Automatic Control of Anesthesia During Surgery Using Fuzzy Controller

Maryam Goodarzian[1,2], Mohamad Reza Yousefi[1,2*], Neda Behzadfar[1,2]

Abstract– Creating the desired depth of anesthesia is done by controlling the amount of anesthetic drug applied to the patient. Applying an excessive amount of anesthetic causes the patient to regain consciousness, and on the other hand, using an amount less than necessary causes the patient to perceive the painful stimuli caused by the surgery. In this article, using the lowest amount of drug as a control input, the desired depth of anesthesia (the desired value of 50%) is created as the output of the model in the patient. The aim of designing an improved control method to adjust the drug dose is to use the second type of fuzzy logic, which is more advanced and has higher accuracy and flexibility than the first type of fuzzy logic. In order to analyze the results of this research, the system has been simulated using MATLAB software, and the effects of disturbance and noise have been considered in the output of the model. The results show that the proposed control structure controls the model well. Based on the simulation done in MATLAB software, the use of type two fuzzy control structure can reduce the amount of fluctuations in disturbance and measurement noise by 25% compared to type one fuzzy method, and in the conditions Without disturbance and noise, the proposed method does not have any subjugation and at the same time, the amount of time to achieve the desired value is improved by 87% compared to the type one fuzzy method.

Keywords: Disturbance Effect, Drug Dose Adjustment, Depth of Anesthesia, Surgery, Fuzzy Controller

1. Introduction

Usually, modern surgical procedures are impossible without the patient going to general anesthesia (GA). The basic features of a successful GA in the patient are the loss of consciousness by stopping movement, which is achieved through muscle relaxation, lack of awareness, and lack of response to painful stimuli through analgesia. Due to the fact that the most important factor of anesthesia is located in the brain, most of the researchers' attention is focused on the analysis of the electrical activity of the brain. New devices for recording the depth of unconsciousness measure only one or two channels of electroencephalogram (EEG) recorded from the patient's forehead [1,2]. Currently, two practical methods are used to determine the depth of anesthesia, which are as follows:

A- Auditory evoked potentials (AEP): which measures the patient's excitability to sound stimuli.

B- Bi-spectral index (BIS): which examines the degree of coupling between different frequencies in the frequency domain.

The range of BIS is between 0 and 100, where 0 indicates deep anesthesia and 100 indicates full consciousness of the patient. Adjusting the level of anesthesia can lead to the improvement of many medical conditions during surgery (absence of feeling pain, realization of the right time for the patient to regain consciousness) and after surgery (reduction of anesthesia side effects of the patient). Therefore, the regulation of anesthesia is considered one of the important factors in surgeries. So far, many control methods have been presented to control the depth of anesthesia.

Among them, we can mention classical and simple proportional-integrator-derivative (PID) controllers, adaptive-fuzzy and self-organizing fuzzy controllers [3,4]. But controllers with fixed gain are not suitable for this purpose and the reason for that is the relatively large difference between patients. Model-based predictive controllers (MPC) have also been used to control the depth of anesthesia [5].

Fuzzy logic controller (FLC) with adaptive structure has been investigated in the face of uncertainty and uncertainty

1* Corresponding Author: Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
2 Smart Microgrid Research Center, Najafabad Branch, Islamic Azad University, Najafabad, Iran
Email: mr-yousefi@iaun.ac.ir, n.behzadfar@pel.iaun.ac.ir

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in linear and non-linear systems [6,7]. FLC can perform properly with noise and changes in system parameters in complex and highly non-linear areas such as medical systems [8,9]. Some of the recent applications of FLC in order to control the injection of automatic infusion have been proposed in [10], [11] and [12]. In these papers, type one FLC is designed in a closed loop system, which is investigated to control the adjustment of drug injection amounts based on the approximation of the outputs of a reference model. Fuzzy adaptive control schemes in which FLC parameters are modified have been widely used to regulate the drug injection process.

In [13] an adaptive method for fuzzy rules is described in order to adapt control of sodium nitroprusside injection while maintaining target values for mean blood pressure. In this paper, FLC uses an online adaptation algorithm to adjust the input and output parameters of type one membership function during simulation execution.

In [14], a fuzzy neural network (FNN) is proposed to automatically control the dynamic variables, blood pressure and cardiac output of patients with hypertension and heart failure by simultaneously injecting cardiac drugs such as vaginosis and entropic factors. slow FNN parameters are determined based on the experience of a specialist doctor. During the simulations, an online recursive learning algorithm adjusts the shapes of the type one membership functions used in the fuzzification layer and the fuzzy output layer according to the neural network. Optimization-based methods can be used in the design of control systems in general anesthesia.

