Comparision between type-1 and type-2 Fuzzy logic Controller to Control Anesthesia

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Abstract— **This paper deals with the automation in the drug administration for the regulation of bispectral (BIS) index, an indicator used in the anesthesia process during any clinical intervention involving the administration of two drugs, a hypnotic drug namely propofol and an opioid namely remifentanil. To realize the automatic drug administration, and imitate the atmosphere and conditions prevailing in the operation theater, compartmental models known as pharmacokinetic and pharmacodynamic models have been considered. These models are intended to describe the dynamics involved in the administration of the input drugs. A closed loop control system has been created using two types of controller, namely type-1 (T1) fuzzy controller and interval type-2 (IT2) fuzzy controller. The gains and membership functions are obtained by minimizing a cost function measuring the control performance. The controllers are then tested for their robustness in terms of their control performance and adaptability. Simulation results obtained in Matlab show that the IT2 fuzzy controller scores better in control strategy for regulating the BIS index as compared to T1 fuzzy controller.**

Index Terms—**Anesthesia, BIS, Closed-Loop, DoA, IT2 Fuzzy Logic Controller, Propofol, Remifentanil, Simulation,T1 Fuzzy Logic Controller.**

I.INTRODUCTION

Anesthesia can be described as a temporary reversible phase from unconsciousness to consciousness during any surgical stimulus ensuring lack of memory of any of the pain or trauma undergone during the surgical procedure [1]. General process of anesthesia can be divided into the phases of induction, maintenance, emergence, and recovery [2]. The depth of anesthesia (DoA) represents the level of consciousness [3], which is to be controlled during the process of anesthesia spanning over a number of control targets such as steady error, settling time, and overshoot. The process of anesthesia needs to be controlled and closely monitored so as to avoid a situation of overdosing or under dosing of the anesthetic drug. In general, control strategies can be categorized into two classes: open-loop control and closed-loop control. In open- loop control, anesthetists manually adjust the drug dosage based on his/her knowledge and experience, so as to maintain the DoA. In closed-loop control, the drug dosage is automatically adjusted according to some predefined and fixed indices of DoA, which ensures that the infusion of the anesthetic drugs is continuously controlled and responsive based on the ever changing requirements of the patient. Closed-loop control also incorporates in itself inter patient variability that arises due to difference in response to the same drug by different individuals[4].Despite of its advantages, the stability of closed-loop control needs to be ensured as it is an automated process without any supervision [5].

The propofol–Remifentanil combination:

Earlier a large dose of an anesthetic agent (propofol) was used to achieve anesthesia. But nowadays, small anesthetic drug quantities are used in combination with an opioid (remifentanil) to achieve balanced state of anesthesia, while the side effects are reduced. A combination of intravenous agents like propofol and remifentanil in boluses results in strong effects that last for a short duration of time. But these types of interactions give rise to significant interactions. Out of the various types of interactions possible like additive, antagonistic etc., the most favored interaction is the synergistic type, which signifies greater resulting effect than just superposition [5].

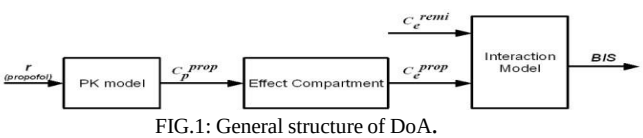

FIG.1: General structure of DoA.

