Self-organizing Fuzzy Logic Controller for the Multivariable Anesthesia System

Samira Mohammadzamani[1,*] - Hamid Mahmoodian[2] - Khoshnam Shojaee[3]

[1] Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

[2] Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

[3] Department of Electrical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

ABSTRACT

In this paper, a Self-Organizing Fuzzy Logic Controller (SOFLC) has been proposed for estimating the depth of anesthesia. The SOFLC is a fuzzy system in which the inference rules are continuously updated by a self-learning procedure. Common drugs such as Isoflurane and Atracurium that apply in modern surgery have been used for controlling blood pressure and muscle relaxation, respectively. The MIMO system includes four inputs and two outputs that consist of errors and change of errors of drugs for inputs plus electromyogram (EMG) signal and blood pressure have been chosen as outputs. The set points of outputs were set at 0.8 normalized scale for muscle relaxation and 110 mmHg for blood pressure. A new method for reducing the computing time and simplifying calculation has been used. The result of this Simulation study showed that excellent regulation of blood pressure and muscle relaxation around set-point targets can be achieved.

Keywords: **self-organizing fuzzy logic controller (SOFLC), anesthesia, atracurium, isoflurane, switching**

1. *INTRODUCTION*

Anesthesia is a part of medicine that makes the patient's body unconscious, unable to feel pain and other stimuli during surgical operations. It contains muscle relaxation (paralysis), analgesia and hypnosis [1, 2].

Muscle relaxation index is measured by using electromyogram (EMG). To measure the level of analgesia, no sensor is able to provide a unique index of the level of analgesia. However, changes in heart rate to estimate the level of this index to be used. The hypnosis level measurement, sensor systems, including auditory evoked potential (AEP), the entropy of the electroencephalography (EEG) and bispectral index of EEG (BIS) and changes in blood pressure can be used [3].

Two approaches are commonly known for controlling depth of anesthesia that are known as "open loop" and "closed loop control". When the anesthesiologist makes a decision to manually change a drug dose based on monitoring clinical status, it is called "open loop control". Closed loop controllers are able to make their own decisions and to try to reach and maintain a targeted effect by adapting the administered amounts of drug [4, 5].

For designing closed-loop control, PK-PD model must be used, that consists of two main parts known as pharmacokinetics (PK) and pharmacodynamics (PD).

Pharmacokinetics is the study of the concentration of drugs, whereas pharmacodynamics is the study of the relationship between drug concentration and effect [6, 7].

In the control of anesthesia, in 1990, the PID controller for anesthesia was introduced by Linkens [4] that because of unexpected changes of the body, such as blocking neuromuscular, blood pressure (BP) and heart rate variability (HRV) during anesthesia, it is difficult to use this controller [8] [9]. In order to improve system performance, in the next study, intelligent control techniques were presented by Linkens. The main challenge was to create fuzzy rules because of the diversity of patients and the lack of adequate notice of the model and parameters of the patient, is difficult [10] [11]. Moreover, in the context, other controllers such as neural networks, adaptive, predictive and robust is offered. Including the activities carried out, evaluation 35 anesthetized patients by atracurium under EMG criteria and neural network-based controller, which was conducted in 1999 by Lendl [12]. After this, Sayafiie proposed nonlinear extended-prediction self-adaptive control (NEPSAC) with using PK-PD model of propofol drug [3]. Later, Abdullah et al. presented robust control based on PID control with Deadbeat technique. [13].

This paper has been organized as follows. The description of the mathematical model of the multivariable anesthesia system is presented in Section 2. The Self-organizing fuzzy logic controller for multivariable anesthesia system is given in Section 3. Section 4 presents the simulation results followed by the conclusions and the related references.

2. MATHEMATICAL MODELING OF DRUGS

In this study, prevalent drugs that apply in modern surgery such as Isoflurane for blood pressure and Atracurium for muscle relaxation have been used. For the purpose of simulation, at first the drugs must be modeled with PK-PD model that it is a mathematical model commonly uses for explaining drug’s effect in patient’s body [14]. PK-PD model of atracurium is shown in figure 1.

