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Control of an Ambiguous Real Time System Using Interval Type 2 Fuzzy Logic Control

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Abstract

The Interval Type-2 Fuzzy Logic Controller (IT2FLC) for a Quadruple Tank Process (QTP) is demonstrated in this paper. Here the Interval Type-2 based Fuzzy membership function is used. The QTP is made to operate in minimum phase mode. The vertices of fuzzy membership functions are tuned with IT2FLC to minimize Integral Absolute Error, peak over shoot and settling time. Performance of IT2FLC and Type-1 Fuzzy Logic Controller (T1FLC) are compared with decentralized PI controller, simulation using MATLAB/Simulink and real time using LabVIEW. Simulation and real time results show that satisfactory performance for both servo and regulatory responses. It has been observed that dynamic performance of IT2FLC is better than the other two controllers. Moreover, compared with the T1FLC controller, IT2FLC performs better, particularly in noisy environments.

Keywords: Quadruple Tank Process, Decentralized PI, T1FLC and.

INTRODUCTION

Chemical Plants are tightly integrated processes, which exhibit non-linear behaviour and complex dynamic properties. Chemical manufacturing processes present many challenging control problems due to their non-linear dynamic behaviour, uncertain and time-varying parameters, constraints on manipulated and state variables, multivariable interactions between manipulated and controlled variables, unmeasured state variables and disturbances, high order and distributed processes.

(Johansson 2000) developed a decentralized PI controller for the Quadruple Tank Process (QTP) but the right half plane zero imposes serious limitations on the performance of the controller in non-minimum phase.

(K.J.Astrom and K.H.Johansson 2002) proposed a new PID design of decoupled PID controllers. The problem of tuning individual loops in a multivariable controller is investigated. It is shown the performance of a specific loop relates to a row in the controller matrix. An algorithm is also presented that estimates the model required for the tuning via a relay feedback experiment. The algorithm does not need any prior information about the system or the controller. Such a design has been illustrated for QTP.

(R.Suja Mani Malar and T.Thyagarajan (2008) modelled the nonlinear QTP with soft computing techniques such as Neural Networks, Fuzzy Logic and Adaptive Neuro Fuzzy Interference System (ANFIS).

(Jerry M.Mendel 2007) developed Interval Type2 Fuzzy Logic Control (IT2FLC) and provided its advantage over Type-1 Fuzzy Logic. Also, IT2FLS models higher levels of uncertainty and thus opens up an efficient way of developing improved control systems and for modeling human decision making.

(Dongrui Wu and Jerry M.Mendel 2007) stated that the five uncertainty measures for Interval Type2 Fuzzy Sets (IT2FSs) -centroid, cardinality, fuzziness (entropy), variance and skewness. The latter four are newly defined. All measures used the Mendel–John Representation Theorem for IT2FSs. Formulas for computing these measures were also obtained.

(Oscar Castillo 2005) introduced the case of type-2 FLC's membership functions, and it can perturb or change the definition domain of the Footprint of Uncertanit (FoU) without losing of stability of the controller, also have shown that a FLC designed fuzzy Lyapunov synthesis is stable and robust.

(Hani Hagras 2007) have implemented a z-Slices based general T2FLS for a two-wheeled mobile robot, which operates in a real-world outdoor environment. IT2FLC applied to dynamic unstructured environments and many other applications such as Coupled-Tank liquid level control systems, DC-DC converter system, etc also proved its robustness.

(Dongrui Wu and Woei Wan Tan 2004) employed a GA (Genetic Algorithm) based T2FLC for the Coupled-Tank liquid-level process and proved the robustness of Type-2 FLC which outperforms Type-1 FLC and showed that the type-2 FLC copes well with the complexity of the plant, and can handle the modelling uncertainty better than its type-1counterpart.

(Mamta Khosla, et al., 2011) designed an Analog CMOS based Interval Type-2 Fuzzy Logic Controller chip. When compared to the previous designs, the proposed design has achieved a considerable high speed along with a significant reduction in power and area.

(Ming-Ying Hsiao and Tzuu-Hseng S. Li 2006) demonstrated the feasibility and effectiveness of the developed IT2FLC simulation results. It shows that the obvious distinction between outputs of IT2FLC and TIFLC is occurred as fewer rules are chosen, and IT2FLC performs better response than that of TlFLC.

