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Tuning of PID Controller for A Sun Seeker System Using Fuzzy Logic

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ABSTRACT

In this paper, we utilize the potential of using computational software based methodology in controllers for a sun seeker system. In sun seeker system, PID controller is used due to simple control structure, robustness, wide range of applicability, etc. The controller can provide control action designed for specific process requirements, by tuning the three constants in the PID controller algorithm. But in the conventional tuning method, the PID controllers are not very efficient because of the presence of nonlinearity in the system of the plant and also it has a quite high overshoot and settling time. This paper presents a formal new methodology that is fuzzy control to design and tune PID controller for obtaining better dynamic and static performance at the output. This paper also discusses the benefits of the soft computing methods.

Key Words: Sun-Seeker, Fuzzy Logic control, PID-controller

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INTRODUCTION

A proportional-integral-derivative controller (PID controller) is a generic control loop feedback mechanism. It was an essential element of early governors, and it became the standard tool when process control emerged in the 1940s. PID controllers are today found in all areas where control is used, approximately 95% of the control loops are of PID type. However, there are three control parameters of PID controller and the response of control loop is greatly dependent on these parameters to achieve the best performance from the system. There are several tuning methods have been proposed, such as Ziegler-Nichols (Z-N) method (Hang et al, 1991; Åström et al, 1984), Cohen-Coon (C-C) method (Yuwana and Dale, 1982), Chien-Hrones-Reswick (CHR) method (Chien, 1972), etc. But these methods fail to obtain the optimum value of control parameters for a nonlinear system where the uncertain variations of system parameters occur. Those tuning methods give time-consuming process (Mang and Atherton, 1993; Åström and Hägglund, 2004), instability (Saeed, and Mahdi, 2003), decrements of control action (Kumar and Negi, 2012), etc.

In recent years, optimization techniques advanced rapidly, and considerable progress has been achieved. Using modern optimization techniques, it is possible to tune a PID controller based on the actual transfer function of the plant to optimize the closed-loop performance. For auto-tuning the control parameters for a non-linear dynamic system, the fuzzy logic control (FLC) has attracted the attention for past several years (Antoniou and Wu-Sheng, 2007; Woo et al, 2000).

The aim of this paper is to tune a PID controller for the sun seeker system by using FLC. But being uncertain in nature, it is difficult to control a sun seeker system using PID controller. It is the reason that FLC strategy is applied. FLC is effective at finding high performance areas in large domains and is the ideal choice to tune the PID controller.

SUN SEEKER SYSTEM

Fig-1 shows a schematic diagram of sun seeker system. It is a navigational instrument used by spacecraft to detect the position of sun. Sun seeker system is the part of altitude control which is often needed so that spacecraft high-gain antenna may be accurately pointed to Earth for communications. It is a simple analogue sensor that measures the angular displacement between solar axis and vehicle axis by two silicon solar cell mounted behind a rectangular solar optical slit or window. The solar cells have been specifically designed to ensure low dark current and low radiation sensitivity.

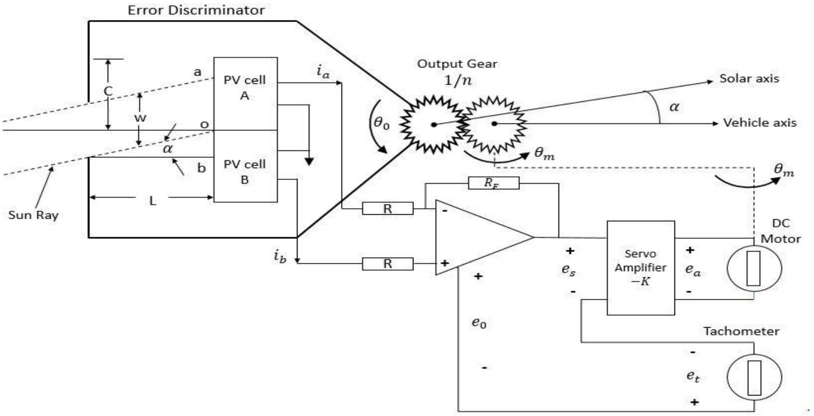

Fig-1: Schematic diagram of a sun seeker system (Golnaraghi and Kuo, 2010)

