ISSN 1996-3343

Asian Journal of Applied Sciences

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Asian Journal of Applied Sciences 1 (1): 33-45, 2008
ISSN 1996-3343

Design of Intelligent Controller for Non-Linear Processes

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Abstract: The aim of this research is to discuss the control issues associated with the non-linear systems in real time using cost effective data acquisition system. The non-linear systems taken up for study are conical and spherical tank. System identification of these nonlinear processes are done using black box model, which is identified to be non-linear and approximated to be a First Order Plus Dead Time (FOPDT) model. In this study, for designing the controllers, we have taken Proportional Integral (PI) controller using Skogestad tuning rule, Fuzzy Logic Controller (FLC) using both Mamdani (M-FL) and Takagi-Sugeno (TS-FL) models are developed for controlling the non-linear processes using MATLAB with ADAM's data acquisition module. The performance comparison of the controllers are compared based on performance indices like Integral Squared Error (ISE) and Integral Absolute Error (IAE). The real time implementation of the results, shows that the TS based FL produces improved control performance the Mamdani fuzzy and conventional controller.

Key words: Model identification, non-linear system, data acquisition system, fuzzy logic PI controller, Takagi-Sugeno model, Mamdani model

INTRODUCTION

Chemical processes present many challenging control problems due to their non-linear dynamic behavior. Because of the inherent non-linearity, most of the chemical process industries are in need of traditional control techniques. Conical tanks find wide applications in process industries. Spherical tanks also find application in gas plants. Control of level in both the tanks is a challenging problem due to its constantly changing cross section. So there is a need to introduce the concept of controllers for a non-linear system.

The primary task of the controller is to maintain the process at the desired operating conditions and to achieve the optimum performance when facing various types of disturbances. Proportional-Integral-Derivate (PID) controllers are extensively used in the process industries for several reasons. The typical transfer function models, used to represent processes can be easily controlled with PID controller. For a process without an integral term, an integrator produces zero steady state to a step input. Only smaller number of parameters is needed for tuning the controller. Astrom and Hagglund

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(1995) provide effective controller tuning for processes with typical transfer functions. A simple PI controller design method has been proposed by Wang *et al*. (2000) that achieves high performance for a wide range of linear self-regulating processes. Ari and Hagglund (2002) have compared the performance of PI, PID and dead-time compensating controllers based on the IAE criterion. A design method for robust PID controller to address the model uncertainty have been proposed by Ming Ge *et al*. (2002). A criterion based on disturbance rejection and system robustness was proposed by Tan *et al*. (2004) to assess the performance of PID controllers. Krajewski *et al*. (2005) have designed PI controllers for industrial processes approximated by a first-order time-delayed model and suggested frequency-domain approach based on a normalized open-loop transfer function to evaluate the effects of uncertainties in the process parameters and thus, control system robustness.

Chidambaram *et al*. (2004) have proposed a method based on matching the coefficient of corresponding powers of s in the numerator to that of the denominator of the closed loop transfer function for a servo problem in designing a PI/PID controller for stable FOPDT systems. Skogestad (2001) has derived analytic rules for PID controller tuning that are simple and still results in good closed loop behavior. Dave *et al*. (1996) have discussed about the effectiveness for linear systems, difficulty of conventional controller in controlling the nonlinear systems, higher order systems and time-delayed systems.

A fuzzy system can be shown to be a non-linear, which is useful for designing the controller for a non-linear process. After the industrial application of the first fuzzy controller by Mamdani (1974) fuzzy systems have obtained a major role in engineering systems and consumer products in the 1980s and 1990s. Takagi and Sugeno (1985) have discussed the main features of fuzzy models like the input space is decomposed into subspaces, then, within each subspace (i.e., fuzzy regions in the input space), the system model can be approximated by simpler models, in particular linear ones, then it is possible to use conventional controller development techniques for controlling these relatively simple local models and finally, the global fuzzy model in the state-space is derived by blending the subsystems' models in terms of the weighted average of rule contributions. Procyk and Mamdani (1979) have suggested the advantage of Fuzzy Logic Controllers (FLC) which can be applied to plants that are difficult to get the mathematical model. Recently, fuzzy logic and conventional control design methods have been combined to design a Proportional-Integral Fuzzy Logic Controller (PI-FLC). Hybriding the fuzzy and PI are to have a better control of non-linear. Qin and Borders (1994) have developed a PI-type fuzzy controller that uses information from the fuzzy regions of a non-linear process such as continuous stirred tank reactor for pH titration. Chao and Teng (1997) have discussed a PD like self tuning fuzzy controller without steady state error. Hu *et al*. (1997) have proposed an optimal design of a fuzzy PI controller based on theoretical fuzzy analysis and genetic based optimizations. Ranganathan *et al*. (2002) have designed a fuzzy predictive PI control for processes with large time delay. Madhubala *et al*. (2004) have discussed the performance of the genetic algorithm based fuzzy controller for a conical tank. They examined that the fuzzy based control is better for compensating the set and load changes than the PI controller. Anandanatarajan *et al*. (2005) have designed the globally linearized controller for a first order non-linear system with dead time for a conical tank level process based on simulation. Anandanatarajan and Chidambaram (2005) have discussed the evaluation of a controller using variable transformation on a hemi-spherical tank which shows a better response than PI controller.

