Fast Geometric T2-Fuzzy Based Improved Lower Extremities Stimulation Response

Hendi Wicaksono
Electrical Engineering Dept. Universitas Surabaya
Raya Kalirungkut, Surabaya, 60293, Indonesia
Phone: +62312981157, Fax: +62312981151
e-mail: hendi@ubaya.ac.id

Abstrak

Penelitian ini menekankan penggunaan Fuzzy tipe-2 (T2-Fuzzy) untuk memperbaiki pengendali proportional-integral-derivative (PID) adaptif pada extremitas bawah. Beberapa masalah yang diidentifikasi dari penelitian sebelumnya adalah pencapaian sudut target lambat dan adanya osilasi pada pencapaian sudut target. Osilasi muncul karena penggunaan PID adaptif belum cukup untuk mengatasi ketidaklinearan otot ekstremitas bawah. Perbedaan antara metode T2-Fuzzy ini dengan metode T2-Fuzzy yang lain terletak pada metode defuzzifikasi. Penelitian ini menggunakan metode defuzzifikasi fast geometric yang menjaga tingkat ketidakpastian T2-Fuzzy, juga bisa diaplikasikan secara real-time. Sebuah stimulator functional electrical stimulation (FES) dirancang dan dihubungkan pada komputer sebagai pengolah T2-Fuzzy. Stimulator ini menstimulasi otot ekstremitas bawah dari subyek normal tiap siklus, dan komputer mencatat sudut capaian yang diukur menggunakan sensor goniometer yang terpasang pada knee joint. Hasil penelitian menunjukkan tercapainya target sudut otot ekstremitas bawah berkisar pada tiga siklus awal, dan tanpa terjadi osilasi pada pencapaian sudut. Selain itu juga didapatkan bahwa T2-Fuzzy mampu segera memulihkan sudut capaian saat parameter pengendali eksternal terjadi.

***Kata kunci**: fast geometric T2-Fuzzy, ekstremitas bawah, stimulator FES, subyek normal.*

Abstract

This study emphasizes the use of type-2 fuzzy (T2-Fuzzy) to improve the adaptive proportional-integrative-derivative (PID) control in the lower extremities. Several problems were identified from previous studies and those were the slow achievement of the target angle and the presence of oscillation in the achievement of the target blade. The oscillation occurred as the consequence of deploying the early adaptive PID which was not sufficient to overcome the lower extremities nonlinearity. The difference between proposed method of T2-Fuzzy and the others lies in the defuzzification. This research adopts a fast geometric defuzzification that maintains the level of uncertainty T2-Fuzzy in real-time. A functional electrical stimulation (FES) stimulator is proposed to design and to be connected to the computer for processing the T2-Fuzzy. This stimulator stimulates lower extremities of normal subjects each cycle, and the computer record the point of measured achievement of using a goniometer sensors mounted on a knee joint. The results show that the target point of lower extremities is achieved within three initial cycles without oscillations in the achievement of the angle. It is also found that T2-Fuzzy is able to immediately restore the point of achievement when the external parameters of control occur.

***Keywords**: fast geometric T2-Fuzzy, lower extremities, FES stimulator, normal subjects.*

1. Introduction

Humans walking with their legs in a sequential will be forms a unique pattern called with human gait. Human inability to transmit signals from the central nervous system to motor system cause they can not stand, locomotion, reaching for something. Incapacity resulting loss of motor skills caused by two things, first, due to brain damage so that the command signals can not be generated, and the second one if the command signals has been raised but it can not be forwarded to the motor system because of the spinal cord injury (SCI). Loss of motor skills is commonly known by the name of paralysis. There are five types of paralysis, namely monoplegia, diplegia, hemiplegia, paraplegia, quadriplegia [1].

