PID CONTROL TO DECREASE FLUCTUATION OF LOAD FOR TOWER CRANE

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Abstract: Tower crane is a multiple-input and multiple-output **(**MIMO) under-actuated system which is popularly used in both goods tranfering and constructing. In operating process, the loads ,which are transferred by tower crane, such as goods, material,…, are fluctuated. Fluctuation of load takes part of decreasing performance in goods transferring. In this paper, we propose a structure of PID to control tower crane to avoid this fluctuation of load. Simulation and Experimental results and demonstrate the success of PID algorithm in this research.

Keywords: tower crane, fluctuation of load, PID control.

1. Introduction

Tower crane (TC) is a popular model in both laboratory and industry. It is a MIMO under-actuated system [1]. This model is developed from gantry crane (GC) which is similar to inverted pendulum on cart. In GC, the pendulum in this case is a string which is connected to a load. The cart in this case is the trolley. Purpose of controlling TC is controlling position for load in 3D space.

Fig. 1. Tower crane

A problem of controlling this model is the fluctuation of load. This phenomenon causes the waste of time when operating system. Moreover, in real operation, this phenomenon can also cause damage for the goods when transferring. Thence, the controller for TC not only moves the load fast to expected position but also terminate the fluctuation. In [2], a fuzzy controller is suggested. In that research, anti-fluctuation controller works well through both simulation and experiment. This algorithm is based on knowledge and experience of experts. Also, the structure of fuzzy algorithms is complicated. Thence, the time of calculation is remarkable. The weight of program is heavy. Linear algorithms, such as LQR and PID, are solutions if the fastness and simplicity of controller are considered. PID controller is the most popular controller in industry [3]. Its characteristics (simple structure, less parameters in controlling) make it suitable for calibration in real operation. PID controller is suggested in [4] for gantry crane. But, the order of crane in that study is lower than in TC. In this paper, we are inspired from PID structure in [4] to develop for TC. In this paper, we regard TC as two separated single-input multiple-output (SIMO) systems:

- Motor A that controls position of trolley and dimensional angle of load
- Motor B that controls angle of jib and rotational angle of load.

2. Dynamic Equations

Mathematical model of TC is shown in Fig. 2. Variables of system is listed in Tab. 1

Tab. 1. Variables of system

Variables	Description	Unit
$x=x_W$	Position of trolley	m
ϕ	Dimensional angle of load	rad
γ	Rotational angle of tower	rad
θ	Rotational angle of load	rad
F_x	Force on trolley	N
T_γ	Moment that affects the tower	Nm

Tab. 2. System paramaters

Parameters	Description	Unit
m	Mass of load	kg
M	Mass of trolley	kg
L	Length of string	m
K_{mx}	Motor coeficcient of motor A	
K_{my}	Motor coeficcient of motor B	

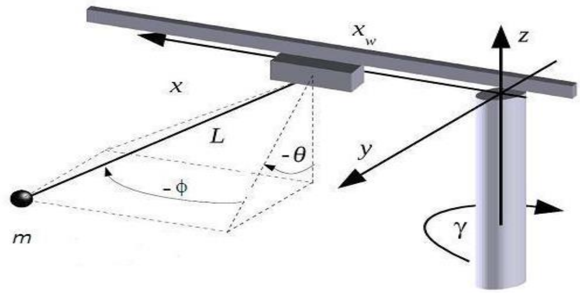

Fig. 2. Mathematical model

We define:

$q=(x, \phi, \gamma, \theta)$ (1)

$Q=(F_x, 0, T_\gamma, 0)$ (2)