In this study, a real time fuzzy logic controller based on both M-FL and TS-FL models are designed for controlling the liquid level in a both the tanks. The processes model is experimentally determined from step response analysis and is interfaced to real time with MATLAB using ADAM's module. The controller tuning model is accomplished using fuzzy based controller and the performances are compared with the conventional controllers.

MATERIALS AND METHODS

The laboratory set up for this system consists of a conical and spherical tanks, a water reservoir, pump, rotameter, a differential pressure transmitter, an electro pneumatic converter (I/P converter), a pneumatic control valve, an interfacing ADAM's module and a Personal Computer (PC). The differential pressure transmitter output is interfaced with computer using ADAM's 5000 Advantech module in the RS-232 port of the PC. This module supports 8 analog input and 4 analog output channels with the voltage range of ±10 volt. The sampling rate of the module is 18 samples per sec and baud rate is 9600 bytes per sec with 16-bit resolution. The programs written in script code using MATLAB software is then linked via this ADAM's module with the sampling time of 60 msec. Figure 1 and 2 show the real time experimental setup of the processes.

The pneumatic control valve is air to close, adjusts the flow of the water pumped to the conical as well as the spherical tank from the water reservoir. The level of the water in the tank is measured by means of the differential pressure transmitter and is transmitted in the form of (4-20) mA to the interfacing ADAM's module to the Personal Computer (PC). After computing the control algorithm in the PC control signal is transmitted to the I/P converter in the form of current signal (4-20) mA, which passes the air signal to the pneumatic control valve. The pneumatic control valve is actuated by this signal to produce the required flow of water in and out of the tank. There is a continuous flow of water in and out of the tank. Table 1 shows the technical specifications of the setup with Common T connection so that the system may selected either conical or spherical tank.

System Identification

For fixed input flow rate and output flow rate of the tank, the tank is allowed to fill with water from initial to their final height. At each sample time the data from differential pressure transmitter i.e.,