Note Solar cells serve as current source and are connected to the two opposite polarity input of an op-amp which is connected to a dc motor via servo amplifier. When the sensor is exactly pointed to the sun, the beam of light equally overlaps on both cells which produce same amount of current. But when the vehicle axis is not aligned with the solar axis, the light from the slit does not overlap on solar cells equally. Thus an error signal will be present at the output of op-amp in form of voltage. The error voltage, feeds to the servo amplifier, causes the motor to drive the system back into alignment. The main objective of a sun seeker control system is to reduce the angular displacement between the solar axis and vehicle axis. The center of output gear is considered as the center of the co-ordinate, and the fixed frame of dc motor is taken as the fixed axis. All rotations are measured on this fixed axis. The solar axis or the line from the sun to the output gear makes an angle,

$\theta_r(t)$ on the fixed axis, and vehicle axis makes an angle $\theta_o(t)$ on fixed axis. The main objective of sun seeker control system is to maintain error, α (t) between $\theta_r(t)$ and $\theta_o(t)$ near zero (Golnaraghi and Kuo, 2010).

$$\alpha(t) = \theta_r(t) - \theta_o(t) \qquad (1)$$

The co-ordinate system is illustrated in Fig-2.

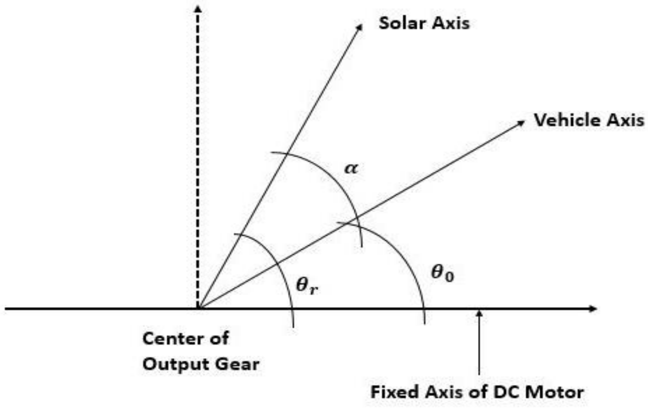

Fig-2: The co-ordinate system of the sun seeker system

When the vehicle is perfectly aligned with sun, then *α(t)* = *0*, and $i_a = i_b = I$ or $i_a = i_b = 0$. The solar cell currents $i_a(t)$ and $i_b(t)$ are proportional to the width of sun ray that shines on solar cell-A and solar cell-B respectively and can be expressed as,

$$i_a(t) = I + \frac{2LI}{W}\tan\alpha(t) \qquad (2)$$

$$i_b(t) = I - \frac{2LI}{W}\tan\alpha(t) \qquad (3)$$

for $0 \le \tan\alpha(t) \le \frac{W}{2LI}$. For $\tan\alpha(t) = \frac{W}{2Li}$ the sun ray is completely on cell A that means $i_a(t) = 2I$ and $i_b(t) = 0$.

The relationship between the out of op-amp and the currents i_a and i_b is,

$$e_o(t) = -R_f(i_a(t) - i_b(t)) \qquad (4)$$

and the output of the servo amplifier can be expressed as,

$$e_o(t) = -R\ (e_o(t) - e_t(t)) \qquad (5)$$

The relationship between angular position of output gear and the motor position can be expressed through the gear ratio $1/n$ as follow,

$$\theta_o = \frac{1}{n}\theta_n \qquad (6)$$

The torque equation of dc motor can be expressed as,

$$T_m(t) = J\frac{d\omega_m(t)}{dt} + B\omega_m(t) \qquad (7)$$

where J is rotor inertia, ω_m is angular velocity of motor and B is the viscous-friction coefficient. A block diagram that characterizes all functional relations described of the system by equation (1-7) is given in Fig-3.

