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Optimal Control of Nonlinear Inverted Pendulum SystemUsing fuzzy controller

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ABSTRACT: An inverted pendulum is a pendulum that has its center of mass above its pivot point. It is unstable and without external support will fall over. It can be suspended stably in this inverted position by using a control system to monitor the angle of the pendulum and move the pivot point horizontally back under the center of mass when it starts to fall over, keeping it balanced. This Paper present the intelligent methods based on fuzzy logic for tuningPID controller. Simulation results reveals that intelligent methods provide better performance than the conventional methods

***KEYWORDS*:** Inverted pendulum, fuzzy PID, intelligent control.

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I. INTRODUCTION:

The main aim of this paper is track the position, and balancing the angle.

An inverted pendulum is inherently unstable and must be actively balanced in order to remain upright; this can be done by applying a torque at the pivot point.This is a systemwhich belongs to the class of under-actuated mechanical systems having fewer control inputs than the degree of freedom[1]. This renders the control task more challenging, making the inverted pendulum system a classical benchmark for the design, testing, evaluating and comparing of different classical control techniques. Being an inherently unstable system, the inverted pendulum is among the most difficult systems, and it is one of the most important classical problems. The control of inverted pendulum has been a research interest in the field of control engineering. Due to its importance, this is a choice of dynamic system to analyze its dynamic model and propose a control law[2,3]. The aim of this case study is to stabilize the inverted pendulum such that the position of the cart on the track is controlled quickly and accurately so that the pendulum is always erected in its inverted position during such movements [4,5].

In general, the control problem consists of obtaining dynamicmodels of systems, and using these models to determine control laws or strategies to achieve the desired system response and performance[6,7]. The simplicity of control algorithm as well as guaranteeing the stability and robustness in the closed-loop system is a challenging task in realsituations[8,10]. Most of the dynamical systems such as powersystems, missile systems,roboticsystems,invertedpendulum,industrial processes, chaotic circuits, etc., are highly nonlinear in nature[2].

The control of inverted pendulum can be divided into three aspects. The first aspect that is widely researched is the swing-up control of inverted pendulum. The secondaspect is the stabilization of the inverted pendulum[11,12]. The third aspect is tracking control of the inverted pendulum. In practice, stabilization and tracking control is more useful for application. It is rather surprising that virtually almost all the technical literature refers to the inverted pendulum with one degree offreedom [13].

The organization of this paper is as follows. Section 1will introduce the structure and models of x inverted pendulum.In Section 2, we will give the design procedure of the PID controllers for stabilizing inverted pendulum. Simulation results for inverted pendulum controlled by PID controllers are discussed in section3. Section 6gives the conclusions of the paper.

II. MATHEMATICAL MODEL OF INVERTED PENDULUM

We will consider a two-dimensional version of the inverted pendulum system with cart where the pendulum is constrained to move in the vertical plane shown in the figure below. For this system, the control input is the force F that moves the cart horizontally and the outputs are the angular position of the pendulum θ and the horizontal position of the cartX.

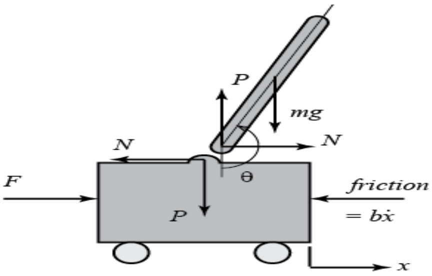


Fig.1

This system is challenging to model in Simulink because of the physical constraint (the pin joint) between the cart and pendulum which reduces the degrees of freedom in the system. Both the cart and the pendulum have one degree of freedom (Xand θ, respectively).

$\ddot{x} = \frac{1}{M}\sum_{cart} F_x = \frac{1}{M}(F - N - b\dot{X})$ ..(1)

$\ddot{\Theta} = \frac{1}{I}\sum_{pend} T = \frac{1}{I}(-NI\cos\theta \ - PI\sin\theta)$..(2)

These expressions can then be substituted into the expressions for N and P from above as follows.