Kinetic energy of TC is:

$$T=T_{load} + T_{trolley} \quad (3)$$

where $T_{load} = \frac{1}{2} m v_1^2 + \frac{1}{2} J_0 \dot{\gamma}^2$; $T_{trolley} = \frac{1}{2} M v_2^2$; J_0 is inertial moment of TC through z-axis; $v_1^2 = \dot{r}_{1x}^2 + \dot{r}_{1y}^2 + \dot{r}_{1z}^2$; $v_2^2 = \dot{x}^2$; $r_{1x} = x - L\cos\theta \sin\emptyset$; $r_{1y} = L\sin\theta$; $r_{1z} = -L\cos\theta\cos\emptyset$; $\dot{r}_{1x} = \dot{x} + \dot{\theta} L \sin\theta \sin\emptyset - \dot{\emptyset} L \cos\emptyset \cos\theta$; $\dot{r}_{1y} = \dot{\theta} L \cos\theta$; $\dot{r}_{1z} = \dot{\theta} L \sin\theta \cos\emptyset + \dot{\emptyset} L \sin\emptyset \cos\theta$

Potential energy of TC is

$$V = -mgL\cos\theta\cos\emptyset \quad (4)$$

From Euler-Lagrange method, we obtain

$$d\left(\partial L / \partial\dot{q}\right)\Big/dt - \partial L\big/\partial q = Q \quad (5)$$

where L is Lagrangian operator; T is kinetic energy; V is potential energy;

From (**5**), dynamic equations of TC are listed from (6) to (9)

$$\begin{aligned}(m+M)\ddot{x} &+ mLcos(\theta)\sin(\emptyset)\,y^2 - (m+M)x\dot{\gamma}^2 - 2mLcos(\theta)\dot{\gamma}\dot{\theta} \\ &+ mLcos(\theta)\sin(\emptyset)\,\dot{\theta}^2 + 2mLcos(\emptyset)\sin(\theta)\,\dot{\theta}\dot{\emptyset} - 2m\dot{L}(\sin(\theta)\,\dot{\gamma} \\ &+ mL\cos(\theta)\sin(\emptyset)\,\dot{\emptyset}^2 - \sin(\theta)\sin(\emptyset)\,\dot{\theta} + \cos(\theta)\cos(\emptyset)\,\dot{\emptyset}) \\ &- mcos(\theta)\sin(\emptyset)\ddot{L} - mLsin(\theta)\ddot{\gamma} + mLsin(\theta)\sin(\emptyset)\ddot{\theta} - mLcos(\theta)\cos(\emptyset)\ddot{\emptyset} \\ &= F_x\end{aligned} \quad (6)$$

$$\begin{aligned}Lcos(\theta)^2\ddot{\emptyset} + \cos(\theta)\Big(&gsin(\emptyset) - Lcos(\theta)\cos(\emptyset)\sin(\emptyset)\,\dot{\gamma}^2 + \cos(\emptyset)\,x\dot{\gamma}^2 \\ &- \cos(\theta)\cos(\emptyset)\,\ddot{x} + 2Lcos(\theta)\cos(\emptyset)\,\dot{\gamma}\dot{\theta} - 2Lsin(\theta)\dot{\theta}\dot{\emptyset} \\ &+ 2\dot{L}\left(\cos(\emptyset)\sin(\emptyset)\,\dot{\gamma} + \cos(\theta)\,\dot{\emptyset}\right)\Big) + Lcos(\theta)\cos(\emptyset)\sin(\theta)\,\ddot{\gamma} = 0\end{aligned} \quad (7)$$

$$\begin{aligned}&(J_0 + mL^2\sin(\theta)^2 + m\cos(\theta)^2 L^2\sin(\emptyset)^2 - 2m\cos(\theta)L\sin(\emptyset)x + mx^2 + Mx^2)\ddot{\gamma} \\ &+ 2m\cos(\theta)\,xL\dot{\theta} - mL\sin(\theta)x\dot{\theta}^2 - 2m\cos(\emptyset)L^2\sin(\theta)^2\,\dot{\theta}\dot{\emptyset} - \\ &m\cos(\theta)\,L^2\sin(\theta)\sin(\emptyset)\dot{\emptyset}^2 - mL\dot{L}\left(2\sin(\emptyset)\dot{\theta} - \cos(\emptyset)\sin(2\theta)\dot{\emptyset}\right) + \\ &x\left(-2m\cos(\theta)\sin(\emptyset)\,\dot{L}\right) + 2(m+M)\dot{x}) + mL^2(\cos(\emptyset)^2\sin(2\theta)\dot{\emptyset}) \\ &\qquad + \cos(\theta)^2\sin(2\emptyset)\dot{\emptyset} + 2mL((\sin(\theta)^2 + \cos(\theta)^2\sin(\emptyset)^2)\dot{L} \\ &\qquad - \cos(\theta)\sin(\emptyset)\dot{x} + \\ &\sin(\theta)\sin(\emptyset)x\dot{\theta} - \cos(\theta)\cos(\emptyset)\,x\dot{\emptyset})) + m\sin(\theta)\,x\ddot{L} - mL\sin\theta\,\ddot{x} \\ &\qquad + (-(m\cos(\theta)^2 L^2\sin\emptyset)) \\ &\qquad - mL^2\sin(\theta)^2\sin(\emptyset) + m\cos(\theta)Lx)\ddot{\theta} + m\cos\theta\cos\emptyset\,L^2\sin(\theta)\ddot{\emptyset} = T_\gamma\end{aligned} \quad (8)$$