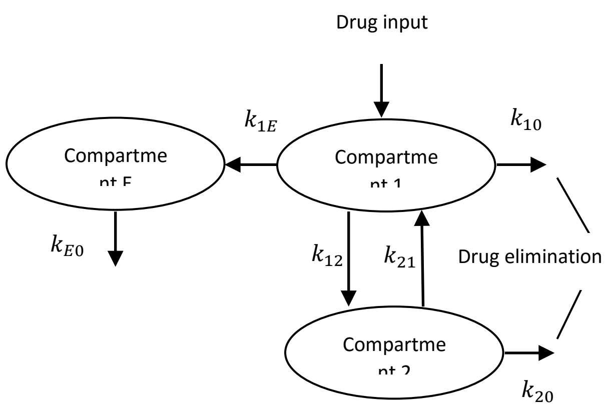


Fig. 1. *Two component PK-PD model of atracurium with effect site*

The PK-PD model is different for each drug and if two drugs use together the interaction between them is added. In this study, common drugs such as atracurium and isoflurane were used for general anesthesia and have been chosen for controlling muscle relaxation and blood pressure. The interaction of atracurium to blood pressure is so small that can be eliminated in dynamic model, but the interaction of isoflurane to muscle relaxation is not small enough to be removed. Moreover, the interaction of isoflurane to muscle relaxation is small but still needs to be considered [15,]. The overall model is shown in equation (1).

$$\begin{bmatrix} Paralysis \\ \Delta MAP \end{bmatrix} = \begin{bmatrix} G_{11}(s) & G_{12}(s) \\ 0 & G_{22}(s) \end{bmatrix} \begin{bmatrix} U_1 \\ U_2 \end{bmatrix} \quad (1)$$

$$G_{11}(s) = \frac{K_1(1+T_4S)e^{-\tau_1 s}}{(1+T_1 s)(1+T_2 s)(1+T_3 s)} \quad (2)$$

(The mathematical atracurium model)

$$G_{12}(s) = \frac{K_3 e^{-\tau_3 s}}{(1+T_6 s)(1+T_7 s)} \quad (3)$$

(The interactive component model)

$$G_{22}(s) = \frac{\Delta MAP(s)}{U_2(s)} = \frac{K_2 e^{-\tau_2 s}}{(1+T_4 s)} \tag{4}$$

(The isoflurane unconsciousness model)

U_1 And $U_2$are the two inputs of system that they are atracurium and isoflurane drugs. *Paralysis* and ΔMAP are muscle relaxation and changing of blood pressure, respectively.

3. *FUZZY LOGIC CONTROLLER*

Self-organizing controller was proposed by Mamdani and Procyk for the first time in 1979. Simple fuzzy controller has been used for regulating outputs around set point [16]. The fuzzy logic controller based on the fuzzy set theory provides a useful tool for converting the linguistic control strategy from the expert knowledge into automatic control rules. However, proper control rules cannot always be established easily for a complex plant [17]. The self-organizing fuzzy logic controller is a heuristic controller that it is able to generate control rules and improved and modified them for achieving best performance automatically [16, 4]. For the first time, Linkens and Hasnain used a self-organizing fuzzy controller for biomedical system in 1991 [18]. Traditional fuzzy controllers still depend on experts for creating fuzzy rules, whereas this knowledge almost always is difficult to obtain [19].

Self-Organizing Fuzzy Logic Control (SOFLC) systems have advantages when the mathematical of the systems are not clear, systems have uncertainty, due to their on-line features (learning algorithm) and clear model-free architecture. However, some models of SOFLC require high computation time when they are applied to multivariable systems with a high dimension [17]. Chou and el proposed a new method that m-input/n-output SOFLC systems decomposed to some two-input/one-output SOFLC sub-systems [19]. According to this method the number of sub-systems will be $n \times C_2^m$ [20] so for this anesthesia system the number of sub-systems was twelve, hence the computing time takes too much time [21].