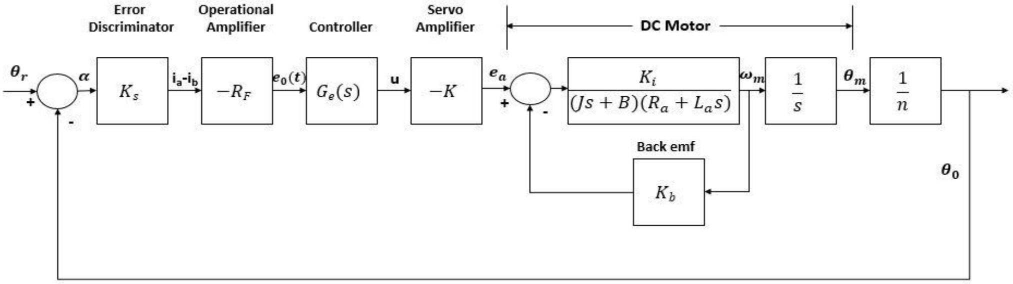

Fig-3: Block diagram of a sun seeker system

The transfer function of the sun seeker system (Golnaraghi and Kuo, 2010) is given below,

$$G(s) = \frac{k_s K_f K K_i}{ns[L_a I s^2 + IR_a s + K_i K_b} \qquad (8)$$

Where,

K_s = Gain of error discriminator
K_i = Torque constant
K = Gain of servo amplifier
K_b = Back *emf* constant of motor
L_a = Armature inductance
R_a= Armature resistance
$\frac{1}{n}$ = Gear-train ratio

PID CONTROLLER

PID controller is the most common form of feedback control. It is often combined with logic, sequential functions, selectors, and simple function block to build a complicated automation system (Ang et al, 2005). PID controller has three control modes (Proportional mode, Integral mode and Derivative mode) and each mode reacts differently on error.

The proportional control mode is the principle controlling action of PID controller. It changes the controller's output proportionally with the error. If the error increases, the control action also increases proportionally. The adjustable setting or controller gain for proportional control is denoted as K_p.

The integral control mode increases or decreases the controller's output over time to reduce error, as long as there is any error. The integral mode will change (increase or decrease) the controller's output according to the nature of error. The gain for integral control is denoted as K_i.

The derivative control mode takes action on basis of the rate of change of error. The derivative mode takes more control action if the rate of change of error is high. If it remains constant with time, then there is no derivative action. The gain for derivative control is denoted as K_d. PID controller is the combination of these three control modes and produces desired control signal for a particular plant or process. The block diagram of PID controller is given in Fig-4.

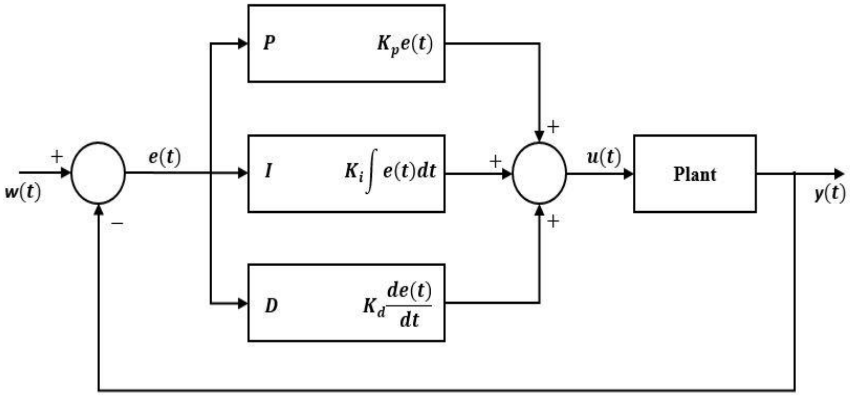

Fig-4: Block diagram of a parallel PID control system (Skogestad, 2003)

The mathematical expression for PID controller can be written from the help of block diagram as,

$$u(t) = k_p e(t) + k_i \int e(t)dt + k_d \frac{de(t)}{dt} \qquad (9)$$

and also in Laplace domain,

$$U(s) = K_p + \frac{k_i}{s} + k_d s \qquad (10)$$

where $u(t)$ is control signal to the system or plant, the error signal $e(t)$ is defined as the difference between the feedback signal $y(t)$ and reference input signal $w(t)$.

As it can be seen from equation (9) and (10), a numerical change in any individual controller gain K_p, K_i and K_d changes the contribution of the corresponding controller to the system dynamic and steady-state responses. Those three control parameters are dependent to each other and changing the value of any of these parameters will affect the others. So it is important to find the optimum value of those parameters to achieve the desired characteristics of a closed loop system.

