

Experimental Fuzzy Control for Tower Crane

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ABSTRACT

Tower crane is a popular model in industry. It helps to move constructing material from lower place to higher place and vice versa. Due to its importance in real application, educational experimental models are necessary to be built in laboratory for researching and training students. In this paper, an experimental platform of tower crane system is presented for testing algorithms. For a real model with un-known system parameters and MIMO under-actuated structure, intelligent control is a suitable selection. Fuzzy control is a primary algorithm in training intelligent control for students. Thence, an 81-rule fuzzy controller is designed and used to control position and anti-sway for this model. This idea is inspired from fuzzy control for SIMO system, such as inverted pendulum. Our controller gives good results under kinds of external effects. The quality of controlling is proved to be better under fuzzy controller than under no-control. Therefore, survey in this paper can be used to train students in fuzzy control structure for MIMO under-actuated system.

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1. Introduction

Tower crane (TC) is a MIMO system (Figure 1). It helps to move constructing material from lower place to higher place and vice versa. Among variety kinds of crane, such as gantry crane, 3D crane... [1], TC can work with higher position and a flexible operation. Thence, it is popularly used in both transportation and construction when gantry crane and 3D crane are only used in transportation.



Figure 1. Real TC in construction [1]

With this model, not only the position of load is controlled but also the vibration of TC must be decreased. Besides, the effect of wind or different weight of load can affect the system. Therefore, controller should be designed to reduce these effects. In laboratory, small real models are created for testing algorithms. As in Figure 2, condition of TC by changing length of cable, position of trolley, height of tower, weight of load... for survey in different experimental situations. In [2], an anti-sway PID controller is utilized and it works well in both simulation and experiment. However, PID is a SISO structure. Therefore, in that study, two PID controllers are combined to solve problem. In [3], an open-loop controller is suggested and proved to work well in simulation. But, this controller work in a fixed situation by the calibration of designer. It is not designed to work under external effect or different condition due to lack of feedback signal.

Fuzzy control is designed due to experience and knowledge of experts on system. Thence, the dynamic equations of system can be neglected. Also, this algorithm is suitable for complex system with different numbers of inputs and outputs (SIMO, SISO, MIMO...). In [4], a T-S fuzzy model imitates TC for developing a fuzzy observer. In that study, fuzzy algorithm is used to create observer for supporting a controller. In [5], a structure of fuzzy algorithm is used to create a controller. In this controller, each variable, which is related to trolley and load, is controlled by a small fuzzy controller. Outputs of these fuzzy controllers are added to get a control signal for motor of trolley. Similarly, we have the control signal for controlling rotation of tower. However, in that study, each variable is assumed to be independent from other variables. Actually, there are strict relations between variables. Thence, a more complex fuzzy controller which includes relations between variables through rule-table is a contribution of our this paper.

In [6], an adaptive fuzzy controller is presented. In that study, nonlinear functions in dynamic equations of TC are imitated by fuzzy blocks. An online updating rule for these fuzzy blocks tracks the nonlinear functions through time. In [6], nonlinear functions should be known or at least, operating range of these functions have to be known. In [7], fuzzy algorithm supports changing value of sliding surfaces and parameters that affect "chattering". The main control rule in that contribution is still sliding mode control. This method requires strictly dynamic equations and exact system parameters of TC. There is no experimental result in [6], [7]. In this our paper, fuzzy rules are presented that are strictly based on knowledge of experts. We do not depend on system structure. Our direction is totally different from [6], [7] and we also present experimental results.

In [8], [9], [13], four fuzzy blocks are utilized. Two blocks are used to control position of trolley and angle of load in one direction. Output signals of these blocks are added to obtain control signal for one DC motor. Two other blocks are used to control the angle of jib and angle of load in other direction. Each block includes of $7 \times 7 = 49$ rules. In our paper, $9 \times 9 = 81$ rules are obtained for each fuzzy block [10]. Two fuzzy blocks are necessary to control trolley and jib, separately, together with angles of load. Though fuzzy controller in [8], [9], [13] are good through simulation and experiment, our fuzzy control method are different. Our contribution is a suggestion for controller designer of TC or related MIMO under-actuated models.

Although fuzzy algorithm is not new in controlling TC, different structures of fuzzy control and different table of rules create varieties of different fuzzy controllers. Thence, our contribution through this paper is presenting a 81-rule fuzzy rule for controlling TC. This opinion is inspired through controlling cart and pole [10]. This structure of fuzzy control is not applied in TC in any study before. Through experimental results, this fuzzy control method is proved to work well for TC in position control and anti-sway for load. Moreover, for the first time in Vietnam, a hardware platform, which is presented in laboratory, is controlled well through fuzzy algorithm. Thence, this study is a reference for students to develop their own real model in researching.