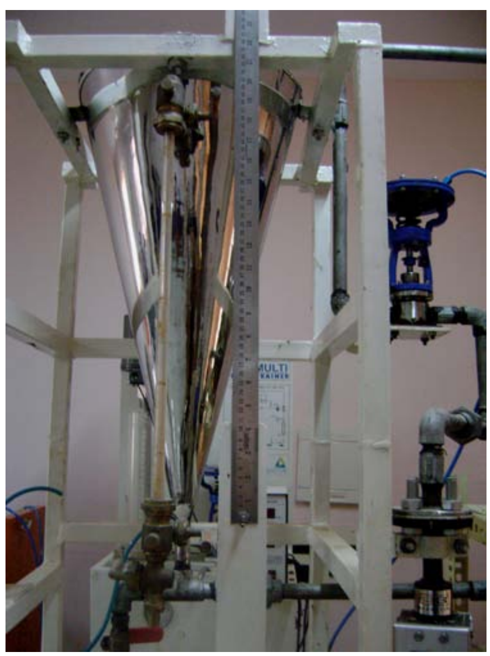

Fig. 1: Real time experimental setup of the conical tank process

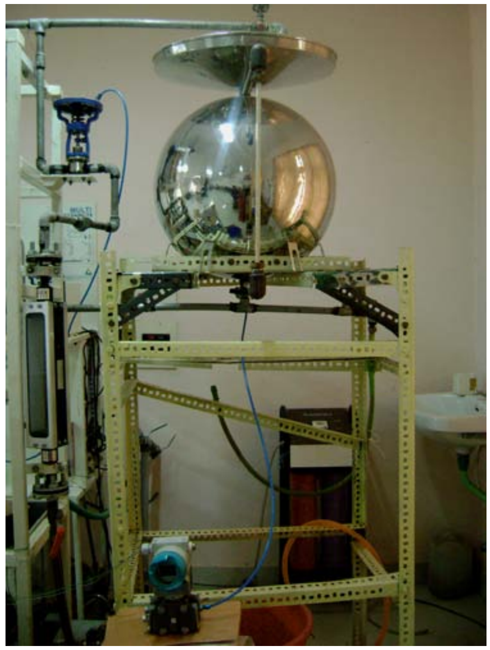

Fig. 2: Real time experimental setup of Spherical Tank

Table 1: Technical specifications of experimental setup

Part name	Details
Conical tank	Stainless Steel
	Height-49.3 cm, Top Diameter-33.74 cm, Bottom Diameter-0.8 cm, α-30'
Spherical tank	Stainless Steel
	Diameter-50 cm
Differential Pressure Transmitter	Type Capacitance, Range (2.5-250) mbar, Output
	(4-20) mA Siemens make
Pump	Centrifugal 0.5 HP
Control valve	Size ¼" Pneumatic actuated
	Type: Air to close
	Input (3-15) psi
Rotameter	Range (0-18) lpm
Air regulator	Size 1/4" BSP
	Range (0-2.2) BAR
E/P converter	Input (4-20) mA
	Output (0.2-1) BAR
Pressure gauge	Range (0-30) psi
	Range (0-100) psi

between (4-20) mA is being collected and fed to the system through the serial port RS-232 using ADAM's interfacing module. Thereby the data is scaled up in terms of level (cm). Chidambaram (1998) has discussed the transfer function models, which are used to design PI/PID controllers. Eykhoff (1974) and Gustavsson *et al*. (1977) have proposed more elegant methods for closed loop identification to determine a suitable dynamic model. However, these methods are complicated and an accurate process model is not necessary since the objective is controller tuning for a closed loop performance rather than model development.

Yuwana and Seborg (1982) have proposed a simple method for identifying a stable FOPDT model from the closed loop response for a step change in set point. The method proposed by Sundaresan and

Krishnaswamy (1978) avoids the use of point of inflection construction entirely to estimate the time delay. The proposed times t_1 and t_2, are estimated from a step response curve. These times correspond to the 35.3 and 85.3% response times. The time constant and time delay are calculated as follows:

$$\tau = 0.67(t_2 - t_1) \quad (1)$$

$$\tau_D = 1.3t_1 - 0.29t_2 \quad (2)$$

Design of PI Controller

After deriving the transfer function model the controller has to be designed for maintaining the system to the optimal set point. This can be achieved by properly selecting the tuning parameters K_P and τ_I for a PI controller. Consider the standard FOPDT model.

$$G(s) = \frac{Ke^{-\theta s}}{\tau s + 1} \quad (3)$$

According to the method proposed by Skogestad (2003) the PI controller settings are

$$K_P = \frac{1}{K}\frac{\tau}{\theta + \tau_C},\ \tau_I = \tau \quad (4)$$

After following the Skogestad settings, the values found for different zones are given in different case studies. The expressions for the PI controller settings in Eq. 4 provide considerable insight. Controller gain K_P depends inversely on model gain K. It is also reasonable that $\tau_I = \tau$ as slow processes have large values of τ and thus τ_I should also be large for satisfactory control. As τ_c decreases, K_P increases because of the faster set point response require more strenuous control action and thus had a larger value of K_P. The PI controller was to run for the different set points. Then load disturbances at different intervals were given in the tanks. The variation in the level was recorded in both the cases.

Design of FLC

Problems treated by humans based on their experienced knowledge usually lack exact mathematical description and cannot be handled by conventional methods of control. But, FLC allows the design of systems based on abstract or imprecise information. Characteristics of a fuzzy controller are based on the behavior of a human operator rather than the behavior of the plant. Fuzzy systems have the ability to transform vague information and expert knowledge into computable numerical data. It incorporates heuristics developed by experts and operators into automatic control. Besides control of highly non-linear, complex systems, FLC can also be used in situations where conventional control is available. In these cases, it is introduced to improve the control performance of the conventional controller to simplify the control algorithm. The majority of FLC systems are knowledge based which is described by if-then rules, which have to be established based on expert's knowledge about the systems, controllers and performances. In fuzzy control, the introduction of input-output intervals and membership functions is more or less subjective, depending on the designer's experience and knowledge about the plant and the available information. The purpose of designing and applying fuzzy logic control system is to tackle the vague, ill-described, complex plants and processes that can hardly be handled by conventional control techniques.

