

INTERVAL TYPE-2 FUZZY CONTROL FOR MEAN ARTERIAL PRESSURE BY ISOFLURANE INFUSION DURING ANESTHESIA

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ضغط الدم الشرياني هو واحد من أكثر التدابير الضرورية المستخدمة لتحديد الجرعة المطلوب استنشاقها للتخدير. فهو يقاس بسهولة و يستجيب بسرعة مما يجعله عامل مناسب للتحكم في عمق التخدير. في هذا البحث تم استخدام طريقة جديدة للتحكم بضغط الدم الشرياني من خلال التحكم بحقن العقار باستخدام النوع الثاني لمسيطرات المنطق المضرب. وقد تم تسليط إشارة ضوضاء بقيم مختلفة وعشوائية على النظام لأختبار قابلية المتحكم المقترح للحفاظ على استقرارية النظام بوجود مقادير كبيرة من عدم التأكيدية و التي يمكن ان تظهر في النظام. علماً ان نموذج متوسط الضغط الشرياني للمريض تم تمثيله بشكل معادلة الزمن المقطع. و لأثبات كفاءة المتحكم الجديد تم اجراء مقارنة بين متحكم المنطق المضرب للنوع الاول مع المتحكم المنطق المضرب للجيل الجديد الذي اقترح في هذا البحث و اظهرت النتائج قابلية تتبع جوده لمتحكمات الجيل الثاني برغم وجود مقادير كبيرة من الضوضاء المسطرة على النظام

Mean Arterial Pressure is one of the most essential measures used to approximate the needed dose of inhaled Anesthetics. It is measured easily and responds quickly which makes it suitable factor for feedback control of depth of Anesthesia.

In this paper, a modified approach to control Mean Arterial Pressure by controlling drug infusion using Interval Type-2 Fuzzy Logic Control is explained. A number of values of uniform random noise were imposed to the system representing uncertainty and un-modeled dynamics that may appear in the model to test the controller robustness, where MAP of the patient is represented as a discrete time transfer function model.

A comparison with Type-1 Fuzzy Logic Control is made to show the superiority of the new generation of the Fuzzy Logic system. Results obtained showed good tracking ability for the proposed controller in spite of the noise imposed on the system.

Keywords: Control, MAP, Anesthesia, T2FLC, hypertension

1. INTRODUCTION

Many earnestly ill patients in Intensive Care Unit experience hypertension and therefore they need treatment to return blood pressure to a required level. A well known treatment for hypertension is to induce vasodilatation with Anesthetic drug, which must be a potent fast-acting vasodilator that can quickly relax the muscle of the peripheral vasculature, resulting in reduction of Mean Arterial Pressure (MAP) within minutes. Intensive Care Unit nurses have to continuously notice the blood pressure from a patient monitor and then correct the rate of the drug infusion to maintain the required blood pressure set point [1].

Although the infusion of Anesthetic drug can speedily lower the MAP in most patients, great

wariness is needed to treat a wide range of patient sensitivities to drugs because toxic side effects may be caused by overdose of an Anesthetic drug. The task of manually control of MAP by Manual adjustment of the Anesthetic drug (like Isoflurane) infusion rate by clinical personnel can be very boring, time-consuming, and may be of poor quality sometimes. These considerations and the improved care of patients demands have persuaded the researchers to investigate automatic control of MAP. A variety control strategies have been developed to regulate MAP by Anesthetic drug infusion and have been tested in simulation, in animal experiments, or on human patients [2, 3].

The automated control of hemodynamic variables such as MAP has been a goal of many research

projects using fuzzy constrained Single Input Single Output (SISO) version of the popular Generalized Predictive Control (GPC) algorithm (Mahfouf et al. 2001) and Fuzzy-Neural control to regulate Mean Arterial blood Pressure in seriously ill patients using sodium Nitroprussido (Xu et al. 2002), [4,1]. Moreover, fuzzy control of MAP of a patient during Anesthesia under plant parameter variation (Hakan) and a supervising algorithm is used for online updating the fuzzy gain scheduler of the PID controller to act stronger against the body reaction this technique (Nguyen et al.) are illustrated in 2005 [5,3]. In 2009, Kumar et al. designed a fuzzy PD controller with 25 rules to administrate three drugs; dopamine, Isoflurane and Phenylephrine; which perform the function of increasing heartbeat rate, decreases, and increases blood pressure respectively which controls the drug delivery unit [6]. In the same year Liu et al. developed an expert body sensor network algorithm for autonomous control of MAP and a robust PID control algorithm based on a statistics model was designated [7]. Finally, in 2010 an intelligent control approach for blood pressure system using self-generating fuzzy neural network (SGFNN) was proposed by Fan and Joo. The proposed SGFNN is simple and effective and is able to generate a fuzzy neural network to model unknown nonlinearities of complex blood pressure system[2].

