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Design and Implementation of Intelligent Controllers for Dynamic System

[1]S. Rajendran and [2]S. Palani

[1]Mookambigai College of Engineering, Keeranur, Pudukkottai, Tamilnadu, India-622502
[2]Sudharsan Engineering College, Sathyamangalam, Pudukkottai, Tamilnadu, India-622501

Abstract: A real time implementation of Fuzzy logic controller (FLC) for a spherical tank to control liquid level is studied. Control of liquid level in a spherical tank is highly non-linear due to variation in the area of cross section of level system with change in shape. System identification of spherical tank system is done using black box model which is identified to be non-linear and approximated to be a First order plus dead time model. Here the conventional controller parameters are designed based on Ziegler-Nicholas method and its servo and regulatory responses are compared with Fuzzy logic controller based on Mamdani model. From the response curve, obtained using the above controllers, that fuzzy logic controller gives much improved performance which is measured in terms of overshoot, rise time, set point tracking and performance indices when compared to other conventional controllers.

Key words: Fuzzy controller · PI controller · Spherical tank · System identification

INTRODUCTION

The industrial application of liquid level control is tremendous especially in refineries petroleum and chemical process industries. Usually, level control exists in some of the control loops of a process control system. An evaporator system is one example in which a liquid level control system is a part of control loop. Evaporators are used in many chemical process industries for the purpose of separation of chemical products. Level control is also very important for mixing reactant process. The quality of the product of the mixture depends on the level of the reactants in the mixing tank. Mixing reactant process is a very common process in chemical process industries and food processing industries. Many other industrial applications are concerned with level control, may it be a single loop level control or sometimes multi-loop level control. In some cases, level controls that are available in the industries are for interacting tanks. Hence, level control is one of the control system variables which are very important in process industries. Nowadays, chemical engineering systems are also at the heart of our economics. The process industries such as refineries petrol, petro-chemical industries, paper making and water treatment industries require liquids to be pumped, stored in tanks and then pumped to another tank. In the design of control system, one often has a complicated mathematical model of a system that has been obtained from fundamental physics and chemistry. The above mentioned industries are the vital industries where liquid level and flow control are essential. Many times the liquids will be processed by chemical or mixing treatment in the tanks, but always the level fluid in the tanks must be controlled and the flow between tanks must be regulated. Level and flow control in tanks are the heart of all chemical engineering systems.

The controller designed using fuzzy logic implements human reasoning that has been programmed into fuzzy logic language. It is interesting to note that the success of fuzzy logic control is largely due to the awareness to its many industrial applications. An industrial interest in fuzzy logic control as evidenced by the many publications on the subject in the control literature has created an awareness of its interesting importance by the academic community.

Mathematical Modeling:

Let

q_1-Inlet flow rate to the tank(m^3/min)

q_2-Outlet flow rate to the tank(m^3/min)

h-Height of the spherical tank(m)

H-Height of the liquid level in the tank at any time't'(m)

R-Top radius of the spherical tank(m)

r-Radius of the spherical tank at a particular level of height h(m)

Corresponding Author: S. Rajendran, Mookambigai College of Engineering, Keeranur, Pudukkottai, Tamilnadu, India-622502.

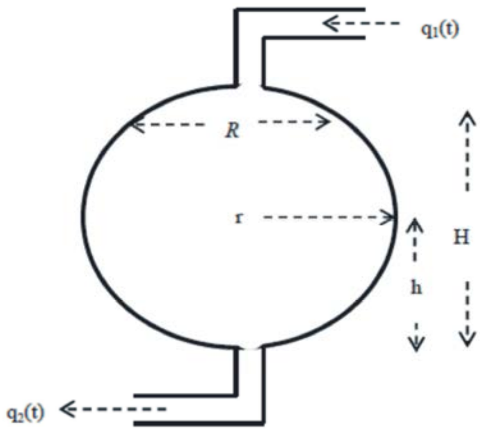

Fig. 1: SPHERICAL TANK

It is quite often the case that we have to design the control system for a process before the process has been constructed. In such a case we need a representation of the process in order to study its dynamic [01] behavior. This representation is usually given in terms of a set of mathematical equations whose solution gives the dynamic or static behavior of the process. The process considered is the spherical tank in which the level of the liquid is desired to be maintained at a constant value. This can be achieved by controlling the input flow into the tank. The spherical tank is shown in Fig. 1. Using the law of mass, Rate of accumulation of mass in the tank = Rate of mass flow in – Rate of mass flow out