Specifically, in [15] the control of the depth of anesthesia with the general approach of optimizing the controller parameters using an evolutionary algorithm to minimize the worst cost function compared to a set of patient models is presented. For this purpose, integrated absolute error is chosen as the optimization function. Due to the fact that the optimization is done locally, it cannot cover a wide range of patients. Another study is conducted with the aim of estimating the depth of anesthesia at a safe and appropriate level by considering the characteristics of the patient in the induction phase. The BIS index signal, as a common method to control the depth of anesthesia, causes noise and delay in the initial stage of injection, which may lead to useless information in the control process. Also, using the BIS index requires a time-consuming process, high equipment cost and lack of access to device accessories.

To overcome these problems, a new model for control without using such an index is proposed in [16]. According to this method, an estimation strategy for anesthesia using a neural network and an adaptive neural-fuzzy inference estimation model is presented. This model estimates the dose of intravenous anesthetic drugs in relation to the needs of the patients, which leads to the optimal dose of the drug and a stable depth of anesthesia. The proposed estimates have been compared with sensitivity analysis and comparison with real data obtained from classical model (PK-PD) and BIS method in 13 patients undergoing surgery. The results show an accuracy of 0.99, which indicates a model with high reliability.

In [17], a new adjustment method for selecting the parameters of a PID controller that adjusts the maintenance stage of general anesthesia is investigated. The proposed method is based on the use of propofol closed loop as an input using the BIS scale as the controlled variable. The simulation results show that according to the data-based PID adjustment approach, it has a robust performance according to the variety of patients. In another study, the preliminary clinical results obtained with the PID control plan for the simultaneous injection of propofol and remifentanil during general anesthesia are presented. BIS scale is considered as the only process variable and PID controller parameters are selected using an optimization method. The proposed control system automatically optimizes for each stage using two different sets of setting parameters in the form of a schedule. The primary clinical evaluation of the controller has been performed on ten patients under general anesthesia during plastic surgery [18]. This system has satisfactorily created and maintained anesthesia in the entire patient population without requiring any manual intervention by the anesthesiologist and confirms the effectiveness of the overall design approach. For a nonlinear model based on the stabilized models of pharmacokinetics and pharmacodynamics of sigmoid-imex, the input-output linearization control method based on PID and LQG controllers has been investigated. In the case of noisy observations, the LQG can be tuned to provide a smoother injection rate while achieving a steady-state response comparable to that of the PID.

In this article, for the automatic control of anesthesia during surgery, a new time interval and type two self-care fuzzy logic controllers (SOFLC) are proposed. SOFLC type two is a hierarchical adaptive fuzzy controller that has the advantages of fuzzy method and adaptive method at the same time. SOFLC controls the level of anesthesia to achieve the optimal amount during anesthesia by using type two fuzzy sets consisting of surgical data and taking physiological variables of the patient.

Comparing the type two fuzzy controller with classical controllers such as PID shows the superiority of the fuzzy system. In the type two fuzzy controller method, the initially measured error inputs are converted into fuzzy levels by the fuzzification process, and in an inference process, the input fuzzy levels are converted into the output fuzzy levels.

The structure of this paper is divided into five parts. In the introduction section of the research problem, the description of the research in the desired research field and the general method proposed to achieve the desired goal are presented, in the second section, the mathematical relationships of patient anesthesia modeling are presented. The third part of the design principles of the type two fuzzy method is designed. In the fourth part, in the simulation space of Matlab software, the control results on the anesthesia model system will be examined and evaluated, and in the fifth part, according to the simulation results, the conclusion of the article will be expressed.

2. Chemical Synchronous Reactor Model

Various processing tools have been used to extract a single standard for this purpose, among which BIS is a relatively good standard and is considered as an index of the depth of anesthesia in this article. Here, in order to simplify the use of the anesthesia model, it is assumed that only propofol, which is an intravenous anesthetic drug, was used. One of the special features of propofol is its rapid distribution and metabolism. Pharmacokinetic-Pharmacodynamic (PK-PD) model is used to express the relationship between the dose of injectable drug (hoshbar propofol) and the effect observed in the patient (BIS). Pharmacokinetics is a branch of pharmacology that studies the distribution of drugs in the body. The phenomenon of receiving medicine, spreading and removing it can be expressed mathematically. Mathematical equations in the form of anesthesia system state space are expressed as follows [19]:

$$\begin{cases} \dot{x}_1 = -[k_{10}+k_{12}+k_{13}]\, x_1 + k_{21}\, x_2 + k_{31}\, x_3 + \dfrac{u(t)}{V_1} \\ \dot{x}_2 = k_{12}\, x_1 - k_{21}\, x_2 \\ \dot{x}_3 = k_{13}\, x_1 - k_{31}\, x_3 \\ \dot{x}_e = -k_{e0}\, x_e - k_{1e}\, x_2 \end{cases} \tag{1}$$

