Fuzzy PI Controller for Single Board Heater System

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***Abstract*—In recent decades, fuzzy logic controllers have grown in significance for managing intricate operations. Clarifying the fuzzy controllers' underlying analytical structure is crucial for improving control performance when utilizing such controllers. In industrial fuzzy logic control design, membership functions with triangles and trapezoids are typically quite prevalent. In this study, a fuzzy PI controller for regulating the system temperature of a single-board heater is designed and implemented. Here, we derive an analytical control structure with singleton fuzzy sets as output variables and Gaussian membership functions as input variables. The suggested controller shows how well fuzzy PI controllers work when used to manage temperature in a single-board heating system in real-time. The standard tracking and disturbance rejection modes of the controllers using proposed controller are efficiently implemented on the single board heating system.**

***Index Terms*—PI Controller, Fuzzy PI Controller (FPI), Formula-based Fuzzy Controller (FBFC), Gaussian Membership Function (GMF), Single Board Heater System (SBHS).**

I. Introduction

CONTROL systems play big role in the growth and development of present-day evolution and technology. Most of the industries use automatic control systems, including quality assurance of manufactured goods, fully automatic assembly lines, machine tool controls, space technology and military systems, computer control, power systems, robotics, and many such applications. Derivative action is utilized to deliver a quicker action, but it cannot reject disturbance modifications. The integral action is employed to reject disturbance and set point changes. PI controllers are frequently employed in many process industries. Discrete PI controller and fuzzy logic controller can be developed using the various discretizing methods listed in [1], that offers quicker response time and better tracking. A conventional PID controller is a very popular industrial controller [2] because of its ease of use and inexpensiveness, but is not appropriate for controlling nonlinear and complex systems.

The Single Board Heater System (SBHS) system developed by Nex-Robotics and IIT-Bombay is useful for implementing variety of discrete PI controller algorithm and Fuzzy Logic algorithms. The heater assembly with a tiny time constant and a dead time of SBHS results into miniature temperature control system [3]. PD controllers offers faster response time but cannot remove offset errors caused by load variations. Multiple discrete PI controller algorithms implemented in SBHS helps the students understand control system [4].

The simplest Takagi-Sugano fuzzy controllers based on modified rules and analytical structure reduces the controller tuning parameters empowers fuzzy controller to beat the linear controllers [5]. A nonlinear fault-tolerant control system with sensor errors by means of T-S fuzzy model approach based on the incorrect reconstruction information can compensate for the consequences of the inaccuracies and boost the system's reliability [6].

Many complex nonlinear processes can be successfully controlled using fuzzy logic controllers (FLCs). The mathematical framework underlying such fuzzy logic control is still unknown. This depicts the need for the analytical structure of fuzzy controllers to be derived to develop a solid foundation for better grasp, fluent analysis, and more realistic design of fuzzy control systems [7]. Analytical structures are necessary for the control system analysis and design such as stability analysis. Deriving the analytical structures requires the input space to be distributed into a set of Input Combination (ICs) regions formed by superimposing input membership functions to get an analytical structure [8]. The membership functions which is triangular one decipher the underlying analytical structure of fuzzy PI/PD controllers to provide various fuzzy controllers, combinations of fuzzy PI & fuzzy PD controllers. The Mamdani inference method and the Zadeh fuzzy logic centroid defuzzification method [9] are commonly used to derive the analytical structure. H. Ying [10] developed such a technique by using the trapezoidal/triangular membership function on various configurations of generalised fuzzy PI, PD, and PID controllers. Kai [11] also developed an efficient way for developing analytical structure-based fuzzy PI controllers for batch sintering operations.

The precise models of fuzzy PI/PD controllers with randomly distributed several fuzzy sets and Center of Area (CoA) defuzzification is presented in [12]. These controllers when tested on a DC series motor nonlinear system and a plant with dead time depicts the effectiveness and excellent performance. The recent study [13] presents mathematical modeling technique using simplest T-S fuzzy, Two-Input, Two-Output PI and PD controller. The resulting model of the fuzzy PI/PD controller reveals a variable gain/structure controller. Application of the same to a two-link manipulator and coupled tank system controller results into an effective & robust behaviour.

Furthermore, the intricate and eloquent nature of fuzzy sets, fuzzy logic, and fuzzy rules makes fuzzy models more natural and easier to understand than neural network models. However, determining the structure and parameters of the controller based on the supplied system model and achieving

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the control performance requested by the user is extremely difficult [14]. The most basic fuzzy controllers analytical structure using a modified rule base [15,16] is created and tested. A rule base consisting only two rules reduces number of controller parameters to be tuned which explores gain variation and computation time feature of fuzzy controller. A mathematical model of the Mamdani type simple PI/PD controller disclosed in [17] uses 2 fuzzy sets for the 2 input elements and 3 fuzzy sets for an output element. Each controller is an individual nonlinear PI/PD controllers having input gains varying with corresponding proportional and derivative gains. The model presented has proved to be the most significant and helpful as it was completely new and with different quality.