The level in spherical tank at any instant is obtained by making mass balance equation as indicated below:

$$\frac{dv}{dt} = q_1 - q_2 \tag{1}$$

where V is the Volume of the tank

$$V = \frac{4}{3}\pi h^3 \tag{2}$$

Applying the steady state value,

$$V - V_s = \frac{4}{3} 3h_s^2 (h - h_s) \tag{3}$$

$$V(s) = 4\pi h_s^2 H(s) \tag{4}$$

$$q_2 = c\sqrt{h_s} \tag{5}$$

where ‘c’ is the valve coefficient

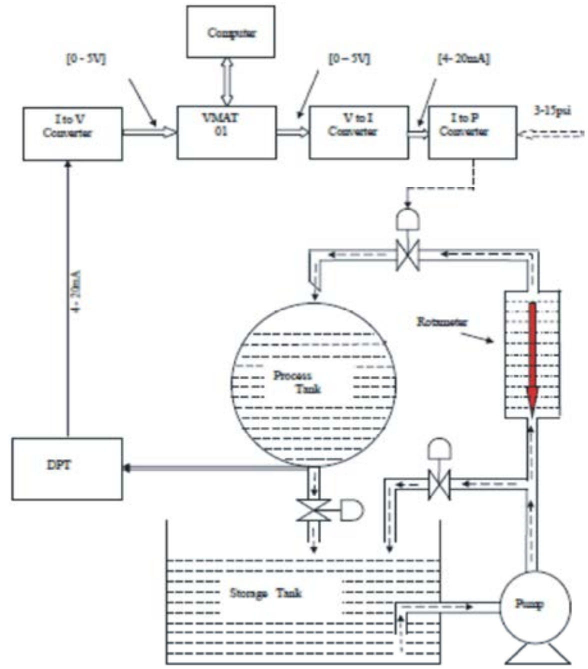

Fig. 2: Block diagram of real time system

$$q_2 - q_2(s) = \frac{1}{2} c h_s^{-\frac{1}{2}} (h - h_s) \tag{6}$$

Linearizing the nonlinearity in the spherical tank

$$Q_2(s) = \frac{c}{2\sqrt{h_s}}, H(s) = \frac{H(s)}{R_t} \tag{7}$$

where $R_t = \frac{2h_s}{Q_2(s)}$

$$Q_1(s) - Q_2(s) = sV(s) \tag{8}$$

$$Q_1(s) - \frac{H(s)}{R_t} = s(4\pi h_s^2)H(s)$$

$$Q_1(s)\mathrm{R}_1 = (4\pi R_1 h_s^2 s + 1)H(s)$$

$$\boxed{\frac{H(s)}{Q_1(s)} = \frac{R_t}{\tau s + 1}} \tag{9}$$

where $\tau = 4\pi R_t h_s^2$

Thus the equation.9 gives the model of the system.

Real Time System

Block Diagram: The real time experimental system consisting of a spherical tank, reservoir and water pump, current to pressure converter, compressor, Differential Pressure Transmitter (DPT), VMAT01 DAQ CARD, I/V converter, V/I converter and a Personal Computer which acts as a controller, forms a closed loop system. The block diagram of this system is shown in Fig. 2.

Real Time System: Fig. 3 shows the real time implementation of the system. The flow rate to the spherical tank is regulated by changing the stem position of the pneumatic valve by passing controlsignal from computer tothe I/P converterthrough VMAT01 DAQ CARD and V/I converter. The operation current for regulating the valveposition is 4-20mA, which is converted to 3-15psi of compressed air pressure. The water level inside the tank is measured with the differential pressure transmitter which is calibrated for 0-40cm and is converted to an output current of 4-20mA.This output current is converted into 0-5V using I/V converter, which is given to the controller through VMAT01 DAQ CARD. The VMAT01 USB based DAQ CARD is used for interfacing the personal computer with the spherical tank [2].