2. Mechanical structure

Mathematical structure is presented in Figure 2 and Figure 3. A trolley can move horizontally on a jib. On trolley, a metal string is fixed.

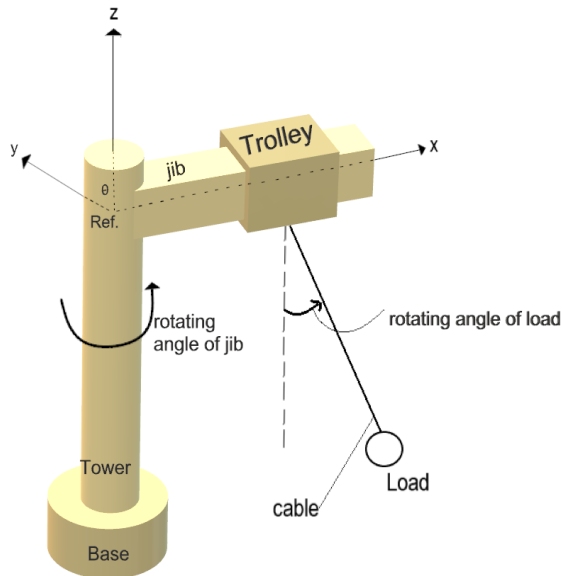


Figure 2. Mathematical structure by down-view

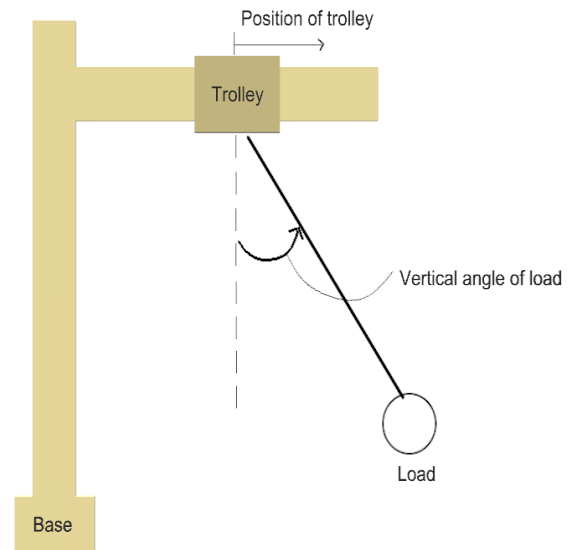


Figure 3. Mathematical structure by side-view

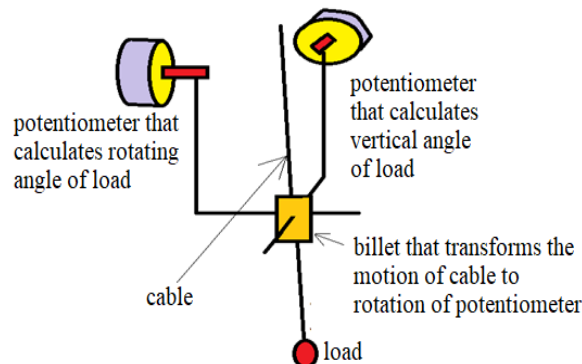


Figure 4. Structure of sensors that measures angles of load

At other side of metal string – the cable, a load is hanged. The jib can rotate around a vertical axis which is called tower. This tower is put on a solid heavy base. The rotation of jib and motion of trolley can move the load to suitable position. In real TC in transportation, length of cable can be changed to control the height of load. Good controller can move load to right position fast and the fluctuation of load is decreased remarkably. That is the purpose of researching control method of this model.

Due to this mathematical structure, a real mechanical structure of TC is created as in Figure 5. On jib, a DC motor is fixed. This motor controls the position of trolley by a belt. On this motor, an encoder is used to calculate the position of the trolley. A cable is connected to trolley. At other side of the cable, there is a heavy load which imitates the material TC transfers in real environment. The length of cable can be calibrated to change the condition of experiment. Another DC motor controls the rotating angle of jib. This angle is calculated by an encoder on this second motor. Rotating and vertical angles of load are calculated by using structure of resistors as in Figure 4.

In Figure 6, sensors including of encoders and potentiometers send electronic signals to DSP TMS320F28335. This DSP board is used as controller in this experiment. The control signals are calculated by embedded program. The control signals are transferred to H-bridges to control DC motors on TC.

