

# A Study on Fuzzy Adaptive Control of Enteral Feeding Pump

Seungwoo Kim, Hyojune Chae, Yongrae Jung and Jongwook Kim

**Abstract**—Recent medical studies have investigated the importance of enteral feeding and the use of feeding pumps for recovering patients unable to feed themselves or gain nourishment and nutrients by natural means. The most of enteral feeding system uses a peristaltic tube pump. A peristaltic pump is a form of positive displacement pump in which a flexible tube is progressively squeezed externally to allow the resulting enclosed pillow of fluid to progress along it. The squeezing of the tube requires a precise and robust controller of the geared motor to overcome parametric uncertainty of the pumping system which generates due to a wide variation of friction and slip between tube and roller. So, this paper proposes fuzzy adaptive controller for the robust control of the peristaltic tube pump. This new adaptive controller uses a fuzzy multi-layered architecture which has several independent fuzzy controllers in parallel, each with different robust stability area. Out of several independent fuzzy controllers, the most suited one is selected by a system identifier which observes variations in the controlled system parameter. This paper proposes a design procedure which can be carried out mathematically and systematically from the model of a controlled system. Finally, the good control performance, accurate dose rate and robust system stability, of the developed feeding pump is confirmed through experimental and clinic testing.

**Keywords**—Enteral Feeding Pump, Peristaltic Tube Pump, Fuzzy Adaptive Control, Fuzzy Multi-layered Controller, Look-up Table..

## I. INTRODUCTION

FOR years it has been common practice to feed patients through an IV(intravenous), but studies have shown this modality to be quite insufficient. An increasing number of hospitals and campuses are implementing the use of feeding pumps to provide their patients the essential vitamins, nutrients, elements, amino acids, probiotics, and nourishment patients need it in order to survive and make full recoveries. Enteral feeding pumps are also used in administering sufferers with a balanced dietary system, comprising suitable proportions of carbohydrates, proteins, minerals, fats, and vitamins. Actually given that enteral feeding pumps initial forayed into the marketplace, there have been a number of alterations in the style and technological innovation of these units in line with the evolving demands of clients and healthcare suppliers, and there

is scope for further growth in long term. Efforts of pump manufacturers have been persistently concentrated on creating products with advanced and practically useful features. But improvement of enteral feeding pumps with a large degree of accuracy and safety none the less remains a problem.[1, 2]

The accuracy and the stability are actually made by a peristaltic tube pump, a core component of enteral feeding pump. A peristaltic pump, with geared DC motor and 3 rollers, is used in this paper. It is a type of positive displacement pump used for pumping a variety of fluids. The fluid is contained within a flexible tube fitted inside a circular pump casing. A rotor with a number of rollers, attached to the external circumference compresses the flexible tube. As the rotor turns, the part of tube under compression closes thus forcing the fluid to be pumped to move through the tube. Additionally, as the tube opens to its natural state after the passing of the cam, fluid flow is induced to the pump. This peristalsis makes a big uncertainty on the pump system. So, this paper proposes a fuzzy adaptive controller to overcome the parametric uncertainty for the accuracy and the stability of enteral feeding pump.

On the other hand, fuzzy control methods have become popular and are being used widely in many practical and industrial situations. Fuzzy control methods have advantages such as robustness, which have been demonstrated through industrial applications [3]. Also, several adaptive fuzzy control methods have been suggested. However, these controllers will change their parameters of membership functions of fuzzy rules used in fuzzy inference at the sampling instants when parameters of controlled system are varied, which results in some problems. That is, the robust property of fuzzy control becomes ineffectual and membership functions must be processed in real-time [4], which makes a look-up table method impossible. This lengthens computational time, which generates the same problems as in classical adaptive control methods. Therefore, this paper suggests an adaptive control scheme which is able to overcome the problems of classical adaptive control and conventional fuzzy adaptive control methods. The theoretic basis and a design procedure are proposed and their validity is demonstrated through application experiments for the precise regulation control of enteral feeding pump. This new adaptive controller uses a fuzzy multi-layered architecture which has several independent fuzzy controllers in parallel, each with different robust stability area. Its fundamental idea is that an adaptive controller can be constructed with parallel combination of robust controllers. Out of several independent fuzzy controllers, the most suited one is selected by a system identifier which observes variations in the controlled system parameter through fuzzy logic inference.