Tuning a control loop means the adjustment of its control parameters (proportional gain, integral gain and derivative gain) to the optimum values at which desired control response is achieved. PID tuning is difficult because it has to satisfy the complex criteria within the limitations of PID controller. There are several tuning methods like (Z-N), (C-C), (CHR) method (Chopra et al, 2014) etc. These methods are called classical or conventional method. But these methods are often failed to achieve the desired performance of controller. So to achieve better performance from PID controller FLC can be applied as an unconventional method.

FUZZY LOGIC CONTROL

Fuzzy logic is based on the mathematical theory of fuzzy sets which is extension or generalization of classical or crisp set theory. Fuzzy logic provides an inference system in which decisions are without discontinuities, flexible and non-linear i.e. closer to human brain. It looks at the world of uncertain and inaccurate terms then responds with precise action (Yen and Reza, 1998). The basic block diagram of a fuzzy logic controller is given in Fig-5.

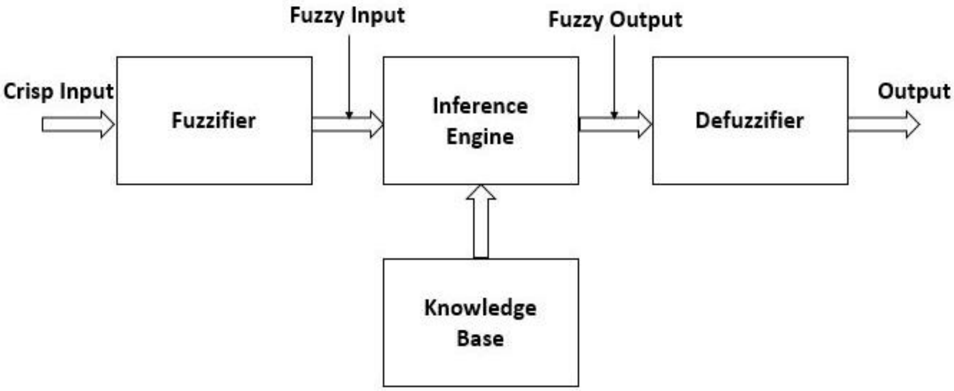

Fig-5: Block diagram of a fuzzy logic controller (Lee, 1990).

A FLC system consists of four basic components as follow,

- ***Fuzzifier***
- ***Knowledge Base***
- ***Inference Engine***
- ***Defuzzifier***

Fuzzifier

The component which performs the fuzzification process *i.e.* converts the classical variable to fuzzy variable, is called fuzzifier. The classical variables are required to convert to fuzzy variable in order to process them in fuzzy inference engine. Fuzzification process involves two tasks: assigning membership function to input and output and representing them in linguistic variable.

Knowledge Base

The knowledge base of fuzzy logic controller consists of a data base and a rule base. The function of data base is to provide the essential information for proper functioning of the fuzzifier, defuzzifier and the rule base. The rule base provides the expert knowledge in form IF-THEN rules for inference engine.

Inference Engine

The fuzzy inference engine is the heart of FLC. According to rule base it has the capability to perform operation on fuzzy input variables. The fuzzy outputs or conclusions are the combination of input-output membership function and the fuzzy rules (IF-THEN rules). Most common type inference engines are as follow,

i. Mamdani Fuzzy Inference System
ii. Sugeno Fuzzy Inference System

These two types of inference system vary somewhat in the way outputs are determined.

Defuzzifier

A de-fuzzifier is a module which carries out the process of de-fuzzification. The de-fuzzification process is meant to convert the fuzzy output back to the crisp or classical output to the control objective.

The output or conclusion of fuzzy inference is linguistic variable and it has to be converting to classical variable or values to understand. There are three commonly used de-fuzzification method as follow,

i. Mean of Maximum (MOM) method
ii. Center of Gravity (COG) method
iii. The Height Method (HM)

ARCHITECTURE OF FUZZY PID CONTROLLER

A fuzzy PID controller is a special kind of PID controller whose three control parameters (K_p,K_i and K_d) are tuned by using fuzzy logic controller. Conventional tuning methods fail to tune the control parameter of a PID controller for a non-linear system which has uncertain parameter variations. Hence it is necessary to automatically tune these parameters. However, since FLC includes the uncertainties and inaccuracies of the system during the processing, it could be possible solution to determine the control parameters of PID controller for a nonlinear system (Rahmat, 2009; Mann et al, 1999). The basic structure of a fuzzy PID controller is illustrated in Fig-6. In fuzzy logic controller takes two inputs: error signal and rate of change of error signal. The outputs of FLC are K_p, K_i and K_d which are fed to a PID controller.