3.1 Controller Design

The closed loop model of self-organizing fuzzy logic controller is shown in Figure 2. Components of the proposed model is marked with numbered blocks. Block (1) shows patient model, block (2) is the proposed self-organizing fuzzy logic controller and self-organizing fuzzy logic controller parameters determination or (SPD) is block (3).

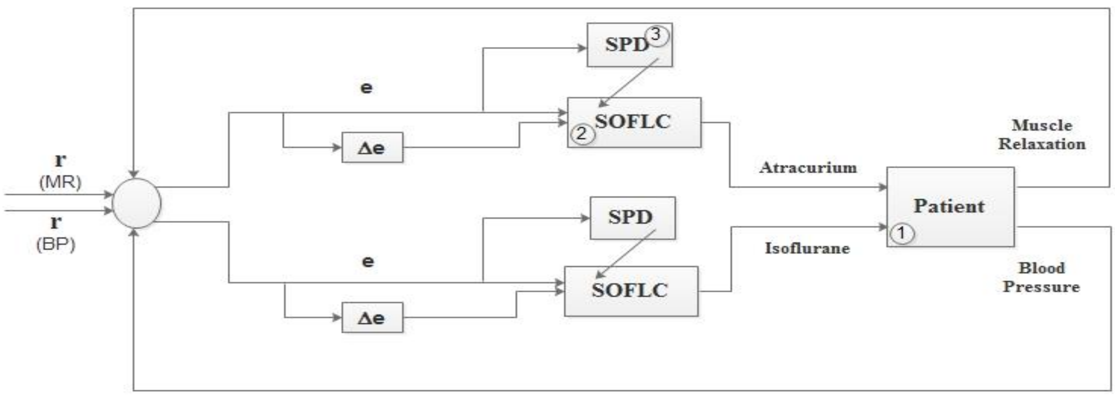


Fig. 2. *The self-organizing fuzzy logic control block diagram of this MIMO anesthesia*

3.1.1 Patient

Inputs of patient model are atracurium and isoflurane. Muscle relaxation and blood pressure changes are outputs, which is regulating the model outputs in 0.8 normalized value for muscle relaxation and 110 mmHg for blood pressure. Full description of the model and its relations were discussed In section 2.

3.1.2 Self-organizing Fuzzy Logic Control(SOFLC)

The proposed controller inputs are error and derivative error of atracurium and isoflurane. The shapes of membership functions were designed as triangular that is shown in figure 3.

In this study, for each drug, seven membership functions for the error (e) and seven membership function for derivative error (de) is considered. So the number of rules reach to 49, but in order to reduce computing time and simplifying, maximum 16 rules fired instead of entire rule table, also other rules that don't fired at all can be eliminated. Then the fired rules modified and improved for desired output. Moreover time of computing reduced and controller design is facilitated. The membership functions by using genetic algorithms in order to minimize the cost, according to (5) have been developed.