Seungwoo Kim is Department of Electrical and Robotic Engineering, Soonchunhyang University, Asan, Chungnam KOREA (phone: +82-41-530-1269; e-mail : seungwo@sch.ac.kr).

Hyojune Chae is Engineer with the R&D Center of Robot-Kisul, Asan, Chungnam Korea (phone:+82-41-530-1678;fax:+82-41-543-1678;e-mail: chyojun@robot-kisul.co.kr).

Yongrae Jung is Senior Engineer with the R&D Center of Robot-Kisul, Asan, Chungnam Korea (phone:+82-41-530-1678;fax:+82-41-543-1678; e-mail: neos001@robot-kisul.co.kr).

Jongwook Kim is C.E.O. with the Robot-Kisul, Asan, Chungnam Korea (phone:041-530-1678;fax:82-41-543-1678;e-mail:kimjw@robot-kisul.co.kr).

The paper is organized as follows: a peristaltic tube pump of the feeding pump and its occlusion model is given in the Section.II. A Fuzzy multi-layered controller and its design method are explained in Section III. Experimental results of the developed feeding pump are reported and clinic test are given, in Section IV. At last, some concluding remarks are addressed in Section V.

## II. DESIGN OF A PERISTALTIC TUBE PUMP

A peristaltic tube pump is a form of positive displacement pump in which an elastomeric tube is progressively occluded externally to allow the resulting enclosed pillow of fluid to progress along it. The occlusion of the tube is usually carried out with two or more rollers or cam lobes attached to a disc which is turned by a precisely controlled geared motor. The use of the peristaltic pump has now extended far beyond its medical applications and is now used in all forms of process pumping where precise metering of fluids is required. In addition, the progressive cavity characteristics, ensures that fluids, sensitive to shear action as in centrifugal pumps, will not be damaged such as blood. Another characteristic of the peristaltic action is that the fluid is entirely kept separate thus making it extremely suitable for clean or aggressive chemical fluids pumping. In this paper, a geared DC motor with high torque is used as rotary actuator and an optical encoder with high resolution is used as feedback sensor.

Since the tubing is subjected to repeated occlusion cycles, the resilience and fatigue resistance of the tubing becomes all important. From the original rubber tubing for low pressure and low dose used by DeBakey, the range of tubing used has expanded to include; Silicone, PVC, Polyurethane and Neoprene. We experimentally use PVC of low cost. This pump employs rollers to squeeze the tube. Except for the 360 degree eccentric pump design as described below, these pumps have a minimum of 2 rollers 180 degrees apart, and may have as many as 8, or even 12 rollers. Increasing the number of rollers increase the frequency of the pumped fluid at the outlet, thereby decreasing the amplitude of pulsing. The increasing number of rollers proportionately increases number of occlusions, on the tubing for a given cumulative flow through that tube, thereby reducing the tubing life. This paper designs it with 3 rollers 120 degrees apart. A peristaltic tube pump developed in this paper is shown in Fig.1..

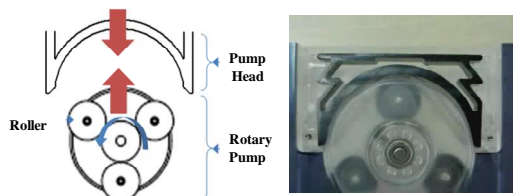


Fig. 1 Configuration Design of Peristaltic Tube Pump

The minimum gap between the roller and the housing determines the maximum squeeze applied on the tubing. The amount of squeeze applied to the tubing affects pumping performance and the tube life - more squeezing decreases the

tubing life dramatically, while less squeezing decreases the pumping efficiency, especially in high pressure pumping. Therefore, this amount of squeeze becomes an important design parameter. The term of occlusion is used to measure the amount of squeeze. It is either expressed as a percentage of twice the wall thickness, or as an absolute amount of the wall that is squeezed. When expressed as a percentage of twice the wall thickness, the occlusion is given in equation (1) for the peristaltic pump of this paper.