(Xinyu Du and Hao Ying 2010) derived the mathematical input–output structure of two Mamdani interval T2 fuzzy-PI controllers and developed a novel structure-derivation method for the T2 controller with the centroid defuzzifier.

(Saeed Jafarzadeh, M. Sami Fadali, and Assem H. Sonbol 2011) presented new stability conditions for type-1 and general type-2 Takagi Sugeno – Kang (TSK) fuzzy systems. New stability condition is applicable to systems with unstable consequents. Results include two classes of type-2 TSK systems with type-1 consequents for which no stability tests are available. The use of the conditions in stability testing is demonstrated using simple numerical examples that include cases where methods that are based on a common Lyapunov function fail.

Since type-1 fuzzy logic is most successful in control, the growth of type-2 control applications—with the exception of (S. Coupland and R. John 2007), all using type-2 interval fuzzy sets. With the Karnik-Mendel iterative algorithms and the Wu-Mendel minimax uncertainty bounds allowing fast execution of type-2 fuzzy systems, control applications began to emerge. (Melin and Castillo 2004) used type-2 interval systems in the context of plant control. (Hagras 2004) demonstrated that a type-2 interval fuzzy logic controller could outperform a type-1 fuzzy controller under large uncertainties. (Wu and Tan 2004) applied type-2 interval systems to the control of a complex multi-variable liquid level process.

(Figueroa et al. 2005) used a type-2 interval control for nonautonomous robots in the context of a robot football game. The authors have performed a comprehensive study of both general and type-2 interval fuzzy controllers for an autonomous mobile robot. Some aspects of these studies are presented by (Coupland and John 2007). (Doctor et al. 2004) used a type-2 interval system to model and adapt to the behaviour of people in an intelligent dormitory room. (Lynch et al. 2005) are continuing to build a type-2 interval control system for large marine diesel engines. (Melgarejo et al. 2004) have developed a limited hardware implementation of a type-2 interval controller.

PHYSICAL MODEL

A schematic diagram of the process is shown in Fig. 1. The target is to control the level in the lower two tanks with two pumps. The process inputs are input voltages to the two pumps and the outputs are the level measurements. Mass balances and Bernoulli's law yield the following simple nonlinear equations (Johansson 2000).

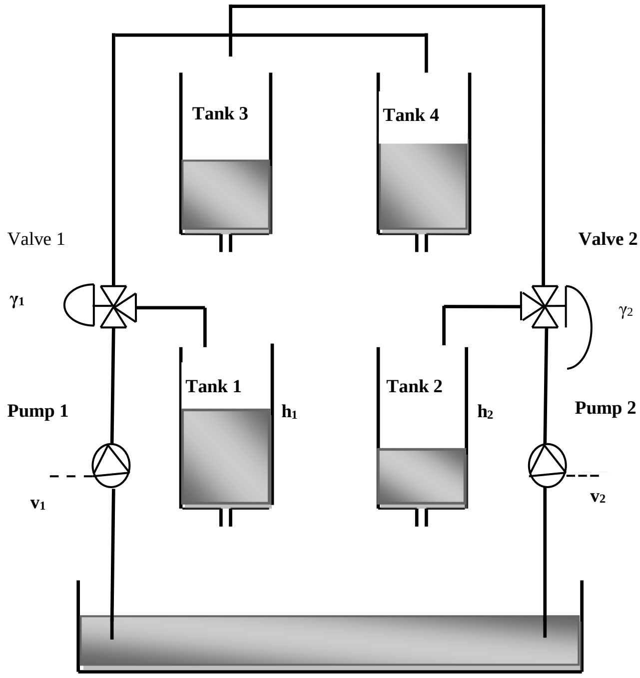

Figure 1: Schematic diagram of the quadruple-tank process.

$$
\begin{aligned}
\dot{h}_1 &= -\frac{a_1}{A_1}\sqrt{2gh_1} + \frac{a_3}{A_1}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}u_1 \\
\dot{h}_2 &= -\frac{a_2}{A_2}\sqrt{2gh_2} + \frac{a_4}{A_2}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}u_2 \\
\dot{h}_3 &= -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}u_2 \\
\dot{h}_4 &= -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_1}{A_4}u_1
\end{aligned} \quad (1)
$$

Where

A_i : Cross-section of Tank i

a_i : Cross-section of the outlet hole i

h_i : Water level i

The voltage applied to pump i is v_i and the corresponding flow is $k_i v_i$. The parameters γ_1, γ_2 ε (0,1) are determined from the position of the valves and set prior to an experiment. The flow to Tank 1 is $\gamma_1 k_1 v_1$ and the flow to Tank 4 is $(1-\gamma_1)k_1 v_1$ and the same applies to Tank 2 and Tank 3 respectively. The acceleration of gravity is denoted as g. The measured level signals are $k_c h_1$ and $k_c h_2$.