FLC's can generally be divided into two models, Mamdani and Takagi-Sugeno (TS) models. Fuzzy systems, with fuzzy sets (linguistic terms) in the consequence, characterized by Mamdani fuzzy models. The Mamdani fuzzy models have been used in controlling various classes of plants

Table 2: Model parameters for different regions

	Model parameters		
Region (cm)	K	τ (sec)	τ_D (sec)
0-7	4.80	3.35	7.69
7-16	7.14	4.69	11.10
16-22	4.20	6.70	4.17
22-29	4.998	22.78	16.40
29-36	4.99	33.50	28.93
37-45	4.284	40.87	10.59

Table 3: PI tuning values for different regions

	Tuning parameters	
Region (cm)	K_c	τ_I (sec)
0-7	0.0456	0.0136
7-16	0.029	0.0063
16-22	0.1912	0.028
22-29	0.1389	0.00609
29-36	0.116	0.00346
37-45	0.450	0.0110

Table 4: Rule base for Mamdani model Fuzzy logic controller

	Level				
Level error	VF*	F	M	S	VS
VLN*	L	L	L	L	L
VN	L	L	L	L	L
N	M	M	M	M	M
M	M	M	M	M	M
P	M	M	M	H	H
VP	H	H	H	H	H
VLP	H	H	H	H	H

*VF: Very Fast, F: Fast, L: Low, H: High, M: Medium, S: Slow, VS: Very Slow, VLN: Very Large Negative, VN: Very Negative, N: Negative, P: Positive, VP: Very Positive, VLP: Very Large Positive

because there is no need for sophisticated mathematical models and the experts' knowledge and experience can be included relatively easy in the model structure. Fuzzy systems, with a crisp function of the inputs in the consequent, characterized by TS fuzzy models.

Case Study 1: Conical Tank Setup

At a fixed inlet flow rate, outlet flow rate, the system is allowed to reach the steady state from 0-45 cm. After that a step increment in the input flow rate is given and various readings are noted till the process becomes stable at different regions in the conical tank. The experimental data are approximated to be a FOPDT model, the model parameters of the transfer functions for the above mentioned are given in Table 2 and the controller settings are given in Table 3.

The design FLC using both Mamdani and TS model for a conical tank in real time is attempted using cost effective data acquisition system. To implement FLC for a non-linear conical 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 functions are chosen for both models of FLC. For fuzzification min-max method is used. For defuzzification using the properties of triangles is employing method of height. The universes of discourse for these parameters are scaled from 0 to 45, -45 to +45 and (4-20) mA for the two input variable and one output 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 M-FL model is shown in Table 4. For optimal response in the conical tank level control in real time the implementation is done using TS Model based FLC at different non-linear regions. The rule base for the TS-FL is shown in Table 5.

Table 5: Rule base for TS model Fuzzy logic PI controller

	Level					
Level error	VL*	L	M	H	VH	VVH
VVVN*	L	L	L	L	L	L
VVN	L	L	L	L	L	L
VN	L	L	L	L	L	L
VLN	L	PI 2	PI 3	PI 4	PI 5	L
N	PI 1	PI 2	PI 3	PI 4	PI 5	PI 6
M	PI 1	PI 2	PI 3	PI 4	PI 5	PI 6
P	PI 1	PI 2	PI 3	PI 4	PI 5	PI 6
VP	PI 1	PI 2	PI 3	PI 4	PI 5	PI 6
VVP	M	M	M	M	M	M
VLP	M	M	M	H	H	H
VVLP	H	H	H	H	H	H

*VVVN: Very Very Very Negative, VVN: Very Very Negative, VN: Very Negative, VLN: Very Low Negative, N: Negative, M: Medium, P: Positive, VP: Very Positive, VVP: Very Very Positive, VLP: Very Large Positive, VVLP: Very Very Large Positive, L: Low, LA: Large, H: High, VH: Very High, VVH: Very Very High

Table 6: Model parameters for different regions

	Model parameters		
Region (cm)	K	τ (sec)	τ_D (sec)
0-8	1.42	12.06	1.85
8-16	1.50	42.38	24.21
17-25	1.71	79.73	56.39
25-33	2.08	71.02	69.25
32-40	1.789	98.58	17.23
40-48	1.917	48.91	82.86

Table 7: PI tuning values for different regions

	Tuning parameters	
Region (cm)	K_c	τ_i (sec)
0-8	2.278	0.01133
8-16	0.5833	0.01376
17-25	0.413	0.00518
25-33	0.246	0.00346
32-40	1.590	0.01620
40-48	0.153	0.00134

Case Study 2: Spherical Tank Setup

The mentioned system identification method is followed for the spherical tank also from 0-50 cm. After that a step increment in the input flow rate is given and various readings are noted till the process becomes stable at different regions in the spherical tank, in order to design the control algorithm for the non-linear region. The model parameters are identified to be FOPDT model, are given in Table 6 and the tuned PI controller settings are given in Table 7.