$$\begin{aligned}L\ddot{\theta} + gcos(\emptyset)\sin(\theta) &+ 2\cos(\theta)\,\dot{x}\dot{\gamma} - \frac{1}{4}Lsin(2\theta)\dot{\gamma}^2 - \frac{1}{4}Lcos(\emptyset)^2\sin(2\theta)\,\dot{\gamma}^2 \\ &- xsin(\theta)\sin(\emptyset)\,\dot{\gamma}^2 + \frac{1}{4}Lsin(2\theta)\sin(\emptyset)^2\,\dot{\gamma}^2 + \dot{L}\left(-2\sin(\emptyset)\,\dot{\gamma} + 2\dot{\theta}\right) \\ &- Lcos(\emptyset)\dot{\gamma}\dot{\emptyset} + Lcos(\emptyset)^2\cos(\emptyset)\,\dot{\gamma}\dot{\emptyset} + Lcos(\emptyset)\sin(\theta)^2\,\dot{\gamma}\dot{\emptyset} \\ &+ Lcos(\theta)\sin(\theta)\dot{\emptyset}^2 + \sin(\theta)\sin(\emptyset)\,\ddot{x} + \left(-Lsin(\emptyset) + xcos(\theta)\right)\ddot{\gamma} = 0\end{aligned} \quad (9)$$

These dynamic equations are complicated. Thence, some approximations are assumed as:

$\sin\theta=\sin\gamma=\sin\phi=0;\quad \cos\theta=\cos\gamma=\cos\phi=1;$ (10)

$\theta\dot{\theta}^2 \approx 0;\ \emptyset\dot{\emptyset}^2 \approx 0;\ \gamma\dot{\gamma}^2 \approx 0;\ \dot{L}=\ddot{L}=0$

Equations (6)-(9) become:

$$\ddot{x} + m_t g\emptyset = \bar{F}_x \quad (11)$$

$$L\ddot{\emptyset} + g\emptyset - \ddot{x} + L\ddot{\gamma}\theta = 0 \quad (12)$$

$$(1 + M_r x^2)\ddot{\gamma} - m_r g x\theta = \bar{T}_\gamma \quad (13)$$

$$L\ddot{\theta} + g\theta + x\ddot{\gamma} - L\ddot{\gamma}\emptyset = 0 \quad (14)$$

where:

$$m_t = \frac{m}{M};\ M_r = \frac{M}{J_0};\ m_r = \frac{m}{J_0};\ \bar{F}_x = \frac{F_x}{M};\ \bar{T}_\gamma = \frac{T_\gamma}{J_0}$$

If we regard the relations of moments of motors and voltages on motor are:

$$\bar{F}_x = K_{mx}V_x; \quad (15)$$

$$\bar{T}_\gamma = K_{m\gamma}V_\gamma$$

3. PID Control

We use four blocks of PID to control TC. These blocks are shown in Fig. 3 and **Error! Reference source not found.**. Control parameters are: Kp(i), Ki(i), Kd(i) are control parameters of PID(i) block (i=1, 2, 3, 4)