Fig.2 shows the experimental setup of the QTP consisting of four interconnected tanks with common water source. This setup is interfaced with a window - based PC via interfacing modules and USB ports. This setup consists of a water supply tank with two positive displacement pumps for water irculation, two pneumatic control valves, four transparent process tanks fitted with level transmitters and rotameters (0-440 lph). Process signals from the level transmitters are interfaced with the PC and it sends outputs to the individual control valves through interfacing units using LabVIEW software. Tanks 1 and 2 are mounted below the other two tanks 3 and 4 for receiving water flow by gravity. Each tank outlet opening is fitted with a valve. Both pumps 1 and 2 takes water by suction from the reservoir. Flow from the pumps is split to top and bottom tanks by manually adjusting the valves. Maximum output flow rate of the pump is 600lph. Ratio of flow split between the top and bottom tanks, substantially alters the dynamics of the system. Pump 1 discharges water to tank 1 and tank 4 simultaneously and the flows are indicated by rotameters 1 and 4. Similarly, pump 2 discharges water to tank 2 and tank 3 and the flows are indicated by rotameters 2 and 3.

Figure 2: Experimental setup of the quadruple-tank process.

The parameters of QTP are given in Table 1.

Table 1: Process Parameter Values of Fig.1

i	Ai(cm2)	ai(cm2)	hi0 (cm)
1	176.71	2.01	6.34
2	176.71	2.01	8.31
3	176.71	2.01	3.06
4	176.71	2.01	4.16

The time constants are T1=42.48 sec, T2=55.64 sec, T3=39.86 sec and T4=55.68 sec.

The transfer function matrix is given in (2)

$$G(s)=\begin{bmatrix} \frac{0.3811}{42.48S+1} & \frac{0.2334}{(42.48S+1)(39.86S+1)} \\ \frac{0.1998}{(55.68S+1)(55.64S+1)} & \frac{0.3934}{55.68S+1} \end{bmatrix} \quad (2)$$

2.1 Relative Gain Array (RGA)

The RGA was introduced by (Ed Bristol 1966) as a measure of interaction in multivariable control systems. The RGA Λ is defined as

$$\Lambda = G(0) \times G^{-T}(0) \quad (3)$$

where × denotes the element by element matrix multiplication and –T inverse transpose.

Properties of RGA:

Sum of rows and columns property of the RGA

Each row of the RGA sums to 1.0 and each column of the RGA sums to 1.0.

(ie) $\lambda_{11}+\lambda_{12}=1$ $\lambda_{11}+\lambda_{21}=1$

$\lambda_{12}+\lambda_{22}=1$ $\lambda_{21}+\lambda_{22}=1$

Use of RGA to determine variable pairing.

It is desirable to pair output i and input j such that λ_{ij} is as close to 1 as possible.

The RGA depends only on the valve settings and not on other physical parameters.

$$\Lambda=\begin{bmatrix} 1.4515 & -0.4515 \\ -0.4515 & 1.4515 \end{bmatrix} \quad (4)$$

From RGA h1 is paired with u1 and h2 is paired with u_2.

CONTROLLER DESIGN

PI Controller Design

The decentralized controller structure is shown in Fig.3 and the decentralized control law (Johansson 2000) u=diag{C_1,C_2}(r-y). The QTP is considered as minimum phase process (the process does not have RHP zeros or time delays).