The design of FLC using both Mamdani and TS 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 functions are chosen for both models of FLC. 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 respectively. The rule base developed using 36 rules for the Mamdani FLC model is shown in Table 8. For optimal response in the spherical tank level control in real time the implementation using TS Model based FLC at different non-linear regions, the rule base is increased to 56 which shown in Table 9.

Table 8: Rule base for Mamdani model Fuzzy logic controller

	Level			
Level error	L*	M	H	VH
VVN*	L	L	L	L
VN	L	L	L	L
N	L	L	L	L
LN	M	M	M	M
M	F	F	F	F
LP	H	H	H	H
P	H	H	H	H
VP	H	H	H	H
VVP	H	H	H	H

*VVN: Very Very Negative, VN: Very Negative, N: Negative, LN: Low Negative, M: Medium, LP: Low Positive, P: Positive, VP: Very Positive, VVP: Very Very Positive, L: Low, H: High, VH: Very High, F: Fix, H: High

Table 9: Rule base for TS model Fuzzy logic controller

	Level					
Level error	VL*	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
M	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

*VVN: Very Very Negative, VN: Very Negative, N: Negative, LN: Low Negative, M: Medium, SM: Slight Medium, LP: Low Positive, P: Positive, VP: Very Positive, VVP: Very Very Positive, L: Low, H: High, VH: Very High, F: Fix, H: High

RESULTS AND DISCUSSION

Case 1: Conical Tank

The FLC is applied to a real time control of a conical tank system using ADAM's module. The performance of the TS based FL controller is compared to Mamdani based FL controller and Skogestad based PI controller tuning settings. The FLC is implemented for a sequence of set points 15 and 22 cm and is compared to the other controllers. The variations of level with time for the sequence of set changes for both the controllers are shown in Fig. 3. It shows TS-FL tracks the set point changes in a faster time than the other controllers. The response to track the given set point in TS-FL is immediate, when compared to the Mamdani fuzzy and PI controller with lesser rise time. The settling time of the TS based FL for a set point change is better than Mamdani fuzzy and PI. It is proved that TS model based FLC is having lesser peak time, provides no oscillatory behavior and exhibits no overshoot compared to that of counterpart controller. A load change of 17% is applied and simultaneously set point changes are given to the system as shown in Fig. 4. The designed controllers are allowed to run under these conditions and variations of level with time are recorded. It is found that the response of FLC based TS controller is faster for the given set point when it is given a sudden regulatory change. Also, it leads to lesser oscillation and no overshoot. The comparison based on ISE and IAE are tabulated for servo and regulatory changes, which is shown in Table 10. From these values, it can be seen that the TS model based FLC performs significantly better than the Mamdani fuzzy and PI controller. It is found that for the load change ISE and IAE values for the TS model based FLC are slightly higher than fuzzy controller but considerably lower than the conventional PI controller.