In this paper, Type-2 Fuzzy Logic Controller (T2FLC) is designed and simulated to regulate MAP on a specified set point. The proposed controller is imposed to a random high number values of noise with zero mean that represent the uncertainties and un-modeled dynamics exist by the real life like movement (ex.: if the patient is shaking), Irregular heartbeats or fat (if there is a thick layer of fat underneath the skin) all these factors may disturb MAP reading [8], and can be represented as noise, and to prove the superiority of the proposed system compared with a traditional or Type-1 Fuzzy Logic Controller (T1FLC).

2. THE INTERPRETATION AND PERCEPTION OF ARCHITECTURE

Fuzzy sets were proposed by L.A. Zadeh in 1965 to process data and information affected by un-probabilistic uncertainty. These were designed to mathematically represent the ambiguous and

uncertainty of linguistic problems [9]. Fuzzy Logic Systems (FLSs) usually employ Type-1 fuzzy sets and represent uncertainty by numbers in the range of [0, 1] which are mentioned as degrees of membership. Type-2 fuzzy sets are a development of Type-1 fuzzy sets with an addition of the third dimension that corresponds to the uncertainty about the degrees of membership. Type-2 fuzzy sets are useful in conditions where it is hard to determine the exact membership function (MF) for a fuzzy set. Type-1 MFs are accurate in the case that once they have been chosen all the uncertainty disappears. However, MFs of Type-2 are fuzzy themselves. Interval Type-2 sets is the simplest Type-2 sets whose elements' degrees of membership are intervals with secondary membership degree of 1.0 [10]. Type-2 fuzzy set like Type-1 fuzzy set include elements that belong to a grade. In Type-2 fuzzy set the grade of belonging of an element is expressed as Type-1 fuzzy number within [0, 1]. This means the degree to which an element belongs to the set is uncertain; a Type-2 fuzzy set $\tilde{F}$ over domain X is given by [11]:

$$\mu_{\tilde{F}}(x): X \rightarrow [0,1] * [0,1] \quad (1)$$

Where X is the domain or universal set, x is an element in the domain X and $\tilde{F}$ is Type-2 fuzzy set.

This is called the primary membership function. In order to distinguish between a Type-1 fuzzy set and Type-2 fuzzy set, a tiled symbol is putted over the symbol of Type-2 fuzzy set. Primary membership grades are the Type-1 fuzzy numbers within [0, 1]. The secondary membership function is given in equation (2) where the grades are values within zero to one [12].

$$\mu_{\tilde{F}}(x, \mu_{\tilde{F}}): X * [0,1] \rightarrow [0,1] \quad (2)$$

The membership function of general Type-2 fuzzy set $\tilde{F}$ is three dimensional as shown in Figure (1).