In the above relationship, x1 is the drug concentration in the central part. Variables x2 and x3 model drug exchange between muscles and fat. Xe and kij are drug transfer rates between different sections. Here, the pharmacokinetic (PK) section is shown with a three-part model. In the three-part model, the body is divided into three parts:

The first part: a small central part containing arterial blood and highly injected tissues such as brain and liver.

The second part: a large part including muscles and viscera.

The third part: a part that basically includes fats and bones, the amount of the drug delivered to the central part is removed at a constant rate of 10 k (usually expressed in minutes). This removal is done using metabolism, liver or excretion. In parallel with the elimination process, the drug is distributed in two side parts with the rate of k12 and k13. Examining how the drug circulates shows that the concentration in the first part C1 decreases rapidly, while the concentrations in the second part C2 and third part C3 increase.

When the concentration in the central part (first) and side parts reached equilibrium; The diffusion process is reversed and the drug stored in the lateral parts returns to the central part with rates of k21 and k31. The (PK) model can be expressed as a transformation function using multipart parameters in the form of relations (2) and (3):

$$pk(s) = \frac{c_p(s)}{I(s)} = \frac{1}{V_1}\,\frac{(s+k_{21})(s+k_{31})}{(s+\pi)(s+\alpha)(s+\beta)} \tag{2}$$

$$\frac{c_p(s)}{I(s)} = \frac{1}{V_1}\,\frac{(s+Z_1)(s+Z_2)}{(s+\boldsymbol{P_1})(s+\boldsymbol{P_2})(s+\boldsymbol{P_3})} \tag{3}$$

V1 is the volume of the central part, α is the constant rate for the diffusion phase and β is the constant rate for the removal phase. Researchers introduce the use of ρ or π symbol to describe the fast dynamics related to the diffusion phase. The pharmacodynamic part of PD is described by the Emax sigmoid model and equation (4).

$$BIS = BIS_0\left(1 - \frac{C_e^{\gamma}(t)}{EC_{50}^{\gamma}(T) + C_e^{\gamma}(t)}\right) \tag{4}$$

BIS indicates the measured anesthesia, EC50 is the concentration at which half of the maximal effect available in the patient is observed, γ term is non-linear and affects the slope of the curve. This model is also called the Hill model. BISo represents the starting point or the patient's BIS in the drug-free state (usually equal to 100).

The work section is also used as a hypothetical section. In fact, this part is a theoretical part and the drug concentration in it is proportional to the measured effect of the drug and is described by equation (5).

$$\frac{K_{e0}}{s+K_{e0}} \tag{5}$$

Figure (1) shows the pharmacokinetic-pharmacodynamic model used in this article. In this figure, Kij is the parameters depending on the person's age, weight and height. In the presented model, the body is divided into three parts. A central part includes arterial blood and highly injected tissues such as brain and liver, a part includes muscles and viscera, a part which basically includes fats and bones. The values of the model parameters based on the patient's weight, height and age are listed in table 1.

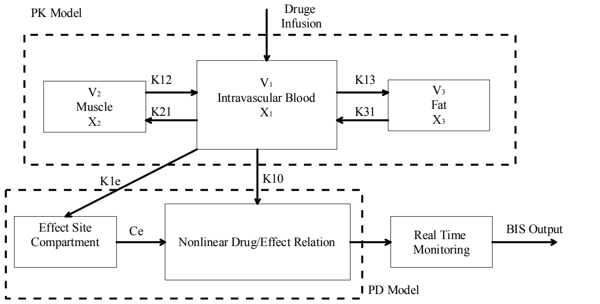

Figure 1: Pharmacokinetic-pharmacodynamic model [18]

Table 1: Values of anesthesia model coefficients

Parameters	*Value*	*Unit*
$k_{10} = \frac{Cl_1}{V_1}$	Cl_1=1.89 + 0.045(weight-77) - 0.068(lmb-59) + 0.026 (height-177) V_1=4.27	*l/min* *l*
$k_{12} = \frac{Cl_2}{V_1}$	Cl_2=1.29 - 0.024(age-53)	*l/min*
$k_{13} = \frac{Cl_3}{V_1}$	Cl_3=.83	*l/min*
$k_{21} = \frac{Cl_2}{V_2}$	V_2=18.9 - 0.39(age-53)	*l*
$k_{31} = \frac{Cl_3}{V_3}$	V_3=2.38	*l*

3. Type Two Fuzzy Controller Design

The PID controller structure has been used in articles to adjust the amount of anesthesia [20,21]. Due to the robust structure and proper performance in different working conditions required by the anesthesia model, the first type fuzzy control method has also attracted the attention of researchers [22,23].