An alternative to spinal cord regeneration for the restoration of function following SCI may be the use of artifac neural signal. In fact, artifac neural signal in the form of functional electrical stimulation (FES) devices are currently used in individuals with SCI and provide limited function in a number of systems, including bladder control, respiration, hand-grasp, standing, and walking. In order to further improve the quality and function of motor neural prostheses, closed-loop control systems that utilize sensory information recorded from peripheral nerves are under development [2].

Until now, the simple application of FES is used in clinical therapy, and new methods continue to be investigated. Proper control method is needed to restore the function of the desired movement using the FES. It is very difficult because the human movements control is very complex considering a nonlinear element of the response of musculo-skeletal system [1] [3], the response varied from muscle stimulated, and muscle fatigue. Many researchers investigate the realization of feedback control with a different control scheme, such as PID controller [4], adaptive controller [5], artificial neural network [6], neuro-PID controller [7], and neuro-fuzzy controller [8]. All the control method has not been applied clinically. The big problem still does not implemented clinically is due to the characteristics of the patient's muscle systems vary widely compared with normal subjects muscular system characteristics [1].

All of the above control scheme using trajectory planning method in pursuit of the target angle. These method can obtain the target angle with very slow response so on research [1] develop cycle-to-cycle control method which very different method from trajectory planning. Trajectory planning method is a method of pursuing the target trajectory angles at each point, while the method of cycle-to-cycle control, achieving the target angle was not pursued in each cycle at each point of trajectory. Generation of FES on the method of trajectory planning is done every point trajectory, while the method of cycle-to-cycle control is only performed in the early cycles [1]. But the results told us that there are still an oscillations for obtain the target angle.

As the T1-Fuzzy set, the concept of T2-Fuzzy set was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set. A fuzzy logic system (FLS) described using at least one T2-Fuzzy set is called a T2-FLS. T1-FLSs are unable to directly handle rule uncertainties, because they use T1-Fuzzy sets that are certain [9]. On the other hand, T2-FLSs, are very useful in circumstances where it is difficult to determine an exact, and measurement uncertainties. This makes for T2-Fuzzy has a higher degree of uncertainty compared with T1-Fuzzy [10]. In addition, T2-Fuzzy has footprint of uncertainty (FOU), which is a shaded area on the membership function. All that has been mentioned that causes T2-Fuzzy architecture is different from T1-Fuzzy architecture. On T2-Fuzzy architecture has the type of reduction process in the defuzzification. Type-reduction functions to change the order of two to order of one and then become a crisp output [11]. Use of T2-Fuzzy algorithm in general form requires a long time because it is very complex mathematic calculations. The duration of the calculation process occurs in both type-reduction stage. Many researchers are finding out how to simplify the type-reduction. One of them is fast geometric defuzzification method [11]. In this method, the defuzzification process is not through the type-reduction stage as on T2-Fuzzy general, but fast geometric defuzzification approaches rely on geometric polyhedron [12].

In this research realize the T2-Fuzzy fast geometric defuzzification method in real-time on the application of normal subjects to increase the response of the lower extremities based on cycle-to-cycle control.

2. T2-Fuzzy Theory

Implementation of T2-Fuzzy developing operation of the process fuzzification, inference, and output processing. All of the development of T2-Fuzzy control method around the output processing. T2-Fuzzy output processing with an important role in determining the level of uncertainty and imprecission of T2-Fuzzy and also determine the time of T2-Fuzzy computation process. Output processing consists of type-reduction and defuzzification. Type reduction is an extended process of T2-Fuzzy defuzzification. And in this type of reduction has more than just uncertainty rules than the defuzzification process. In Figure 1 can be shown the structure of T2-Fuzzy. One way to represent T2-Fuzzy membership of fuzzy sets by using the footprint of uncertainty (FOU) in 3D representation. On T2-Fuzzy FOU actually formed from multiple T1-Fuzzy sets with membership function. On the inner side called the LMF or lower membership function. And on the outer side is called UMF or upper membership function. 3D representation can be shown in Figure 2.