$$J = \sum_{i=0}^{300} (e_{re}(i))^2 + \left(e_{bp}(i)\right)^2 \quad (5)$$

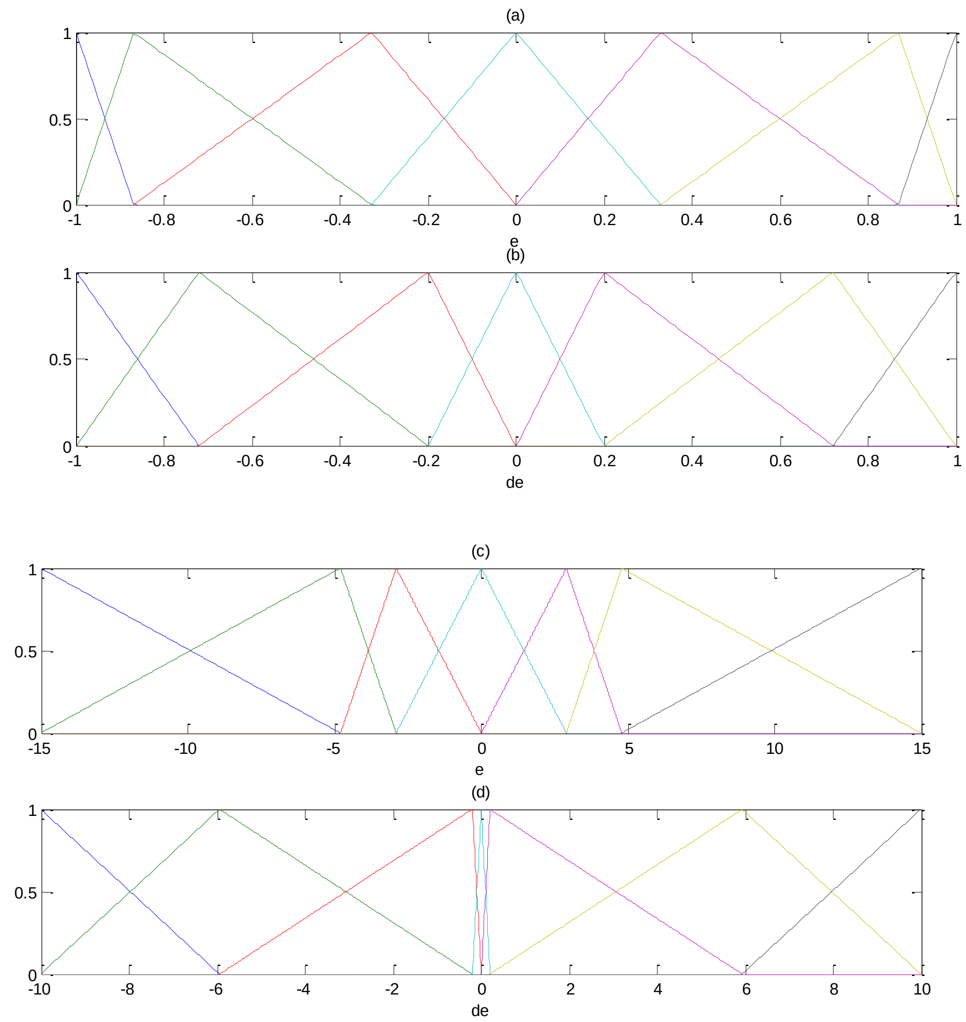


Fig. 3. *The membership function of error and derivative error of inputs*

The rules of this controller is changed according to (6) [22]. In this regard, ξ and M parameters are effective.

$$Rule(nT + T) = Rule(nT) + We_i Wce_j \frac{\gamma}{M} [(1 - \xi)e(nT) + \xi ce(nT)] \quad (6)$$

Including γ/M in (6) can be considered as a factor in learning design. In this regard, ξ is effective weight of the output signal that the effect of input errors and derivative determines in the control signal. In this article, γ constant and ξ and M parameters are presented as impressive parameters. We_i and Wce_j are the amount of belonged to error and derivative error in fuzzy functions the i-th rule.

3.1.3 SPD

In this controller SOFLC Parameters Determination which calls SPD define to estimate designing parameters (M and ξ). The SPD have two cases for providing M and ξ for the best performance.1) constant 2) Switching.