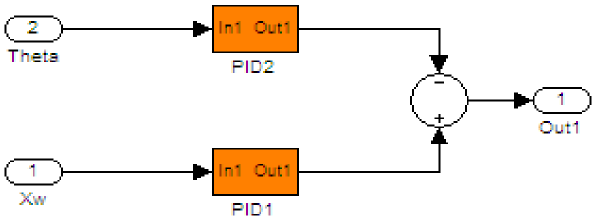

Fig. 3. PID structure that controls position of trolley and dimensional angle of load

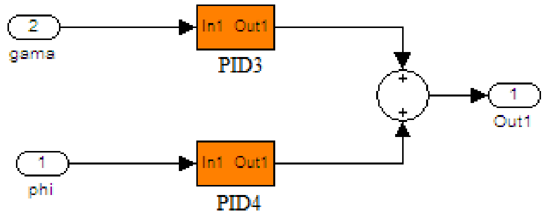

Fig. 4. PID structure that controls angle of tower and rotational angle of load

Formula of PID control signal is

$$u_{control} = K_p e + K_i \int e dt + K_i \frac{de}{dt} \quad (16)$$

4. Simulation

System parameters in Tab. 2 are chosen as [5]. Then, we obtain

m=0.32; M_t=0.7; K_{mx}=5.58; K_{my}=11.91; L=0.5 (17)

In simulation, we have survey in two cases. In case 1, the selection of control parameters in simulation is chosen through genetic algorithm (GA). In case 2, with PID controller that we get from 10th generation, the length of string is changed into 0.5m, 0.8m, 1m. Then, PID controllers are examined in different situation.

Case 1: There are methods to find PID parameters for SISO system, such as Zeigler-Nichols [6]. But, in under-actuated system, with the combined structure of PID (as in Fig. 3, **Error! Reference source not found.**), the calibration is chosen by searching algorithm, such as GA [7]. To find control parameters, in this case, we use GA for searching. There are four sets of PID controller listed in Tab. 3. They are corresponding to 10th, 15th, 20th, 25th generations. Responses of TC are listed from Fig. 4 to Fig. 7. In all situations, the trolley is moved to expected position (0.4m) (Fig. 4) after about 10s. The fluctuation of load is terminated after 12s (Fig. 5 and Fig. 6). Vibration of tower moves to zero after 6s. However, the motion of tower can be chosen differently from zero as load is move in 3D space.

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Tab. 3. Searching results of finding PID parameters

Number of generations	Kp1	Ki1	Kd1	Kp2	Ki2	Kd2	Kp3	Ki3	Kd3	Kp4	Ki4	Kd4
10	4.96	0.23	-3.47	4	0.58	1.04	4.86	-1.46	-0.17	1	0.24	0.58
15	3.99	0.9	-2.1	2.33	-3.55	-0.6	2.7	4.25	-0.57	4.08	2.98	1.33
20	3.25	0	-1.5	4.58	1.7	1.93	3.86	-0.53	-0.17	4.66	0.73	0.58
25	4.06	0.33	-3.21	1.83	-2.42	0.33	4.57	-3.02	1.25	0.33	0.04	-0.42

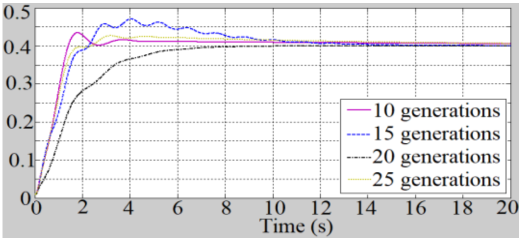

Fig. 4. Position of trolley (m)

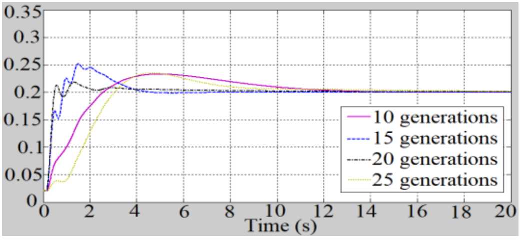

Fig. 5. Angle θ (rad)