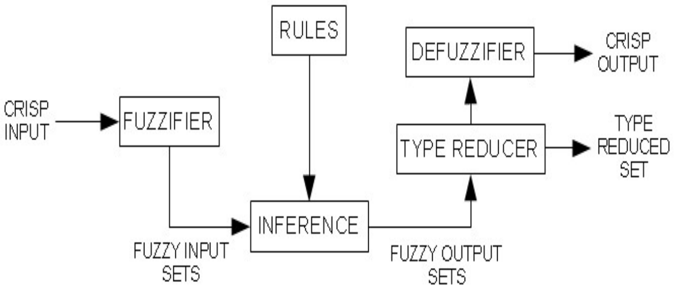


Figure 1. T2-Fuzzy architecture.

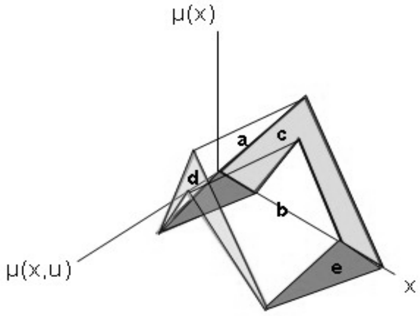


Figure 2. Footprint of uncertainty (FOU) and five areas geometric.

On T1-Fuzzy discretization process imposed, as well as on T2-Fuzzy discretization process is also applicable. Judging from its name geometric certainly take one geometric shape for general T2-Fuzzy modelling. A triangle is a geometric shape used in the modeling. By using a triangular shape, the modeling of the general T2-Fuzzy form of modern geometric form polihedron. This method also introduces a fuzzy set that is slightly different in terms of writing. Geometric discretization of fuzzy sets to take on three axis, the x-axis, y-axis, and z-axis This is done because all the membership grades in the form of a function, not a crisp value as in the interval T2-Fuzzy sets. According to [19], the geometric shape of T2-Fuzzy sets can be shown in equation 1. In this geometric model, values on the y-axis represent primary membership grades and values on the z-axis represent secondary membership grades.

$$\tilde{A} = \bigcup_{i=1,\dots,n} t^i \qquad \text{where } t^i = \begin{bmatrix} x_1^i & y_1^i & z_1^i \\ x_2^i & y_2^i & z_2^i \\ x_3^i & y_3^i & z_3^i \end{bmatrix} \tag{1}$$

$$\text{where } x_1^i, x_2^i, \text{and } x_3^i \in X \text{ and } y_1^i, y_2^i, \text{and } y_3^i \in [0,1]$$
$$z_1^i, z_2^i, \text{and } z_3^i \in [0,1]$$

T2-Fuzzy geometric construction sets made during the process of defuzzification. The following geometric construction techniques T2-Fuzzy sets. T2-Fuzzy membership function set is broken down into five areas as shown in Figure 2. They are the top surface (a), bottom surface (b), the rear surface (c), the front surface (d), the bottom surface (e).

To find the triangle fuzzy sets of the five areas could be used algorithm [19] as follows below. With five algorithms, obtained the value of each point x, y, and z. Then from each point can be calculated centroid value of each triangle area. After getting the centroid of each triangle area can then be sought from the centroid value of T2-Fuzzy sets. The equation to find the centroid can be shown in equation (2), (3), and (4). The *i* th triangle *t* in the polyhedron $t^i = \begin{bmatrix} x_1^i & y_1^i & z_1^i \\ x_2^i & y_2^i & z_2^i \\ x_3^i & y_3^i & z_3^i \end{bmatrix}$, the area of $t_i = A^i$, the centroid of a geometric T2-Fuzzy set is given in equation (2), where $C_{\tilde{A}}$ is the centroid of a T2-Fuzzy set $\tilde{A}$ made up of *n* triangles.

