Overhead Crane Fuzzy Control with Anti-Swing Compensation

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ABSTRACT: *This is to minimize the oscillations while carrying loads from the initial point to the final point in minimum time to prevent security hazards. A Proportional Derivative (PD) Fuzzy controller is proposed to control the overhead crane with minimal load swing. A Non-Linear dynamic model is used to investigate and compare the results of Fuzzy PD controller (Mamdani & Takagi Sugeno) with conventional PD controller. The controllers are compared in terms of load swing, Time taken to reach final point, Steady state performance and Transient performance. The proposed control strategy has been designed and validated with MATLAB. Simulation results are obtained and discussed.*

Keywords: Overhead Crane, Gantry crane, Fuzzy PD

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1. Introduction

Overhead cranes have been used for years in industries to carry heavy loads from one point to another. The current trends suggest that the height and load capacity of the cranes are increasing, therefore it is required that they operate at higher speeds to reduce the transfer time, as a consequence of which these cranes suffer higher load oscillations which is extremely dangerous for the working labour.

Cranes can be broadly categorized into three types according to their mechanical structure.

- Overhead Crane
- Rotary Crane

- Boom Crane

Overhead cranes consist of a trolley which moves along a fixed track and undergoes translational motion along horizontal axis [1]. The load is suspended to the trolley via a rope or cable therefore it swings along the horizontal axis due to inertia, and this swing can become excessively large when operated at higher speeds. Moreover, the gantry crane needs a skilful operator to control manually based on his or her experiences to stop the swing immediately at the right position. Furthermore to unload, the operator has to wait the load stop from swinging. The failure of controlling crane also might cause accident and may harm people and surrounding [2].

Anti-Swing control of overhead cranes has been a topic of interest for a long time, in past several open loop control strategies were being proposed [3, 4]. For example open loop time optimal strategies were used to control the cranes but ended up with poor results especially under dynamic conditions and when system parameters are changing.

The current work presents a Proportional Derivative (PD) type Fuzzy controller to effectively and efficiently control the OHC. It ensures a smooth transition of carte/trolley from initial to final point with minimal load swing. The performance of Fuzzy PD controller is compared with that of conventional PD controller, furthermore the fuzzy controller is implemented using both Mamdani and Takagi – Sugeno inference system and the results are compared.The proposed strategy has been validated using MatLAB/Simulink model; numerical results are collected and discussed.

2. Dynamic Model of OHC

There are four variables of interest or the control variables which are as follows

- Y – Load Position
- $\dot{Y}$ – Load Velocity
- ϕ – Swing Angle
- $\dot{\phi}$ – Rate of Swing Angle (Angular velocity)

The free body diagram in figure 1 shows the principle of an overhead crane, which consists of a crate moving on rails. The load hangs on a rope from the crate such that the rope and load together can be viewed as a pendulum.

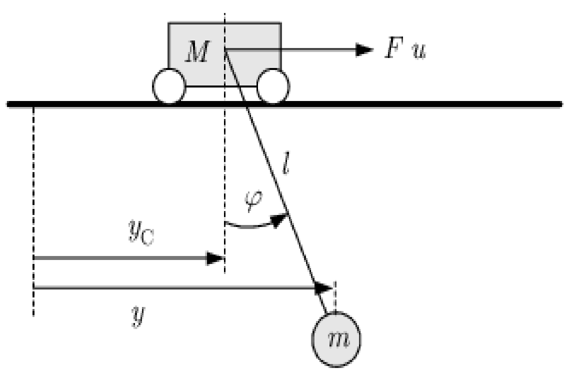

Figure 1. OHC free body diagram

Where, L is the length of rope/cable, M is the mass of Crate/Trolley, m is the mass of load, Y is the position of load, Y_c is position of crate/trolley, F is the drive coefficient and U is control input. The carne dynamical model can be described by two coupled equations (1) and (2). [5]

$$\ddot{Y}_c = \frac{1}{M + m\sin^2\phi}[m\sin\phi(g\cos\phi + l\phi^2) + Fu - S\,\mathrm{sgn}(\dot{Y}_c) - D\dot{Y}_c] \qquad (1)$$

$$\ddot{\phi} = \frac{-1}{l(M + m\sin^2\phi)}[m\sin\phi(g + l\dot{\phi}^2\cos\phi) + Mg\sin\phi + \cos\phi(Fu - S\,\mathrm{sgn}(\dot{Y}_c) - D\dot{Y}_c)] \quad (2)$$

$$Y = Y_C + l\sin\phi \quad (3)$$

The model shown is a dynamic Non-linear, this model is used further, to simulate the proposed control structure. The model is not linearized so as to keep the results as close to original as possible however we have made certain assumptions which are discussed in the next section.