Specifications: The specifications of the real time can be represented as follows

Parts Name		Details
Spherical tank	Body Material	:SS 316
	Diameter	:500mm
	Capacity	:200 litres
Storage Tank	Capacity	:200 litres
	Body Material	:SS 316
Differential Pressure Transmitter	Make	: AB
	Type	: Capacitance
	Input	: 2.5 -250)mbar
	Output	: 4-20mA
Rotameter	Make	:Tellien/Equivalent
	Flow Rate	:(100 - 1000)LPH
	Type	:Variable Area
	Float Material	:SS 316
Control Valve	Type	: Pneumatic air to close
	Input	: 3-15psi
Pump	Make	:Tullu/Kirlosker
	Flow Rate	:1500 LPH
	Supply Voltage	:230VAC/50Hz
Air Regulator	Size	: ¼" BSP
	Range	: 0-2.2bar
I/P Converter	Make	: ABB
	Input	: 4-20m
	Aoutput	: 0.2 -1bar
V/I Converter	Model	: Electronic
	Input	: 1-5V
	Output	:4-20mA
I/V Converter	Model	: Electronic
	Input	: 4-20mA
	Output	:1-5V
Pressure Gauge	Range	: (0-30)psi
	Range	:(0-100)psi
NI6009 DAQ CARD	Input	: 8 Nos.
	Output	: 2 Nos.

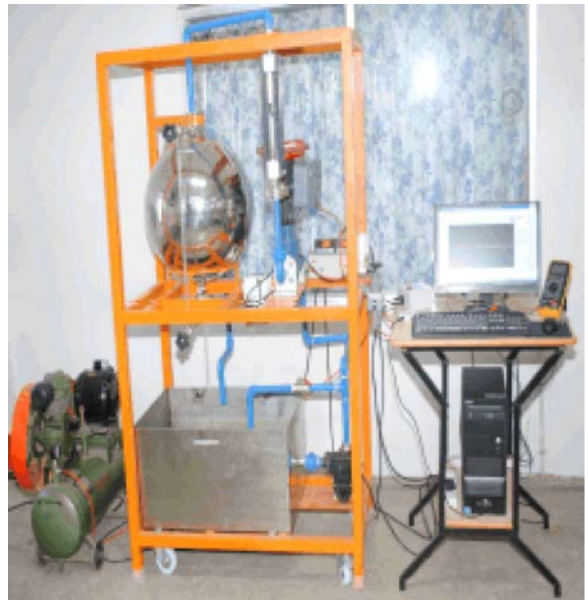

Fig. 3: Real time implementation

Black Box Modeling: System identification for the spherical tank is done using back box modeling in reak time. For fixed input flow rate and output flow rate, the spherical tank is allowed to fill with water from (0-40) cm height. At each sample time, the data from differential pressure transmitter i.e. between (4-20) mA is being collected and fed to the system through the serial port RS-232 using VMAT01 interface module. Thereby the data is scaled up in terms of level (cm). Using the open loop method, for a given change in the input variable, output response for the system is recorded. Ziegler and Nichols [02] have obtained the time constant and time delay of a FOPTD.First order plus time delay] model by constructing a tangent to the experimental open loop step response at its point of inflection. The tangent intersection with the time axis at the step origin provides a time delay estimate; the time constant is estimated by calculating the tangent intersection with the steady state output value divided by the model gain. Cheng and Hung have also proposed tangent and point of inflection methods for estimating FOPTD model parameters. The major disadvantage of all these methods is the difficulty in locating the point of inflection in practice and may not be accurate. Prabhu and Chidambaram [03] have obtained the parameters of the first order plus time delay model from the reaction curve obtained by solving the nonlinear differential equations model of a distillation column. Sundaresan and Krishnaswamy have obtained the parameters of FOPTD transfer function model by letting the response of the actual system and that of the model to

Table 1: Model Parameters for Different Regions

Operating Region	Height (cm)	K_p	τ	L
I	0 -7 cm	2.01	270.68	60.6
II	7 -16 cm	4.94	387.93	835.02
III	16-22 cm	6.273	575.53	822.5
IV	22- 29 cm	5.78	894.45	502.66
V	29 -36 cm	6.32	866.98	506.47
VI	36 - 40 cm	6.35	805.56	456.57