For proper representation of the control system involved in anesthesia, a three compartment

Pharmacokinetic (PK) and Pharmacodynamics (PD) model is used. Main difficulties involved in such a modeling procedure are the determination of PD model parameters. It is customary that the parameters of PK and PD models be determined beforehand. For the PK model, parameters are estimated depending on sex, age, and weight of patients. But on the other hand, for the PD model, it is not possible to estimate the parameters for certain patient. As such in this context, the controller which controls the DoA, needs to be robust [6].In this paper a closed loop control system using a fuzzy controller has been designed for anesthesia control. Closed-loop systems are designed to automatically achieve and maintain the desired output condition by comparing it with the actual condition. This is achieved by generating an error signal which is the difference between the output and the reference input. In other words, a "closed-loop system" is a fully automatic control system in which its control action is dependent on the output in some way. Once the infusion of the anesthetic drug has been controlled using the closed loop control theory, the bispectral (BIS) index [7] is an extensively accepted index to measure the DoA. It is a dimensionless parameter measured in a scale from 0 to 100,where a value of 100 signifies awake state,80 to 100 shows sedated state,60 to 80 signifies a moderate hypnotic level and 40 to 60 indicates deep hypnotic level [8].The process of closed-loop control of anesthesia is tested on the basis of: stability-which is the basic control objective of any controller; robustness-which accounts for the uncertainty of PD model parameters, and adaptiveness- which ensures that the controller is adaptive to different patients. Commonly used controllers include PID controllers, model-based controllers, and knowledge-based controllers [9],[10].The model-based controller is a reflection of the patient's current pharmacological behavior. For this reason, the patient model needs to be updated continuously. In this paper the Fuzzy logic Controller (FLC), which is used in the closed loop structure is based on Fuzzy Logic Theory proposed by L.A.Zadeh in 1965. Fuzzy logic is the logic which is used in fuzzy controllers and it stands out amongst all other controllers as it mimics human thinking and natural language much better than any other traditional logical systems [11],[12].As such during the past several years, fuzzy control has emerged as one of the most active area for research in the applications of fuzzy set theory. It provides an artificial but appropriate platform of capturing the uncertain nature of the real world [13]. This research paper comprises of the following sections organized in the sequence: in Section II, a multivariable PK-PD anesthesia model (DoA) used in this paper is described; in Section III, the background of T1 fuzzy PID controllers and IT2 fuzzy PID controllers has been discussed; in Section IV, all the control strategies have been discussed so as to perform simulation; in Section V, simulation results are provided and comparison of controller output has been done; finally in Section VI, results have been discussed.

II. DEPTH OF ANESTHESIA (DOA) MODEL

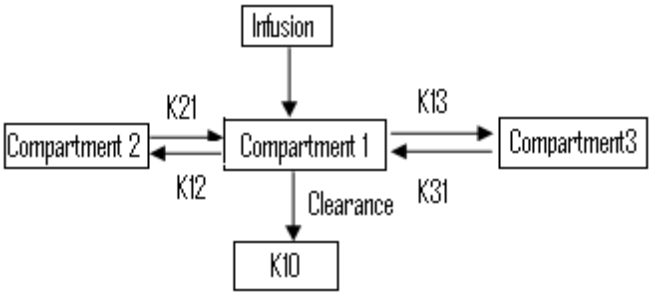

FIG.2General structure of three compartment PK-PD Model

A model can be best understood as a concept of reality, which accounts for those properties of a system or a process that are inherent to the function of the model [12]. Models are used in anesthesia to identify the various physiologic, pharmacological and physical processes that take place during general anesthesia. The distributions of anesthetic medications in the body are dependent on transport and metabolic processes [13]. Diverse models have been proposed for modeling the drug effect, such as experimental models, compartmental models and physiological models .Out of all the modeling options available, the standard modeling paradigm that has been commonly used to describe the relationship between anesthetic input and patient output is that of compartmental models [14].Compartmental models are formulated based on the minimum number of compartments that effectively fit the observed data. Physiologically based models are more near to the actual representation of drug kinetics. In this paper a three compartment PK model and a corresponding PD model has been used [15], [16]. The PK model is dependent on the input-output data sequences. An input drug is administered and the time course is measured by taking blood samples. The infusion time of the bolus is neglected and therefore the response is an approximation of an impulse response. The plasma compartments are used as central compartment (compartment 1) [17],[18].The purpose of the effect-site concentration is only to account for the time lag between drug concentration and drug effect [8].Since remifentanil does not contribute significantly to the effect site, as such Ce is assumed to be given and as such the modeling is then done only for propofol. The DoA model is divided into three main parts (FIG.1). The PK model

describes how the hypnotic drug (propofol) administered with an infusion rate r spreads through the blood and tissue resulting in a plasma concentration Cp. The second part, the effect compartment, models the transport of a certain plasma concentration Cp to the brain resulting in a concentration effect Ce. Finally the third part, the interaction model, describes the actual effect the drug has on the body measured by BIS.