3. Assumptions

To avoid complexity we have made certain assumptions which are as follows.

- The load moves only in the plane that contains the direction of the rail
- The force of the electrical drive, which moves the crab, is proportional to the control signal, fed into the drive system
- The position of the crab and the rope (pendulum) angle are measured
- The real manipulated variable (U) to control the drive is limited to +/- 10V

Following are the system constant parameters, which are either constant or changed on simulation time.

- M: mass of crate = 1000 Kg
- m: mass of load = 20 - 1250 kg
- l: length of rope = 10 - 20 m
- g: acceleration due to gravity = 9.80665 m/sec2
- F: drive coefficient = 1000 V/N
- S: static friction force = 500 N
- D: dynamical friction coefficient = 777 kg/sec

4. Controller Design

In this section two different feedback control strategies are discussed, first we discuss a conventional PD type control structure and then a PD type Fuzzy control structure, and look into the detail of each. The control objective is to transfer the load from initial point to the final point such that the load does not swing at the target position and the transition is smooth with minimal oscillations and no overshoots.

We want to control the position and swing angle of the crane therefore we choose two independent variable as input to the controller for position we take position of load and for swing compensation we select swing angle each with a proportional and derivative component.

4.1 Conventional PD Controller

A conventional PD controller has two inputs a proportional input and a derivative input. As mentioned in the previous section we have taken have two input variables position of load and swing angle of load each with proportional and derivative components as shown in figure 2.

This structure employs two differentiating filter for each input, which is the usual practice with PD controllers however in the case of cranes most crane systems measure the speed of the crate for internal drive purposes so here we assume that the speed

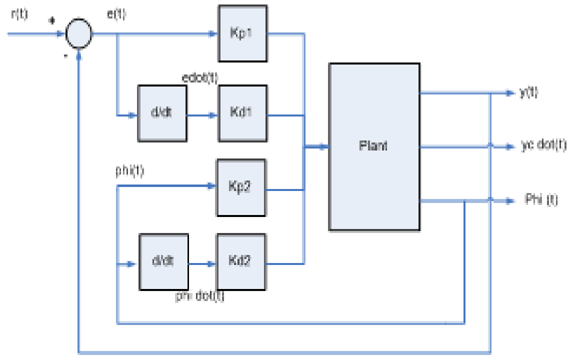

Figure 2. Conventional PD block diagram

of load and crate are almost equal hence we are using the measured speed of the crate Y_c instead calculating the derivative of load position using the differentiating filter. Now the new PD controller structure is given in figure 3.

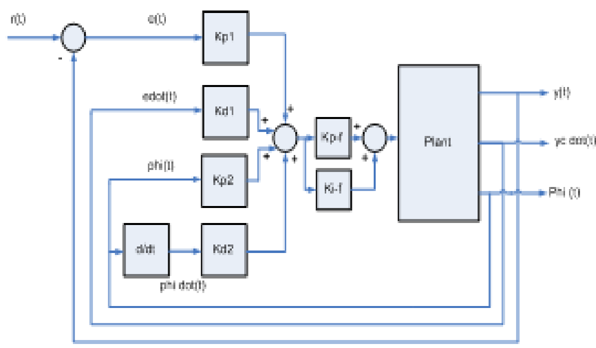

Figure 3. Conventional PD block diagram with carte speed as edot

Notice that an additional filter stage is added before the plant input to compensate for any step disturbances such static frictions.The filter is provided with an integrator in parallel so as to reduce the steady state error [5].

The equation of the above control structure without the output filter is given as.

$$u(t) = \{K_{p1}e(t) + K_{d1}Y_c^{\cdot}(t)\} + \{K_{p2}\phi(t) + K_{d2}\dot{\phi}(t)\} \quad (4)$$

4.2 PD-type Fuzzy Controller (Mamdani & Takagi Sugeno)

The PD-type fuzzy logic controller is an extension of conventional PD controller with the application of fuzzy logic control. It also has two inputs i.e. proportional and derivative. We are using the same inputs that were given to the conventional PD controller. The block diagram of the fuzzy PD controller implemented is shown in figure 4.

If we look into the block of fuzzy controller this is a general fuzzy controller since the PD structure is implemented outside the overall structure is known as Fuzzy PD Controller. Now we will look into the fuzzy controller block. The fuzzy controller has four inputs e, e_dot, phi, and phi_dot corresponding to error in load position, speed of crate, swing angle and rate of swing angle respectively. All the inputshave 3 triangular membership functions Negative ‘N’, Zero ‘Z’, Positive ‘P’ [4].Refer to figure 5, 6.