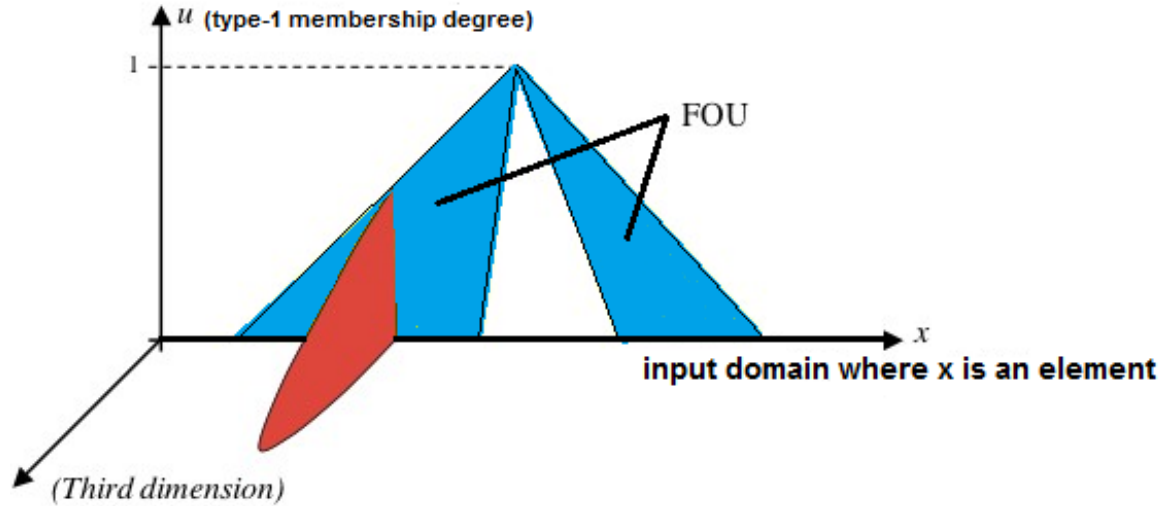


Figure 1: Type-2 fuzzy set representation

The additional dimension is the value of the membership function at each point on its two dimensional domain which is called Footprint of Uncertainty (FOU). the third dimension value is the same everywhere. For an Interval Type-2 (IT2) fuzzy set, this means there is no new information, are contained in the third dimension of an Interval Type-2 Fuzzy Set [11]. A block diagram of a Type-2 fuzzy logic system is depicted in Figure below:

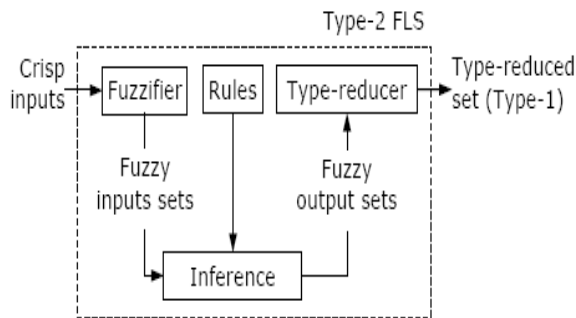


Figure 2. Block diagram of a Type-2 fuzzy logic system [10]

Measured (crisp) inputs are first converted into fuzzy sets by the fuzzification process that fired the rules which are described using of fuzzy sets and not numbers. The Inference process transforms the resulting input fuzzy sets or (the fuzzified measurements) into fuzzy output sets, This is

accomplished by first specifying each rule using fuzzy set theory, then by using the mathematics of fuzzy sets to find the output of each rule, with the help of an inference mechanism. Rules, that are either rendered by subject experts or are drawn out from numerical data, are expressed as a collection of IF-THEN statements, e.g., the activated-rule output fuzzy sets have to be converted into a crisp number, and this is done using the output processing block. two steps are required To convert an IT2 fuzzy set to a crisp number, These are Type-reduction step, where an IT2 fuzzy set is reduced to an IT1 fuzzy set, and The other step is Output Processing, which is still called defuzzification process. Since the Type-reduced set of an IT2 fuzzy set is always finite interval of numbers, the defuzzified value is just the average of the two end-points of this interval. For detailed information about IT2FLC see [12].

3. MATHEMATICAL MODEL OF A PATIENT UNDER ANESTHESIA

The relation between inflow concentration of Isoflurane (input variable) and the resulting MAP is represented in discrete time transfer function given in by equation the following equation [5]:

$$MAP(z) = \frac{-0.20282z^{10} + 0.10834z^9 + 0.077855z^8 - 0.38375z^2 + 0.30585z + 0.037436}{z^{13} - 1.8466z^{12} + 0.85214z^{11}} \quad (3)$$

The nominal MAP value used in the simulation is 100 [5]. The control action is limited with an anti-wind up integrator in order to avoid any overdose and improve the steady state performance. The upper and lower limits for the Isoflurane concentration are

chosen to be 4% and 0% respectively, i.e., the control action saturates at values above 4 and below 0 [5]. Matlab/Simulink representation of the patient model is shown in the Figure below:

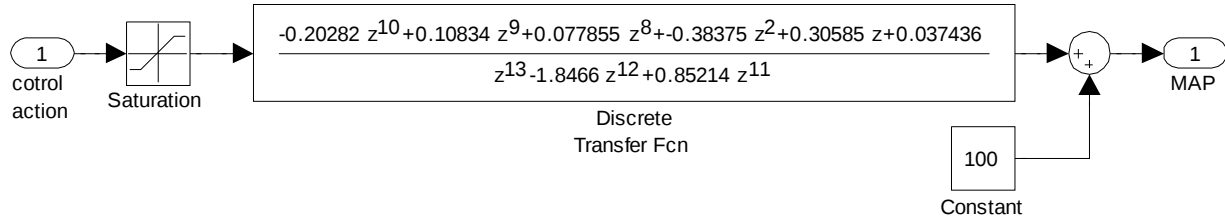


Figure 3. Simulation of Mathematical model of a patient using Matlab/Simulink.