Table 2: PI Tuning Values for Different Regions

Region	Tuning Parameters	
	Kp	τ_I(sec)
0 -7 cm	0.0456	0.0136
7 -16 cm	0.029	0.0063
16-22 cm	0.1912	0.028
22- 29 cm	0.1389	0.00609
29 -36 cm	0.116	0.00346
36 - 40 cm	0.45	0.0110

meet at two points which describe the two parameters τ and L. The proposed times t_1 and t_2, are estimated from a step response curve [3]. This time corresponds to the 35.3% and 85.3% response times. The time constant and time delay are calculated as follows

$$\tau = 0.67(t_2 - t_1)$$

$$L = 1.3t_1 - 0.29t_2$$

At a fixed inlet flow rate, outlet flow rate, the system is allowed to reach the steady state. After that a step increment in the input flow rate is given and various readings are noted till the process becomes stable in the system. The experimental data are approximated to be a FOPDT. Therefore the model for the above system is given by

$$K_p = \frac{\textit{Change} \text{ in output}}{\textit{Change} \text{ in input}}, \text{ K}_\text{P} \text{ -Proportional gain}$$

where

$$L = 1.3 \times t_1 - 0.29t_2 \rightarrow \text{delay time}$$
$$\tau = 0.67(t_2 - t_1) \rightarrow \text{time constant}$$

Controller Design: With its three - term functionality covering treatment to both transient and steady-state responses, PID [Proportional+Integral+Derivative) control offers the simplest and yet most efficient solution to many real- world control problems. The popularity of PID controller has grown tremendously after the introduction of the Ziegler - Nichols's straightforward tuning methods. This is due to the fact that the PID controller structure is simple and its principle easy to understand compared to most other advanced controllers. On the other hand, the general performance of PID controller is satisfactory in many applications. For these reasons, the majority of the controllers used in industry are of PI [Proportional+ Integral] and PID type [4].

Design of Pi Controller: After deriving the transfer function model, the design of controller tuning is done using the method proposed by Skogestad. The PI controller settings are

$$K_P = \frac{1}{K}\frac{\tau}{L + \tau_c}, \tau_I = \tau$$

Controller gain K_P depends inversely on model gain K. As τ_c decreases, K_P increases. This is because a quicker approach to set point requires more strenuous control action and thus there is justification for a larger value of $_{\text{Kp}}$. Using the PI [04] controller tuned values; the setup was run for the different set points in real time. Then load disturbances at different intervals were given in the tank. The variation in the level was recorded in both the cases. The above mentioned Skogestad setting is also used to find the controller settings for different zones which are given in Table 2.

Design of Fuzzy Logic Controller: Fuzzy logic is a part of artificial intelligence or machine learning which interprets a human's actions. Fuzzy technique have been successfully used in control in several fields. Fuzzy logic is a form of logic whose underlying modes of reasoning are approximate instead of exact. The general idea about fuzzy logic [05] is that it takes the inputs from the sensors which is a crisp value and transforms it into membership values ranging from 0 to 1. Unlike crisp logic, it emulates the ability to reason and use approximate data to find solutions. Fuzzy logic controllers (FLCs) are knowledge-based controllers consisting of linguistic "IF-THEN" rules that can be constructed using the knowledge of experts in the given field of interest. Variety controller structures are used in the literature. However for the present study, the fuzzy logic controller whose block diagram represented in Fig. 4 is used.

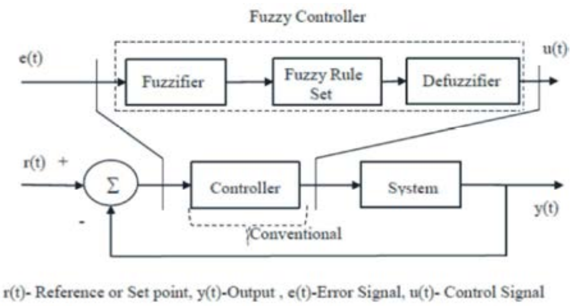

Fig. 4: Block diagram of Fuzzy logic controller

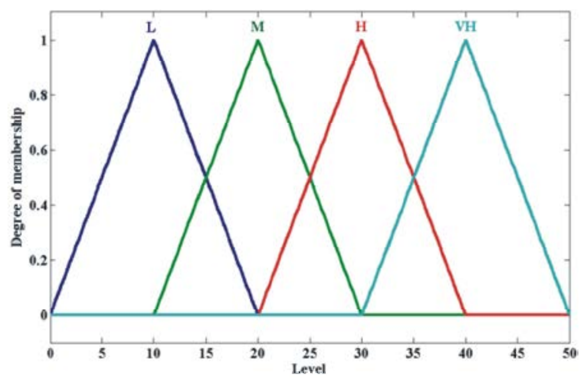

Fig. 5: Membership for Error (E)

