass and chain length. Crane operations have been successfully performed in traditional installations which are totally reliant on the skill of human operators without having any quantitative knowledge of the underlying dynamics. It is an example where fuzzy control may be applied to obtain a controller which can cope well with non-linearity, and is more robust to external disturbances and parameter variations. Through control of this model students learn to apply fuzzy thinking to solve engineering problems. It can also serve as an object for studying other techniques in relevance to fuzzy control applications.

II. Physical Description of the Plant

A simple two-degree-of-freedom controlled model of the overhead crane system is used. It consists of a trolley, which can be moved along tracks carved out from the wooden base of the model. The trolley position is controlled using a dc motor, connected to a pulley system. A pendulum in the form of a metal rod is suspended from the centre of the trolley and imitates the cable and load of an actual crane as shown in Fig. 1. The sensing potentiometers provide feedback signals to a computer via a PC30 card. The PC30 card performs the analogue-to-digital conversion of the input signals from the potentiometers to the computer. It also carries out the digital-to-analogue conversion which is necessary to provide the analogue control voltage signal for the dc motor via its drive circuitry. The position of the trolley and the load swing angle are measured using the attached rotary potentiometers. A reasonable accuracy is required in the measurement of the analogue input signals from the potentiometers. To achieve this, a simple circuit was designed to equip the potentiometer circuits with attached voltage regulators which would provide steady reference voltage for the potentiometers. The position-sensing potentiometer was connected such that it would give a voltage range of 0 to 5V as the trolley moved from one extreme end of the track to the other. The angle-sensing potentiometers were connected to give a centre voltage of 2.5V when the pendulum is at its rest position. Due to the phisical construction of the crane model, and in particular its trolley, the maximum amplitude of swing was limited to ±45°.

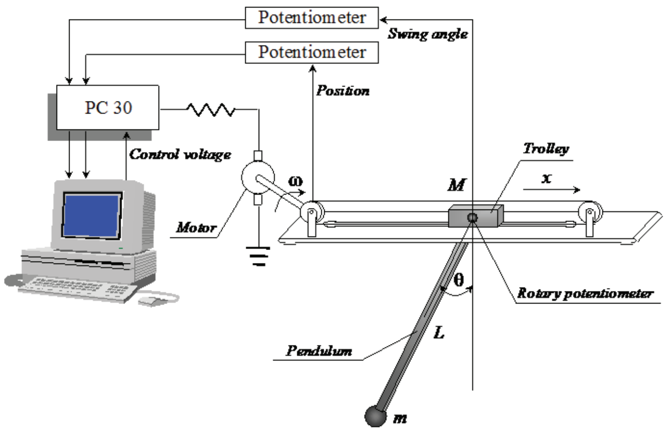

Fig. 1. Overhead crane model.

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The control goal is to move the trolley and the mass underneath from an initial horizontal position to a final one as fast as possible while suppressing the load swinging. This model is well known and used in many laboratories. The second equation of Lagrange is applied to find the crane dynamics. The horizontal position of the trolley, the velocity of the trolley, the angle of the chain, the angular velocity of the chain, and the force exerted by the drive onto the trolley are denoted by x_1, x_2, x_3, x_4 and f, respectively. The plant state equation obtained is a non-linear one which can then be written as

$$\dot{x}_1 = x_2,\ \ \dot{x}_2 = -\Phi \frac{L}{\cos x_3} - g \tan x_3,\ \ \dot{x}_3 = x_4,\ \ \dot{x}_4 = \Phi, \qquad (1)$$

with $\Phi = -\dfrac{g(M+m)\sin x_3 + (f + Lmx_4^2 \sin x_3)\cos x_3}{L(M + m\sin^2 x_3)}$

and $f = K_t \dfrac{u - K_b\, x_2/\rho}{R\rho}$,

where g is the gravitational acceleration, M is the trolley mass, ρ is the trolley motor drum radius, and K_t, K_b and R are the motor torque constant, back emf constant and armature resistance, respectively. The load mass m and the chain length L are the changing parameters of the crane system. The motor voltage u is used to control both the trolley position and the load mass. In order to demonstrate the capability of the fuzzy control system to suppress the load swinging due to any disturbance deviations of the swing angle, the non-linear state equations are used to describe the crane system dynamics instead of the linearized ones.