4. DESIGN OF TYPE-1 FUZZY LOGIC CONTROLLER (T1FLC)

The discrete form of PI-Like Type-1 Fuzzy controller (T1FLC) is [13]:

$$\Delta u(k+1) = K_p e(k) + K_d \Delta e(k) \quad (4)$$

where:

$$u(k) = \Delta u(k) + u(k-1) \quad (5)$$

The indices (k) and (k-1) represent the present sample and the previous sample instants respectively, the inputs are defined as follows:

$$e(k) = r(k) - y(k) \quad (6)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (7)$$

A Mamdani type with Seven Gaussian membership functions is used for each input which results in 49 rules and minimum operation is used for implication process and Centre of Gravity (CoG) defuzzification method. The selection of these rules is based on the knowledge of the behavior of the system response. The Simulink of T1FLC of MAP for a Patient under Anesthesia is shown in Figure (4).

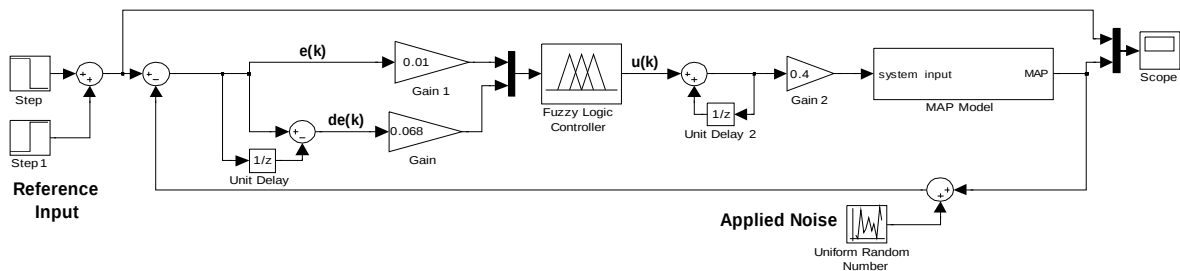


Figure 4. Simulink of T1FLC of MAP for a Patient under Anesthesia.

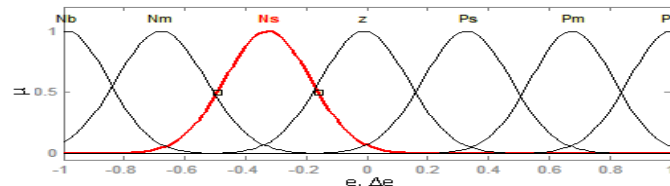


Figure 5. Membership functions for input variables of T1FLC.

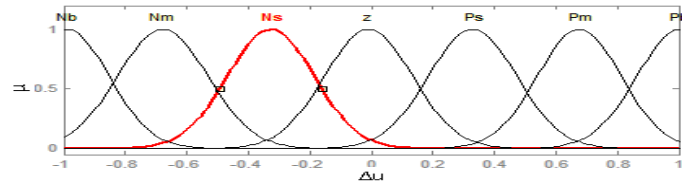


Figure 6. Membership functions for output variable of T1FLC

The characters NB, NM, NS, Z, PS, PM, PB are the linguistic variables of the inputs and output fuzzy sets. The letters N, P, Z, B, S, M, represent Negative, Positive, zero, Big, Small and Medium respectively. μ is the certainty of the membership. The rule base is explained in Table (1). The selection of rules shown is based on the knowledge of the behavior of the error equation.

Table 1. Rule base of the T1FLC.