$N = m[\ddot{x} - I\theta^{\cdot 2}\sin\theta + I\ddot{\Theta}\cos\theta]$ ..(3)

$P = m[I\theta^{\cdot 2}\cos\theta + I\ddot{\Theta}\sin\theta + g]$..(4)

We will assume that F= u(1), N= u(2) $\dot{X}$= u(3) these value putting in equation

$\dot{X} = \frac{1}{M}\,[u(1) - u(2) - b * u(3)]$..(5)In equation 2 we will assume thatN= u(1) , P= u(2) , θ= u(3) these value putting in

$= \frac{1}{I}\sum_{pend} T = \frac{1}{I}(-NI\cos\theta - PI\sin\theta)$..(6)

$= \frac{1}{I}\ [-u(1) * I\cos u(3) - u(2) I \sin u(3)$ ..(7)

In equation 3 we will assume thatθ= u(1) ,θ˙ =u(2) ,$\ddot{\Theta}$=(3) ,ẍ= u(4) these value putting in equation

$N = m[\ddot{x} - I\theta^{\cdot 2}\sin\theta + I\ddot{\Theta}\cos\theta]$ ..(8)

N=m[u(4)-I*u(2)sinu(1)+Iu(3)cosu(1)] .(9)

In equation 4 we will assume that θ= u(1) , θ˙= u(2) ,$\ddot{\Theta}$= u(3)these value putting in equation

$P = m[I\theta^{\cdot 2}\cos\theta + I\ddot{\Theta}\sin\theta + g]$ ..(10)

P=m[I*u(2)cosu(1)+I*u(3)sinu(1)+g] ..(11)

These value are putting in command window:

m, mass of the cart 0.5 kg
M, mass of the pendulum 0.2 kg
b, coefficient of friction for cart 0.1N/m/sec
l, length to pendulum center of mass 0.3m
I, mass movement of inertia to the pendulum 0.06kg

III. CONTROLLER DESIGN:

A proportional integral derivative (PID) controller is the most commonly used controller in controlling industrial loops.To stabilize the inverted pendulum in the upright positionand to control the cart at the desired position using the PID control approach, two PID controllers: Angle PID controller and cart PID controller have been designed for the two control loops of the system. We are denoted a P, I and D respectively (proportional integral and derivative). The structure of PID Controller is taken as.

$$\mathbf{u = K_{P,}\ e + K_{I,} \int e\ dt + K_d\ (de/dt)}$$

Where:-
u is PID output control action,
e is the error i.e. difference between set point input and actual output

$e = Y_{ref} - Y_{actual}$

$\mathbf{K_{P,} K_{I,} K_d}$ are the proportional, integral and derivative gains respectively.

In this paper two tuning methods for PID controller have been used.

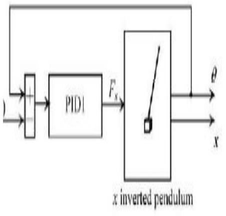
IV. FIRST STEP TRAIL ERROR METHOD:

In this method the PID parameters are obtained by hit and trial. First PID1 is designed for controlling the position x and then the secondController PID2 is designed for controlling the angle. In this step, the goal of the control PID1 controller design is to stabilize the angle of the x inverted pendulum. The parameters of PID1 controller of the inverted pendulum are given as following.

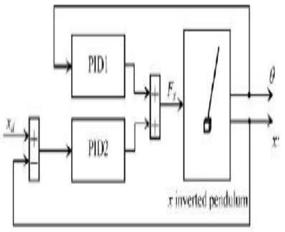
PID1: $P_1 = 52$ $I_1 = 102$ $D_1 = 10$

4.1. The second step with two PID controllers design: This is a same design of PID1 controller in the first step.We add PID2 controller to control the position of the pivot. In this step, PID1 need not change any more. We can adjust the parameters of PID2.The parameters of PID2 controller of the inverted pendulum are given as follows.

PID2: $P_2 = 19$ $I_2 = 13$ $D_2 = 3$



(a)



(b)

2.(a) one PID control design [4]
2.(b) two PID controller design [4]

4.2 MAKING THE FUZZY CONTROLLER :

The design procedure is to gradually make the linear fuzzy controller. It is common practice to build a rule base from term such as Pos, Zero, and Neg, representing labels of fuzzy sets. An input family may consist of those three terms. Consequently, with two inputs it is possible to build 5X5=25 rules. Nine rules is amanageable amount often used in practice. The shape of the sets and the choice of rules affect the control strategy and the dynamics of the closed loop system. There are essentially four characteristic shapes of the control surface.