A. Pharmacokinetic (PK) model

Pharmacokinetics is the affect of the body on the administered drug, which ranges from the administration of the drug, to its absorption, metabolism and finally its excretion from the body. As such pharmacokinetics can be expressed as the relation between blood plasma concentration Cp(t) to the administered dose I(t).The main purpose of the PK model is to predict the blood plasma concentration of the drug[19].This is done on the basis of the study of the absorption, distribution and the metabolism and finally the elimination of the drug from the body. The PK model relates the blood plasma concentration Cp(s) to the drug infusion I(s).

$PK(S) = Cp(s)/I(s)$ (1)

When the drug is administered in the body, then the blood plasma level increases. This process is known as absorption and involves a time delay [9].This time delay process can be expressed as:

$Cp(t) = Xe^{-At} + Ye^{-Bt} + Ze^{-Ct}$ (2)

Where Cp (t) is measured in microgram/milliliter, A is the rate constant of the distribution phase is the rate constant of the distribution phase and C is an additional constant that is associated with the dynamics distribution phase and can be used if required

$PK(s) = Cp(s)/I(s) = X/(s+A) + Y/(s+B) + Z/(s+C)$ (3)

Both infusion and elimination of the anesthetic drug takes place from the central compartment as the carrier of the drug is blood plasma (FIG.2).Infusion is denoted by I and the elimination takes place according to the rate constant k_{10}.After infusion, the drug is distributed to Compartment 2 and Compartment 3 according to the rate constants k_{12} and k_{13}.As such the concentrations of both the compartments increases until any one of them have the same concentration as the central compartment. When this condition is achieved, the process of distribution stops. The mathematical expression pertaining to the above arrangement can be represented as:

$$\begin{bmatrix} \dot{c_1} \\ \dot{c_2} \\ \dot{c_3} \end{bmatrix} = \begin{bmatrix} -k_{10}-k_{12}-k_{13} & k_{21} & k_{31} \\ k_{12} & -k_{21} & 0 \\ k_{13} & 0 & -k_{31} \end{bmatrix} \begin{bmatrix} c_1(t) \\ c_2(t) \\ c_3(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{V_1} \\ 0 \\ 0 \end{bmatrix} I(t)$$

(4)

If the plasma concentration of the central compartment becomes equal to the concentration of compartment 1, then

$$Cp(t) = C_1(t)$$

In simplified form:

$$PK(S) = \frac{Cp(s)}{I(s)} = \frac{(s+k_{21})(s+k_{31})}{v_1(s+A)(s+B)}$$

(5)

B. Pharmacodynamic (PD) model

Pharmacodynamics can be described as the effect of the drug on the body which involves both the biological and physiological aspects. When two drugs with different schemes of action but inherent similar therapeutic effects are used in combination, it results in a cumulative effect.

PD model represents the observed effect of the drug to the drug plasma concentration.

$$PD(s) = \frac{O(s)}{Cp(s)}$$

(6)

The above relation (6) can be observed in the effect site. The effect site is in turn related to the DoA (Depth of Anesthesia) by the Hill Equation

$$E(t) = E_0 - E_{max}\left[\frac{Ce^{\gamma}(t)}{ce^{\gamma}(t) + Ec50^{\gamma}}\right]$$

(7)

Where E_0 denotes the awake state and is allotted a value of 100,E_{max} denotes patient sensitivity to the drug ,Ce is the concentration of the effect site, and γ represents steepness of the curve:

$$c_e(s) = \frac{1}{\frac{1}{k_{e0}}s+1} c_p(s)$$

(8)