	$\Delta e(k)$						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	NS
NS	PB	PB	PM	PS	Z	NS	NM
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NB	NB	NB
PB	Z	NS	NM	NB	NB	NB	NB

The successful design of a FLC depends on the right selection of the input and output scaling factors, and in many cases this task is done through trial and error or based on some training data [14]. In this paper, the scaling factors of FLC are tuned using trial and error. Gains used in this paper are obtained and shown in Figure (4).

5- DESIGN OF INTERVAL TYPE-2 FUZZY LOGIC CONTROLLER:

In this section a PI-Like IT2FLC is designed. The system developed assumes the same design parameters that are used in T1FLC in order to compare the impact of the third dimension added to fuzzy sets in T2FLC. The memberships of inputs and output are in a normalized range (-1, 1), as shown in Figures below:

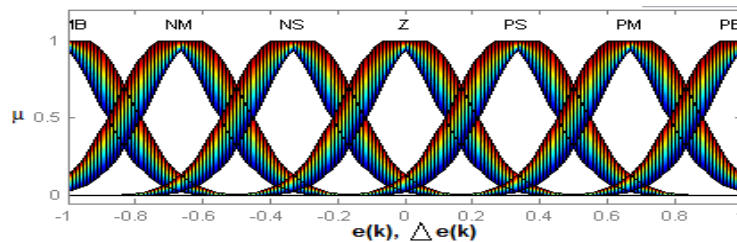


Figure 7. Membership functions for input variables of T2FLC.

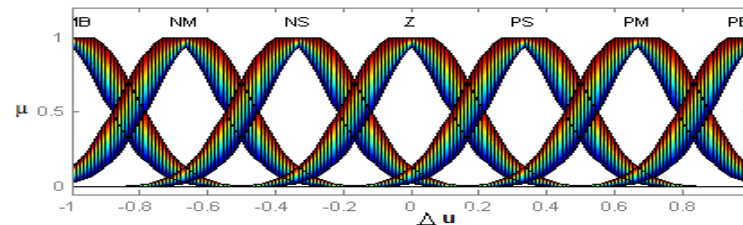


Figure 8. Membership functions for output variable of T2FLC

The Simulink of T2FLC of MAP for a Patient under Anesthesia is shown in figure (9).

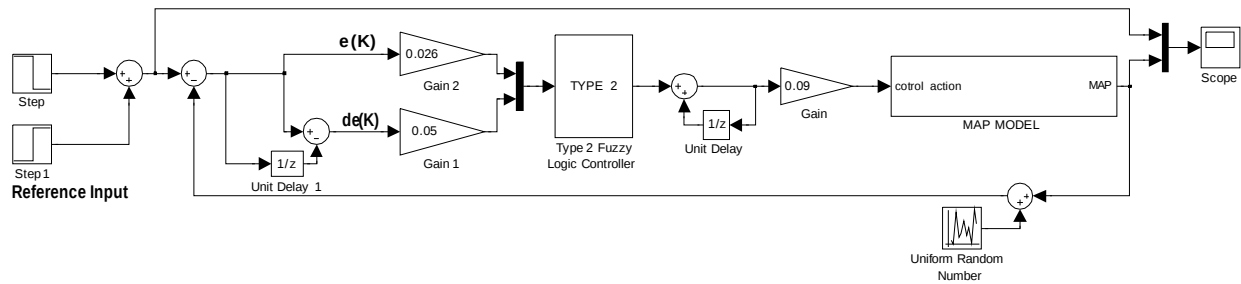


Figure 9. Simulink of T2FLC of MAP for a Patient under Anesthesia.

5. SIMULATION RESULTS

The closed loop systems shown in Figure (4) and Figure (9) are tested to check their ability to track a reference signal of MAP and to check their robustness of control performance at different levels of uniform random values of noise.

6.1 Simulation of T1FLC and T2FLC using Noise free model:

A step change in MAP is applied in the second of 1000 from 70 and 90 mmHg) to test the patient model controlled by T1FLC and the patient model controlled by T2FLC separately, see Figure (10). The comparison between the obtained responses is done as summarized in Table (2).