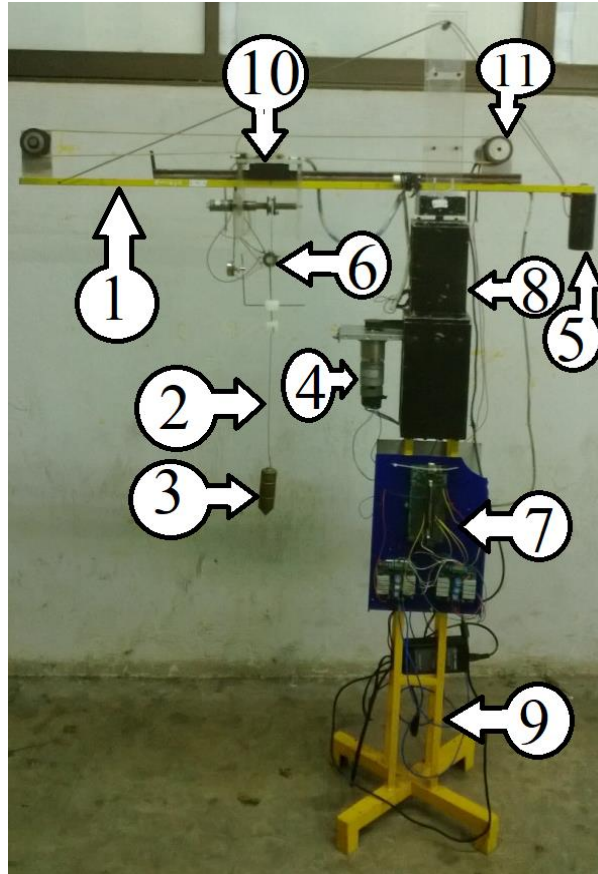


Figure 5. Experimental TC model in laboratory

- 1- Jib
- 2- Cable
- 3- Load
- 4- DC-motor that controls jib
- 5- Balancing part for jib
- 6- Resistant structure to calculate angles of load
- 7- Controlling board
- 8- Rotating tower
- 9- Base
- 10- Trolley
- 11- DC motor that controls trolley

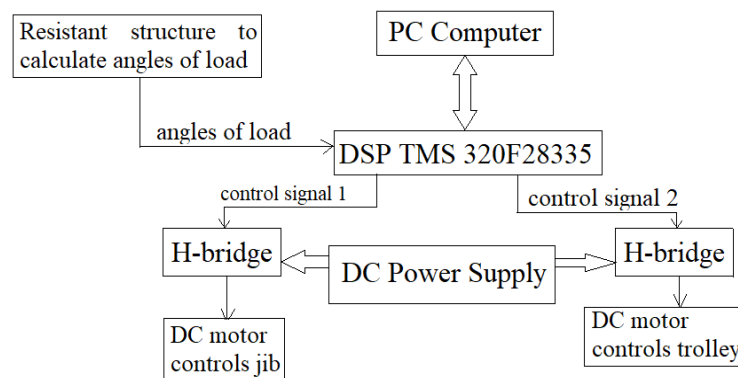


Figure 6. Electrical structure of TC model

3. Fuzzy controller

We can regard TC to be combined by two separate SIMO systems:

- a. System 1: control signal is voltage on motor that controls the angle of jib; variables are angle of jib and rotating angle of load (in Figure 2).
- b. System 2: control signal is voltage on motor that controls position of trolley; variables are position of trolley and vertical angle of load (in Figure 3).

Actually, these two systems affect one another. However, we assume they are independent to one another.

Controlling trolley and load is equivalent to control a gantry crane. This model is close to inverted pendulum on cart (IP-C) if we regard the load is pendulum. The 81-rule fuzzy controller is applied for IP-C [10]. This structure is also registered for 2D crane –gantry crane in patent [11]. This kind of fuzzy structure is suitable for gantry crane and shown in studies [12]. Experimental model of gantry crane in that research is IP-C of Quanser. But, in that case, pendulum operates as load. We develop that idea of 2D crane for 3D crane (TC).

Two control inputs of TC are two voltages that are supplied to DC motors. Variables that need to be controlled are position of trolley, angle of jib, two angles of motion of load. Thence, TC is an under-actuated MIMO system. Fuzzy structure to control TC is proposed in Figure 7 to solve this problem. There are two fuzzy controllers to control separately position of trolley and angle of jib beside angles of load. So, each system can be controlled by a different fuzzy controller (Figure 7). From [10], an 81-rule fuzzy rule (Table 1 in Appendix) is presented for IP-C - a SIMO system. System 1 and 2 are also SIMO. Thence, we are inspired to apply these rules for creating two fuzzy controllers for TC.

In Figure 7, fuzzy controllers are designed to have suitable output that makes inputs to value “zero” (Table 1 in Appendix). Thence, position of trolley and angle of jib are controlled to track the expected reference signals. That supports the “position control” of fuzzy algorithm. Also, vertical and rotational angles of load are controlled to be “zero” when operating. That supports the “anti-sway” of fuzzy algorithm.