By using SOFLC controllers with learning ability to create the fuzzy rule tables, the time of trial-and-error process get reduced and makes the design of controller easier [21]. Error and the change of error of isoflurane and atracurium are chosen as input variables of controller. This method fired four fuzzy rules in the fuzzy rule table and is also modified in each sampling time. The fuzzy rules were regulated by means of a simple modification equation (according to (6)) for each rule instead of a performance decision table [21]. SPD uses error of isoflurane and atracurium to estimate the designing parameters with two different methods that are described as follows:

- SPD-1: In this method, constant values of M and ξ with trial and error have been given. To improve the response of the system, these two parameters are initialized by using genetic algorithms.
- SPD-2: In the latter case, design parameters (M and ξ) change in two modes. According to this method, in a transient state (the range where the error is high) and in the steady-state, two different values for M and ξ are considered. The values was obtained by the genetic algorithm.

$$\xi_{atr} = \begin{cases} p(2) & if \quad e_{rel} > p(1) \\ p(3) & o.w \end{cases} \tag{7}$$

$$\xi_{iso} = \begin{cases} p(5) & if \quad e_{bp} > p(4) \\ p(6) & o.w \end{cases} \tag{8}$$

$$M_{atr} = \begin{cases} p(8) & if \quad e_{rel} > p(7) \\ p(9) & o.w \end{cases} \tag{9}$$

$$M_{iso} = \begin{cases} p(11) & if \quad e_{bp} > p(10) \\ p(12) & o.w \end{cases} \tag{10}$$

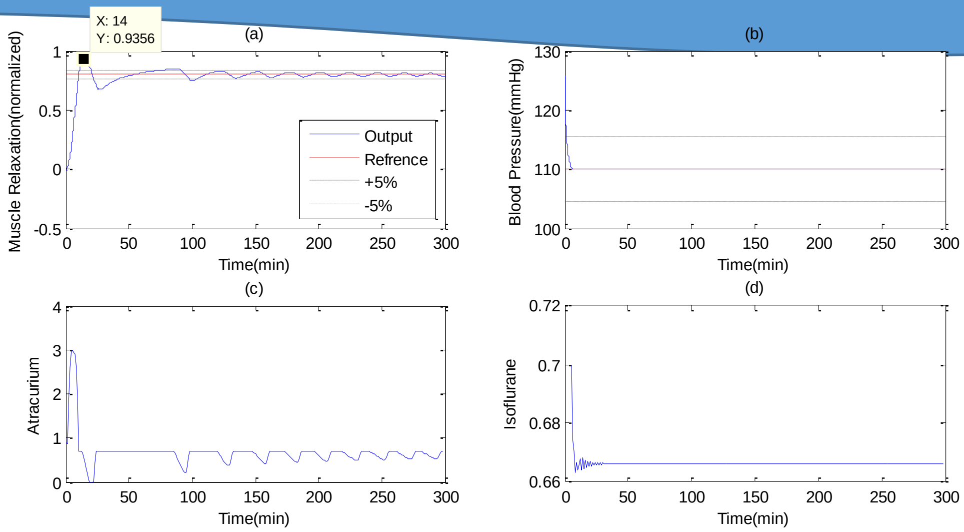
4. *SIMULATION RESULT*

Here, one SOFLC controller with different type of SPD is designed to regulate the blood pressure and muscle relaxation to desired value, respectively.