$$y = (2 \times t - g) / (2 \times t) \times 100 \quad (1)$$

where,  $y$  = occlusion,  $g$  = minimum gap between the roller and the housing,  $t$  = wall thickness of the tubing

## III. FUZZY ADAPTIVE CONTROL OF AN PERISTALTIC TUBE PUMPS

The occluding of the tube requires a precise and robust controller of the geared motor to overcome parametric uncertainty of the pumping system which generates due to a wide variation of friction and slip between tube and roller, as shown in Fig.2.

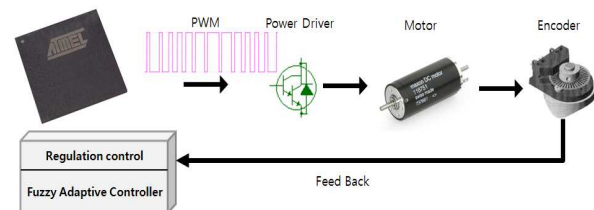


Fig. 2 Control Configuration of Peristaltic Pump

We propose a fuzzy adaptive algorithm for the robust control of the peristaltic tube pump as Fig.3.

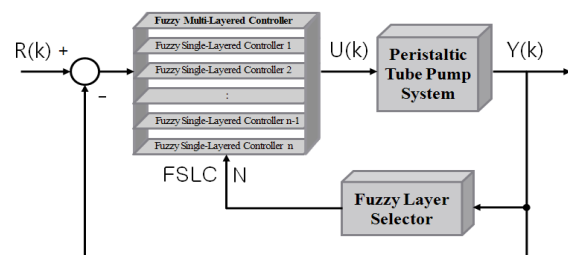


Fig. 3 Fuzzy Adaptive Control Algorithm

In Fig. 3,  $R(k)$  is reference input,  $U(k)$  is controlled input and  $Y(k)$  is output. Each single layer is a conventional fuzzy controller having the robust property. If each single layer is appropriately designed by a robust control design method, robustness of the total system is guaranteed against big parametric disturbances of the controlled system.

The researchers say that the robust stability condition of the fuzzy nonlinear feedback system is independent of the premise parametric uncertainty  $\Delta w_i$ . But when consequent parametric uncertainty  $\Delta A_i$  in the controlled system is come into existence,  $G'_{ij}$  becomes  $A_i + \Delta A_i + B_i H_j$ , even though  $G_{ij}$  is satisfied with equation (12), the robust stability of  $G'_{ij}$  cannot be guaranteed

due to the influence of  $\Delta A_i$ . Then, what magnitude is the range of  $\Delta A_i$  within which the robust stability is able to be guaranteed. An answer of this question will be given in this paper.

For simple design algorithm, the controlled system is represented by a linear model, and as far as adaptive control is concerned, this model is thought to represent a real system perfectly, since the real controlled system can be seen as a linear one at one instant. A controlled system and a fuzzy controller are represented as in equation (2) and (3), respectively.

$$X(k+1) = AX(k) + Bu(k), \quad (2)$$

$$u(k) = \frac{\sum_{j=1}^r \mu_j H_j X(k)}{\sum_{j=1}^r \mu_j} \quad (3)$$

In upper equations,  $X(k)$  is a state vector that elements are a dose and a flow rate of the peristaltic pump.  $u(k)$  is a input voltage of the motor. Then, the resulting fuzzy controlled feedback system becomes

$$X(k+1) = \frac{\sum_{j=1}^r w_i (A + BH_j) X(k)}{\sum_{j=1}^r w_i} = \frac{\sum_{j=1}^r w_i G_j X(k)}{\sum_{j=1}^r w_i} \quad (4)$$

where  $G_j = A + BH_j$  and  $w_j = \mu_j$

The condition for the robust stability of a fuzzy nonlinear feedback system given can be modified into Corollary 3.1.