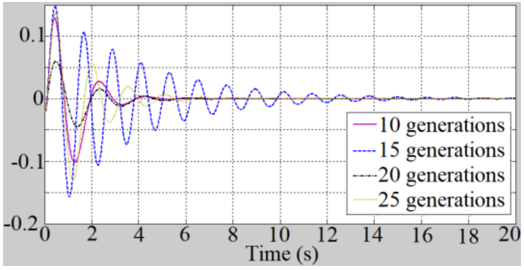

Fig. 6. Angle ϕ (rad)

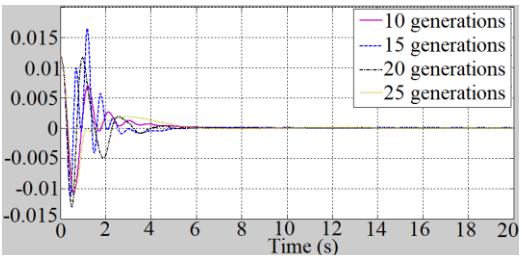

Fig. 7. Angle γ (rad)

Case 2: Control parameters are chosen as generation 10 in Tab. 3.

Kp1=4.96; Ki1=0.23; Kd1=-3.47; Kp2=4; (18)
Ki2=0.58; Kd2=1.04; Kp3=4.86; Ki3=-1.46;
Kd3=-0.17; Kp4=1; Ki4=0.24; Kd4=0.58

Simulation results are shown from Fig. 8 to Fig. 11. PID controller in (18) shows its success in control position of trolley, angle of tower and anti-fluctuation of load. The length of string is changed from 0.5m to 0.8m and 1m. The fluctuation of load is terminated faster when string is shorter through these results:

- In Fig. 8, settling time of position of trolley is 4s, 5s, 6s when L is 0.5m, 0.8m, 1m, correspondingly.

- In Fig. 9, settling time is the same in all case of L. Thence, dimensional angle of load is not affected by the length of string.

- In Fig. 10, setting time is 4s, 7s, 9s when L is 0.5m, 0.8m, 1m. Thence, the settling time of rotational angle of load is shorter under PID when length of string is shorter.

- In Fig. 11, settling time of angle of tower is 4s, 4s, 5s when L is 0.5m, 0.8m, 1m.

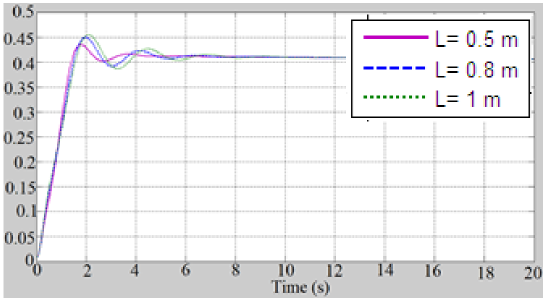

Fig. 8. Position of trolley (m)

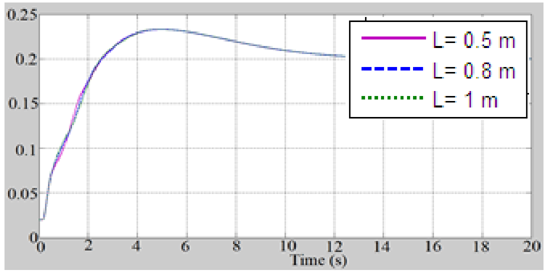

Fig. 9. Angle θ (rad)

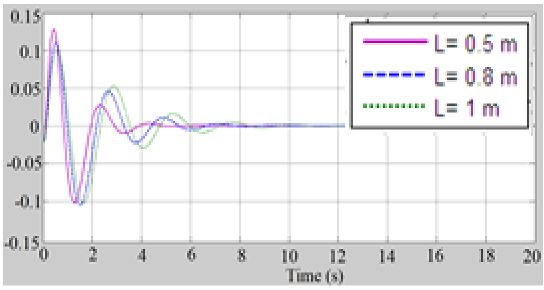

Fig. 10. Angle ϕ (rad)