- Error (E) = { N, Z,P}
- Error derivative (E_dot) = {N, Z, P}
- Swing Angle (Phi) = {N, Z, P}

- Rate of Swing Angle (Phi_dot) = {N, Z, P}

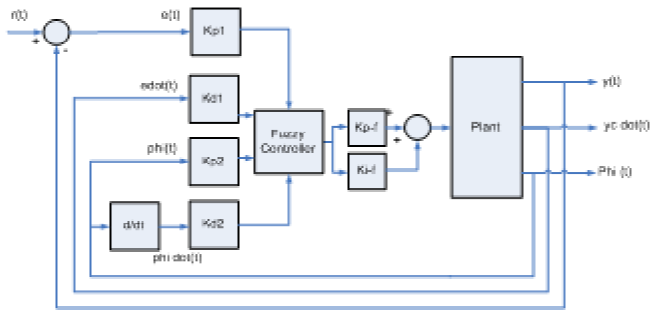

Figure 4. Fuzzy PD block diagram

A general formula for calculating the number of rules is given by.

$$R = m^n \tag{5}$$

Where m is the number of membership functions and n is the number of inputs. Therefore in our case we should have a rule base comprising of 81 rules. This is very large therefore to avoid such large number of rules it is easier to split the rule base into two different rule bases one for E, E_dot and other for Phi, Phi_Dot. Therefore each rule base will have 9 rules and a total of 18 rules, we can still ignore some of the unfired rules hence we finally get two rule bases with total 14 rules as shown in table1,2 [4].

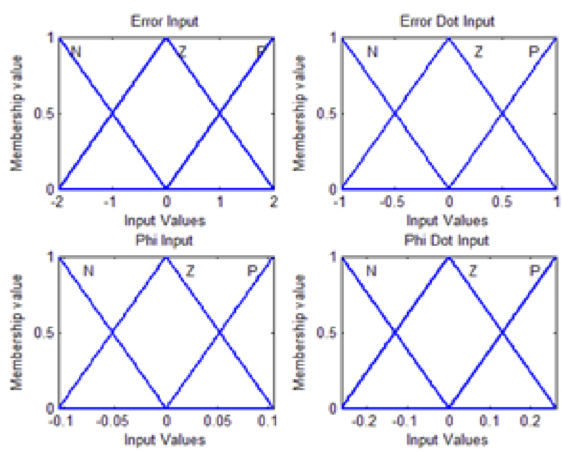

Figure 5. Input Membership functions

The rules shown above are of the form for exampleconsidering rule 1 and 10.

- **Rule 1:***If E is N and E_dot is N then U is N*
- **Rule 10:***if Phi is N and Phi_Dot is Z then U is N*

The two rule bases are linked together using the Union (MAX) operation.

The Fuzzy controller is implemented using the both Mamdani and Takagi Sugeno Fuzzy Model. The output membership functions of the Mamdani type fuzzy controller are shown in figure 6. It has three triangular membership functions Negative, Zero and Positive.For Takagi Sugeno type fuzzy controller a 0th order (constant singletons) TS model is used in this controller

Error Dot (e')				
Error (e)		N	Z	P
	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

Table 1. Rule Base Error (e) & Error Dot (e')

Phi Dot (φ')				
Phi (φ)		N	Z	P
	N		N	
	Z	N	Z	P
	P		P	

Table 2. Rule Base Phi (φ) & Phi Dot (φ')

the output membership function is shown in figure 7. There are three singletons N, Z and P for negative zero and positive respectively.

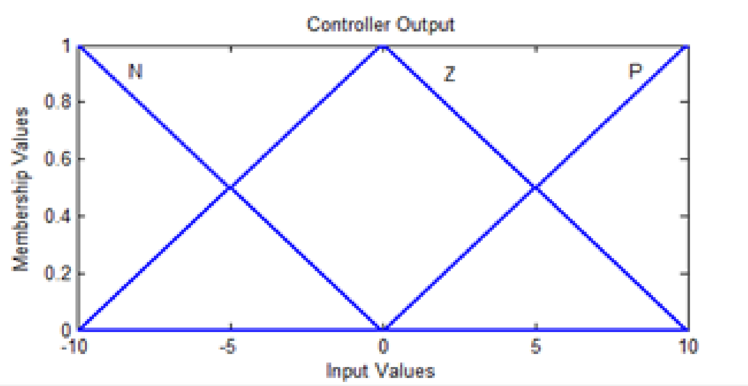

Figure 6. Output Membership Function (Mamdani)