Inside fuzzy controller, the blocks are shown in Figure 8. The gains K_1, K_2, K_3, K_4, K_5 are weighing gains which correspondingly each input variables and the signal control. These gains are chosen by try-and-error test. In fuzzy block, the membership functions are shown in Figure 9 and Figure 10. The fuzzy law is shown in Table 1 (Appendix).

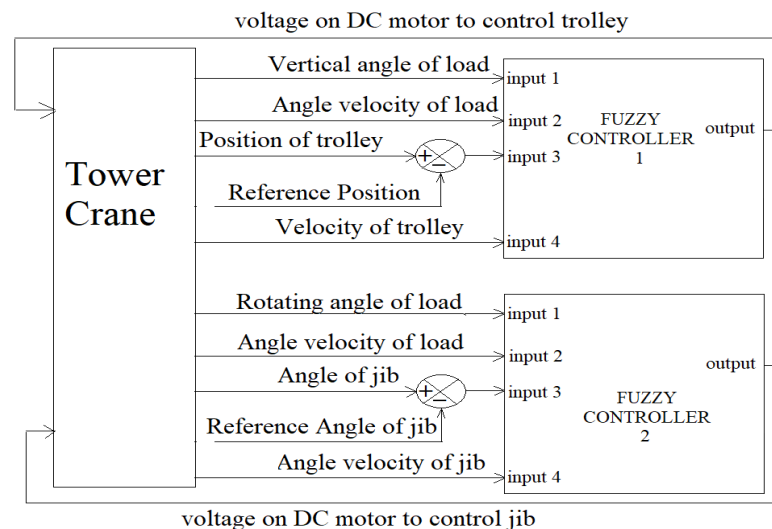


Figure 7. Control structure for TC

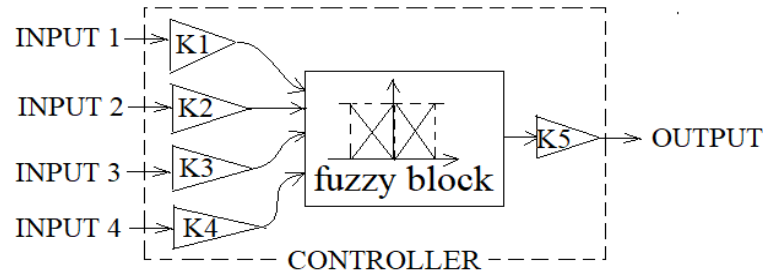


Figure 8. Structure of fuzzy controller 1 and 2

In controller 1, to control the position of trolley and the vertical angle of the load, a fuzzy algorithm is used to get suitable voltage on DC motor. The membership functions of input signals - position of trolley (cm), velocity of trolley (cm/s), vertical angle of load (degree), velocity of load (degree/s) are presented in Figure 9. Also, these membership functions are used for other input signals for controller 2. The input signals of controller 2 are angle of jib (degree), angle velocity of jib (degree/s), rotational angle of load (degree), velocity rotational angle of load (degree/s). We use an only “standardized” set of membership functions in Figure 9 for all inputs. The parameters K1, K2, ..., K5 of controllers 1 and 2 are calibrated through experiment.

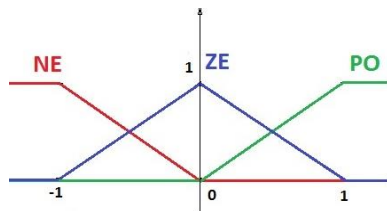


Figure 9. Membership functions of inputs 1, 2, 3, 4 if controller 1 and 2 in Figure 7

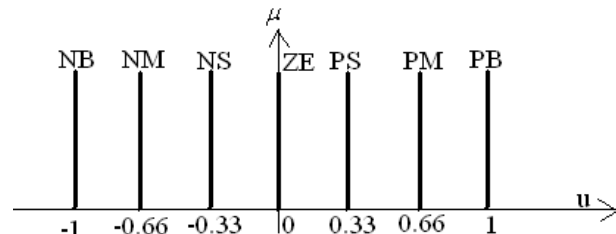


Figure 10. Membership functions of output signals

4. Experimental results

In experiment, expected reference values of angle of jib and position of trolley are “zero”. We propose 4 experiments.

- In experiment 1, an external force affects the load under no control signal at 4th second.
- In experiment 2, an external force affects the load under fuzzy controller at 4th second.
- In experiment 3, an external force affects the jib under fuzzy controller at 12th second.
- In experiment 4, an external force affects the trolley under fuzzy controller at 3.5th second.

Simulation results in experiments 1 and 2 are shown from Figure 11 to Figure 14. These figures are listed in two columns. In left column, responses of system in experiment 1 are shown and they are compared to those from experiment 2 in right column.