PI controllers have the form (Bequette 2004)

$$C_l(s) = K_l\left(1+\frac{1}{T_{il}s}\right), \quad l = 1,2 \tag{5}$$

The direct synthesis controller for a first order process gives

$$K_l = \frac{T_{il}}{K_P T_c}$$

$$T_c = 0.5T_{il}$$

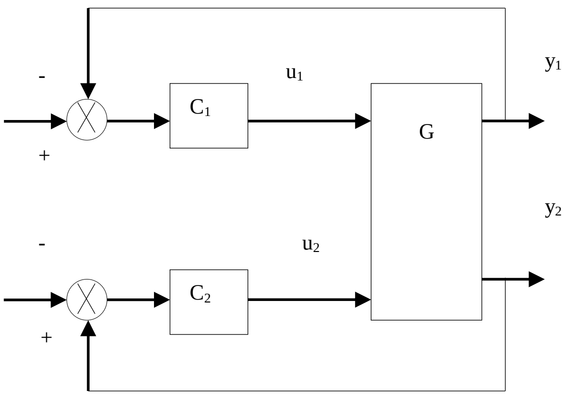

Figure 3: Decentralized control structure with two PI controllers

Type-1 Fuzzy Logic Controller

In general, Type-1 Fuzzy logic (Oscar Castillo 2008),uses simple rules to describe the system of interest, rather than the analytical equations, making it easy to implement. An advantage, such as robustness and speed, fuzzy logic is one of the best solutions for non-linear system modeling and control. Type-1 Fuzzy logic controller has four main components. They are fuzzifier, knowledge base, inference mechanism and defuzzifier. Fuzzifier converts the crisp input signal into fuzzified signals identified by membership functions into fuzzy sets. The knowledge base consists of rule base and data base. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be. Finally the defuzzification process converts the fuzzy output into crisp controlling signal. The block structure of T1FLC is shown in Fig.4 below

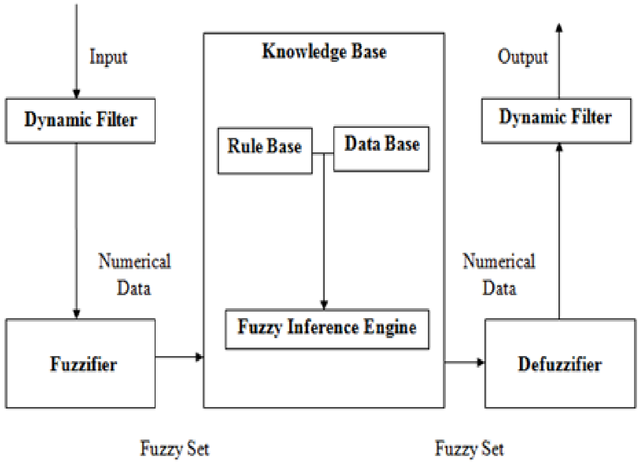

Figure 4: Block structure of T1FLC

The Control inputs, error (e) and change in error (ce) for Type-1 FLC and its membership function is shown in Fig. 5 below.

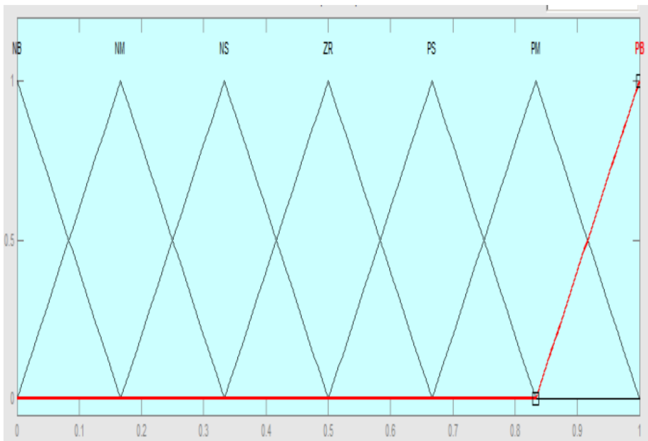

Figure 5: Membership function for T1FLC

Interval Type-2Fuzzy Logic Controller

Type-1 Fuzzy Logic Controllers (FLCs) have been applied to date with great success to many different applications. However, for dynamic unstructured environments and many real-world applications, there is a need to cope with large amounts of uncertainties. The traditional type-1 FLC using crisp type-1 fuzzy sets cannot directly handle such uncertainties. A type-2 FLC using type-2 fuzzy sets can handle such uncertainties to produce a better performance. Hence, type-2 FLCs will have the potential to overcome the limitations of type-1 FLCs and produce a new generation of fuzzy controllers with improved performance for many applications, which require handling high levels of uncertainty. The block structure of IT2FLC (Oscar Castillo 2008) is shown in Fig.6.