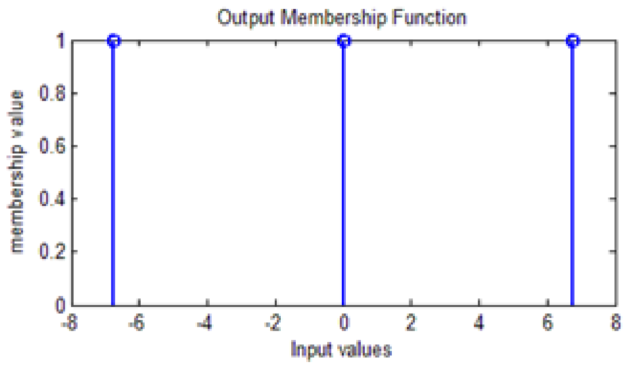

Figure 7. Output Membership function (Takagi Sugeno)

5. Simulation Results

The Non Linear Model presented in section 2 has been implemented using MATLAB and SIMULINK and results are collected for all the three control variations discussed in section 4. The constant simulations parameters are as follows.

- Y_0 = 0 m (initial position)
- Y_t = 10 m (final position)
- Simulation time = 50 secs
- Fixed sampling interval = 1 e-3 secs
- Except for l all the system parameters mentioned in section 3 remains same.

The simulation results are shown in figures 8, 9. At first simulations are carried out with length of rope/cable l = 10m for conventional PD and Fuzzy PD controller with mamdani TS variations and numerical results are collected for Load position vs. Crate Position and Swing Angle and control input.

Figure 8 presents a comparison of conventional PD and the Fuzzy PD controllers simulation results for rope length l = 10m. The first row show the Load position vs. Crate position graph, it can be seen that the conventional PD reaches the desired output in around 40 secs while Mamdani fuzzy takes around 35 secs and TS fuzzy controller takes only 25 secs to reach the desired set point and has also the smoothest transfer curve. Notice the crate position and load position curves closely follows each other in TS fuzzy controller since the greater the difference between the crate and load position greater the swing angle will be this can be seen in the next row which presents a comparison of the load swing angle of the above mentioned controllers. The conventional PD and mamdani shows more or less the same swing angle variations except that the mamdani settles a little earlier however for TS fuzzy controller the swing angle variation is significantly small(+/- 1.5 degrees) and smoother.The third row presents a comparison of the control effort required to produce the above mentioned results.The control output of mamdani fuzzy controller seems abrupt but this is due to the fact that these controllers are manually tuned. Here also the TS fuzzy controller has the best output.

Figure 9 shows the results for l = 20 m with longer cable length the most affected was the conventional PD controller which suffers significant load oscillations as can be seen in the 2^{nd} row 1^{st} column of figure 9 even though it doesn't increase the magnitude of the peak load oscillation. The mamdani fuzzy controller shows slight increase in load oscillations and increase response time. However the lease affected is TS fuzzy controller which shows minimal increase in load oscillations and response time. with slightest variations in control output it handles the increase cable length.

Figure 8compares the simulation results with rope length l = 20m the load position vs. Crate position profile of conventional PD controller shows significant increase in the amount of oscillations and overshoots while on the other hand Fuzzy PD shows slightest of difference from the previous result. Similarly for the Swing angle profile shows a peak oscillation of magnitude +/- 5 degrees for conventional PD and decay of oscillations are even slower than the previous one (l = 10m) while Fuzzy PD peak oscillation is still the same i.e. +/- 1.2 degrees. Finally the control input profile tells the same story the output of fuzzy PD is much smoother than its conventional counterpart.