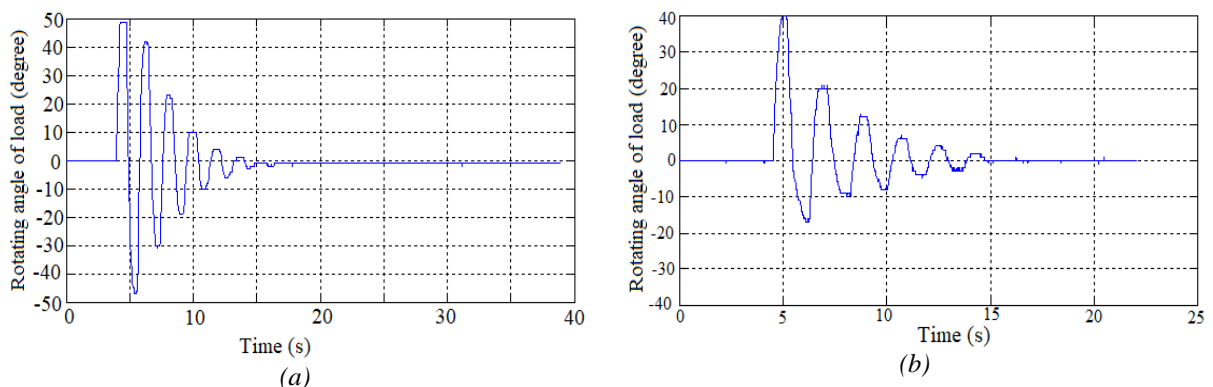


Figure 11. Rotating angle of load under no-control (degree): (a) in experiment 1; (b) in experiment 2

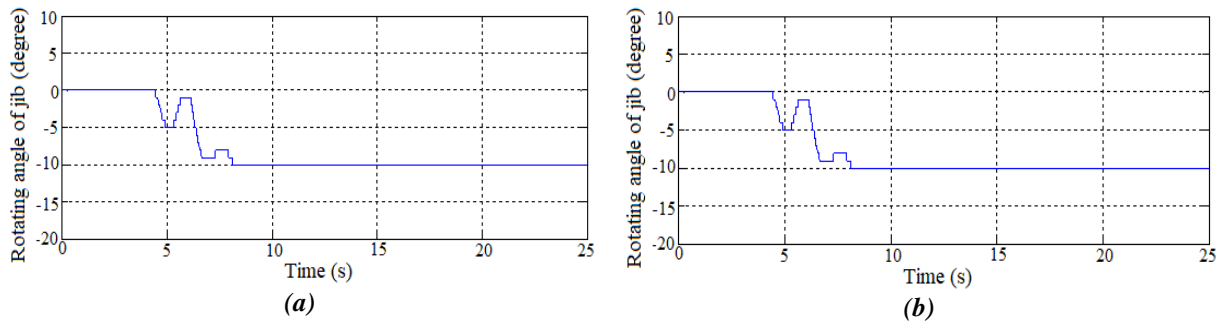


Figure 12. Rotating angle of jib (degree): (a) in experiment 1; (b) in experiment 2

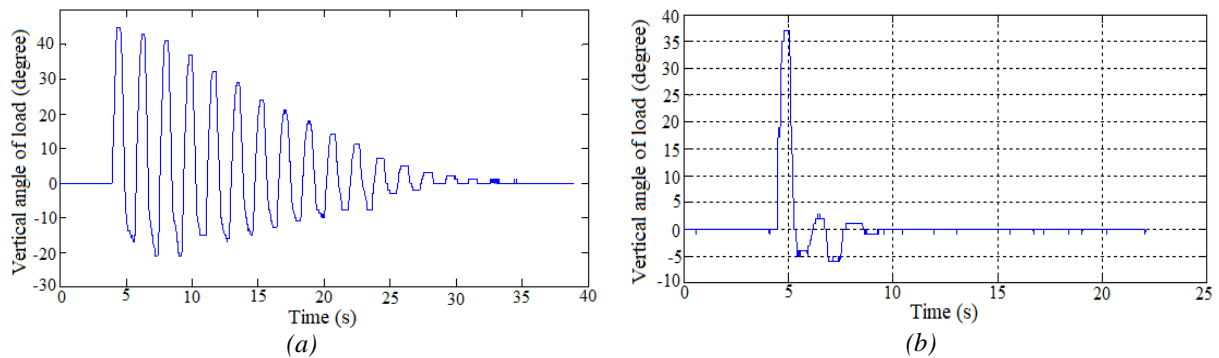


Figure 13. Vertical angle of load (degree): (a) in experiment 1; (b) in experiment 2