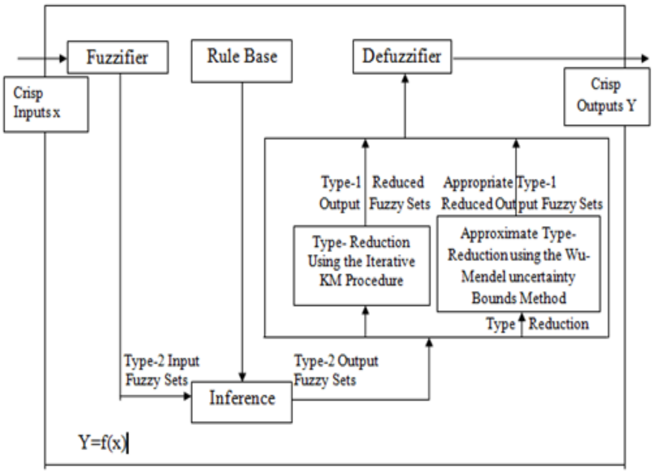

Figure 6: Block Structure of IT2FLC

The Control inputs, error (e) and change in error (ce) for Interval Type-2 FLC and its membership function is shown in Fig. 7 below.

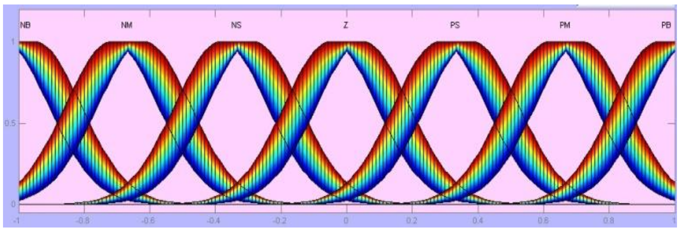

Figure. 7: Membership Function for IT2FLC inputs e and ce

From the defined rules, using the error, change of error and output the fuzzy surface is generated in MATLAB.

Vertices and the bases of the membership functions are tuned for a given system to get required response. Once the membership ship functions are created the next step is the formation of rules between input and output membership functions. Fuzzy rules are as shown in Table 2.

Table 2: Rule Base for T1FLC & IT2FLC

e \ ce	NB	NM	NS	ZR	PS	PM	PB
NB	NB	NB	NB	NM	NS	NS	ZR
NM	NB	NB	NM	NS	NS	ZR	PM
NS	NB	NM	NS	NS	ZR	PS	PM
ZR	NM	NM	NS	ZR	PS	PM	PB
PS	NM	NS	ZR	PS	PS	PM	PB
PM	NS	ZR	PS	PS	PM	PB	PB
PB	ZR	PS	PS	PM	PB	PB	PB

RESULTS AND DISCUSSION

Simulation and Experimental results are carried out to evaluate the proposed control method by utilizing the LabVIEW software. The performance of the different control strategies are compared based on IAE for the two controlled outputs h_1 and h_2. The design of the disturbance is also satisfactory for characterizing the performance of the two different control strategies. Type 1 fuzzy and Type 2 fuzzy are designed and implemented for both simulation experimental QTP. The step responses for level h_1 and h_2 of the QTP are shown below.

SIMULATION RESULTS

System response for heights h_1 and h_2 of QTP, for the set point of 23.5cm and 27.5cm are shown in Fig.8 and 9 respectively.

The servo response for the level h_1 for two different step changes i.e. a negative step change of 23.5-20cm at 2000s and a positive step change of 20-25cm at 4000s are shown in Fig. 10. Similarly the servo response for the level h_2 for two different step changes i.e. a negative step change of 27.5-23cm at 2000s and a positive step change of 23-29cm at 4000s are shown in Fig. 11.

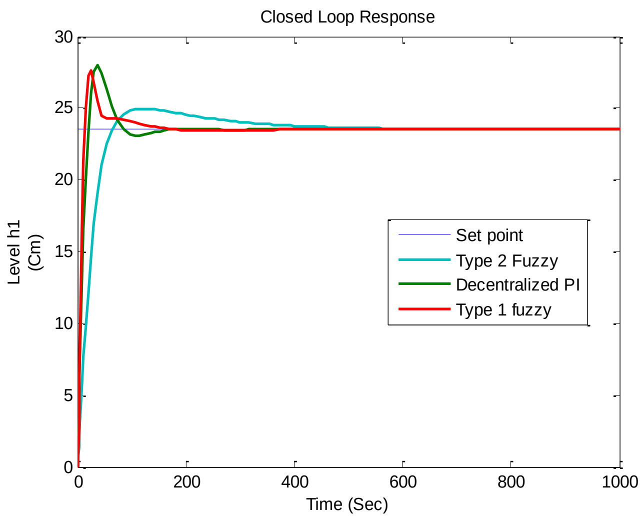

Figure 8: Closed loop response for level h_1

The regulatory response of the QTP for the process variables (i.e. level h_1 respectively and h_2) are shown in the Fig. 12 and 13 respectively. After reaching a steady state, an input disturbance of 33% is given at 2000sec.