4.3 STRUCTURE OF INVERTED PENDULUM:

4.3.1. Fuzzy PID controller: fuzzy PID controller is a automatically tunning a value. And outputparameters of PID is $K_P, K_I, \& K_d$.The fuzzy PID controller has been implemented using fuzzy logic. It is a closed loop system the reference signal is taken, fuzzy self-tuning controller is governed by two inputs & three out puts. Inputs used are error & derivative of error .outputs are parameters of PID is $K_P, K_I, \& K_d$ these parameter are given to PID controller and further controlling of system is done. Fuzzy self-tuning controller if we do not take an account of fuzzy self-tuning controller then.Our output will show non linearity It will be affected by time lagging or time delay.

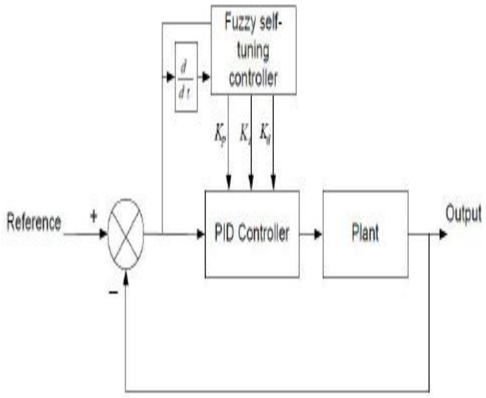


Fig.3
Block Diagrom Fuzzy PID Controller[4]

4.3.2.Fuzzy Logic Controller FLC structure:

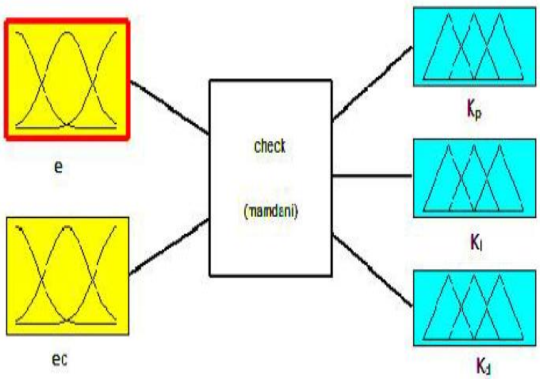
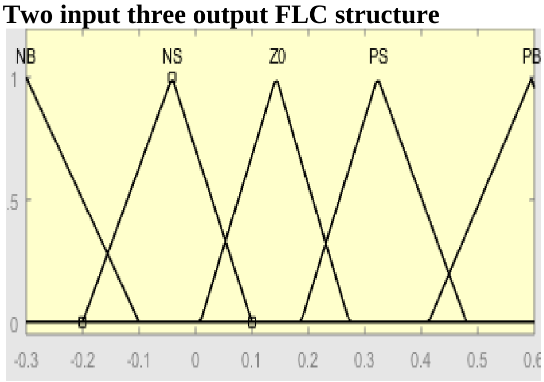
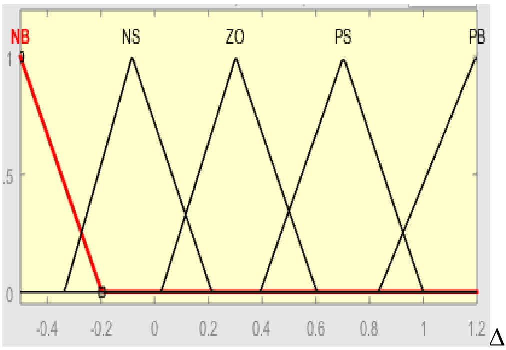


Fig.4
Two input three output FLC structure



e

Fig.5(a)Membership function structure of error e



Δe

Fig.5(b)Membership function structure of error(Δe)

The output membership functions are shown in Figure 4. For the output fuzzy sets the scaling of range has been done corresponding to the formulas.

$$K_p' = \frac{Kp - K_{pmin}}{K_{pmax} - K_{pmin}}$$

$$K_i' = \frac{Ki - K_{imin}}{K_{imax} - K_{imin}}$$

$$K_d' = \frac{K_d - K_{dmin}}{K_{dmax} - K_{dmin}}$$

The minimum and maximum values of various gains have been obtained by analyzing the step response using trail error method.

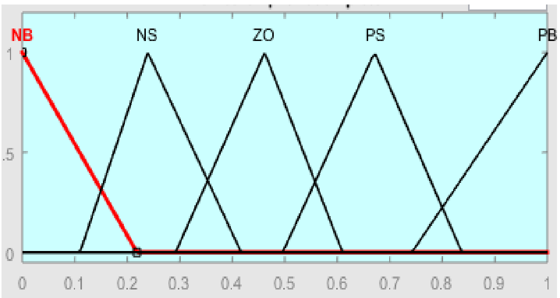


Fig.5(c)

Output fuzzy setK_P, K_I, K_d

The rule base for the fuzzy-PID controller is shown in Table1 which can be implemented for tuning the PID Controller.