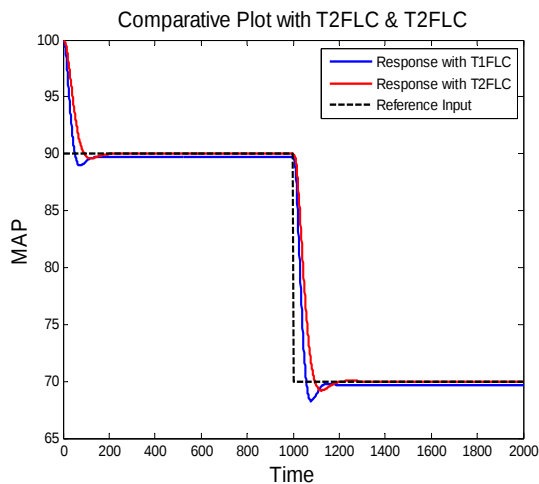


Figure 10. Comparative plot of T1&T2FLCs

Table (2) Comparison between Results.

MAP reference	T1FLC	T2FLC
70	ess 0.3 P.U 2.3000	ess 0 P.U 1.1600
90	ess 0.3 P.U 1.0500	ess 0 P.U 0.4000

Where ess is the steady state error

P.U: Peak Undershoot

It can be noticed that the both controllers, IT1 and IT2, have achieved good tracking ability for the applied reference MAP, but T2FLC was superior in the response performance where the steady state error (ess) was eliminated to zero and the Peak Undershoot (P.U) was decreased by 49.5% for 70 mmHg reference input and 61.9 for 90 mmHg reference input, see Table (2).

6.2 Simulation of T1FLC and T2FLC using patient model affected by Noise:

The robustness of the T1FLC and T2FLC to handle the model of a patient in a noisy environment, unmodeled dynamic, uncertainty in the model or controller parameters, is tested. The closed loop system exposed to different levels of uniform random value of noise [15, 16] with maximum values of ± 30 of amplitude applied at zero mean. An example of the noise applied is shown in Figure (11). It is clear from Figure (12) that the patient model controlled by T2FLC was robust in dealing with noise compared with the T1FLC that fail completely in controlling the model by producing completely oscillated response. T2FLC stabilizes the model with smoother response in spite of noise effect; see Figure (12) and Figure (13).

In the case of oscillation, the MAP was fluctuating above and below the set point for both controllers.

The fluctuations around 5 mmHg is regarded as acceptable oscillation [17, 16].

By examining the results listed in tables (3) through (6) it can be noticed that T2FLC had only exceeds the 5 mmHg value once and that happened when a step input of 70 mmHg is applied with uniform number of noise of peak value of ± 30 (i.e., the noise is nearly 50% of the input), while T1FLC begun to exceed this value when the peak value of noise begun to exceed ± 10 .

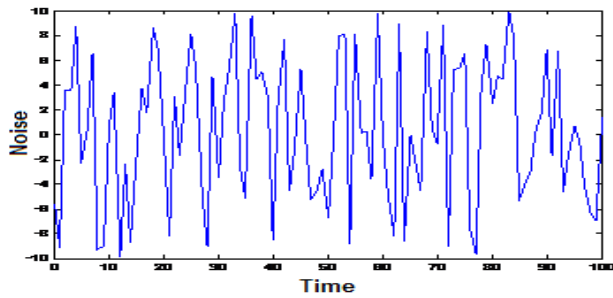


Figure 11. Noise signal applied to the system

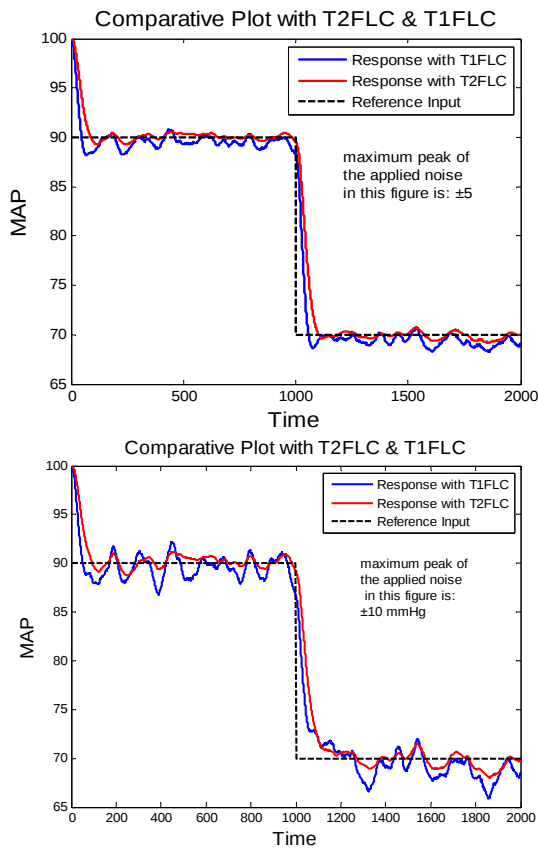


Figure 12. Responses of the closed loop systems
(a) with applying ± 5 of peak of noise
(b) with applying ± 10 of peak of noise

Table 3. Comparison between Results for ± 5 of peak of noise.