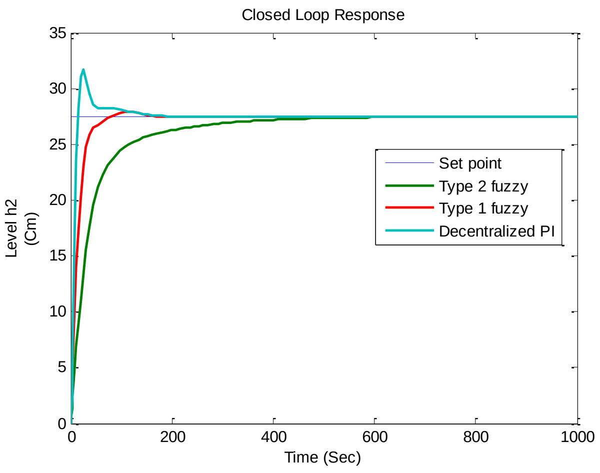

Figure 9: Closed loop response for level h_2

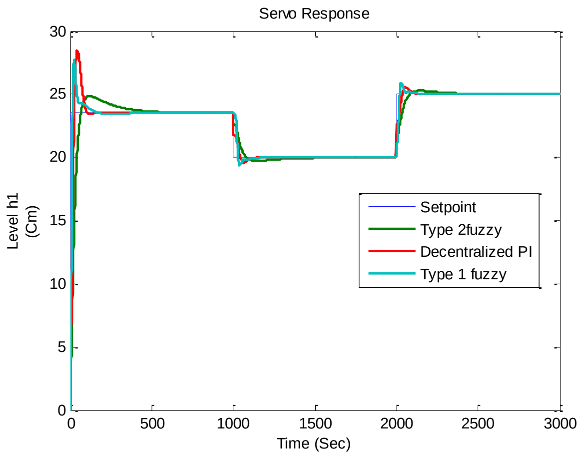

Figure. 10: Servo response for level h_1

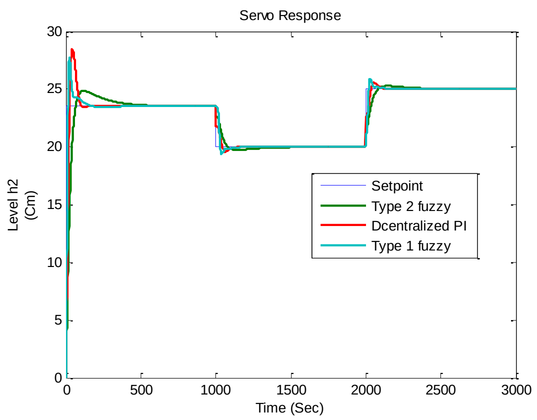

Figure 11: Servo response for level h_2

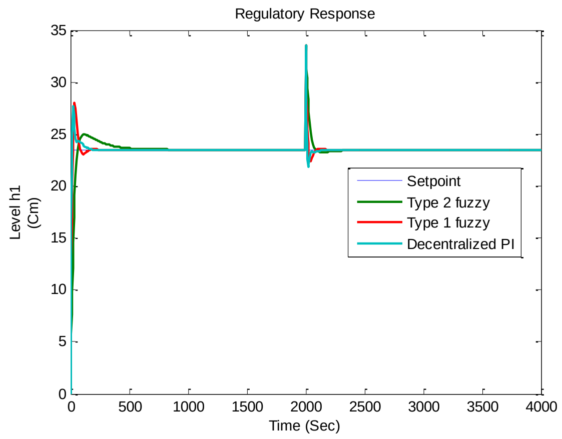

Figure 12: Regulatory response for level h_1

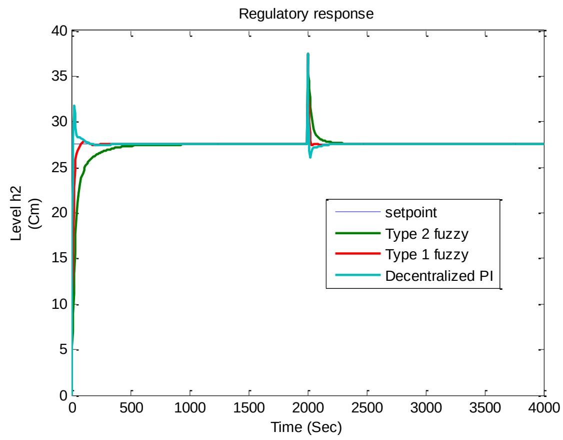

Figure 13: Regulatory response for level h_2

Comparison of performances of decentralized PI, T1FLC and IT2FLC are given in Table 3. It can be observed that IT2FLC has less settling time and over/undershoot in all the three responses. But in servo response the IAE is very less in T1FLC.

Table 3: Comparison of step response of decentralized PI, T1FLC & IT2FLC.

Type of Control	Settling Time (s)		Peak Overshoot (%)		IAE	
	h_1	h_2	h_1	h_2	h_1	h_2
Decentralized PI	110	92	9.78	3.87	128.19	149.76
T1FLC	100.2	78	4.25	2.54	126.6	145.8
IT2FLC	80.3	60	0	0	82.9	73.7