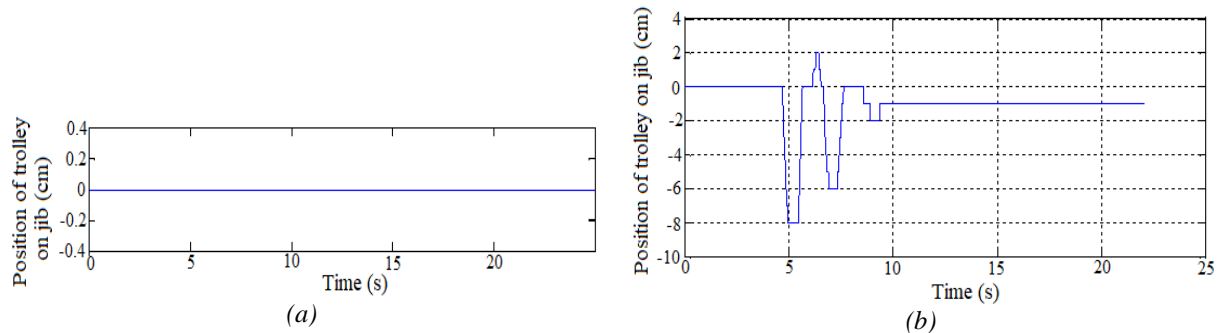


Figure 14. Position of trolley on jib under no-control (cm) : (a) in experiment 1; (b) in experiment 2

In experiment 1, when TC is being stable, at second 4, we affect an external force on the load. Then, TC fluctuates. Due to friction, this fluctuation will decrease by time. In Figure 11a, rotating angle of load takes 13s to be stable again under effect of friction. By using fuzzy controller, this variable moves to balancing position faster due to settling time is 11s in Figure 11b. Under controller, the fluctuation is kept smaller (40 degrees in Figure 11b instead of 50 degrees in Figure 11a). Vertical angle of load is decreased from 27s (Figure 13a) to 7s (Figure 13b). Also, the fluctuation of this variable is small under controller (36 degrees in Figure 13b and 43 degrees in Figure 13a). Thence, by using the fuzzy controller, the fluctuation of load is decreased and the settling time is also shorter. Rotating angle of jib in experiment 1 (Figure 12a) moves to new position 10 degrees and keeps balance. By using the controller, jib is kept at stable position (settling error is 1 degree) after being fluctuated in 4s in Figure 12b. Under no-controller, the trolley does not move when the load is affected due to friction (Figure 14a). Under fuzzy controller, trolley moves to balance position within 5s (Figure 14b) with settling error is 1cm. Thence, the fuzzy controller can keep the trolley at expected position with small settling error.

In experiment 2, the voltages on motors are shown in Figure 15. Voltage on motor that controls trolley needs 11s to be stable at -8V. After second 16, the friction force keeps trolley at one place even there is -8V on motor. The effect of jib is unremarkable and voltage on corresponding motor only

needs 5s to keep jib at expected position. When the jib is kept at exact place, no voltage is supplied to corresponding motor.

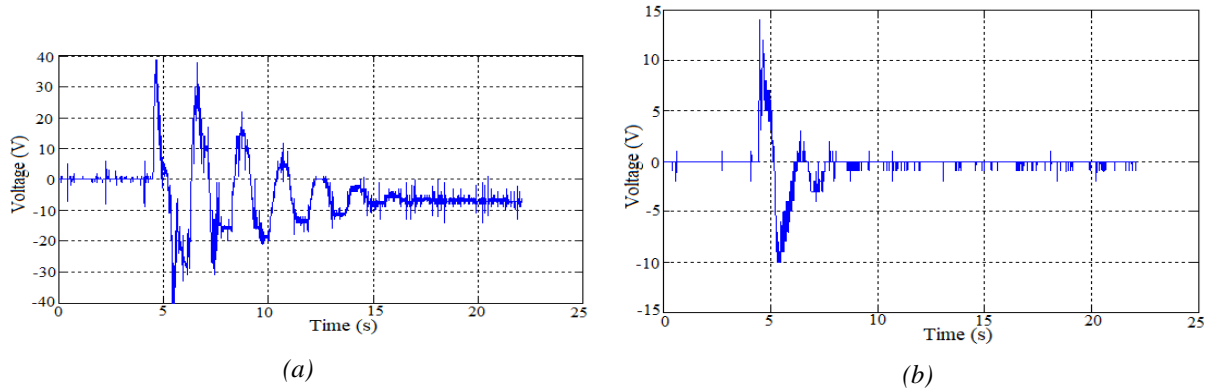


Figure 15. Voltage on motor in experiment 2: (a) which controls the trolley; (b) which controls the jib

In experiment 3, a separate survey of fuzzy controller 2 is obtained. In this experiment, only the jib and rotary angle of load are considered. Results are shown in Figure 16 and Figure 17.