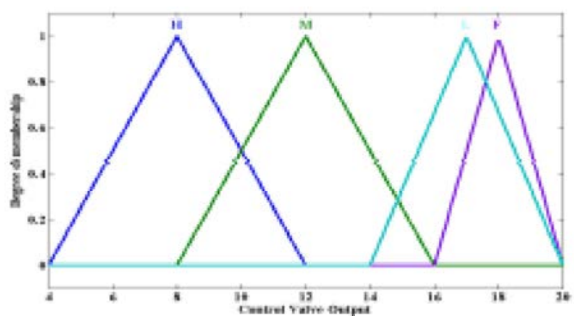

Fig. 6: Membership for Change of Error (CE)

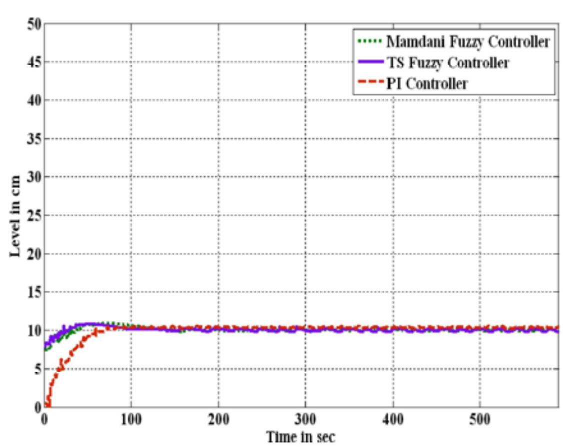

Fig. 7: Membership for Control Valve Output (CV)

Table 3: Rule base for Mamdani model FLC

E / CE	L	M	H	VH
VVN	L	L	L	L
VN	L	L	L	L
N	L	L	L	L
LN	M	M	M	M
Z	F	F	F	F
LP	H	H	H	H
PO	H	H	H	H
VP	H	H	H	H
VVP	H	H	H	H

The design of fuzzy logic controller using Mamdani model for a spherical tank in real time is attempted using cost effective data acquisition system. To implement FLC for a non-linear spherical tank system in real time, level and level error are taken as the two inputs and controller as output by changing the position of valve opening. Here triangular membership [06] functions are chosen for model of FLC. For fuzzification min-max method is used. For defuzzification using the properties of triangles is employed for the measurement of height. The universes of discourse for these parameters are scaled from 0 to 50, -50 to +50 and (4-20) mA for the two input variable and one output variable respectively. The scaling is very essential because the fuzzy system can be retrofitted with other devices or ranges of operation by just changing the scaling of the input and output variables. The rule base developed for the Mamdani FLC model is shown in Table 3.

The control scheme programmed using the FLC is designed based on the relationship between the input and the output variables. In order to maintain the level in a spherical tank, the optimum height is achieved based on the level and change in the level which are sensed by the DPT. The relationship between the Error (E), Change of Error (CE) and Control Valve (CV) position is nonlinear and depends on the current level. So it is difficult to obtain a unique numerical formula relating level and valve position. For fuzzy inference processing, the range of possible values for the input and output variables are determined from experiments. These are the membership functions which are used to translate real time values to fuzzy values and back. The membership functions of the input variables, the type of E and CE are shown in Fig. 5 to Fig.7. These membership functions [07] are defined as triangular functions. The triangular membership function has the advantage of simplicity and easier implementation and is chosen in this application.