$$C_{\tilde{A}} = \frac{\sum_{i=1}^{n} C^i A^i}{\sum_{i=1}^{n} A^i} \tag{2}$$

$$C^i = \frac{x_1^i + x_2^i + x_3^i}{3} \tag{3}$$

$$A^i = 0.5\sqrt{\begin{aligned}&((y_2^i - y_1^i)(z_3^i - z_1^i) - (y_3^i - y_1^i)(z_2^i - z_1^i))^2 + \\ &((x_2^i - x_1^i)(z_3^i - z_1^i) - (x_3^i - x_1^i)(z_2^i - z_1^i))^2 + \\ &((x_2^i - x_1^i)(y_3^i - y_1^i) - (x_3^i - x_1^i)(y_2^i - y_1^i))^2\end{aligned}} \tag{4}$$

3. Design and Experiment

The research method began with designing FES stimulator, and then design the T2-Fuzzy software, the later is the implementation on lower extremities normal subjects. It is known from previous explanations that an electrical stimulator shall have the same specs and characteristics with the specifications and characteristics of the central nervous signals. Central nervous impulse-shaped signal which can be shown in

Figure *3*. In [1], stimulation pulse has a frequency of 20Hz, and has a pulse duration of 200us. In addition to the voltage specification, of the maximum current allowed out of the FES at 60mA. Complete, the characteristics of FES stimulator designed as follows: the form of an impulse with an impulse width of 200 us, impulse frequency of 20Hz, the current of FES less than 50mA, the polarity of the FES stimulator only 1 polarity only (monophasic), and DC voltage from 0 to 100V.

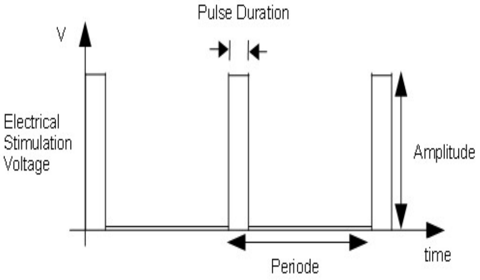


Figure 3. Periodic unidirectional stimulation pulse voltage.

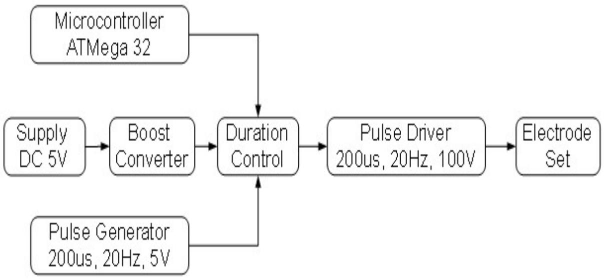


Figure 4. Block diagram of FES stimulator.

FES stimulator design block diagram is shown in

Figure *4*. There are seven parts necessary to build this stimulator FES system, namely the input voltage DC 5V, boost converter circuit, pulse generator circuit 200us 20Hz 5V, ATMega32 microcontroller circuit as a controller of the durations, the duration of the regulator circuit, a pulse driver circuit 200us 20Hz 0-100 V, and the last electrode itself, which will connect the voltage output of the FES stimulator to the skin surface stimulated the muscle beneath it.

In Figure 5 can be shown boost converter circuit topology, the working principle as follows: when first switch is closed, the inductor voltage of 5 V to fill fully achieve the voltage V_L=5V. Then when the switch is opened, the voltage from the inductor, the current flow to fill the capacitor V_C=5V. The switch is closed again, voltage 5 V return to fill the inductor so that the V_L back to 5V. Followed by the switch opens again, then the inductor will charge the capacitor and current V_C=10V. and so on until the voltage V_C according to the desired output voltage. To close and open the switch, use circuit switching square signal setting method using pulse frequency modulation (PFM) with a frequency that can be switched while the duty cycle constant.

Image of a complete range of boost converter with component values shown in Figure 6. By using ATTiny2313, square signal generated by the PFM method and is set to get a DC voltage tailored to each subject. For the pulse generator circuit, in this research using LM555 component that is configured to be astable multivibrator circuit. From the datasheet LM555, easily obtained astable multivibrator circuit. After going through the calculation with guide datasheet, can be obtained much the value of each component that can be viewed at Figure 7. While the pulse driver circuit formed by transistor switching circuit. Pulse driver circuit configuration can be shown in Figure 8.