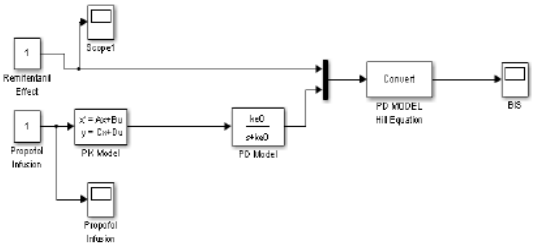

FIG. 3: The interaction block diagram of DoA in simulink

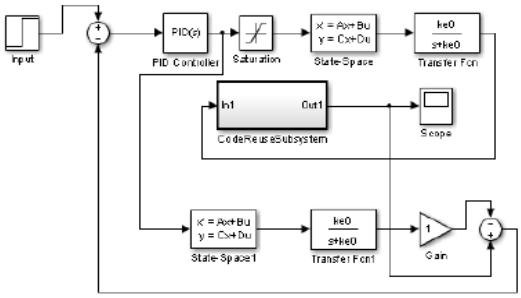

FIG. 4: The block diagram of the Simplified DoA model in Simulink

To deal with automatic infusion of anesthesia, a direct adaptive fuzzy logic controller was proposed for multivariable anesthesia systems [14].Due to the advantages of closed-loop control, in this paper, we aim to implement the closed-loop control for anesthesia model. The performance and robustness of controllers is ensured by simulation and optimization. In the anesthesia model, the co-administration of both propofol and remifentanil is taken into consideration [15]. To realize the drug administration, we propose two strategies: a type 1 fuzzy logic controller and a type 2 (IT2) fuzzy logic controllers. All gains, scaling factors and parameters of membership functions are optimized in terms of performance index which in turn helps to quantify the performance of the controllers. A BIS reading is considered as a reference mark to set the targets for both the controllers used, keeping in mind the real anesthesia situation. Comparisons are made among both controllers to demonstrate the characteristics and suitability of each control strategy.

III. TYPE-1 AND TYPE-2 FUZZY PID CONTROLLERS

Fuzzy logic controllers (FLC) provide a platform for designing and implementing robust controllers that are able to perform robustly under conditions of uncertainty and imprecision that is close to real world scenario [16]. FLCs operate by transforming numerical data into linguistic values and infer output control responses by using fuzzy rules that imitate nonlinear relationships between the system inputs and controlled outputs with or without the need for any mathematical model [17], [18]. FLCs are therefore capable of exhibiting robustness with regards to noise and variation of system parameters that are so much associated with any complex nonlinear system. [19],[20]. Two types of controllers can be used to control anesthesia namely type-1(T1) and type-2 (IT2).But the main limitation of using T1 controller is that its grades of membership are crisp and therefore they are incapable to handle the uncertainties in parameter variability associated with a highly nonlinear process like anesthesia. In order to minimize the drawbacks of type-1 systems, type-2 fuzzy systems which use type-2 fuzzy sets have been applied to control anesthesia [21]. Type-2 FLCs show a good performance in terms of control and produce accurate and stable control performances in face of different sources of uncertainties [22–25].Due to the dynamic changes caused by inter-patient variably to different drugs on patients during surgical stimuli, the fuzzy logic controller is faced with the challenge to adapt its control rules to facilitate regulation and adjustment of administered anesthetic in the best possible way so as to ensure that the depth of anesthesia(DoA) is optimally maintained.Traditionally,fuzzy rules were obtained in consultation with experts based on their knowledge and individual experience [26], [27]. In recent years, there have been some studies on extracting fuzzy rules using machine learning approaches.