Table 4: Rule base for TS model FLC

E / CE	VLO	L	SM	M	H	VH
VVN	L	L	L	L	L	L
VN	L	L	L	L	L	L
N	L	PI2	PI3	PI4	PI5	L
LN	PI1	PI2	PI3	PI4	PI5	PI6
Z	F	F	F	F	F	F
LP	PI1	PI2	PI3	PI4	PI5	PI6
P	L	PI2	PI3	PI4	PI5	PI6
VP	M	M	M	H	H	H
VVP	H	H	H	H	H	H

The type of E is divided into four levels: Low (L), Medium (M), High (H) and Very High (VH), type of CE into nine levels: Very Very Negative (VVN), Very Negative (VN), Negative (N), Low Negative (LN), Medium (M), Low Positive (LP), Positive (P), Very Positive (VP) and Very Very Positive (VVP). The CV positions are divided into four levels: Low (L), Medium (M), Fix (F) and High (H) shown in Figure7. The decision-making capabilities of the fuzzy controller are coded in a set of rules. The rules are intuitive and easy to understand. The rules for the spherical tank are derived from common sense, data obtained from experiments and from expert's knowledge. These rules are represented in the form of rule matrix table for the Mamdani based Controller which is shown in Table 3.

The rule base is developed [08] using 36 rules for the Mamdani FLC model. For optimal response in the control of level in spherical tank in real time implementation using TS Model, the rule base is increased to 56 which is shown in Table 4.

RESULT AND DISCUSSION

The FLC of both Mamdani and TS controllers is applied in real time to the control of level in a spherical tank system. The performance of the FLC with tuned variables is compared with a PI controller designed using Skogestad tuning rule. The fuzzy controller is run for a sequence of set points, that is, 7, 10,15,20,25 and 38 cm and is compared with a PI controller for the same sequence of set point changes. The performance of the proposed controllers namely, Mamdani fuzzy controller, TS fuzzy controller and PI controller are obtained for step level changes in the set point [09]. The time response curves for step changes from 7 cm to 38 cm are obtained and are shown in Fig. 8 to Fig. 13. From these figures, it is