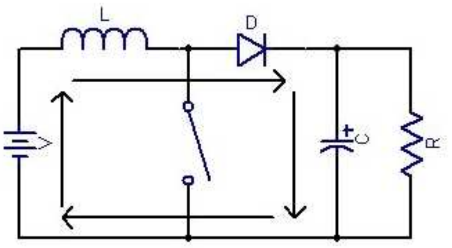


Figure 5. Boost converter basic circuit.

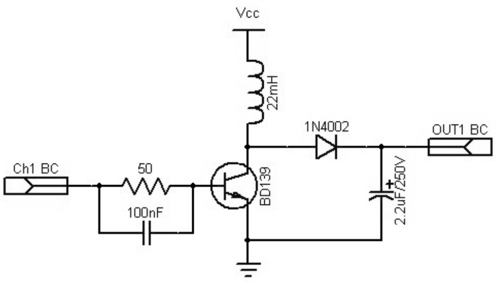


Figure 6. Boost converter circuit.

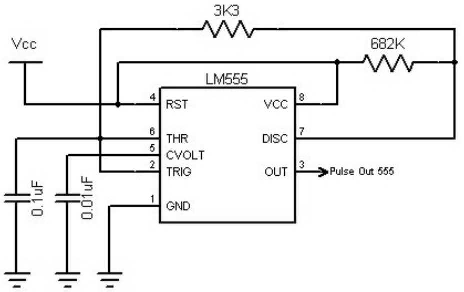


Figure 7. Pulse generator 5V.

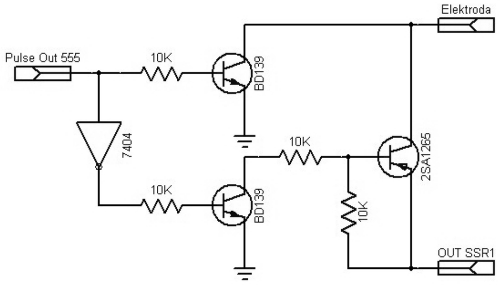


Figure 8. Pulse driver 200us, 20Hz, 100V.

Figure 9. Electrode’s position.

When finished designing the FES stimulator, then design the T2-Fuzzy with fast geometric defuzzification. In this research, T2-Fuzzy ΔTB produce output. Input from the T2-Fuzzy for vastus muscle stimulation is an error [n-1], and the desired range [n-1]. While T2-Fuzzy inputs for error only hamstring muscle stimulation [n-1]. The definition of error is the difference between the target angle extension with extension angle achieved. While the definition of desired range is the difference between the target angle extension with flexion angle achieved. In Figure 10, Figure 11, Figure 12 may be shown block diagram T2-FLC system and plant. Following input from the membership function for error vastus muscle and the desired range of vastus muscle can be see on Figure 13, Table 1, Figure 14, and Table 2. And also input from the membership function for error hamstring muscle can be see on Figure 15, and Table 3.

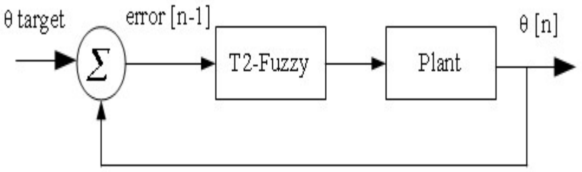


Figure 10. Block diagram system.

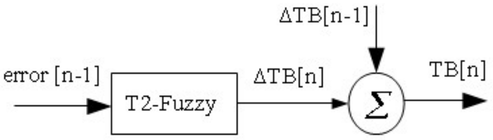


Figure 11. Block diagram FLC.