The simplest fuzzy PI controller using triangular membership function [18] reveals the comparative study of derived fuzzy PI controllers and traditional PI controllers with effectiveness of fuzzy PI controllers. The stability of this fuzzy PI controller was investigated via the well-known small gain theorem. The similar work in which a mathematical model of the simplest fuzzy PID controller is derived using two fuzzy sets for three input elements each and four fuzzy sets for an output element is discussed in [19]. A nonlinear T-S fuzzy PID controllers with several fuzzy sets is presented in [20]. In this a rule-base with four rules is recommended to lessen the number parameters to be tuned. The controller is modeled as a nonlinear variable gain/structure controllers where the gain is a function of the input variables, and structure of the controller in turn varies in input space.

A similar work on parallel fuzzy proportional, integral and derivative controllers with variable gain is published in [21,22]. The bounded input, bounded output stability of the fuzzy controller was investigated using "small gain theorem". It is observed that the controller offers much better tracking with high disturbance and noise rejection compared to conventional PID controller. Therefore, to understand exactly why and how fuzzy controllers work, it becomes essential to understand the underlying analytical form of such controllers.

According to the literature review, many individuals have experimented with the triangular membership function for deriving formula based fuzzy PID controllers as it becomes easy to calculate formulas due to their idealized properties. As the nature of membership function plays an important role in controller design it is also possible to substitute a different membership function & evaluate its performance [2,23]. Gaussian functions have gained more popularity in fuzzy literature as the function derivative is much smooth and continuous, which could ease their mathematical analysis than any other function. Most of the traditional real-time fuzzy controllers typically use Gaussian membership functions (GMFs) [24].

The GMF representation is very simple. All other membership functions require many parameters to express them, while this one requires only two parameters. Reducing the number of parameters results in decreasing degrees of freedom (DOF), resulting in a robust fuzzy controller. In addition, GMF guarantees a continuous control surface regardless of the type of reduction and elimination methods used. The experimental results also show that GMF is faster when the rule base is smaller [25,26]. From a statistical point of view, a Gaussian membership function might be more in line with your point of view. Because people often describe their thought processes as normally distributed. Therefore, it is very important to study fuzzy controllers based on analytical structures with Gaussian membership functions.

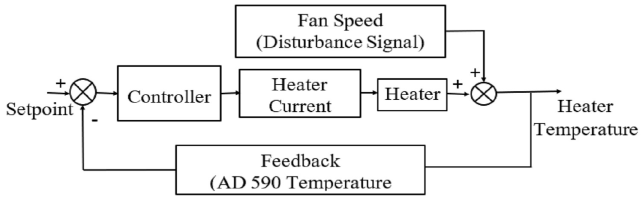

Fig. 1. SBHS Block Schematic

II. SYSTEM DESCRIPTION

The SBHS is a portable, low-cost laboratory device suitable for performing a variety of control experiments, from the characterization of open-loop systems such as step and ramp tests, to two degrees of freedom (2DOF) closed-loop control systems. SBHS is a very small plant or process with a time constant of around 1 minute. Figure 1 shows the SBHS conformation which mimics the temperature control problem. It consists of a coil, 5x2 cm steel plate, fan, and a temperature sensor. An 8-bit ATmega16L microcontroller, LCD display, instrumentation amplifier, and related circuitry are integral part of it.

The main task is to keep the temperature of the plate at the chosen level. Evenly spaced 20 turns of nichrome wire forms 5x11 mm coil of 0.7mm diameter. The coil fits on a 3.5mm metal plate which in turn acts as a system heating element. The AD590 acts as a temperature sensor, attached to a metal plate. The metal plate temperature changes in accordance with current flowing through the coil. The fan placed near heating plate is interfered with the heating system.

Microcontroller is the heart of SBHS setup. It converts the analog signal of temperature into a digital signal, does serial communication with the computer and displays the temperature on the LCD display. It also generates PWM signals for the heating coil and the fan. Microcontroller has on-chip programmable flash memory, 4 PWM channels, an 8-channel 10-bit ADC, universal programmable serial asynchronous receiver and transmitter (UART), and 32 input lines and general-purpose outlet which makes it suitable for the intended application. The heater configuration takes one ADC channel for temperature measurement and 2 PWM channels for the heater coil and fan. The LCD screen installed above the MCU displays the temperature, fan and heater coil and the serial port set point values.