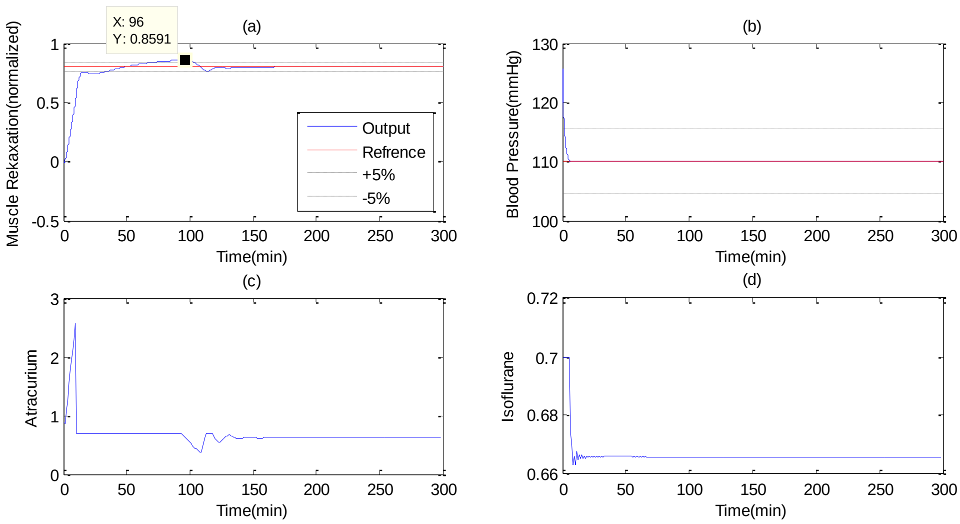
Self-organizing fuzzy controller outputs with SPD-1 and SPD-2 is shown in Figure 4. According to Figure 4 (a), isoflurane output that change blood pressure has been satisfied with SPD-1, but output of atracurium it means muscle relaxation has not been properly convinced. Hence, for improving system response, SPD-2 was chosen. According to Figure 4 (b) self-organizing fuzzy controller output for blood pressure with SPD-2 is similar to SPD-1. Fortunately, self-organizing fuzzy controller output of muscle relaxation with SPD-2 dramatically outperformed the first case, the overshoot in second case is lesser than first case that shows in table 1.

Atracurium and isoflurane output, in this two cases were set to 0.8 normalized value and 110 mmHg that is ideal for system, respectively.

Comparing Figs. 4(a) and (b), it is also clear that the performance of controller with SPD2 is much better, where the settling time is approximately 103 minutes and overshoot 7%. SOFLC controller in Fig.9 of reference number 19 had a good performance, but designing a SOFLC controller with 12 sub system was so difficult, in addition it has swung above and below the set point while the proposed SOFLC with SPD2 set rapidly to set point without any swinging around it. Thus, proposed controller was easy to design and the performance was convincing.



(a)



(b)

Fig. **4**. *Inputs and Outputs of MIMO anesthesia system with SPD1 (a) and SPD2 (b)*

Table 1. *System Characteristics*

	Settling time	Overshoot
SPD-1	103	16%
SPD-2	103	7%

5. CONCLUSION

This study investigates a SOFLC control technique in multivariable anesthesia control. It was originally designed to reduce the time of computing and facilitates design system parameters. This technique was applied to accommodate the differences among the patients for anesthesia control. The proposed method was evaluated in simulation by admissible performance. The results are compared with those obtained using another method that is used in reference [19]. The comparisons show that the proposed SOFLC control scheme performs well in settling time and overshoots.

REFERENCES

[1] Mahfouf, M., Asbury, AJ., Linkens, DA. (2001). Physiological Modeling and Fuzzy Control of Anaesthesia via Vaporization of Isoflurane by Liquid Infusion. *International Journal of Simulation, Systems, Science and Technology*, vol. 2(1), p. 55-66.

[2] *M.* Mahfouf. (2006). Intelligent Systems Modeling and Decision Support in Bioengineering. illustrated ed., *Artech House*. *ISBN*

[3] Syafiie S., Ni˜no J., Ionescu C., and De Keyser R. (2009). NMPC for propofol drug dosing during anesthesia induction, nonlinear model predictive control, Lecture notes in control and information sciences, *Springer-Verlag Berlin Heidelberg*, vol. 384, p. 501-509.

[4] El-Bardini, M., El-Nagar, AM. (2011). Direct Adaptive Interval type-2 Fuzzy Logic Controller for the Multivariable Anaesthesia System. *Ain Shams Engineering Journal*. vol. 2, p. 149-160.

[5] Struys, MM., Mortier, EP., Smet TD. (2005) Closed loops in anaesthesia. Best Pract Res Clin Anaesthesiol, *National Center for Biotechnology Information*, vol. 20(1), p. 211–20.

[6] Chuang, CT., Fan, SZ., Shieh, JS. (2006) The Use of Intensive Manual Control to Model Cisatracurium Pharmacokinetic and Pharmacodynamic for neuromuscular block. *Journal of Medical and Biological Engineering*, vol. 26(4), p. 187-193.