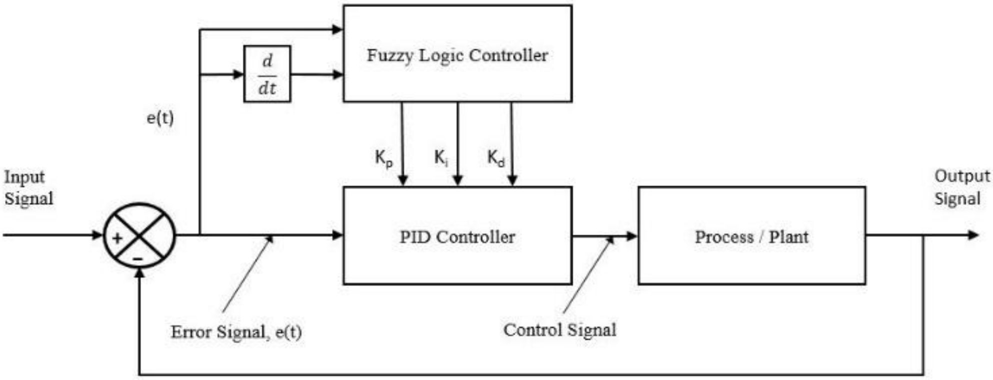

Fig-6: Block diagram of a fuzzy PID controller (Carvajal et al, 2000).

DESIGN PROCEDURE OF FUZZY PID CONTROLLER

The design procedure of fuzzy PID controller is mostly involves designing fuzzy logic controller which includes the process of assigning membership functions for input-output signals, selecting the type of inference engine and de-fuzzification method, and creating rule base for inference engine. Fuzzy logic controller generally takes two inputs: error signal *e* and rate of change of error *ec*, and gives three outputs as K'_p, K'_i and K'_d, which is the initial tuning parameters of PID controller. Mamdani inference model is taken as the fuzzy inference system to obtain the optimum value for K_p, K_i and K_d. Block diagram of fuzzy inference system for PID controller is shown in Fig-7.

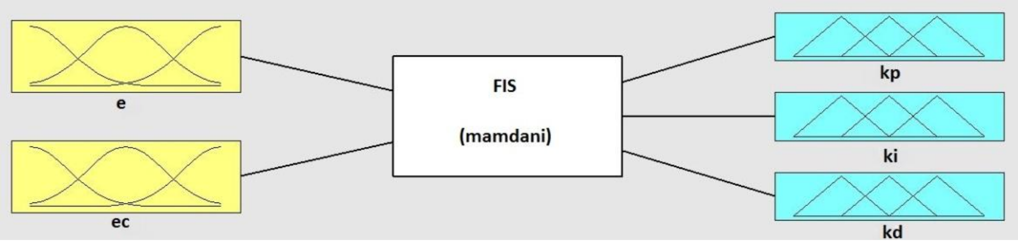

Fig-7: Presentation of fuzzy inference engine in MATLAB fuzzy logic toolbox.

It is assumed that the ranges of parameters K_p, K_i, and K_dK_d are $[K_{p,\min}, K_{p,\max}]$, $[K_{i,\min}, K_{i,\max}]$, $[K_{d,\min}, K_{d,\max}]$ respectively. The appropriate ranges are determined manually. These ranges are given in equations (Xu et al, 2000) as shown below to get optimum value of K_p, K_i and K_d respectively,

$$K_p = K_{p,\max} - K_{p,\min})K'_P + K_{P,\min} \tag{11}$$

$$K_i = K_{i,\max} - K_{i,\min})K'_i + K_{i,\min} \tag{12}$$

$$K_d = K_{d,\max} - K_{d,\min})K'_d + K_{d,\min} \tag{13}$$

The range for each parameter of PID controller for sun seeker system, $K_P \in [10, 62.5]$, $K_i \in [20, 30]$, and $K_d \in [0.01, 0.08]$.