The Timer 1 of the microcontroller is used to generate an 8-bit PWM signal of frequency 488 Hz, which is transmitted to the heating coil and the fan. The microcontroller is programmed to control the current going to the heater coil and fan speed. It also displays and communicates the metal plate temperature by using Scilab an opensource software for monitoring and numerical calculations. The SBHS communicates with 9600 baud using 8-bit data, no parity, and no protocol. It supports serial and USB communication ports so one can use a laptop or PC. The fan speed and coil current are the inputs and plate temperature is the output of SBHS. A discrete controller built in Scilab sends 254 bytes

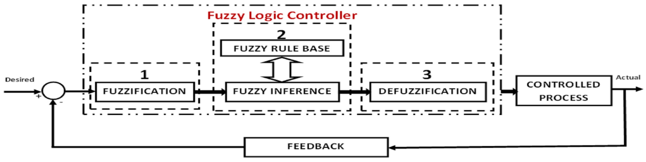

Fig. 2. Basic Fuzzy Logic Controller

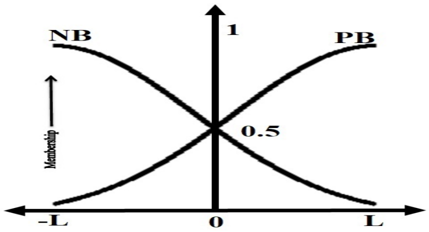

Fig. 3. Input Gaussian Membership Functions

to manipulate the coil current. A sampling time of 1s is used to perform experiments on the SBHS.

III. DESIGN OF FUZZY CONTROLLER

Figure 2 shows fuzzification, fuzzy rule base & fuzzy inference and defuzzification as the building blocks of a general fuzzy logic controller. The error; $e(nT)$ and the error rate; $r(nT)$, are the two input variables.

$$e(nT) = SP(nT) - y(nT)$$
$$r(nT) = e(nT) - e(nT - T) \quad (1)$$

where, n is a positive number, T is the sampling time, $SP(nT)$ is the point, and y(nT) is the output. Every input is initially divided into two fuzzy variables, Positive Big (PB) and Negative Big (NB). The proposed formula-based fuzzy PI controller is built on equation 2,

$$\Delta u_{PI}(nT) = K_p.r(nT) + K_r.e(nT) \quad (2)$$

where, $\Delta u_{PI}(nT)$ is the additive controller output. where; the error; $e(nT)$, the error rate; $r(nT)$ are the two inputs of the controller, and $\Delta u_{PI}(nT)$ the relevant output.

The proposed formula-based fuzzy PI controller uses two Gaussian membership functions at the input and three singleton membership functions at the output, as shown in Figure 3 and Figure 4, respectively. The membership function is defined over the interval -L to L, called universe of discourse (UoD). The Figure 5 shows every possible input combinations (ICs) of scaled error and error rate for which a separate formula needs to be derived. The mathematical expression for the Gaussian membership function is given by equation 3,

$$f(x, c, \sigma) = exp^{-(x-c)^2/(2.\sigma^2)} \quad (3)$$

where 'σ' is a factor which decides the shape of the Gaussian curve i.e., the curvature, and 'c' represents midpoint of the curve. These two membership functions are positioned at the centers -L and L. The 'σ' value 'L/1.15' ensures approximate 50 % overlap with adjacent membership function.

The fuzzy controller is derived using following control rules,

Rule 1: IF the Error is NB AND the Error Rate is NB THEN $\Delta u_{PI}(nT)$ is ONB