A. Type-1 fuzzy PID controller

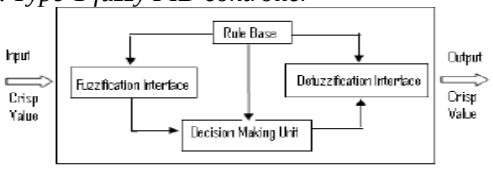

FIG. 5: Basic configuration of type-1 fuzzy logic controller

It is a general practice that all Fuzzy Logic Systems usually employ Type-1 fuzzy sets and represent the uncertainty associated with the system by numbers in the range of [0, 1] which are mentioned as degrees of membership[28].The design of fuzzy controller are based on different steps .In the first step fuzzy controller is used to determine the inputs and the output of the fuzzy system where the error between reference and actual model output is denoted by e(t) and its time derivative are taken as the system input and the controller output is considered as fuzzy system output [29].The linguistic variable which are tabulated in table-1 in below are considered as the size of the input and the output. The shape of the membership function of these rules play a very important part in the design of a controller .The shapes of the membership functions are trapezoidal, bell curve function ,triangular function .Out of these shapes triangular function is the most commonly used and has been considered in this paper because of its simple computation method. The other important factor that must be considered for the design of membership function are the number of curve and their position.The input and output are normalized to vary between -1 to +1 using the scaling factor of the gain in the simulation block .The linguistic variable ‘PS’, ‘NS’ and ‘NB’,’PB’ and ‘Z’ represent the steady state error of the system and the initial undershoot, overshoot, respectively following disturbances such as noise. The magnitude of

controller input is strongly influenced by both error and the deviation error .To improve the robustness of the controller against parameter uncertaintities and external disturbances, the controller must ensure that the error input dominates the output of the fuzzy controller. In view of the linear PID controller, as the proportional, integral and derivative gains are constant; it is not able to handle satisfactorily a highly nonlinear system [30]. This void creates the requirement for the use of T1 fuzzy PID controller [31] [32] of which the gains undergo modifications depending on the requirement. A T1 fuzzy PID control system is shown in Fig. 4, which consists of a T1 fuzzy PID controller and a patient's model (detailed in Fig. 1) connected in a closed loop. Unlike the linear PID controller having a set of constant gains, the T1 fuzzy PID controller in turn has a fuzzy inference system which results in providing a set of feedback gains. The behavior of the fuzzy inference system is governed by a set
Of fuzzy

Rule $If\ x_1(t) = M_1^i\ and\ \dots x_\emptyset\ (t) = M_\emptyset^i$

Then y(x(t)) = y_i
Where $x_n(t)$ is a linguistic variable and n= 1,2,3…Ø
M_n^i is a fuzzy term and n= 1,2,3…Ø
Ø is a positive integer;
y(x(t)) is the output of the fuzzy inference system.

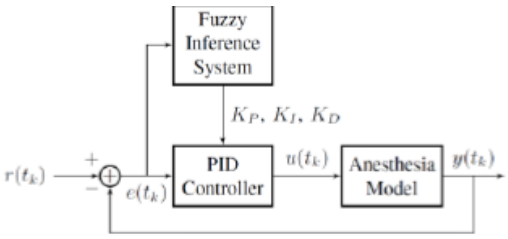

FIG.6:Block Diagram of a fuzzy PID controller.

The output obtained can be represented as

$$y(x(t)) = \sum_{i=1}^{m} w_i(x(t))y_i$$

$$x(t) = [x_1(t)\ x_2(t) \dots x_\emptyset(t)]$$

$$\sum_{i=1}^{m} w_i(x(t)) = 1 \qquad (10)$$

$$w_i x(t)) \geq 0 \qquad (11)$$

$$w_i x(t)) = \frac{\prod_i^\emptyset \mu_{M_1^i(x(t))}}{\sum_{j=1}^{m} \prod_i^\emptyset \mu_{M_1^i(x(t))}} \qquad (12)$$