From Table 3 there is no peak over shoot. The settling time and IAE are less when compared to decentralized PI and T1FLC.

REAL TIME RESULTS

The closed loop response for level h_1 and h_2 of QTP, for the set point of 23.5cm and 27.5cm are shown in Fig.14 and 15 respectively. From Figure 14 there is no peak over shoot and settling time is also less in T2FLC when compared to decentralized PI and T1FLC.

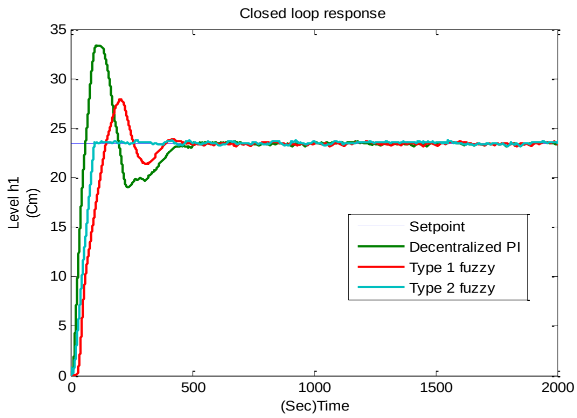

Figure 14: Closed loop response for level h_1

Comparison of decentralized PI, T1FLC and T2FLC are given in Table 4.

From Table 4 settling time, peak overshoot and IAE values of T2FLC is less when compared to decentralized PI and T1FLC.

Table 4: Comparison of step response of decentralized PI, T1FLC & IT2FLC

Type of Control	Settling Time (s)		Peak Overshoot (%)		IAE	
	h_1	h_2	h_1	h_2	h_1	h_2
Decentralized PI	970	608	37.6	6.9	4.6	3.7
T1FLC	633	466	14.5	0.7	4.5	3
IT2FLC	134	224	0	0	2.7	2.9