Hence equation (11), (12) and (13) can be represented as,

$$K_p = 52.5K'_P + 10 \tag{14}$$

$$K_i = 10K'_i + 20 \tag{15}$$

$$K_d = 0.07K'_d + 0.01 \tag{16}$$

The initial value of K'_P, K'_i and K'_d are obtained from fuzzy logic controller.

The input fuzzy sets of e and ec are represented with Gaussian membership function ranging from [-1, 1] and the output PID parameters K'_p, K'_i and K'_d are also represented with Gaussian membership function ranging from [0, 1]. The fuzzy variables of fuzzy sets are NB, NM, NS, ZO, PS, PM and PB which represent "negative big", "negative medium", "negative small", "zero", "positive small", "positive medium" and "positive big" respectively. The membership function for e and ec is illustrated in Fig-8, and the membership function for K'_p,K'_i and K'_d is illustrated in Fig-9.

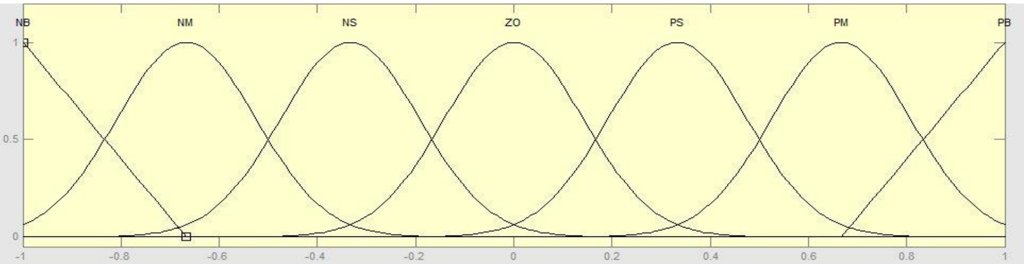

Fig. 8: Membership functions for e and ec

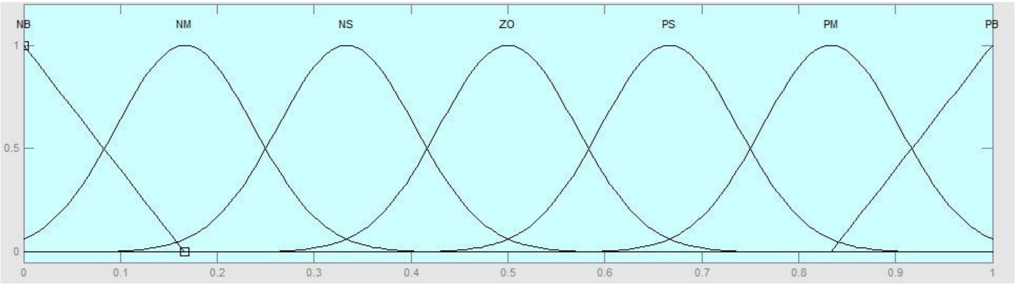

Fig. 9: Membership function for K'_P , K'_i and K'_d K'_p.

According to the number of fuzzy variables of input-output fuzzy sets, each output PID parameter contains $7 \times 7 = 49$ rules as shown in Table-I based on the rules (Lin et al, 2013) are shown as follow,

a. When $|e|$ becomes large, K_p should be set to bigger value, K_d should be set to smaller value for better tracking performance and K_i should be set to zero to prevent integral saturation and heavy overshoot.

b. When $|e|$ and $|ec|$ have medium value, K_i should be set to smaller value while K_p and K_d should be maintained moderate value for rapid response.

c. When $|e|$ becomes smaller, K_p and K_i should be increased for better steady performance while K_d should be set to moderate value to prevent unnecessary oscillation.

Similarly, for K'_i , and K'_d, the fuzzy logic rule base can be created according to above conditions. According to above table the fuzzy rule base is created in form of IF-THEN relationship such as: If $|e|$ is A, and $|ec|$ is B then K'_P is C, K'_i is D K'_d is E.