Where m> 0 denotes the number of rules incorporated,$w_i(x(t))$ is membership in the normal form, $\mu_{M1i(x(t))}$ is fuzzy membership, the output of the PID controller is replaced by (9),so that the system converts into a T1 fuzzy PID controller. The fuzzy inferences obtained now is used to replace the factors of K_P,K_I and K_D and as such the crisp and constant values of these terms give way to changing values governed by membership functions. Type-2 fuzzy sets are an extension of Type-1 fuzzy sets with an addition of a third dimension that represents the uncertainty of the membership functions. A Type-2 fuzzy set can therefore be represented as over domain X is given by [33]:
$\mu F(x)$:X→[0,1]∗[0,1] (13)
Where X is the domain or universal set, x is an element in the domain X and F is Type-2 fuzzy set[17].

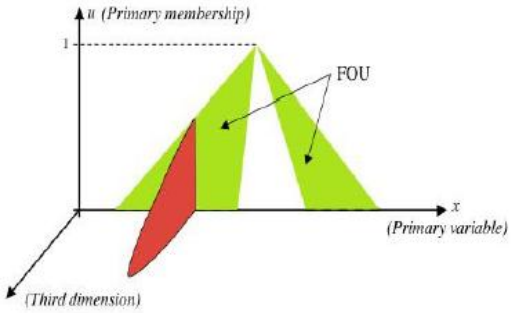

FIG.7: Type-2 Fuzzy set

The membership function of a general type-2 fuzzy set is three-dimensional (Fig.7), where the third dimension is the value of the membership function at each point on its two-dimensional domain that is called its footprint of uncertainty (FOU).For an interval type-2 fuzzy set that third-dimension value is the same everywhere, which means that no new information is contained in the third dimension of an interval type-2 fuzzy set. So, for such a set, the third dimension is ignored, and only the FOU is used to describe it. It is for this reason that an interval type-2 fuzzy set is sometimes called a *first-order uncertainty* fuzzy set model, whereas a general type-2 fuzzy set (with its useful third-dimension) is sometimes referred to as a *second-order uncertainty* fuzzy set model. If (13) is replaced by interval fuzzy sets, it transforms into an IT2 fuzzy system. The rule is represented by

Rule $If\ x_1(t) = \widetilde{M_1^1}\ and\ \dots x_\emptyset\ (t) = \widetilde{M_\emptyset^1}$
Then $y(x(t)) = \widetilde{yi}$

$$W_i(x(t)) = [w_i(x(t)), \overline{w_i(x(t))}$$

$$\widetilde{yi} = [y_l, \bar{y}_l] \quad i=1,2\dots m$$
$$w_i x(t)) = \prod_{\alpha=1}^{\emptyset} \mu_{M_\alpha}(x(t))$$

$$\overline{w_i} x(t)) = \prod_{\alpha=1}^{\emptyset} \bar{\mu}_{M_\alpha}(x(t))$$
$$\bar{\mu}_{M_\alpha}(x(t)) \geq \mu_{M_\alpha}(x(t))$$
$$\overline{w_i} x(t)) \geq w_i x(t))$$
$$\bar{y}_i \geq y_i$$

Where $w_i x(t))$ denotes lower grade of membershi
$\overline{w_i} x(t))$ denotes upper grade of membersl
$\mu_{M_\alpha}(x(t))$ membership reducer
$\bar{\mu}_{M_\alpha}(x(t))$ membership reducer

The output of an IT2 fuzzy system is given by

$$y(x(t)) = \frac{\sum_{i=1}^{m} \overline{w_i} x(t)) y_i}{\sum_{i=1}^{m} \overline{w_i} x(t))} = [y_i \quad y_n]$$