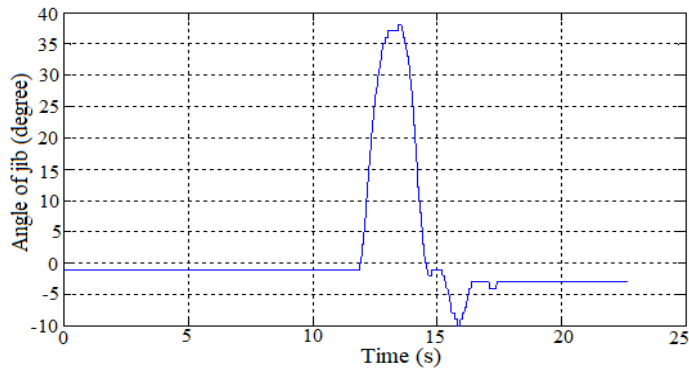


Figure 16. Angle of jib (degree) in experiment 3

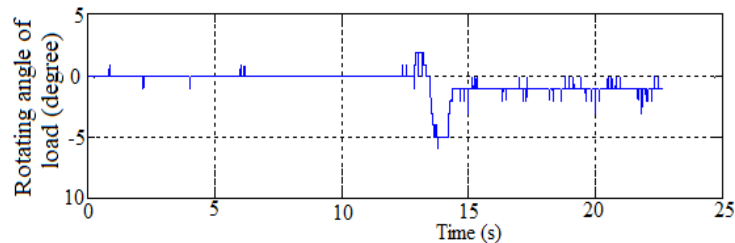


Figure 17. Rotating angle of load (degree) in experiment 3

The fuzzy controller 2 successfully controls these variables. However, there is settling error of angle of jib is about 3 degrees. The settling time is about 5s. The settling error of rotating angle of load is 1 degree. This settling error is created by the structure of billet of potentiometer. This structure has a hole on billet in Figure 4 and it causes the feedback error.

In experiment 3, a separated survey of fuzzy controller 1 is obtained. In this experiment, only the trolley and vertical angle of load are considered. Results are shown in Figure 18 and Figure 19. In these figures, fuzzy controller 1 controls trolley and vertical angle of load well. The settling time of position of trolley is 1s but the settling error is 1 degree. The friction force causes this problem because the control signal is not big enough to move the trolley to zero. Considering the vertical angle of load, the settling time is 4s and settling error is 1 degree. The cause of settling error is the structure of billet when connecting to potentiometers. It is similar to Figure 17.

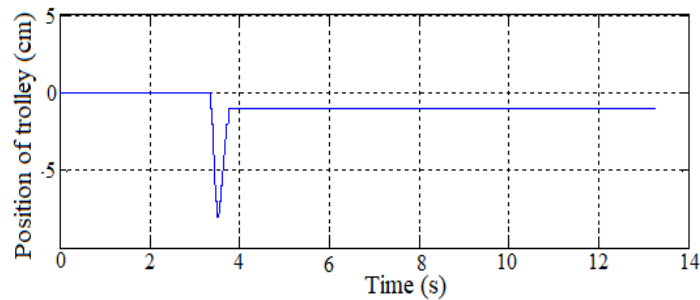


Figure 18. Position of trolley (cm) in experiment 4

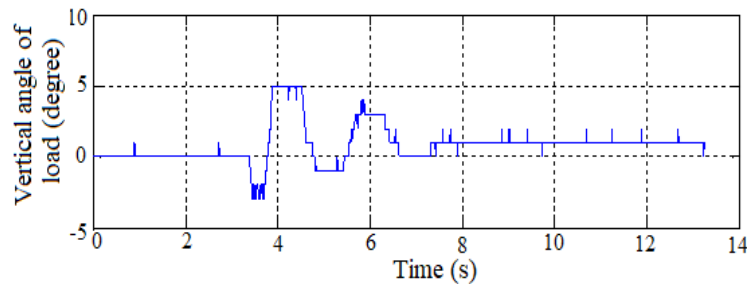


Figure 19. Vertical angle of load (degree) in experiment 4

In order to obtain suitable control parameters and simplify the process of calibration, we suggest these experiences of adjusting:

- The 81 rules in Table 1 are kept by us. But, in our opinion, in other real model, the rules can still be adjusted due to knowledge of engineers.

- Membership functions in Figure 9 and Figure 10 are in triangle form. The other forms, such as Gauss, trapezoid..., do not affect the quality of control. So, these characteristics should not be changed.

- In each controller in Figure 7, input i seems to be focused more in controlling if we increase value of K_i or decrease other K_j ($j \neq i$) (Figure 8). This focus can make settling time shorter and settling error smaller. But, an over value of K_i can also cause strong vibration of that input. This can cause system un-stable or longer settling time. A wrong calibration of one K_i can cause the useless calibration of other K_j ($j \neq i$). For example, we want the trolley to move fast to position „zero”. Thence, K_3 in Figure 8 of fuzzy controller 1 should be increased. This act makes quality of control is better for position of trolley while other variables seem to be a little worse. However, over-high value of K_3 makes trolley cannot be balanced at expected position but it moves left and right around „zero” point for long time before being unstable. Other example is controlling anti-sway of load. In that case, values of K_2 of fuzzy controller 1 and 2 should be adjusted.