III. Fuzzy Logic Controller Design

The control goal can be achieved by conventional methods (cascade controller, pole placement, optimal control, etc.). However, a skilful operator is also perfectly capable of accomplishing the task. In this project the students learn how to adapt the human experience to design the controller using fuzzy logic.

Dealing with some uncertainty about the load mass or the chain length, an operator should control the motor voltage coarsely to move the trolley to a specified position and finely to reduce the load swing. In other words, because the swing of the load is to be kept minimal throughout the motion of the trolley, ie. the swing should be minimal irrespective of the trolley position, the position of the trolley and the swing of the load are controlled using two separate fuzzy control units. The position fuzzy controller (XFC), consequently, depends on the position error e and the past value u_1 of the controller output u. Then, the output v of the XFC and the swing angle θ are used to adjust the controller output through the swing fuzzy controller (SFC). Fig. 2 shows the overall structure used for the control of the overhead crane. These fuzzy controllers are cascaded with the output the XFC fed into the SFC. As the swing of the load is dependent on the acceleration of the trolley, the output of the SFC gives the change δu of the control voltage u to the system. The control signal u to the system is obtained as by a PI-type fuzzy logic controller [5]:

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$$u(k) = u(k-1) + \delta u \qquad (2)$$

A delay voltage $u_1 = u(k-1)$ is used as the input to the XFC instead of the current system control value to reduce the acceleration of the trolley and thus, to minimise the load swing. The first step for designing a fuzzy controller is to fuzzify the controller inputs and outputs. These variables are described by linguistic labels NB, NM, NS, ZE, PS, PM and PB which mean negative big, negative medium, negative small, zero, positive small, positive medium and positive big, respectively. The problem is how to choose the corresponding membership functions for each label of the inputs (position error e, delay voltage u_1, SFC input v, and swing angle θ) and outputs (XFC output v and control voltage change δu).

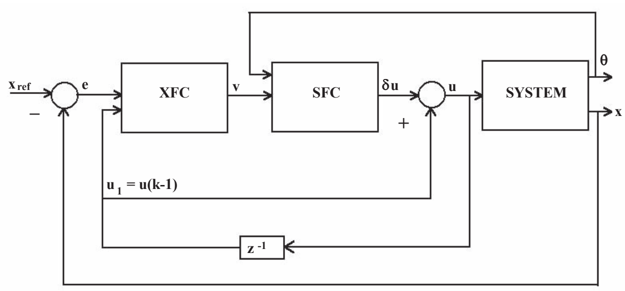

Fig. 2. Fuzzy logic controller for the crane system.

A proposed choice of membership functions are shown in Fig. 3. The singletons are used for the output membership functions because of its computational efficiency in a simple inference method. Then fuzzy rules are written as a representation of human operations to control the trolley and the load underneath. Following typical instructions of an operator for the control task, a fuzzy rule can be expressed like

- IF the position error is positive big

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AND the delay voltage is negative big

THEN the position controller output is positive big

- IF the swing angle is positive medium

  AND the position controller output is positive small

  THEN the control voltage change is positive medium

A proposed set of fuzzy rules for the XFC and SFC are presented in Tables 1(*a*) and 1(*b*). They are developed in MATLAB Fuzzy Logic Toolbox. The crane dynamics is represented by the fourth order Runge-Kutta integration algorithm for the non-linear state Eq. (1).