**Corollary 3.1.**[4] The equilibrium of a fuzzy controlled feedback system described by equation (6) is asymptotically stable in the large if there exists a common positive definite  $P$ , such that

$$G_j^T P G_j - P < 0 \quad \text{for } j = 1, 2, \dots, r, \quad (5)$$

where  $G_j = A + BH_j$

For the design of a fuzzy multi-layered controller which has good adaptability to big parametric disturbances of a controlled system, a new robust stability condition is necessary, which shows the range of a parametric uncertainty matrix  $\Delta A_{\text{robust}}$  where in the robust stability of the total system is guaranteed. The robust stability condition giving a stability-guaranteed parametric uncertainty range is given in Theorem 3.2.

**Theorem 3.2.**[5] Assume that the fuzzy controlled feedback system represented as in equation (4) is stable and there exists  $\varepsilon > 0$ ,  $P \in R^{n \times n}$ ,  $P > 0$ , such that

$$\begin{aligned} \frac{1}{g} G_1^T P G_1 - P &= -Q_1 < 0, \\ \frac{1}{g} G_2^T P G_2 - P &= -Q_2 < 0, \\ &\vdots \\ \frac{1}{g} G_r^T P G_r - P &= -Q_r < 0, \end{aligned}$$

where  $g = [\max_j (\Lambda_{\max} |G_j|) + \varepsilon]^2$ . If the following condition is satisfied:

$$\begin{aligned} \sigma_{\max}(\Delta G^T P \Delta G) &< (1-g) \min[\sigma_{\min}(Q_i)] \\ &= \left\{ 1 - \left[ \max_j (\Lambda_{\max} |G_j|) + \varepsilon \right]^2 \right\} \min[\sigma_{\min}(Q_i)] \end{aligned} \quad (6)$$

where  $\Lambda_{\max} |G_j|$  means  $|\Lambda_{G_j}|_{\max}$  and  $\Lambda_{G_j}$  means eigenvalues of  $G_j$ . Then a new fuzzy system represented in equation (7) is stable:

$$X(k+1) = \frac{\sum_{j=1}^r w_j (G_j + \Delta G) X(k)}{\sum_{j=1}^r w_j} \quad (7)$$

#### IV. RESULTS AND CONSIDERATIONS

An enteral feeding pump, which consists of peristaltic tube pump using fuzzy adaptive control method, is developed in this paper. It is shown in Fig.4.



Fig. 4 Appearance of the Developed Pump

We implement a fuzzy adaptive controller using multi-layered algorithm for the accurate control of peristaltic tube pump. The dominant model for a controlled system of the motored pump is given by using equation (8).

$$x(k+1) = -1.1658x(k) - 1.1672x(k-1) + 0.3874u(k) \quad (8)$$

The overall parametric uncertainty of the controlled system is given in equation (9) through returning an experiment and deviation of the controlled systems in reference of a dominant model.

$$-0.5 \leq \Delta a_1 \leq 0.5 \quad -0.8 \leq \Delta a_2 \leq 0.8 \quad (9)$$

We can design the first fuzzy layer through the third fuzzy layer by using theorem 3.1. It is given in the follows.

Single-layered Controller 1: For

$$\begin{aligned} \Delta a_1 &= 0, \Delta a_2 = 0.70, \\ \Delta A_2 &= \begin{bmatrix} 0 & 0.70 \\ 0 & 0 \end{bmatrix} = 0.70 \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \\ H_3^1 &= H_1^1 - (B^T B)^{-1} B^T \Delta A_3 = [0.97 \quad 37.45] \\ H_3^2 &= H_1^2 - (B^T B)^{-1} B^T \Delta A_3 = [0.77 \quad 37.72] \end{aligned}$$