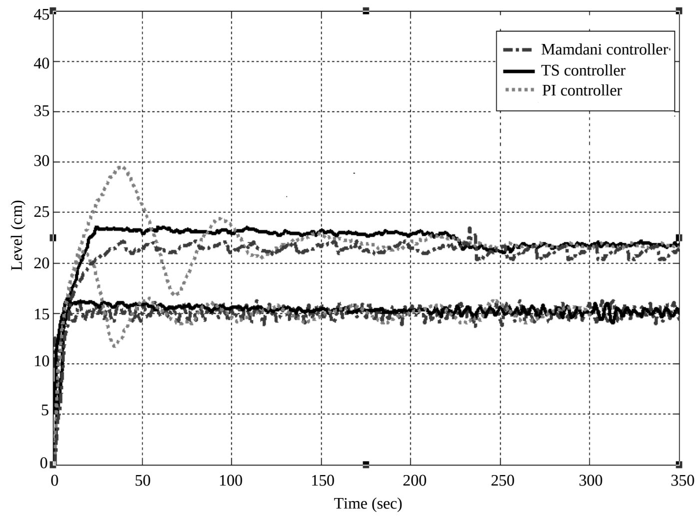

Fig. 3: Servo response for a set point 15 and 22 cm

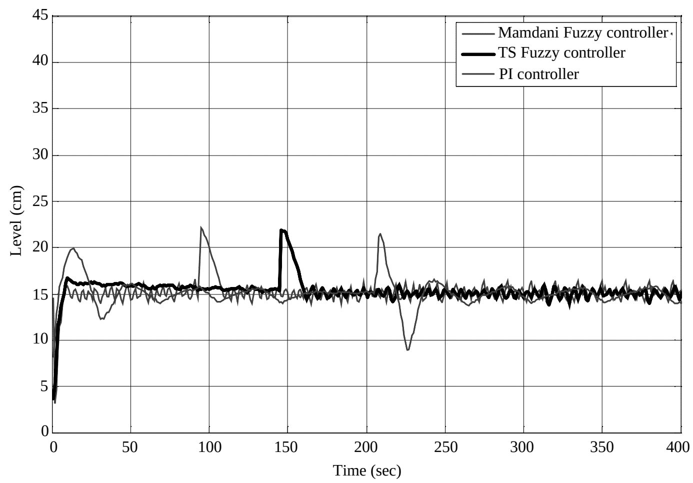

Fig. 4: Regulatory response for set point 15 cm

Table 10: Performance indices comparison for a conical Tank setup

Set point	Controllers	ISE	IAE
15 cm	TS-FL	227.8840	188.12
	M-FL	223.6049	179.45
	PI	883.2052	283.40
22 cm	TS-FL	1991.10	401.69
	M-FL	2425.20	456.72
	PI	2702.60	547.01
Load 15 cm	TS-FL	767.50	280.45
	M-FL	743.53	274.56

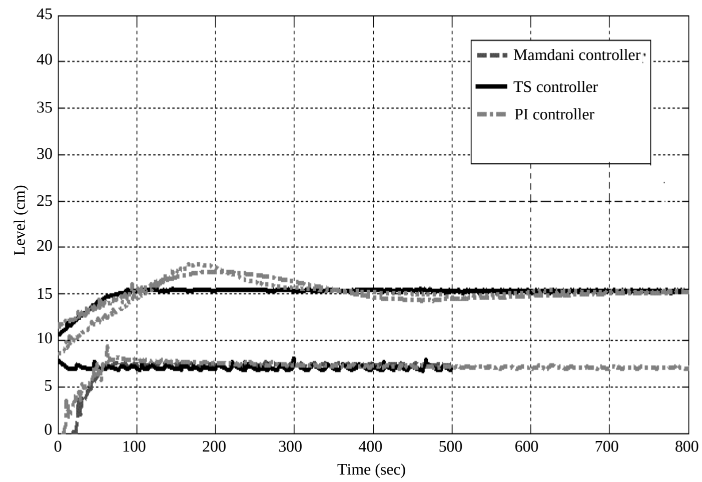

Fig. 5: Servo response for a set point 7 and 15 cm

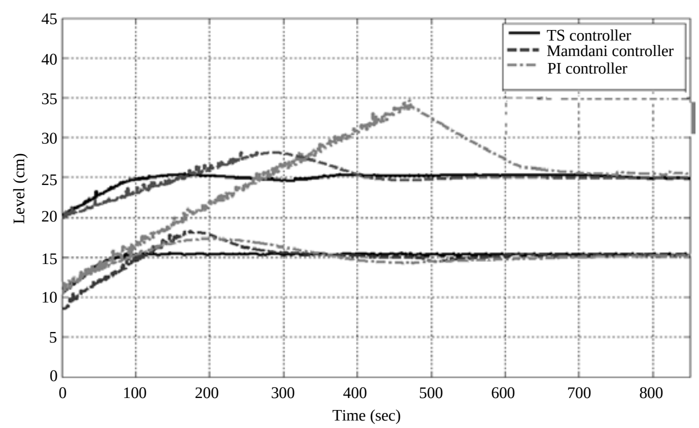

Fig. 6: Servo response for a set point 15 and 25 cm

Case 2: Spherical Tank

The FLC of both Mamdani and TS controllers is applied to real time to the control of spherical liquid level system. The performance of the FLC with tuned variables is compared to a PI controller designed using Skogestad tuning rule.

Variation of Set Point

The fuzzy controller is run for a sequence of set points, that is, 7, 15 and 25 cm is compared with a PI controller for the same sequence of set point changes. The variation of level with time for the sequence of set point changes for both the controllers are shown in Fig. 5 and 6. It is observed the level oscillates very much high for PI and Mamdani fuzzy controllers where as oscillation is very much less in TS based fuzzy controller. Also it is observed that TS-FL tracks the given set point in less time

Table 11: Performance indices comparison for a set point change

Set point	Controllers	ISE	IAE
7 cm	TS-FL	422.17	76.88
	M-FL	978.86	384.23
	PI	1580.50	401.89
15 cm	TS-FL	349.09	492.32
	M-FL	2108.50	771.11
	PI	1146.30	740.41
25 cm	TS-FL	740.14	396.44
	M-FL	2320.60	882.48
	PI	26988.00	3725.80