Table 1(*a*). Fuzzy rules of XFC

XFC *e*	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	PS	PM	PB	PB	PB	PB
NM	NS	ZE	PS	PM	PM	PM	PB
NS	NM	NS	ZE	PS	PS	PM	PB
ZE	NB	NM	NS	ZE	PS	PB	PB
PS	NB	NM	NS	NS	ZE	PS	PM
PM	NB	NM	NM	NM	NS	ZE	PS
PB	NB	NB	NB	NB	NM	NS	ZE

Table 1(*b*). Fuzzy rules of SFC

SFC θ v	NB	NM	ZE	PM	PB
NB	NB	NB	NB	NM	NS
NM	NB	NM	NM	NS	ZE
NS	NB	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PS	NS	ZE	PS	PM	PB
PM	ZE	PS	PM	PM	PB
PB	PS	PM	PB	PB	PB

IV. Simulation and Experimental Results

The numerical parameters of the overhead crane model are given in the Table 2. MATLAB Fuzzy Logic Tool Box provides facilities for debugging, analysing, and fine tuning the membership functions and fuzzy rules to improve control quality. The position and swing responses obtained by simulation are shown in Fig. 4(*a*) and 4(*b*) (dotted lines). A reference position for the trolley is achieved after a settling time of about 3 seconds with a maximal swing less than 5 degrees.

Table 2. Crane model parameters

Chain length, *m*	0.5
Trolley mass, *kg*	1
Load mass, *kg*	0.25
Motor torque constant, *Nm/A*	0.0066
Motor back emf constant, *V/rad/s*	0.0066
Motor armature resistance, *ohm*	0.67
Trolley motor drum radius, *m*	0.01
Gravitational acceleration, m/s^2	9.81

The crane model is driven by a 57W DC-motor supplied with a Pulse-Width Modulation (PWM) bridge. A rotary potentiometer connected to a shaft to which the pendulum rod is connected, is used to obtain a measurement of the pendulum swing angle. The trolley position is measured by using another rotary potentiometer, mounted on the motor shaft. The analogue readings are converted to digital values with an ADC. The membership functions and fuzzy-rule-base for the XFC and SFC are realized using C++ code generated from MATLAB. The host computer, performs on-line processing of the appropriate crisp output control voltage. This voltage is fed to the PWM circuit for the dc motor through a DAC. The experimental position and swing responses are as shown in Fig. 4(*a*) and 4(*b*) (solid lines) to compare with the simulation results (dotted lines). The results obtained coincide well with those obtained from simulation. The experimental responses with proportional (P) and proportional-integral (PI) controllers are shown in Fig. 5 to confirm the fuzzy logic controller advantage in reducing load swing. The influences of external disturbances on the load swing and variations of the load mass and chain length are investigated. Fig. 6 depicts the swing responses of the crane system with an initial swing angle of 36 degrees and different load masses. The results obtained demonstrate the system insensitivity with respect to any variations.

V. Conclusions

Some experiences in applying fuzzy logic to control a laboratory overhead crane model have been reported. The design procedure, simulation and experimental results are included. Fuzzy control has the advantages over some conventional methods in suppressing the crane load swing and increasing robustness to disturbances and parameter variations. The possibility of using this laboratory model to study fuzzy logic and relevant techniques in tertiary education environments is considered.

Acknowledgment

The author wishes to thank L.P. Chee, T.H. Ting and Q.P. Ha, former students of the University of Tasmania, whose desire for new knowledge brought this project into life.

References

1] L. Zadeh, "Fuzzy sets", *Informat. Contr.*, vol.8, pp.338-353, 1965.

[2] D.G. Schwartz, G.J. Klir, H.W. Lewis III, and Y. Ezawa, "Application of fuzzy sets and approximate reasoning", *Proc. of the IEEE*, vol. 82, no. 4, pp. 482-497, 1994.

[3] Q.P. Ha and M. Negnevitsky, "New trends in control theory and their reflection in elctrical engineering education", in *Proc. of the PRCEEE'95*, Victoria, Australia (February 23-24, 1995), pp. 109-112, 1995.