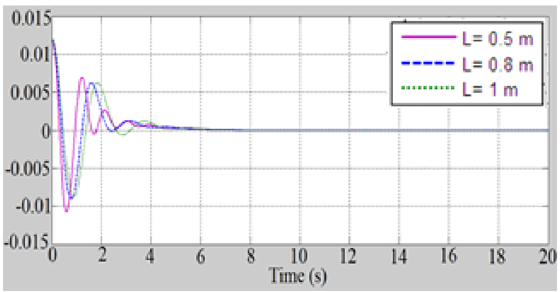

Fig. 11. Angle γ (rad)

5. Experiment

5.1. Experimental Platform

An experimental TC model is created for testing algorithms in Ho Chi Minh city University of Technology and Education (HCMUTE) (Fig. 12).

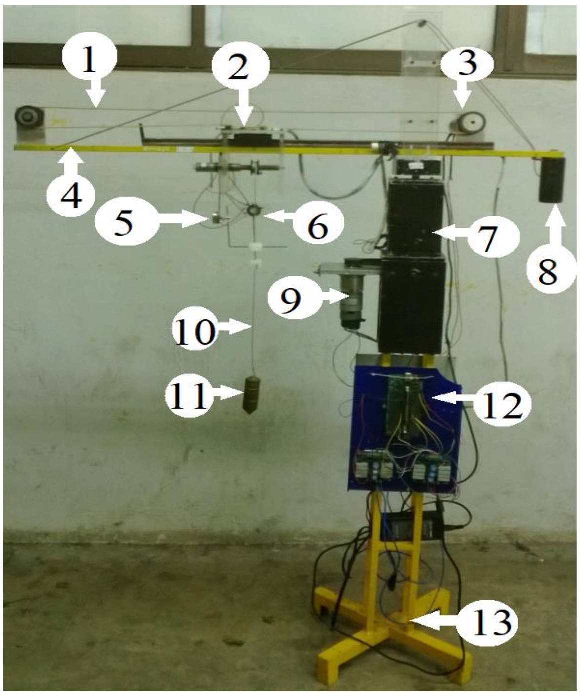

Fig. 12. Experimental model

1- String that transfers rotational motion of motor A to dimensional motion of trolley;
2- Trolley;
3- Motor A that controls the motion of trolley;
4- Jib;
5- Potentiometer that measures θ;
6- Potentiometer that measures ϕ;
7- Tower;
8- Balancing part of jib;
9- Motor B that controls the rotation of tower;
10- String that connects load and trolley;
11- Load which is made of metal;
12- Electronics board;
13- Basement.

5.2. Experimental Results

Because the difficulties in measuring the system parameters of TC in real situation, the PID controller is chosen through trial-and-error test as

Kp1=20; Ki1=0; Kd1=40; Kp2=10; Ki2=0; Kd2=2; Kp3=1; Ki3=0; Kd3=0.2; Kp4=0.2; Ki4=0; Kd4=0.02 (19)

Two cases are examined. In case 1, length of string is shorter than in case 2. Thence, the quality of PID method is checked in different operating situation of TC. The experimental results are listed from Fig. 13 to Fig. 20.

Case 1: L=20cm; m=0.3kg. At second 1.8, a force is created to afect the load. Thence, PID controller begin to stabilize the TC.

In Fig. 13, trolley needs 2.1 seconds to be again at position zero. It vibrates around 8 cm (from -2 cm to 6 cm). In Fig. 14, after 4s, the dimensional vibration of load is terminated. The maximum fluctuation of load in 35 degrees in dimension. The rotational angle of load vibrates less, only 5 degree and it is stablized afetr 4s (in Fig. 15). In Fig. 15, there is 1 degree of vibrating appears after the stability of system. That is because of the resolution of potentiometer is not good. The vibration of 1 degree is the noise of sensor. In Fig. 16, the settling time of angle of tower needs 9s to be stabilized. Thence, the PID controller works well to terminate the fluctuation when still controlling the position of trolley and the angle of tower..