In order to increase the margin of resistance and the adaptive mode of the fuzzy controller for the patient model in anesthesia, the second type fuzzy control method is proposed. In this research, the structure of the PID controller process is used in order to design the first type and the second type fuzzy method for the type one fuzzy controller. A fuzzy structure is defined for each of the PID controller coefficients [24,25]. Fuzzy structure inputs are two important process parameters in controller design, i.e. system error and error changes. In this case, for the inputs of the structure, different states that happen in practice are assumed, and in this condition, the design of a type one fuzzy controller is presented [26,27].

For each fuzzy controller input, 7 input membership functions are defined, including PM, PS, Z, NS, NM, NB, and PB, which represent very negative, medium negative, low negative, and zero respectively from left to right, low positive, medium positive and very positive are considered. These seven membership functions are actually the number of states that can occur in the model.

The membership functions associated with the error input are defined for each PID controller coefficient in specific ranges in the general interval [30-30] and for error changes [10-10] according to the practical error of the patient model. The structure of each membership function is considered to be Gaussian, considering that the closer the input data is to the center of the membership function, the higher the membership ratio will be. The type two fuzzy set has new definitions and terms compared to the type one fuzzy method, which are mentioned in this section. To distinguish between type two and type one fuzzy set, the type of that set is specified with a sign above the name of that set. The type two fuzzy set is represented as relation (6) or (7).

$$A = \int \frac{M_A(X)}{X} = \int \left[\int \frac{F_X(U)}{u} \right] / x \quad (6)$$

$$A = \{(x).M_A(x) \; \forall X \in J_x \} \quad (7)$$

4. Simulation Results

In this part, the model used for patient anesthesia is examined using MATLAB software. The database used in this research is based on reference [19], the parameters of the considered patient model are presented in table 2.

The design of the PID controller is done using the optimal setting of the PID toolbox and the proportional, integrator and derivative coefficients are designed as 0.5, 0.03 and 2 respectively. The simulation has been done in 100 minutes.

In figure (2), three type two fuzzy controllers are designed and with the rules defined for its seven two-dimensional membership functions, the amount of control input is adjusted. In figure (3), the input of drug injection using the structure A type two fuzzy control is shown.

Table 2. Values of anesthesia model coefficients

Parameter	*First patient*	*Second patient*	*Third patient*
Weight (kg)	50	65	75
Height (cm)	163	164	187
Age	36	38	37
Gender	Man	Female	Female
γ	4.29	2.46	2.1
EC_{50}	6.76	4.93	8.02

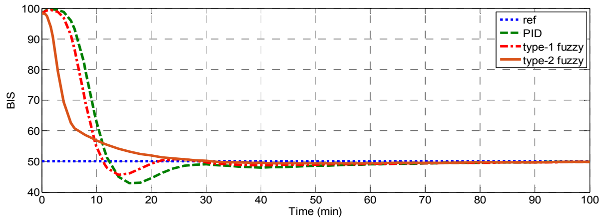

Fig. 2. The output value of the bispectrality index with the presence of a type two fuzzy controller

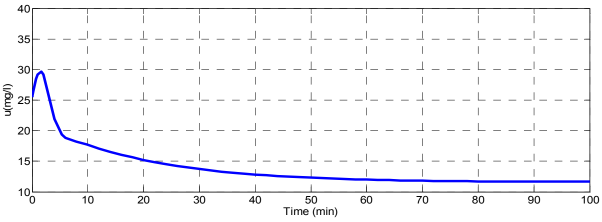

Fig. 3. Input for drug injection related to type 2 phase

According to the results of the simulation in MATLAB software, by using the two-type fuzzy control structure, the desired value is followed faster than the two controllers, and as a result, the system error has reached zero in 30 minutes. On the other hand, despite increasing the speed of the system, the output of the anesthesia model has reached the desired value without any regression, while the two PID and fuzzy control methods, respectively, have regression in the distance of achieving the desired value. Figure (4) also shows the control input associated with the type two fuzzy method, which indicates the faster performance of the controller in order to achieve a level of anesthesia of 50%. In this section, due to the presence of measurement noise in practical mode, the simulation of the anesthesia model has been done considering the white noise in the output sensor. White noise is an example of noise signals that have characteristics such as zero mean and one variance. In this case, the proposed controller, i.e., fuzzy type two, was used and the results were compared with the case of using PID and fuzzy type one control structure. Noise is applied to the system during the period of 40 to 80 minutes.