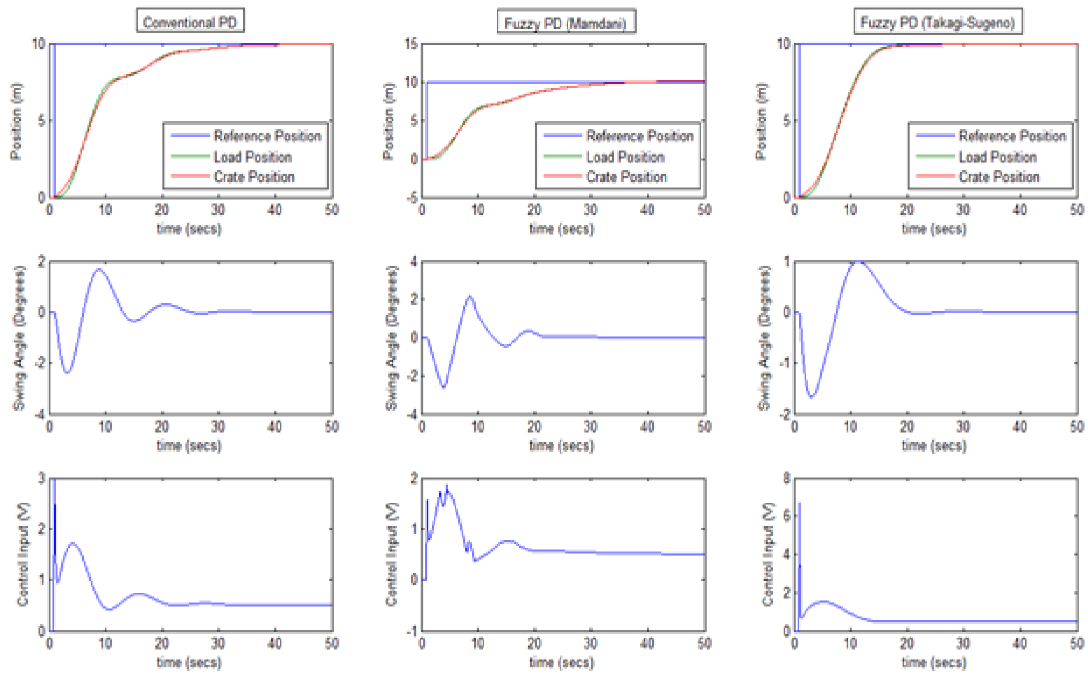

Figure 8. Conventional PD vs. Fuzzy PD (Mam) vs. Fuzzy PD (TS) for (l = 10 m)

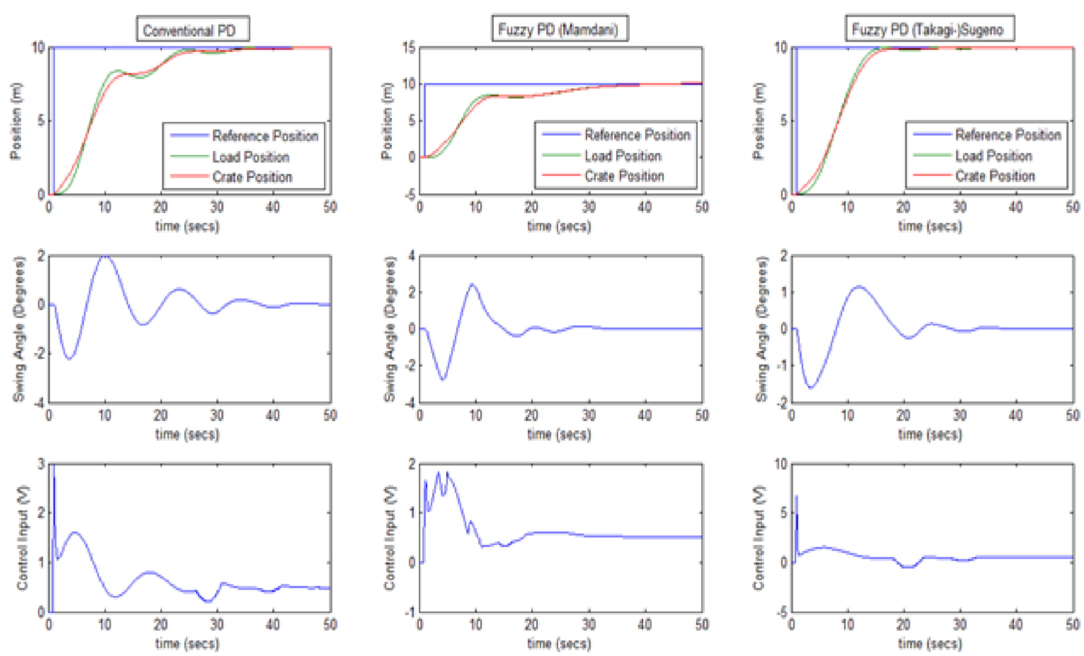

Figure 9. Conventional PD vs. Fuzzy PD (Mam) vs. Fuzzy PD (TS) for (l = 20)

6. Conclusion

From the results shown above we can conclude that the performance of the fuzzy PD (Takagi Sugeno) controller is much better than the conventional PD controller and its mamdani counterpart. The TS Fuzzy PD controller has not only reduced the load oscillation but also the transfer time.

Moreover TS Fuzzy PD controller has shown robustness to changing system parameters most important of all was the rope/ cable length. For now these controllers were tuned manually, for further improvement and to achieve better results the gains of the controller should be auto tunned.

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