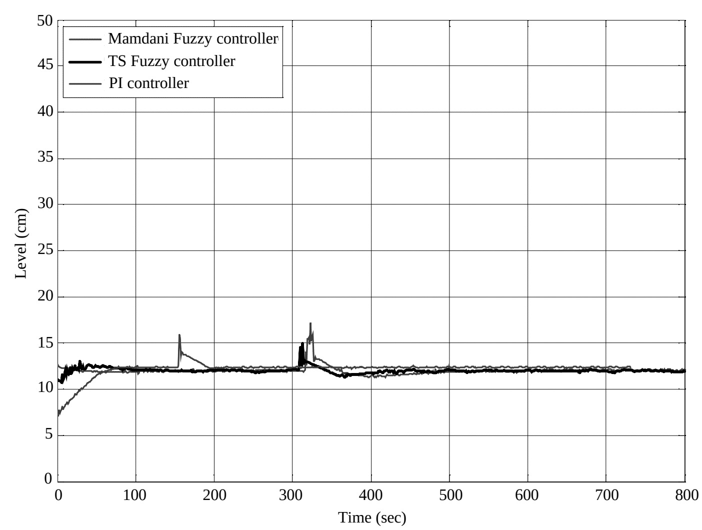

Fig. 7: Regulatory response for a set point 12 cm

compared to M-FL and PI controller. It is also seen from Fig. 6 there is no overshoot in TS-FL based controller when compared to other two controllers. Also it is observed that TS-FL based controller follows the smooth tracking towards the given set point. The performance indices calculations for all the three controllers are shown in Table 11. From the values shown in Table 11, it can be seen that the TS based fuzzy controller performs better than the other two controllers.

Changes in Load

The tuned fuzzy controller is used to control the spherical level system while applying a load change of 12.5% is recorded. The system is also run with a PI controller while applying the same load changes. The variation in level with time is shown in Fig. 7 and 8 for a set point of 12 and 32 cm. It is clearly observed from the figures that for a sudden load change TS based FLC returns to the given set point immediate. Also it is observed the fuzzy controller follows without any overshoot for a load change compared to PI controller. The performance indices calculations for all the designed controllers are shown in Table 12. From the values shown in Table 12, it is clear that fuzzy based controller gives better values when compared to PI controller. The fuzzy controller is able to compensate for the load changes considerably better than PI controller.

Table 12: Performance indices comparison for a regulatory change

Set point	Controller	ISE	IAE
12 cm	TS-FL	164.55	123.71
	M-FL	171.67	157.94
	PI	559.44	402.86
32 cm	TS-FL	54.14	154.93
	M-FL	2849.50	806.16
	PI	9316.60	2393.00

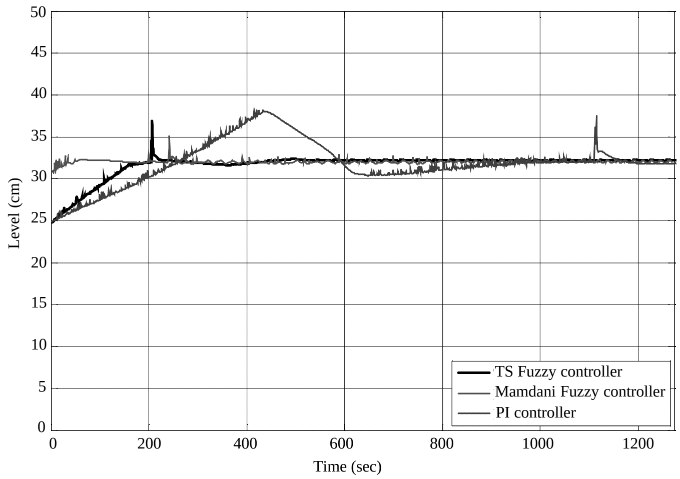

Fig. 8: Regulatory response for a set point 32 cm

CONCLUSION

For non-linear processes an intelligent Mamdani and TS model based FLC is designed. Its performance is tested in real time by using the ADAM's module. Comparison with a fuzzy logic and conventional PI controller gives testimony to the effectiveness of the fuzzy logic based PI control technique in the non-linear system. Experimental results prove that the response is smooth for both set point and regulatory changes for TS based FLC compared to Mamdani fuzzy logic and conventional controller. The settling time and overshoot in the TS model based FLC shows the better response, than the Mamdani fuzzy and PI controller. The influence of set and load changes on FLC using TS model indicate that it is able to compensate faster, when compared to the other two controllers. The result proves that FLC implemented using TS model could be used in real time control using cost effective data acquisition system. Hence, it is concluded that FLC based on TS model is implemented using ADAM's module outperforms Mamdani fuzzy logic and the conventional controller in terms of statistical parameter for both conical and spherical tank systems. This is also validated by the ISE and IAE values of the FLC of TS model.