$$\text{So, } y(x(t)) = \frac{y_i + y_n}{2}$$

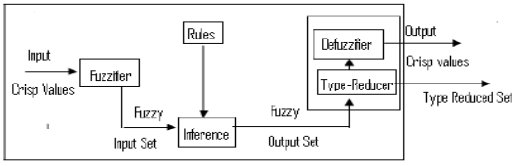

FIG.8: Basic configuration of type-2fuzzy logic controller

IV. CONTROL STRATEGIES

When the type-2 FLC is used, the input signals from the patient anesthetic model to the controller are taken at each sampling instant in the form of four inputs: the error of muscle relaxation, integration error of muscle relaxation, error of BP, and integration error of BP [34].The fuzzifier performs its task of converting crisp data into type-2 fuzzy sets. The inference engine uses the rule-base given in table-2 to infer the output type-2 fuzzy sets from the input value. The next job is to combine the output type-2 fuzzy sets to form a type-1 fuzzy set called the type reduced set [35]. This operation is performed by the type reducer. The defuzzifier is comparable to the one used in traditional type-1 FLCs, which has the ability to defuzzify the type-reduced sets so as to produce the crisp control outputs [36]. There are two output control signals which are based on the integration of these output values in order to provide for the adjustments in anesthetic dosage which are required in the operation theatre. The crisp output values thus obtained are sent to the patient anesthetic model and the responses obtained are then fed back to the type-2 SOFLC to be compared with the pre-decided standard values so as to calculate the error of the input control signals.

A. Self-organizing Component

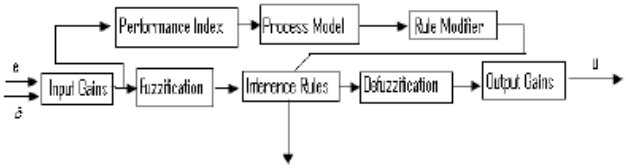

FIG.9: Basic configuration of SOFLC

The Self-organizing (SO) mechanism is responsible to modify the control rules so that the output falls in line with the desired control responses [37]. It comprises of three functional blocks: the previous rule-base generation, Process Model or Performance Index, and rule-base modification as shown in (Fig.9) .The previous rule-base block is generated from human expert experience (in this case an anesthesiologist). During the control process, the rule-base in the previous rule-base block/process model undergoes modification according to the requirement by the self-organizing component included in the system. The next functional block-performance index is a measure of the deviation from the desired response and calculates the appropriate changes that are required so as to get the output of the controller as close as possible to the desired output. The modification of the control rules are carried out by assigning a credit or reward value to the individual rule. New rules can be added to the Type-2 FLC rule-base, if required, provided they help in improving the output [38]. This particular action is aimed at providing fast convergence somewhere around the equilibrium state so as to achieve a higher degree of accuracy. This also ensures that the rule base generated is different for different patients according to their needs and requirement in the system, and in turn ensures robustness of the controller. Since it is practically impossible to handle performance index and control rule-base under multidimensional space, so the common practice is to use a method for decomposing an n-input/m-output system into a set of 2-input/1-output systems [39].

B. Fuzzy Rule-Base System

The rule-base comprises of a set of fuzzy rules used in the fuzzy process to infer output control response. The
fuzzy rules can be represented as IF x is $\tilde{F}$, y is $\tilde{F}$, THEN z is $\tilde{G}$ (14) where x and y are inputs, $\tilde{F}$ are the input fuzzy sets, z is output, and $\tilde{G}$ is the output fuzzy set. The input fuzzy sets correspond to a series of linguistic labels: negative big (NB), negative middle (NM), negative small (NS), zero (ZE), positive small (PS), positive middle (PM), and positive big (PB), over the ranges of the input variables. The output fuzzy sets correspond to the labels: zero (ZE), positive small (PS), positive middle (PM), and positive big (PB) over the two the output variable ranges.

Δe/e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NS	NB	NM	NM	NM	NS	ZE	PS
NM	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PS	PB	PB	PB	PB

Table1: Rule-Base for type-1 FLC.