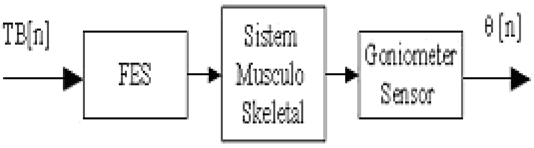


Figure 12. Block diagram plant.

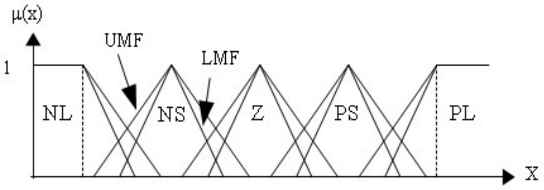


Figure 13. IMF vastus muscle's error.

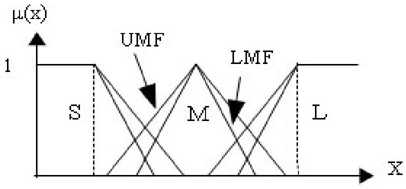


Figure 14. IMF vastus muscle's desired range.

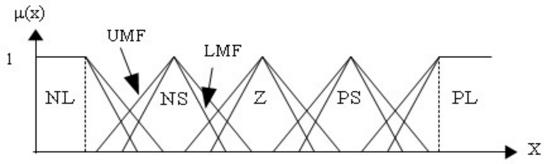


Figure 15. IMF hamstring muscle's error.

Table 1. Error MF vastus muscle.

Error Membership Function Vastus Muscle															
LMF	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14
UMF	-14	-12	-11	-7	-6	-5	-1	0	1	5	6	7	11	12	14

Table 2. Desired range MF vastus muscle.

Desired Range Membership Function Vastus Muscle									
LMF	10	20	30	40	50	60	70	80	90
UMF	10	20	25	45	50	55	75	80	90

Table 3. Error MF hamstring muscle.

Error Membership Function Hamstring Muscle															
LMF	-14	-12	-10	-8	-6	-4	-2	0	2	4	6	8	10	12	14
UMF	-14	-12	-11	-7	-6	-5	-1	0	1	5	6	7	11	12	14

The following sequence of steps Fast Geometric defuzzification using this method.

1. Do three point on the geometric discretization of fuzzy set of crisp input as many as twelve points x.
2. Make forming geometric triangular matrix of 5 areas, areas (a), area (b), area (c), area (d), and area (e) according to the algorithm above.
3. After getting the point x, y, z of each discretization, use of data x, y, z to find the value of the geometric centroid of each triangle, then look for the centroid of the five areas. By using one of the high language, T2-Fuzzy Calculation designed according to the algorithm above.

After the design all the circuit, also software design is finished, the next step is the experiment with clinical procedure. The clinical procedures are carried out as follows:

1. Each subject performed the test 3 times in a row with a time delay test is 30 minutes.
2. Each test carried out 30 cycles using the FES stimulation, and between the cycle there is no lag time.
3. Electrodes used in each test in the new conditions so that the occurrence of motion artifacts is very minimum.
4. For a given type of foot stimulation is random so that it can be stimulated on the left foot and right foot.

4. Results And Analysis

Testing was first performed at the FES stimulator. FES stimulator has several block diagrams, one of the main circuit is boost converter. By using the method as an input from a wide PFM boost converter has to generate voltage swings from 0 to 100 V. This test aims to see the great characteristics of a given frequency of the voltage generated by the boost converter circuit, while also aiming to see the level of linearity of the magnitude of the frequency PFM boost converter with the voltage generated can then be taken so that a line equation representing both. In Figure 16 can be shown between the frequency characteristic graph PFM boost converter with a voltage generated. From the test is obtained by increasing the frequency of the PFM is given, then the voltage boost converter increases. By looking graph test data, the voltage boost converter voltage reaches close to 100 V at a frequency of 350 Hz. From the test, found the relationship between the increasing frequency with increasing voltage boost converter to form an equation of order of 1. In equation (5) is the equation representing the relationship between frequency PFM boost converter with voltage.