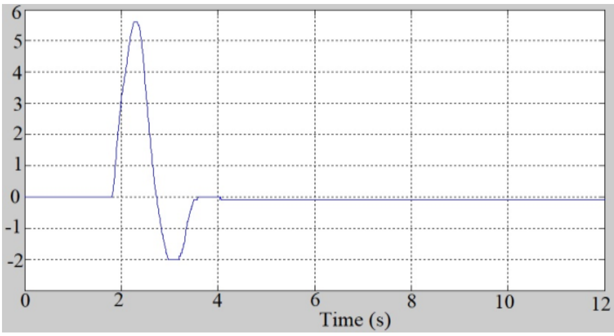

Fig. 13. Position of trolley (cm)

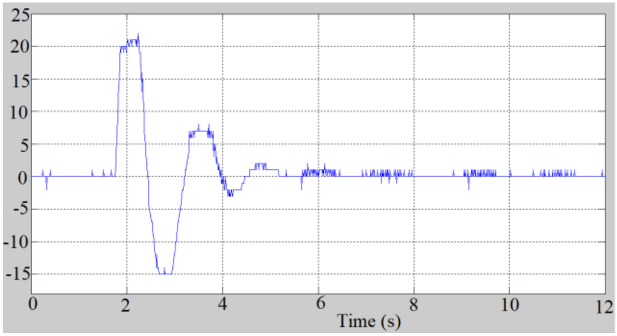

Fig. 14. Angle θ (degree)

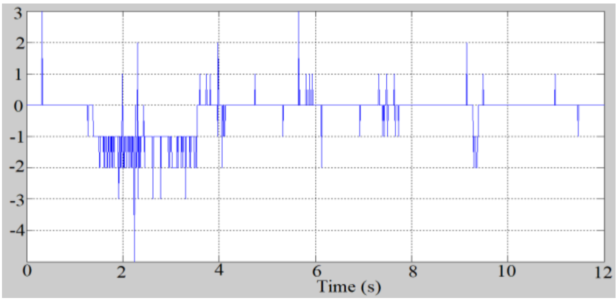

Fig. 15. Angle ϕ (degree)

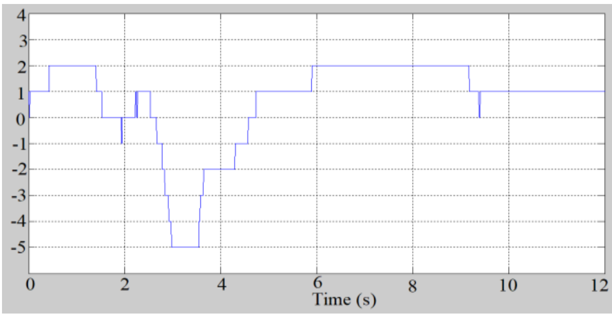

Fig. 16. Angle γ (degree)

<u>Case 2:</u> L=40cm; m=0.3kg. In this case, trolley is moved far from expected position (zero) (5cm), tower is rotated to be far from zero position. Initial value of rotational angle of tower is 48 degrees. At time 0, the power is supplied for system and PID controller makes trolley to zero point.

In Fig. 17, it takes 3s for trolley to move to expected position. The settling error is 2mm. In Fig. 18, dimensional angle of load needs 5s to be stabilzed, the maximum fluctuation is 15 degrees. In Fig. 19, settling time of rotational angle of load is 4s and maximum fluctuation is 6 degrees. In Fig. 19, the error of measurement is 1 degree as in Fig. 15. In Fig. 20, settling time of rotational angle of tower is 7s. Thence, PID controller still controls well TC to move to expected position even the initial position is far.