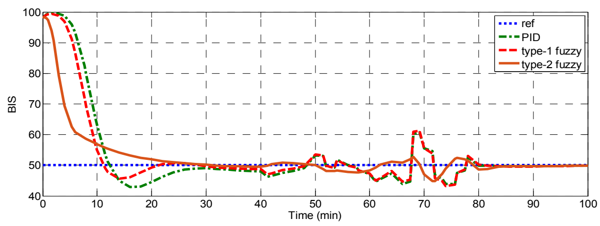

Fig. 4. Output value of bispectrality index with different controllers

Based on the obtained results, it can be seen that the output of the model in the case of using PID and phase one control methods are accompanied by many fluctuations, the maximum overshoot in the time period of applying noise is 10 units, and the maximum undershoot is equal to 8 units. Meanwhile, in the second type of fuzzy control method, despite the effects of noise in the time period of 40 to 80 minutes, the output of the model has a maximum overshoot of 2 units and a maximum undershoot of 5 units, which has a good performance compared to other simulated methods. And it is resistant to noise. This noise signal can be affected by the electronic equipment of medical devices and according to the results of the fuzzy controller, it can be used in this collection. The control input signals using the PID controller, phase one and phase two, considering the effects of noise in the system, are shown in figures (5), (6) and (7).

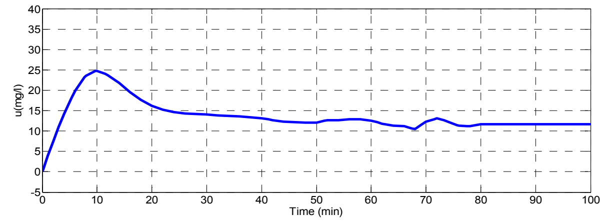

Fig. 5. PID controller input for drug injection

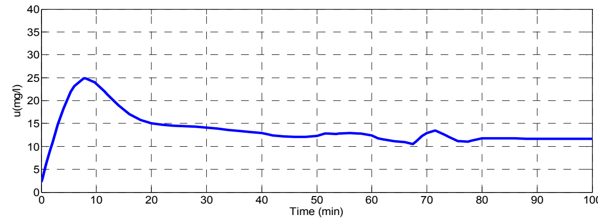

Fig. 6. Type one fuzzy input for drug injection

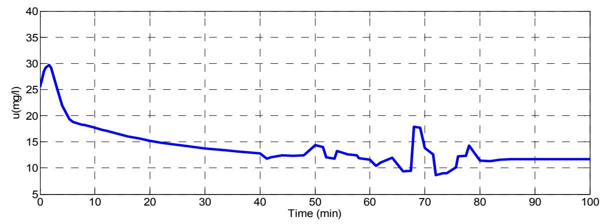

Fig. 7. Type 2 fuzzy input for drug injection

In this simulation, two reference signals are followed by the use of a fuzzy control structure with the presence of measurement noise, and minimal fluctuations in the patient's BIS are observed under the conditions of using this controller. Therefore, according to the simulation results, the control inputs set by the controllers have been applied to the patient in the presence of measurement noise. In noisy conditions, the type two fuzzy control input has applied different inputs compared to the type one PID and fuzzy controllers and is more sensitive to the changes in the model output due to the measurement noise. And in order to achieve the desired level of anesthesia, the appropriate dose is designed.

5- Conclusion

Creating the desired depth of anesthesia in surgery is not only a guarantee of not perceiving and recalling pain, but also causes the patient to regain consciousness after surgery, which increases the safety of the anesthesia process.

Despite the progress that has been made in the field of monitoring devices for patient's vital signs, the depth of anesthesia of the patient is controlled by a specialist. The anesthesiologist, using his personal knowledge and experience, determines the rate of medicine required for injection to the patient. In this article, the control of anesthetic dose adjustment has been investigated. The type two fuzzy method for anesthesia model control has been presented, which has been able to perform better than many previous controllers such as type one fuzzy and conventional PID controller. The simulation results indicate the effectiveness of the type two fuzzy method in controller design, which eliminates both the dependence on expert information in the design and the uncertainty in the control structure. Also, the comparison of the proposed method with the type two fuzzy method One, the PID control method indicates that the method is resistant to changes caused by measurement noise.

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