Input fuzzy sets (a) error (e) (b) Change of error (Δe)

The rule base is defined as follows:

IF error e is NB and derivative of error de/dt is also NB then output variable i.e. K_P, K_I, K_d will be NB and if e is Z and derivative of error de/dt is NS then output will NS and soon.

Δe/e	NB	NS	ZO	PS	PB
NB	NB	NB	NS	NS	ZO
NS	NB	NS	NS	ZO	PS
ZO	NS	NS	ZO	PS	PS
PS	NS	ZO	PS	PS	PB
PB	ZO	PS	PS	PB	PB

Table-1 Rule base for fuzzy PID controller

5. RESULTS AND DISCUSSION

In this work the PID controller is used to stabilize the Inverted pendulum. The PID controller is tuned with different techniques and there simulation results are compared and discussed in this section.

5.1Trial And Error Method:In this method the PID controllers are tuned by hit and trial method.
The simulation results are shown in figure 6(a) and 6(b)

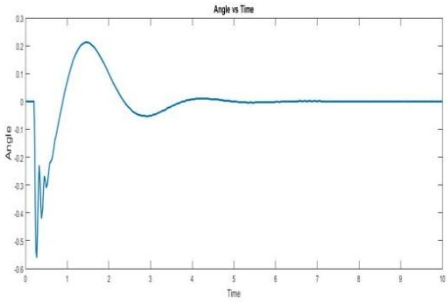


Figure 6(a) Angle vs. time curve

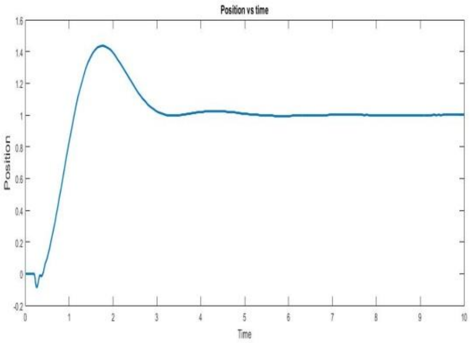


Figure 6(b) Position vs. time curve

5.2Result using fuzzy PID control and technique:

The fuzzy PID controller has been implemented using fuzzylogic. It is a closed loop system the reference signal is taken, fuzzy self-tuning controller is governed by two inputs &three out puts. Inputs used are error & derivative of error .outputs are parameters of PID is Kp, ki, & kd these parameter are given to PID controller and further controlling of system is done. In figure 7 results of position controller for fuzzy PID are shown

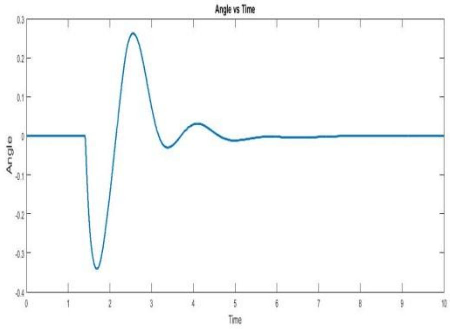


Figure7(a) Angle vs. time curve

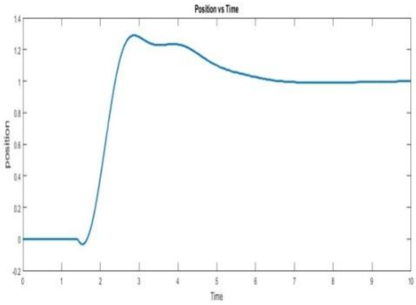


Figure 7(b)Position vs. time curve

In table (2) performance parameters of Position controller & angle controller of Fuzzy PID and trial and error are compared

parameter	PID	Fuzzy PID
overshoot	1.435	1.28
Settling time	6.5	5.2

Table 2.1 performance parameter of position curve

parameter	PID	Fuzzy PID
overshoot	0.215	0.265
Settling time	6.4	

Table 2.2 performance parameter of angle curve

V. CONCLUSION

The stabilization of inverted pendulum system has done .using PID controllers tuned by trail error techniques are also by using fuzzy logic controllersThe result have been shown the conclusion which can be drawn from the results is that the parameter of fuzzy PID controller is better than PID controller tuned by trail error techniques for position tracking and angle stabilization in terms of overshoot and undershoot.

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