$$y=0.24\,x + 28 \qquad (5)$$

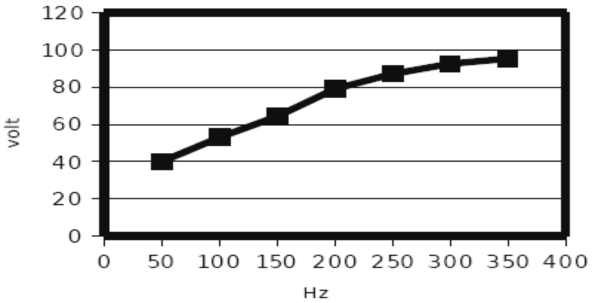
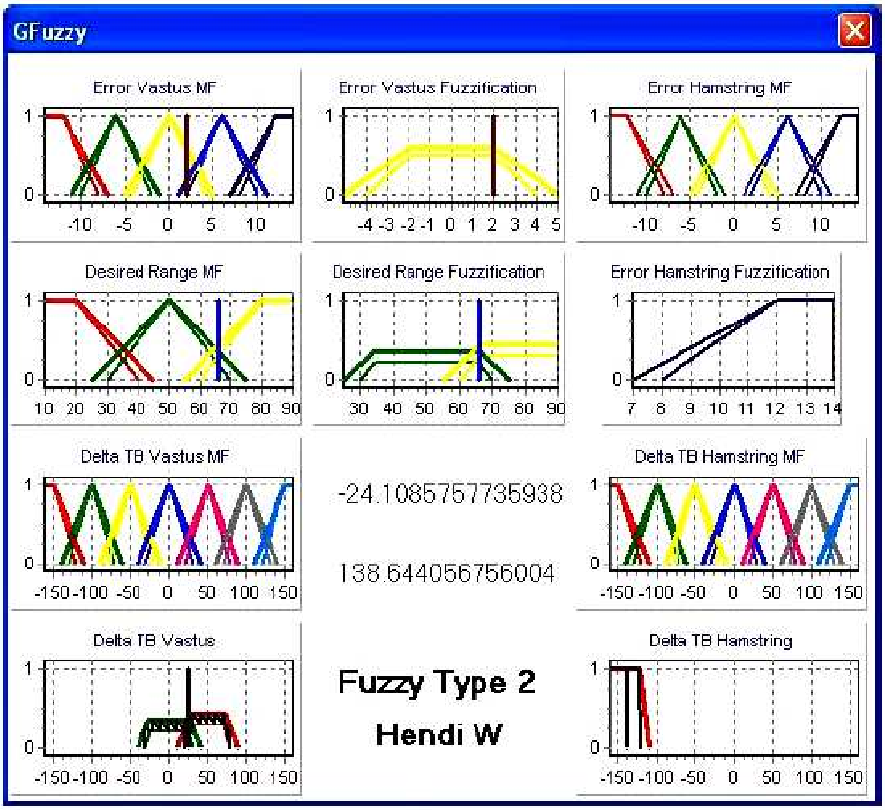


Figure 16. Boost converter circuit test.

After testing the FES stimulator, then performed tests on the performance of T2-Fuzzy program that has been made. The purpose of this test is to try the response of the T2-Fuzzy control whether the algorithm is completely accurate written in a programming language so as to produce responses as expected, before the T2-Fuzzy is applied to the subject. In

Figure 17 can be shown some of the results of T2-Fuzzy testing programs. From this test it was found that T2-Fuzzy algorithm mainly from fast geometric defuzzification algorithm has been successfully written to one of high language.

The main thing that worked on this research is the improvement of lower extremities stimulation control response from a previous research using adaptive PID [1]. This research examined the T2-Fuzzy Control as a whole in five normal volunteer. There are some terms related to internal factors and external factors of the T2-Fuzzy control. Response oscillation that oscillates when the resulting error range exceeds ± 5 degrees. As for the external factor is the factor that comes from muscle characteristics of each subject. External factors are muscle force potentiation, muscle fatigue. Muscle force potentiation behavior can be recognized by the addition of knee-joint swing angle rate, which exceeded the range of ± 5 degrees without a preceded by the addition of TB (Time Burst). While muscle fatigue can be recognized by the behavior of decline in the rate of knee-joint swing angle, which exceeded the range of ± 5 degrees without a preceded by a decline in TB (Time Burst).