REFERENCES

Anandanatarajan, R. and M. Chidambaram, 2005. Experimental evaluation of a controller using variable transformation on a hemi-spherical tank level process. In: Proceedings of National Conference on Process Identification, Control and Diagnosis, NCPICD, Madras Institute of Technology, Chennai, 16-17 December, pp: 195-200.

Anandanatarajan, R., M. Chidambaram and T. Jayasingh, 2005. Design of controller using variable transformations for a nonlinear process with dead time. ISA. Trans., 44 (1): 81-91.

Ari, I. and T. Hagglund, 2002. Performance comparison between PID and dead-time compensating controllers. J. Process Control, 12 (8): 887-895.

Astrom, K.J. and T. Hagglund, 1995. PID Controllers: Theory. Design and Tuning. 2nd Edn. ISA Pub., North Carolina.

Chao, C.T. and C.C. Teng, 1997. A PD like self tuning fuzzy controller without steady state error. Fuzzy Set Syst., 87 (2): 141-154.

Chidambaram, M., 1998. Applied Process Control. Allied Publishers, New Delhi, India.

Chidambaram, M., R.P. Sree and M.N. Srinivas, 2004. A simple method of tuning PID controllers for stable and unstable FOPTD systems. Comp. Chem. Eng., 28 (10): 2201-2218.

Dave, M., A. Heider and G.C. Malki, 1996. Design and analysis of a fuzzy PID controller. Fuzzy Sets Syst., 79 (3): 297-314.

Eykhoff, P., 1974. System Identification. Wiley, United States of America, New York.

Gustavsson, I., L. Ljung and T. Soderstorm, 1977. Survey paper, Identification of process in closed loop-Identifiability and accuracy aspects. Automatica, 13 (1): 59-75.

Hu, B.G., G.K.I. Mann and R.G. Gosine, 1997. Theoretic and genetic design of a three-rule fuzzy PI controller. In: Proceedings of 6th IEEE International Conference Fuzzy Systems, Barcelona, Spain, July, pp: 489-496.

Krajewski, W., A. Lepschy, S. Miani and U. Viaro, 2005. Frequency-domain approach to robust PI control. J. Franklin Inst., 342 (6): 674-687.

Madhubala, T.K., M. Boopathy, J. Sarat Chandra Babu and T.K. Radhakrishnan, 2004. Development and tuning of fuzzy controller for a conical level system. Intelligent Sensing and Information Processing. Proceedings of International Conference ICISIP., pp: 450-455.

Mamdani, E.H., 1974. Application of fuzzy algorithms for the control of a dynamic plant. Proc. IEE, 121 (12): 1585-1588.

Ming Ge, Min-Sen Chiu and Qing-Guo Wang, 2002. Robust PID controller design via LMI approach. J. Process. Control, 12 (1): 3-13.

Procyk, T.J. and H. Mamdani, 1979. A Linguistic self organizing process controller. Automatica, 15 (1): 15-30.

Qin, S.J. and G. Borders, 1994. A multi-region fuzzy logic controller for nonlinear gain. Proc. IEEE Trans. Fuzzy Syst., 2 (1): 74-81.

Ranganathan, R.S., H.A. Malki and G. Chen, 2002. Fuzzy predictive PI control for processes with large time delays. Exp. Syst. Int. Knowledge Eng. Neural Networks, 19 (1): 21-33.

Skogestad, S., 2001. Probably the best simple PID tuning rules in the world. A.I.Ch.E Annual Meeting, pp: 276.

Skogestad, S., 2003. Simple analytical rules for model reduction and PID controllers tuning. J. Process Control, 13 (4): 291-309.

Sundaresan, K.R. and R.R. Krishnaswamy, 1978. Estimation of time delay, time constant parameters in time, frequency and Laplace domains. Can. J. Chem. Eng., 56: 257.

Takagi, T. and M. Sugeno, 1985. Fuzzy identification of systems and its application to modeling and control. IEEE Trans. Syst. Man Cybernetics, 15: 116-132.

Tan, W., H.J. Marquez and T. Chen, 2004. Performance assessment of PID controllers. J. Control Intel. Syst., 32 (33): 158-166.

Wang, Ya-Gang and Hui-He Shao, 2000. Optimal tuning for PI controller. Automatica, 36 (1): 147-152.

Yuwana, M. and D.E. Seborg, 1982. A new method for online controller tuning. A.I.Ch.E. J., 28: 434-440.