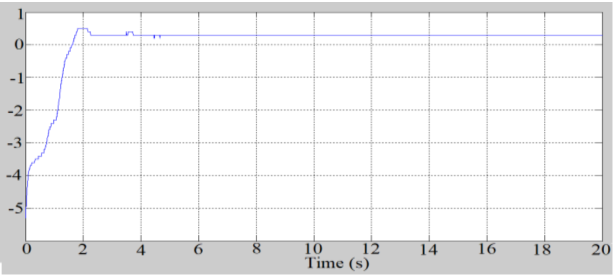

Fig. 17. Position of trolley (cm)

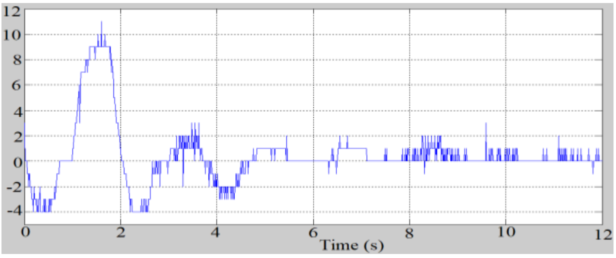

Fig. 18. Angle θ (degree)

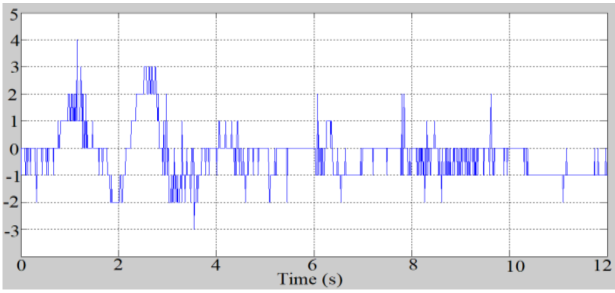

Fig. 19. Angle ϕ (degree)

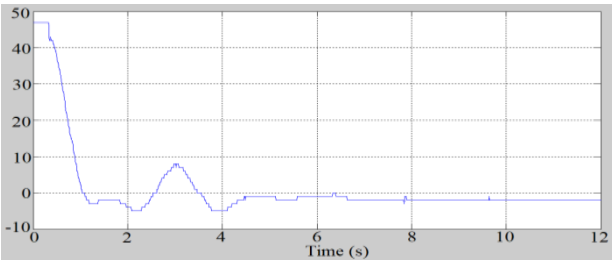

Fig. 20. Angle γ (degree)

6. Conclusions

In this paper, we present a PID structure to control TC. Besides controlling trolley and tower to expected positions, the fluctuations of load are considered. In simulation, the PID parameters are found through GA. This control method is proved to satisfy the purpose of designer. Different situations of simulation are assumed for survey. Thence, we built an experimental TC. The PID parameters are selected by trial-and-error test. We test PID method through this model in two cases: TC is affected by external force on TC and initial condition of TC is far from expected condition. In both cases, PID controller shows its ability in controlling TC and satisfying the control purposes. Thence, our structure of PID can also be developed for other MIMO under-actuated system, such as other kinds of 3D cranes.

7. Acknowledgement

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8. References

[1] Čápková R., Kozáková A.: "Experimental Modelling and Control of a Tower Crane", 22nd International Conference on Process Control (PC19), pp. 97-101, 2019.

[2] Ramli, L. et al: "Modelling and Fuzzy Logic Control of an Underactuated Tower Crane System", Journal of Applications of Modelling and Simulation, eISSN: 2600-8084, Vol. 4, pp. 1-11, 2020.

[3] Devanathan R., Keong C.C., Pei T.L. Ting Y.T.: "Expert PID controller for an industrial process", Fourth IEEE Region 10 International Conference TENCON, pp. 404-407, 1989.

[4] Okubanji A., Oyetola O., Adekomaya O.: "Vision Based Control of Gantry Crane System", Eskisehir Technical University Journal of Science and technology, Vol. 19, No. 4, pp. 1023-1032, 2018.

[5] Altaf, F: "Modeling and event-triggered control of multiple 3D tower cranes over WSNs", Master's Thesis, School of Electrical Engineering, Stockholm, Sweden, 2010.

[6] Meshram P.M., Kanojiya R.G.: "Tuning of PID controller using Ziegler-Nichols method for speed control of DC motor," IEEE-International Conference On Advances In Engineering, Science And Management (ICAESM -2012), 2012, pp. 117-122.

[7] Grefenstette J.J.: "Optimization of Control Parameters for Genetic Algorithms", in IEEE Transactions on Systems, Man, and Cybernetics, vol. 16, no. 1, pp. 122-128, 1986.