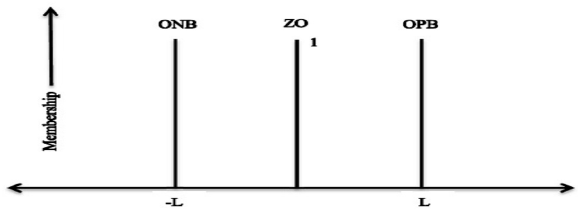

Fig. 4. Output Singleton Membership Functions

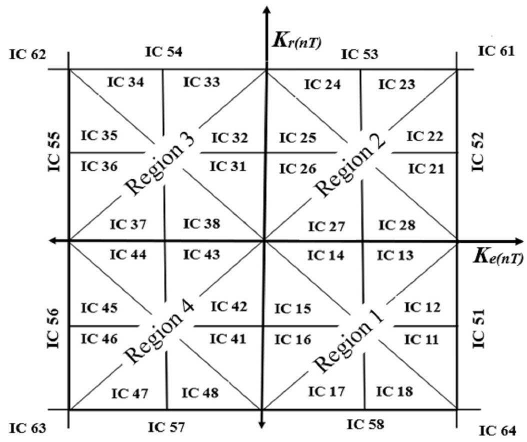

Fig. 5. Regions of FPI controller input IC values

TABLE I
GAUSSIAN MEMBERSHIP FUNCTION DEFINITION

-	Error	Error Rate
Negative	$e_{NB} = e^{-\left(\frac{(Ke+L)^2}{2(L/1.15)^2}\right)}$	$r_{NB} = e^{-\left(\frac{(Kr+L)^2}{2(L/1.15)^2}\right)}$
Positive	$e_{PB} = e^{-\left(\frac{(Ke-L)^2}{2(L/1.15)^2}\right)}$	$r_{PB} = e^{-\left(\frac{(Kr-L)^2}{2(L/1.15)^2}\right)}$

TABLE II
FORMULAE FOR REGION 1, 2

Cell No.	Region 1	Cell No.	Region 2
11,12,13,14	$\frac{L\times(r_{PB}-e_{NB})}{(2(e_{NB})+1)}$	21,22,27,28	$\frac{L\times(r_{PB}-e_{NB})}{(2(e_{NB})+1)}$
15,16,17,18	$\frac{L\times(r_{PB}-e_{NB})}{2((r_{PB})+1)}$	23,24,25,26	$\frac{L\times(e_{PB}-r_{NB})}{2((r_{NB})+1)}$

TABLE III
FORMULAE FOR REGION 3, 4

Cell No.	Region 3	Cell No.	Region 4
31,32,33,34	$\frac{L\times(e_{PB}-r_{NB})}{(2(r_{NB})+1)}$	41,42,47,48	$\frac{L\times(r_{PB}-e_{NB})}{(2(r_{PB})+1)}$
35,36,37,38	$\frac{L\times(e_{PB}-r_{NB})}{2((e_{PB})+1)}$	43,44,45,46	$\frac{L\times(e_{PB}-r_{NB})}{(2(e_{PB})+1)}$

TABLE IV
FORMULAE FOR REGION 5, 6

Cell No.	Region 5	Cell No.	Region 6
51,52	$L\times r_{PB}$	61	L
53,54	$L\times e_{PB}$	62	0
55,56	$-L\times r_{NB}$	63	$-L$
57,58	$-L\times e_{NB}$	63	0

Rule 2: IF the Error is NB AND the Error Rate is PB THEN $\Delta u_{PI}(nT)$ is OZ

Rule 3: IF the Error is PB AND the Error Rate is NB THEN $\Delta u_{PI}(nT)$ is OZ

Rule 4: IF the Error is PB AND the Error Rate is NB THEN $\Delta u_{PI}(nT)$ is OPB

further, the yield of each execution is evaluated using Zadeh Fuzzy logic AND operator with Centroid Defuzzifier. The

TABLE V
STEP RESPONSE PARAMETRIC ANALYSIS OF CONTROLLERS

Sr. No.	Specification Parameter	Conventional PI Controller (%)	Fuzzy PI Controller (%)
1	Peak Overshoot	7.5	1
2	Settling Time	35	20
3	Peak Time	12	25
4	Rise Time	8	19

incremental control output is then given by equation 4 below,

$$\Delta u\,(nT) = \frac{\sum_{i=1}^{4} \Delta ui.\mu i}{\sum_{i=1}^{4} \mu i} \tag{4}$$

The fresh control output of the proposed controller at (n+1)T can be calculated by,

$$u(n+1)T = u(nT) + \Delta u(nT) \tag{5}$$

The steps to be followed [25] in deriving separate formula for 44 different IC regions shown in fig.5 are,

- Define the Universe of Discourse (UoD) L.
- Calculate $e(nT)$ & $r(nT)$ the n^{th} sampling instant using equation 1.
- Multiply it with the respective gains k_{er} and k_{der}, which becomes, Ke(nT), Kr(nT) , where, $K_e(nT) = k_{er}.e(nT)$ and $K_r(nT) = k_{der}.r(nT)$.
- Evaluate the respective membership values $e(NB), e(PB)$ and $r(NB), r(PB)$ using equations given in Table 5.
- Apply the rules from the Control rule base given above in the form of **If-Then–Else** and use the Zadeh **MIN** operator.
- Evaluate the formula using the Centroid Defuzzifier given in equation 4.

All such derived formulae are listed in Tables 2, 3, and 4, respectively.