[4] M. Negnevitsky, "Artificial Intelligence: A Guide to Intelligent Systems", 3rd edn, Addison Wesley, Harlow, England, 2011, 504 p.

[5] L. Reznik, "Fuzzy Controllers", Newnes, Oxford, 1997.

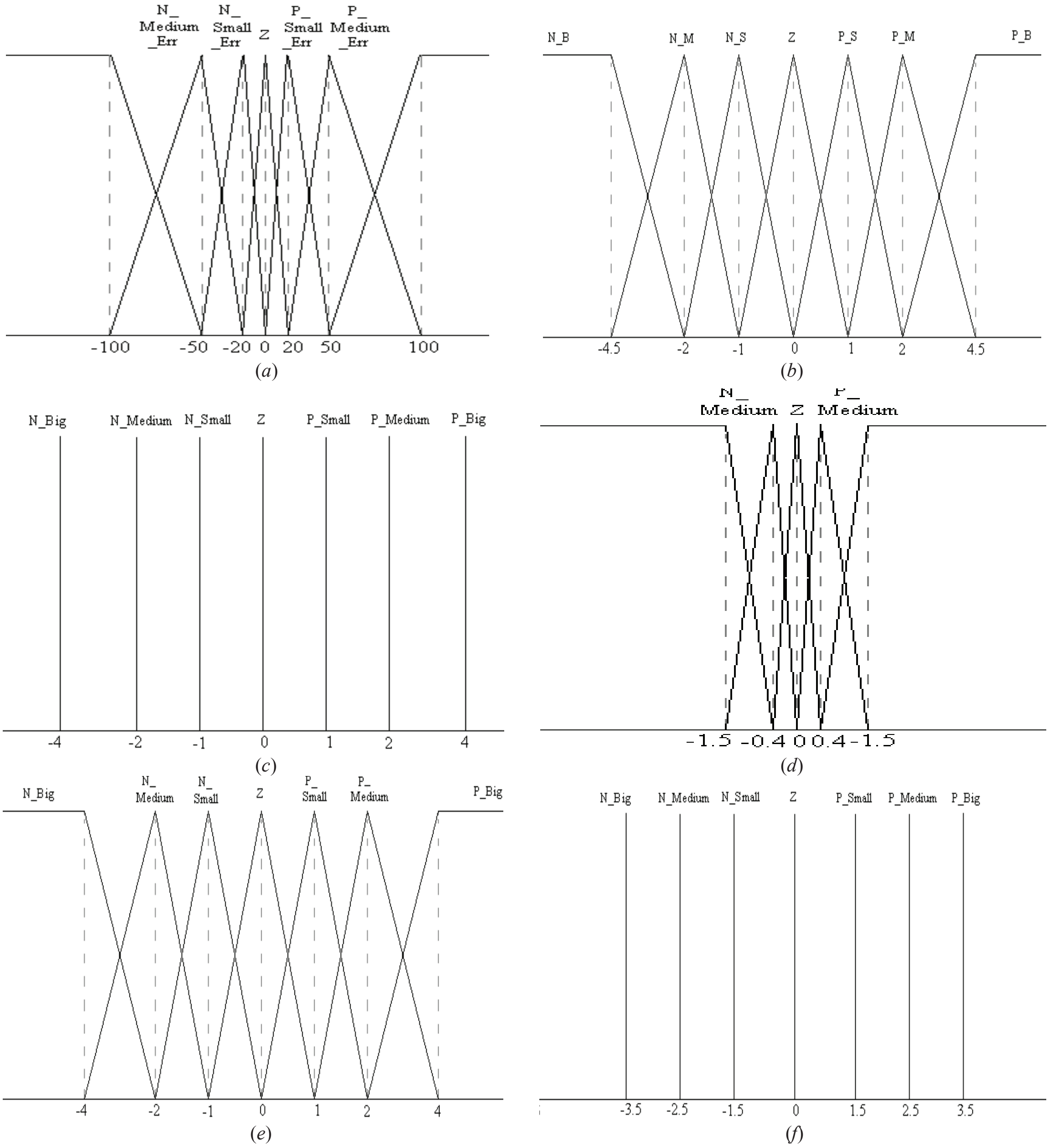

Fig. 3. Membership functions for (*a*) trolley position error, (*b*) delay voltage, (*c*) XFC voltage output, (*d*) swing angle, (*e*) SFC voltage input, and (*f*) control voltage change.