[7] *K.* Soltesz, JO. Hahn, T. Hägglund, GA. Dumont, JM. Ansermino. (2013) Individualized Closed-loop Control of Propofol Anesthesia: A preliminary study. *Journal Biomedical Signal Processing and Control*, vol. 8, p. 500– 508

[8] Lan, JY., Abbod, MF., Yeh, RG., Fan, SZ., Shieh, JS., (2012) review: intelligent modeling and control in aneshthesia. *Journal of Medical and Biological Engineering*, 294 vol. 32, no. 5, p. 293-308.

[9] Linkens, DA., (1992) Adaptive and intelligent control in anesthesia. *IEEE Control Systems Magazine*, p. 6–11.

[10] Linkens, DA., Mhfouf, M., Abbod, M., (1992) Self-adaptive and self-organising control applied to nonlinear multivariable anaesthesia: a comparative model-based study. *In Proceeding of IEE Conference on Control Theory and Application*, vol.139, p. 381-394.

[11] Linkens, DA., (1994) Introduction to intelligent control paradigms and system modeling. chapter. 1, *Taylor & Francis*, Bristol, p. 1–18.

[12] Lendl, M., Schwarz, UH., Romeiser, HJ., Unbehauen, R., Georgieff M., Geldner, GF. (1999) Nonlinear model-based predictive control of non-depolarizing muscle relaxants using neural networks. *Journal of Clinical Monitoring and Computing*, vol. 15, no. 5, p. 271-278.

[13] Abdullah, S., Wen, P. (2011) Depth of anaesthesia patient models and control. Complex Medical Engineering (CME), *2011 IEEE/ICME International Conference*, p. 37-41.

[14] Bamdadian, A., Towhidkhah, F., Marami, B., (2008) Controlling the depth of Anesthesia by using Extended DMC. *Cairo International Biomedical Engineering Conference* (CIBEC 2008), p. 1-4, 2008

[15] Weatherley, B., Williams, S., Neill, E., (1983) Pharmacokinetics, Pharmacodynamics and Dose-Response Relationships of Atracurium Administered iv. *British Journal of Anaesthesia*, vol. 55, p. 39S-45S.

[16] *Fang, M.*, Tao, Y., Wang, Y., (2014) An Enriched Simulation Environment for Evaluation of Closed-loop Anesthesia. *Journal of Clinical Monitoring and Computing*, vol. 28, no.1, p. 13-26.

[17] Procyk, TJ., EH. Mamdani, (1979) A linguistic Self-Organizing Process Controller. *Automatica*, vol. 15, issue 1, p. 15-30.

[18] Linkens, DA., Hasnain, SB. (1991) Self-Organizing Fuzzy Logic Control and application to muscle relaxant Anesthesia. *Control Theory and Applications*, IEE Proceedings D, vol. 138, issue 3, p. 274 – 284.

[19] Chou, YC., Abbod, MF., Shieh, JS., Hsu CY., (2010) Multivariable Fuzzy Logic /Self-Organizing for Anesthesia Control. *Journal of Medical* and Biological *Engineering*, vol. 30, p. 297—306.

[20] Chen, CL., Chen YM., (1993) Self-Organizing Fuzzy Logic Controller Design. *Computers in Industry*, vol. 22, issue 3, p. 249-261.

[21] Lu, Q., Mahfouf, M., (2012) Multivariable Self-Organizing Fuzzy Logic Control Using Dynamic Performance Index and Linguistic Compensators. *Engineering Applications of Artificial Intelligence*, vol. 25, issue 8, p. 1537-1547.

[22] Chen, HY., Huang, SJ., (2004) Ti6A14V Laser Alloying Process Control by Using a Self-organizing fuzzy Controller. *International Journal of Machine Tools and Manufacture*, vol. 44, p. 1653-1665.