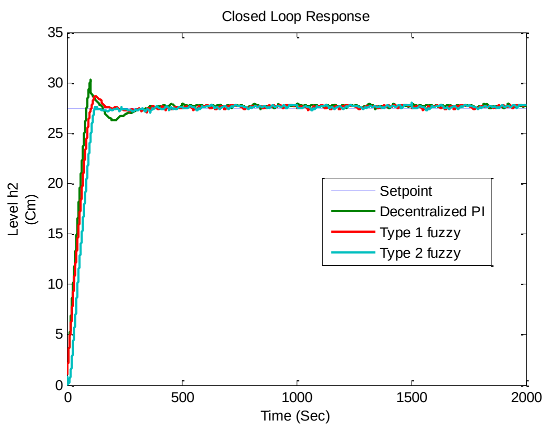

Figure 15: Closed loop response for level h_2

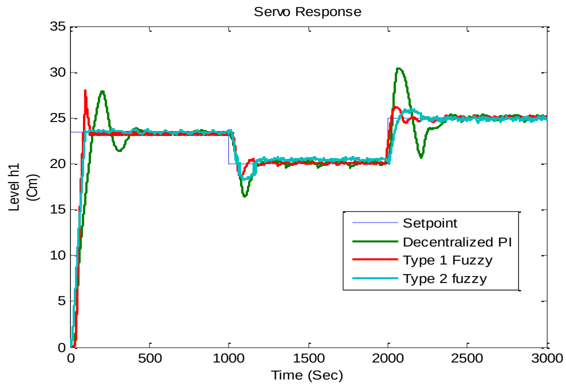

Figure 16 Servo response for level h_1

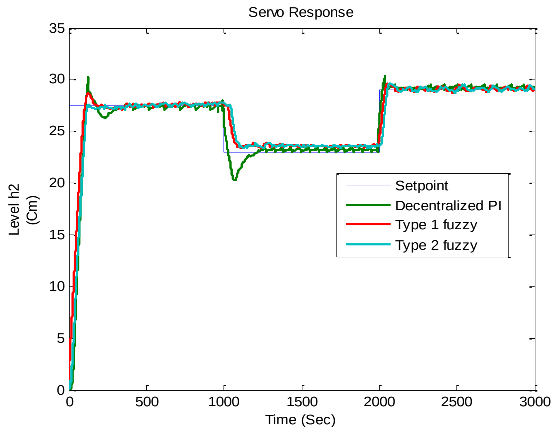

Figure 17: Servo response for level h_2

Figs 16 and 17 are the servo response of level h_1 and level h_2. Initially the level h_1 of decentralized PI is settled at the set point of 23.5cm. After that it increased from 23.5cm to 20cm for 1250 sec. After that it increased from 20cm to 25cm. Similarly the level h_2 of decentralized PI is settled at the set point of 27.5cm. After that it increased from 27.5cm to 23cm for 1250 sec. After that it increased from 23cm to 29cm.

Fig 18 and 19 are the regulatory responses of level h_1 and level h_2. 1 litre of water is externally added for tank 1 and tank2 at 2250 sec, the responses are shown below.

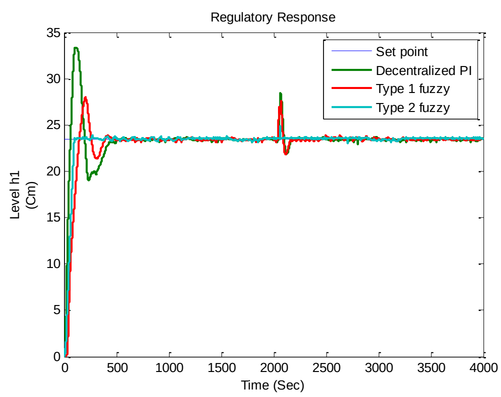

Figure 18: Regulatory response for level h_1

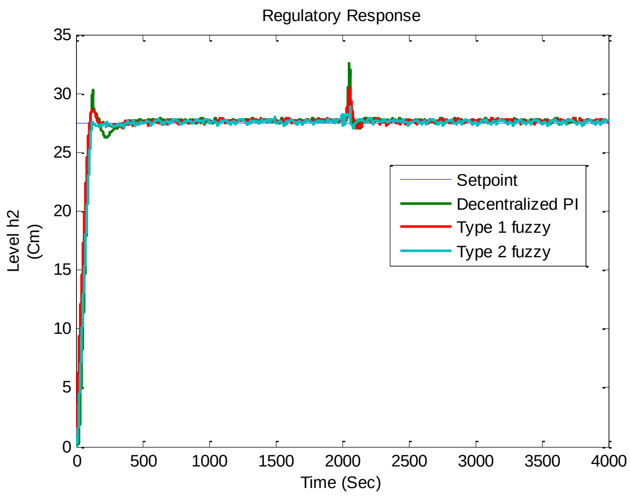

Figure 19: Regulatory response for level h2

CONCLUSION

The performance comparison of nonlinear system with closed loop, servo and regulatory responses are investigated and solved using a IT2FLC. Decentralized PI, T1FLC and IT2FLC are designed to control the liquid level of the laboratory QTP. The IT2FLC responses are compared with other responses. From these responses it is observed that the peak over shoot and IAE values are low with IT2FLC controller than with decentralized PI and T1FLC controller. In the regulatory response the large amount of uncertainty produces better performance in IT2FLC. The results show that IT2FLC controller performance is better for both servo and regulatory responses.

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