Table I: Fuzzy control rule table for k'_P (Wang et al, 2013)

e ec	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PB	PM	PM	PS	ZO	ZO
NM	PB	PB	PM	PS	PS	ZO	NS
NS	PM	PM	PM	PS	ZO	NS	NS
ZO	PM	PM	PS	ZO	NS	NM	NM
PS	PS	PS	ZO	NS	NS	NM	NM
PM	PS	ZO	NS	NM	NM	NM	NB
PB	ZO	ZO	NM	NM	NM	NB	NB

SIMULATION RESULT AND PERFORMANCE ANALYSIS

The transfer function of sun seeker system is obtained from equation (8) by putting the value of different constant parameters as follow,

$$G(s) = \frac{1562500}{s^3 + 625s^2 + 156250s} \qquad (17)$$

The tuned values of control parameters obtained for PID controller by using FLC are $K_p = 18925$, $K_i = 28.3$, and $K_d = 0.0405$. The step response of system represented in equation (18) by using fuzzy PID are illustrated in Fig-10.

So it can be seen from the Table-II that the fuzzy PID controller considerably reduces the rise time and settling time. Though some overshoot is appeared but the value of overshoot too much less to cause any disturbance in system. The comparative illustration of step response of the sun seeker system between the fuzzy PID controller and without controller is shown in Fig-11.

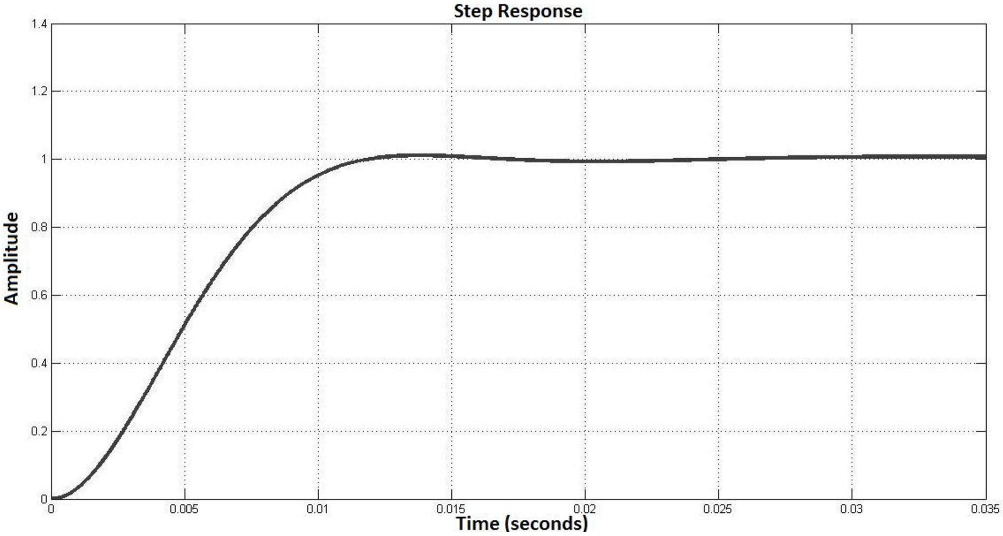

Fig-10: Step response of sun seeker system by using fuzzy PID controller

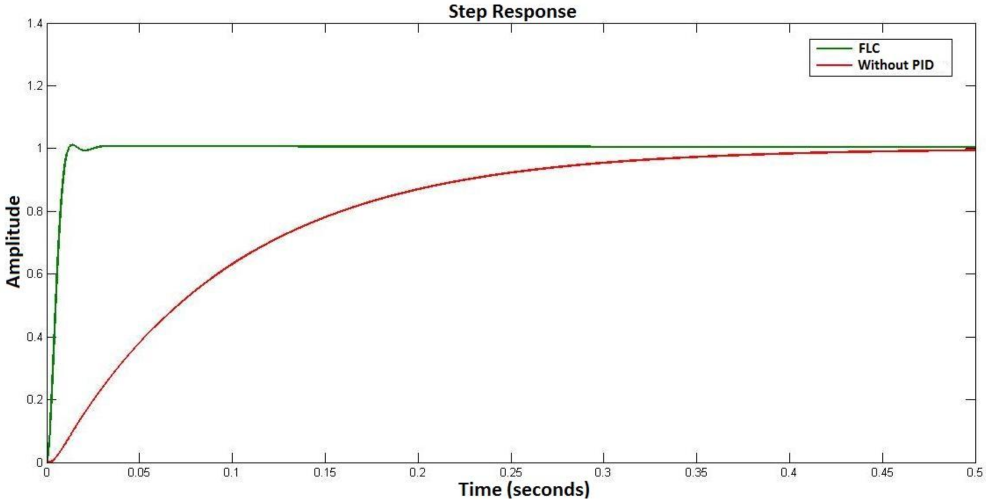

Fig-11: Step response of sun seeker system using FLC and without controller.