Single-layered Controller 2: For

$$\begin{aligned} \Delta a_1 &= 0.70, \Delta a_2 = 0.70, \\ \Delta A_2 &= \begin{bmatrix} 0.70 & 0.70 \\ 0 & 0 \end{bmatrix} = 0.70 \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix} \\ H_4^1 &= H_1^1 - (B^T B)^{-1} B^T \Delta A_4 = [37.23 \quad 37.45] \end{aligned}$$

$$H_4^2 = H_1^2 - (B^T B)^{-1} B^T \Delta A_4 = [37.03 \quad 37.72]$$

Single-layered Controller 3 : For

$$\Delta a_1 = 0, \Delta a_2 = -0.70,$$

$$\Delta A_2 = \begin{bmatrix} 0 & -0.70 \\ 0 & 0 \end{bmatrix} = 0.70 \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}$$

$$H_5^1 = H_1^1 - (B^T B)^{-1} B^T \Delta A_5 = [0.97 \quad -35.08]$$

$$H_5^2 = H_1^2 - (B^T B)^{-1} B^T \Delta A_5 = [0.77 \quad -34.81]$$

The operations flowchart of Enteral Feeding Pump using the fuzzy adaptive control is shown in Fig.5.

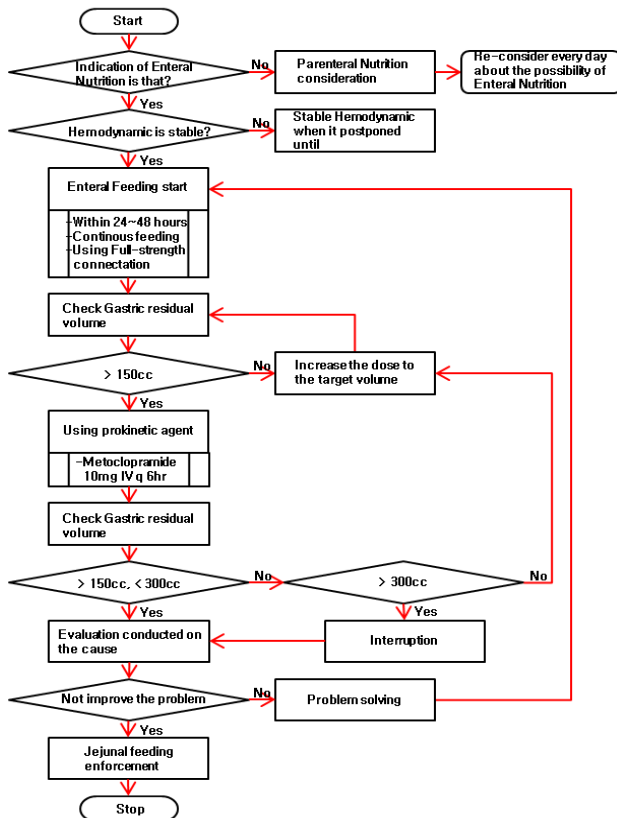


Fig. 5 The Operating Flowchart of Enteral Feeding Pump

The results, which perform a regulation control for a variety of desired flow rate value, are given in Fig.6.

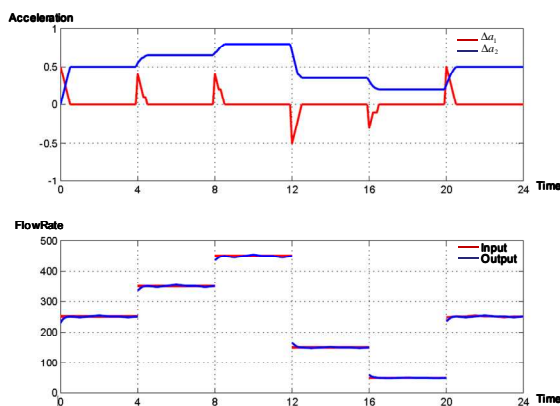


Fig. 6 Response Characteristics of Peristaltic Pump

As we can see in Fig. 6, the fuzzy adaptive controller is precisely tracking reference values. That is why it can overcome the big parametric uncertainty of the controlled system. In other words, we confirm that it has a wide of robustness area which can cover the parametric uncertainty deviation.