IV. RESULT AND DISCUSSION

The conventional PI and fuzzy PI controllers have been used to achieve the desired control target. A generic approach is used to tune controller settings. The control objective is to keep the temperature of the SBHS at the chosen level, even in the presence of fan disturbances. A comparison of the results is presented in Figures 6, 7, and 8. The formula-based fuzzy PI controller exhibits less oscillation, reduced overshoot, improved tracking, and offers better rejection to the disturbance as compared to the traditional controllers. The SBHS offers effective parameter tuning techniques for PID controllers, fuzzy logic controllers, and advanced control algorithms based on fuzzy logic. In the experimental testing, the fuzzy PI controller was manually tuned with k_{er} set at 30.4, k_{der} set at 2, and k_{out} ranging from 0.2 to 0.4. The traditional PI controller maintained the parameter values of K_p=9 and K_i=18. The UoD, L is chosen as 1.5 for this controller. The time-domain performance specifications of both the controllers are presented in Tables 5, 6, and 7. The results obtained manifest that the fuzzy PI controller outperforms the conventional PI controller.

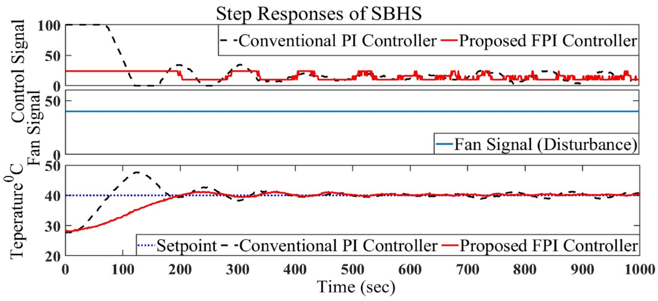

Fig. 6. Step response SBHS for PI TA and Fuzzy PI Controller

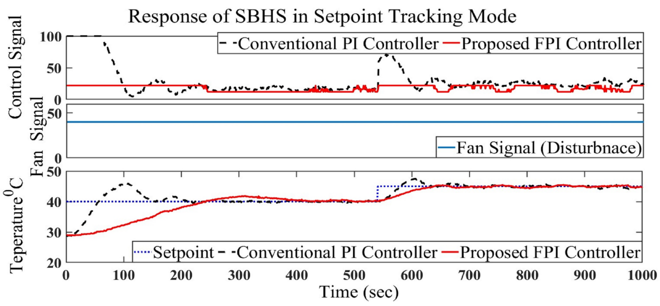

Fig. 7. Set point Tracking response SBHS for PI TA and Fuzzy PI Controller

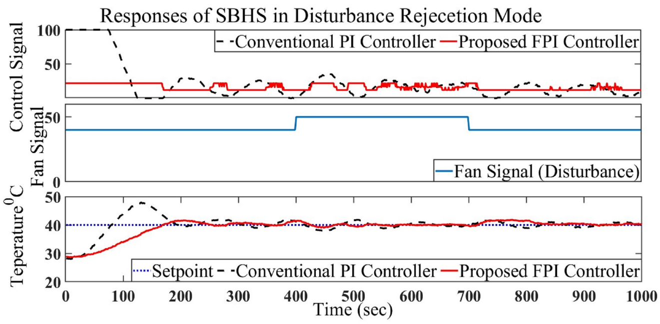

Fig. 8. Disturbance rejection response of SBHS for PI TA and Fuzzy PI Controller

TABLE VI
DISTURBANCE REJECTION PARAMETRIC ANALYSIS OF CONTROLLERS

Sr. No.	Specification Parameter	Conventional PI Controller (%)	Fuzzy PI Controller (%)
1	Peak Overshoot	8	2
2	Settling Time	30	24
3	Peak Time	13	20.8
4	Rise Time	8	17

TABLE VII
SET POINT TRACKING PARAMETRIC ANALYSIS OF CONTROLLERS

Sr. No.	Specification Parameter	Conventional PI Controller (%)	Fuzzy PI Controller (%)
1	Peak Overshoot	7.5	1
2	Settling Time	45	38
3	Peak Time	12	31
4	Rise Time	9	24

V. CONCLUSION

Here, the analytical structure for Fuzzy Proportional Integral (F-PI) controller is derived using Gaussian membership functions. The conventional PI controller exhibits large overshoots & fluctuations despite steeper initial responses. For the system noise rejection test, the fuzzy PI controller response shows very little or no overshoot with shorter settling time. A similar observation was recorded when testing the proposed controller in set-point tracking mode. The research with this focus is most desired to get the bright depiction about formula based fuzzy PI controllers.

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