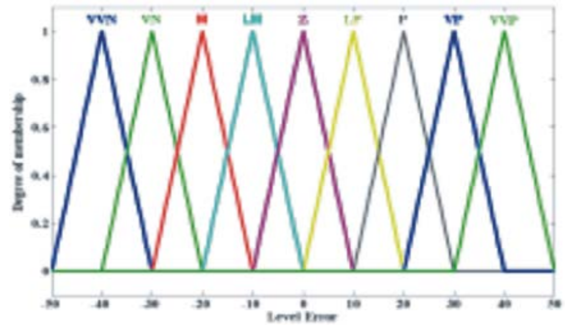

Fig. 8: Servo Response for set point 7 cm

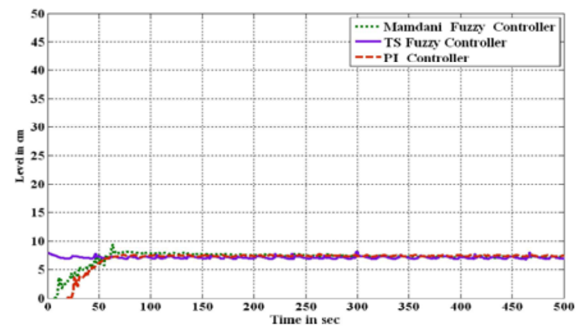

Fig. 9: Servo Response for set point 10 cm

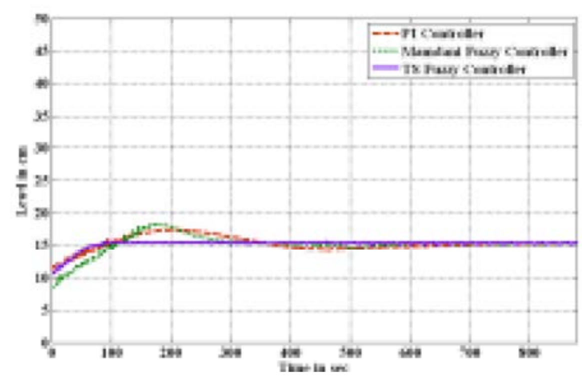

Fig. 10: Servo Response for set point 15 cm

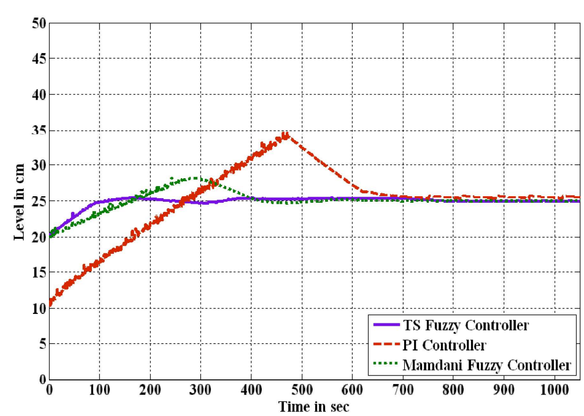

Fig. 11: Servo Response for set point 20 cm

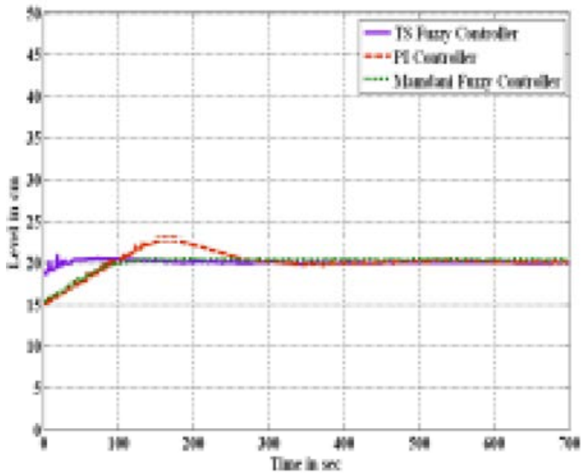

Fig. 12: Servo Response for set point 25cm

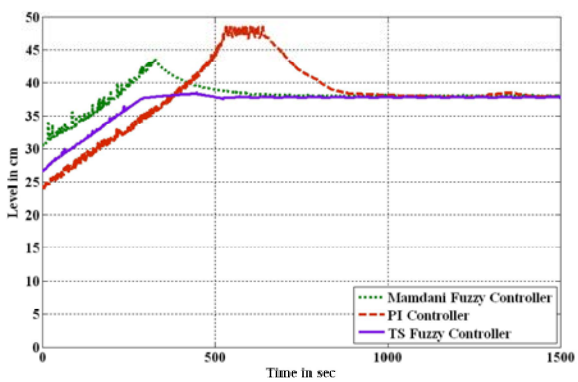

Fig. 13: Servo Response for Set Point 38 cm

Table 5: Performance Indices Comparison for a Set Point Change

Set Point	Controllers	ISE	IAE
7 cm	TS - FL	422.17	76.88
	M - FL	978.83	384.23
	PI	1580.50	401.89
10 cm	TS - FL	63.1082	112.00
	M - FL	113.43	116.19
	PI	1429	456.85
15 cm	TS - FL	349.09	492.32
	M - FL	2108.5	771.10
	PI	1146.3	740.41
20 cm	TS - FL	33.251	86.41
	M - FL	705.98	441.36
	PI	1353	568.43
25 cm	TS - FL	740.14	396.44
	M - FL	2320.6	882.48
	PI	2698.3	3725.8
38 cm	TS - FL	1240.3	2200.2
	M - FL	6403.3	1605.3
	PI	4367.2	5353.6

observed that, the water tank level oscillations during disturbance is much higher with PI and Mamdani based Fuzzy based controllers, whereas oscillations is very much less in TS based fuzzy controller. Also, it is observed that TS - FL tracks the given set point in less rise time compared to M - FL and PI controller. It is also seen from Fig. 10 there is no overshoot in TS - FL based controller when compared with other two controllers. From Figure 11 to Figure 13, it is observed that TS - FL based controller follows a smooth tracking towards the given set point. Also the performance indices are calculated for all the three controllers at all operating conditions and are shown in Table 5. From the values shown in Table 5, it is observed that that the TS based fuzzy controller performs better than the other two controllers at all operating levels [09].

CONCLUSION

For non-linear processes, an Intelligent Controller is designed. Its performance is tested in real time by using the VMAT-01 module for a Spherical tank level process. Comparison with a Mamdani based fuzzy logic and conventional PI controller gives testimony to the effectiveness of the TS based fuzzy logic control technique in the non-linear system. From the transient response curves and also from performance Indices, it is observed that T S based fuzzy logic controller gives much improved performance when compared with PI Controller and Mamdani based fuzzy logic controller at all operating conditions.

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