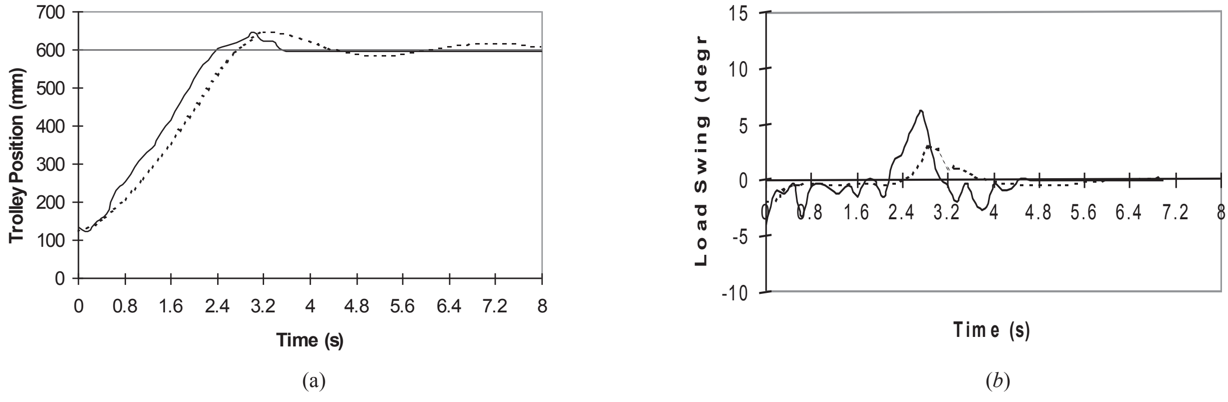

Fig. 4. Simulation (dotted lines) and experimental (solid lines) (*a*) position, and (*b*) swing responses

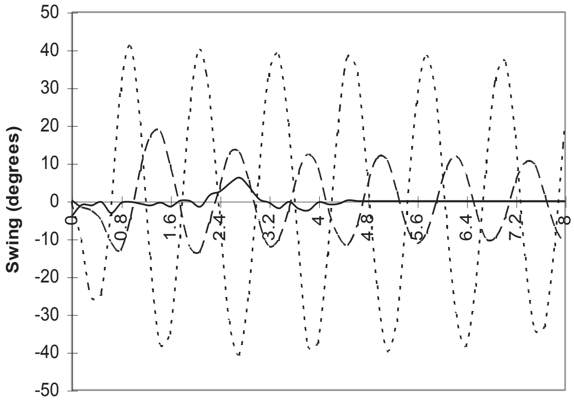

Fig. 5. Swing responses with FLC (solid line), P (dotted line), and PI (slashed line) controllers.

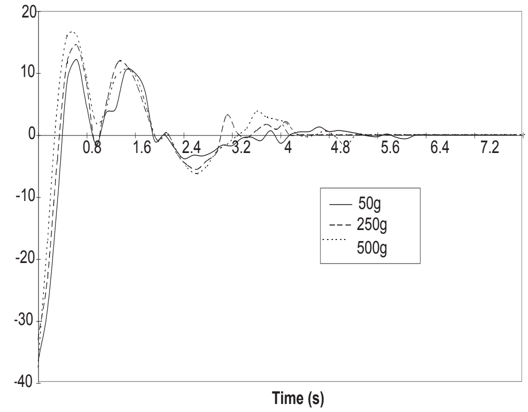

Fig. 6. Swing responses with an initial angle deviation and different masses (50, 250, 500 *g*).