MAP reference		T1FLC	T2FLC
70	P.O	0.702	0.734
	P.U	1.735	0.800
90	P.O	0.800	0.540
	P.U	1.860	0.726

P.U: Peak Undershoot

P.O: Peak Overshoot

Table 4. Comparison between Results for ± 10 of peak noise.

MAP reference		T1FLC	T2FLC
70	P.O	2.000	1.530
	P.U	4.140	1.946
90	P.O	2.200	1.220
	P.U	3.240	1.250

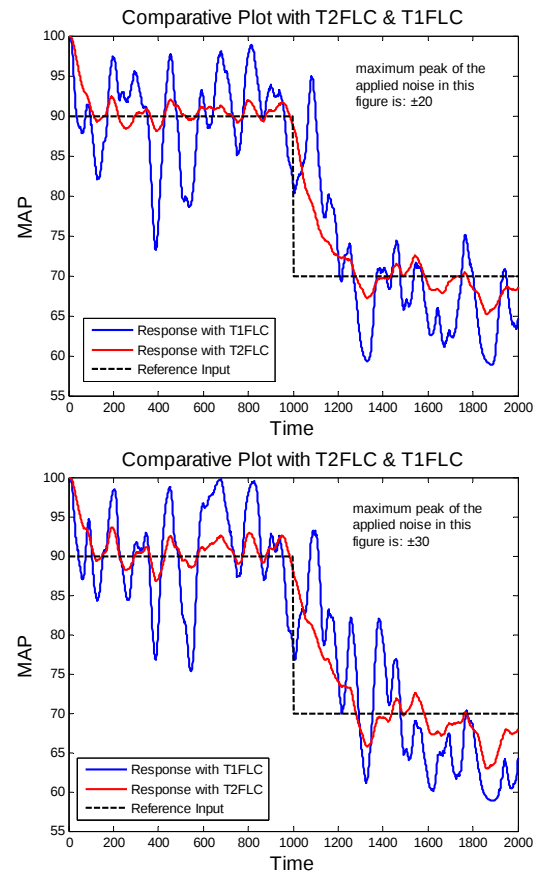


Figure 13.: Responses of the closed loop systems
(a) With applying ± 20 of peak of noise
(b) with applying ± 30 of peak of noise

Table 5. Comparison between Results for ± 20 of peak noise

		noise	
MAP reference		T1FLC	T2FLC
70	P.O	5.100	2.573
	P.U	11.128	4.805
90	P.O	8.912	2.375
	P.U	3.200	1.915

Table 6. Comparison between Results for ± 30 of peak noise

		noise	
MAP reference		T1FLC	T2FLC
70	P.O	5.100	2.530
	P.U	11.128	7.132
90	P.O	8.911	3.660
	P.U	16.800	3.217

7. CONCLUSIONS:

In this paper, the control of the MAP for a patient under anesthesia is studied in order to design a suitable controller to be the step for the real life applications. There are many factors that affect the reading of MAP at every moment. Also, the difference in sensitivity for different human beings as a response to the injected drugs makes any mathematical model proposed to represent the MAP to be considered as Uncertain and had many unmodeled dynamics. So, Interval Type-2 FLC controller (IT2FLC) is designed for the control of MAP due to its ability to handle modeling uncertainties. To prove the superiority of the proposed controller compared with Type-1 Fuzzy Logic Controller (T1FLC), the comparison showed that IT2FLC was able to achieve better control response than IT1FLC. The steady state error is reduced to zero using T2FLC for noise free model while T1FLC was having a steady state error.

Furthermore, the other advantage of a T2FLC appears to be its ability to eliminate the effect controlling noisy model and was maintaining the steady state error not exceeding the value of 5 mmHg; for different types of noise levels. This arises from the extra degree of freedom provided by the FOU added to this type of controller which is not exists in T1FLCs.

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