The clinic test of the developed feeding pump is done in department of surgery, Samsung Medical Center. The dose accuracy data, which are secured through the clinic test, is shown in table 1. As we can see in table 1, the high accuracy is guaranteed in the peristaltic tube pump.

TABLE I  
CLINIC TESTING RESULTS

	Dose										Dose Accuracy
	FP1	FP2	FP3	FP4	FP5	FP6	FP7	FP8	FP9	FP10	
1st	105	97	96	94	100	103	99	100	105	100	Min:-6% Max:+5%
2nd	101	104	106	105	104	105	104	102	103	105	Min:+1% Max:+6%
3rd	100	100	100	104	95	100	96	98	97	98	Min:-5% Max:+4%
4th	102	99	100	103	100	100	103	101	102	100	Min:-1% Max:+3%
5th	103	100	99	102	97	100	108	100	103	100	Min:-3% Max:+8%
6th	30	30	30	31	30	30	30	31	31	30	Min:0% Max:+3%
7th	15	15	16	15	15	15	16	15	15	14	Min:-6% Max:+6%
8th	105	103	104	105	103	103	101	103	99	99	Min:-1% Max:+5%
9th	103	100	100	103	99	101	97	100	97	96	Min:-4% Max:+3%
10th	105	100	103	102	104	99	98	99	99	102	Min:-2% Max:+5%
Total Average Accuracy											Min:-2.5%Max:4.5%

FP : Feeding Pump, Desired Dose: 1st(100ml), 2nd(100ml), 3rd(100ml), 4th(100ml), 5th(100ml), 6th(30ml), 7th(15ml), 8th(100ml), 9th(100ml), 10th(100ml)

## V. CONCLUSION

In this paper, an enteral pump using peristaltic tube pump has been developed and a new fuzzy adaptive controller has been proposed. The peristalsis of peristaltic pump makes a big uncertainty on the pump system. So, we proposed a fuzzy adaptive controller to overcome the parametric uncertainty for the accuracy and the stability of feeding pump. The proposed multi-layered fuzzy adaptive controller was implemented as a look-up table, which allowed shortened processing time and easing of design, on the microcontroller. Finally, an accurate dose rate and robust system stability of the developed feeding pump was confirmed through experimental and clinic testing results.

## REFERENCES

- [1] Moller P, Lindberg CG, Zilling T. Gastrostomy by various technique: evaluation of indications, outcome, and complications. *Scand J Gastroenterol.* 1999; 34: 1050-1054.
- [2] Jordan, A, Casppary WF, Stein J. Enteral feeding in malnutrition. *Z gerontol Geriatr.* 1999; 32(suppl.1): 169-174.
- [3] Fay DE, Poplasky M, Gruber M, Lance P. Long-term enteral feeding pump: a retrospective comparison of delivery via percutaneous endoscopic gastrostomy and nasogastric tubes. *Am J gastroenterol.* 1991; 86: 1604-1609.
- [4] Tanaka K, Sugeno M. Stability analysis and design of fuzzy control systems. *Fuzzy Sets Syst.,* 1992; 45: pp 135-156.
- [5] Kim SW, Ma YK. A Study on Development of Home Mess-Cleanup Robot McBot. In: *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics,* 2008; pp 114-119.
- [6] Wang LX. *A Course in Fuzzy systems and Control.* Prentice-Hall International, Inc., 1997.
- [7] Polycarpou MU, Mears MJ. Stable adaptive tracking of uncertain systems using nonlinearly parameterized approximators. *Int. J. Control.,* 1998; 70: pp 363-384.
- [8] Cho JS, Park DJ. Novel fuzzy logic control based on weighting of partially inconsistent rules using neural network. *J intell. Fuzzy Syst.,* 2000; 8: pp 99-110. W. D. Doyle, "Magnetization reversal in films with biaxial anisotropy," in *1987 Proc. INTERMAG Conf.,* pp. 2.2-1-2.2-6.