The comparative values of different characteristics of the step response of sun seeker system by using fuzzy PID controller and without any controller are represented in Table-II.

Table II: Comparison of Characteristics Values

System	Overshoot (%)	Rise time (sec)	Settling time (sec)
Without Controller	0	0.211	0.379
With Fuzzy PID Controller	1.14	0.0071	0.0108

The PID controller of sun seeker system is also tuned by conventional methods (Z-N, C-C and CHR) and then obtained characteristic values are compared with the characteristic values obtained by using fuzzy tuning method. The comparative characteristic values for different tuning method are shown in Table-III.

Table III: Comparison of Characteristics Values for different *PID* controller tuning methods

Characteristics	Z-N	C-C	CHR	FLC
Overshoot (%)	55.5	62.5	65.9	1.14
Rise time (sec)	0.0036	0.00958	0.0123	0.0071
Settling time (sec)	0.0343	0.17	0.282	0.0108

From Table-III, it could be concluded that the FLC gives the optimum value of control parameters for PID controller. Though the Z-N tuning method gives less rise time than the FLC, it suffers from the tendency of introducing high overshoot which causes large disturbance in system. The comparative step response of sun seeker system for different PID controller tuning method is illustrated in Fig-12.

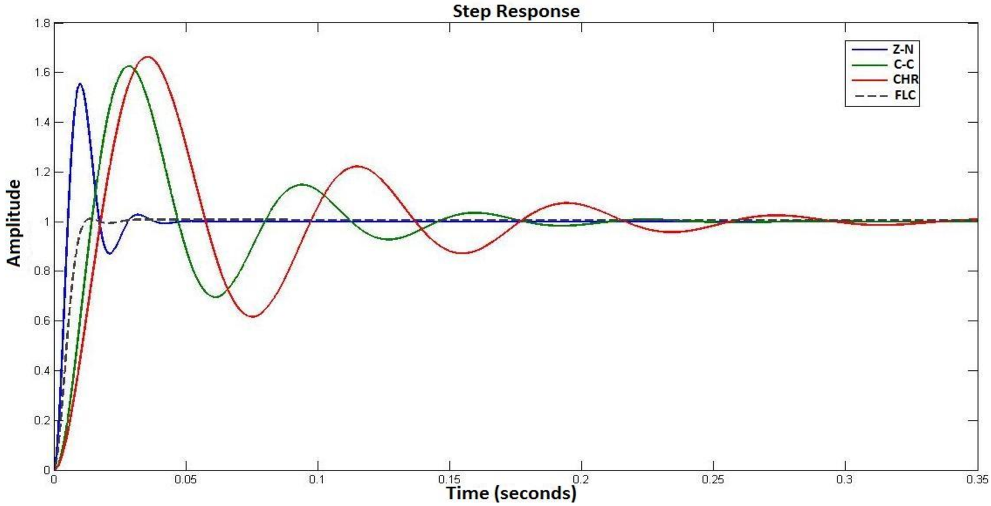

Fig-12: Step response for different PID controller tuning methods

CONCLUSION

To get the better performance from a control system, it is necessary to reduce both the rise time and settling time simultaneously. Fuzzy logic technique successfully eliminates the most part of overshoot from the output response. As well as, settling time and rise time will also be reduced by using this type of control system. The simulation results show that compared to the traditional PID controller, fuzzy self-tuning PID controller has a better dynamic response curve, shorter response time, small overshoot, high steady precision, good static and dynamic performance. The tuning of fuzzy mechanism parameters plays a key role in the practical applicability of the methodologies, since it determines the improvement in the cost per benefit ratio with respect to standard methods.

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