Δe/e	NB	NM	ZE	PM	PB
NB	NB	NB	NB	NM	ZE
NM	NB	NB	NM	ZE	PM
ZE	NB	NM	ZE	PM	PB
PM	NM	ZE	PM	PB	PB
PB	ZE	PM	PB	PB	PM

Table2: Rule Base for type -2 FLC

V. SIMULATION RESULTS

In real life scenario, anesthesia is usually administered to maintain different level of DoA and muscle relaxation at different stages of a surgical procedure. During certain types of highly complex surgical procedures, the patient is required to be under deep anesthesia during more invasive preliminary stages, while they are required to be in a shallower anesthetized state during the course of the procedure.

The amount of propofol injected to the patients is about 5 normalized units for the first 5 minutes. This ensures that the muscle relaxation reaches almost near to the desired set point and is so maintained for the next 10 minutes. Following the initial bolus effect, the SOFLC controller is turned on to control multivariable anesthesia system. Slight interference is obtained in the form of noise measuring a maximum up to 20% which can be considered as white noise and is due to fluctuations in physiological factors like muscle relaxation [40]. Simulations were performed using Matlab.

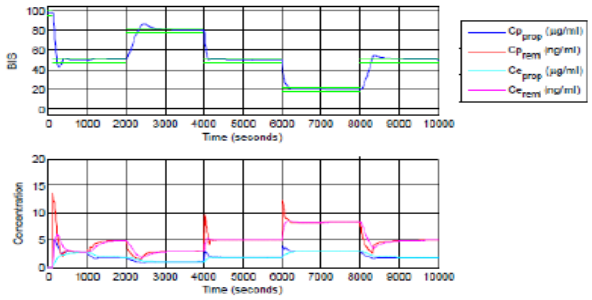

FIG.10: Simulation for BIS and Concentration of drug using type-1 FLC.

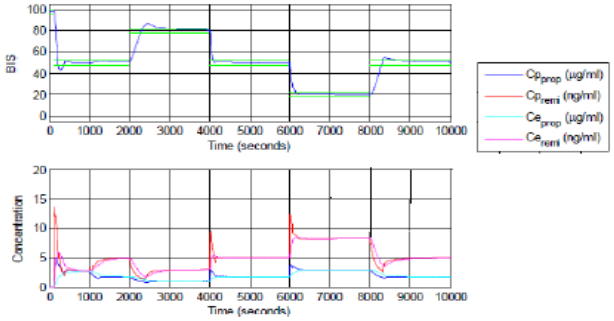

FIG.11: Simulation for BIS and Concentration of drug using type-2 FLC.

VI. RESULTS AND DISCUSSIONS

In this paper, drug administration for anesthesia has been realized by using type-1(T1) and type-2(IT2) SOFLC. SOFLCs provide a qualitative adaptive control mechanism for maintaining the controller's behavior by incorporating the expert knowledge and experience in the initial stage and later train these derived rules to reach a desired control range. In this paper, the type-2 SOFLC of anesthetic drug delivery is carried out to maintain physiological set points for muscle relaxation based on a patient model for regulating propofol and remifentanil, in the presence of signal noise.

We have first constructed a three compartment PK-PD patient model with propofol and remifentanil. Simulation has been conducted to regulate the output BIS value and concentration of drugs involved governed by this model T1 fuzzy PID controllers and IT2 fuzzy PID controllers. Scaling factors have been added to coordinate the simultaneous administration of the two drugs.Type-2 fuzzy sets derived from variable sets of data were used for modeling the system parameters so that more accurate and stable control performances is guaranteed pertaining to different sources of uncertainties. The performance difference between the experts derived and extracted SOFLC rule-bases were mainly observed not in terms of steady state errors, but in terms of control stability. The extracted rule base was much more accurate than the expert knowledge system, because at the very beginning of the simulations the extracted rule-base can reach the set point over a steady state more quickly and stably than the expert derived rule-base. Also, the extracted rule-base is able to use fewer rules to reach the same kind of steady state error performance as the expert derived rule-base. This can be an important advantage in terms of reducing real-time computational processing. Also it can be seen that Type-2 performance [41–44].

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