5. Conclusions

In this paper, we present an experimental model of TC. Using this model, a structure of fuzzy controllers is used to control this system. Fuzzy algorithm is proved to work well in anti-sway for load, controlling trolley and jib. Anyway, through experiment, the billet, which is used in potentiometer structure, causes the error in measuring the angles. The friction force of trolley is other problem in mechanical hardware. Although hardware needs to be improved, the fuzzy controller is a solution for control this system.

Acknowledgments

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Appendix

Table 1. Fuzzy law [10]

No.	Input1	Input2	Input3	Input4	Output
1	NE	NE	PO	NE	NB
2	NE	NE	PO	ZE	NB
3	NE	NE	PO	PO	NM
4	NE	NE	ZE	NE	NB
5	NE	NE	ZE	ZE	NM
6	NE	NE	ZE	PO	NS
7	NE	NE	NE	NE	NM
8	NE	NE	NE	ZE	NS
9	NE	NE	NE	PO	ZE
10	NE	ZE	PO	NE	NB
11	NE	ZE	PO	ZE	NM
12	NE	ZE	PO	PO	NS
13	NE	ZE	ZE	NE	NM
14	NE	ZE	ZE	ZE	NS
15	NE	ZE	ZE	PO	ZE
16	NE	ZE	NE	NE	NS
17	NE	ZE	NE	ZE	ZE
18	NE	ZE	NE	PO	PS
19	NE	PO	PO	NE	NM
20	NE	PO	PO	ZE	NS
21	NE	PO	PO	PO	ZE
22	NE	PO	ZE	NE	NS
23	NE	PO	ZE	ZE	ZE
24	NE	PO	ZE	PO	PS
25	NE	PO	NE	NE	ZE
26	NE	PO	NE	ZE	PS
27	NE	PO	NE	PO	PM
28	ZE	NE	PO	NE	NB
29	ZE	NE	PO	ZE	NM
30	ZE	NE	PO	PO	NS
31	ZE	NE	ZE	NE	NM
32	ZE	NE	ZE	ZE	NS
33	ZE	NE	ZE	PO	ZE
34	ZE	NE	NE	NE	NS
35	ZE	NE	NE	ZE	ZE
36	ZE	NE	NE	PO	PS
37	ZE	ZE	PO	NE	NM
38	ZE	ZE	PO	ZE	NS
39	ZE	ZE	PO	PO	ZE
40	ZE	ZE	ZE	NE	NS
41	ZE	ZE	ZE	ZE	ZE
42	ZE	ZE	ZE	PO	PS
43	ZE	ZE	NE	NE	ZE
44	ZE	ZE	NE	ZE	PS
45	ZE	ZE	NE	PO	PS
46	ZE	PO	PO	NE	PM
47	ZE	PO	PO	ZE	NS
48	ZE	PO	PO	PO	PS
49	ZE	PO	ZE	NE	ZE
50	ZE	PO	ZE	ZE	PS
51	ZE	PO	ZE	PO	PM
52	ZE	PO	NE	NE	PS
53	ZE	PO	NE	ZE	PM
54	ZE	PO	NE	PO	PB
55	PO	NE	PO	NE	NM
56	PO	NE	PO	ZE	NS
57	PO	NE	PO	PO	ZE
58	PO	NE	ZE	NE	NS
59	PO	NE	ZE	ZE	ZE
60	PO	NE	ZE	PO	PS

61	PO	NE	NE	ZE	ZE
62	PO	NE	NE	ZE	PS
63	PO	NE	NE	PO	PM
64	PO	ZE	PO	NE	NS
65	PO	ZE	PO	ZE	ZE
66	PO	ZE	PO	PO	PS
67	PO	ZE	ZE	NE	ZE
68	PO	ZE	ZE	ZE	PS
69	PO	ZE	ZE	PO	PM
70	PO	ZE	NE	NE	PS
71	PO	ZE	NE	ZE	PM
72	PO	ZE	NE	PO	PB
73	PO	PO	PO	NE	ZE
74	PO	PO	PO	ZE	PS
75	PO	PO	PO	PO	PM
76	PO	PO	ZE	NE	PS
77	PO	PO	ZE	ZE	PM
78	PO	PO	ZE	PO	PB
79	PO	PO	NE	NE	PM
80	PO	PO	NE	ZE	PB
81	PO	PO	NE	PO	PB

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