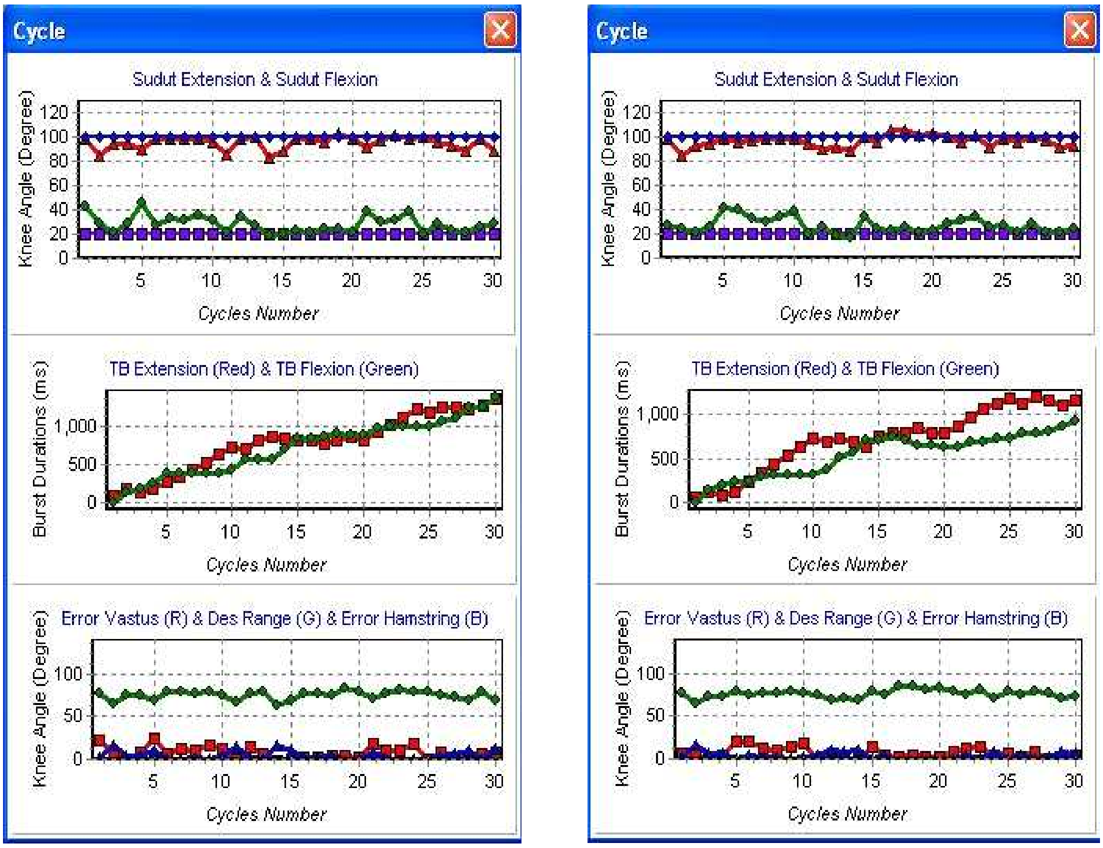
-24.1085757735938

138.644056756004

Figure 17. T2-Fuzzy programming results.

Here are some test results T2-Fuzzy randomly sampled response shown in Figure 18. Figure 18 (a) can be shown angle and response of TB to the subject 1 in the first trial. In the first trial for subject 1, the angle flexion reached during the 3rd cycle, whereas the extension angle, is reached during the 4th cycle. While the largest flexion error angle is 15 degrees, and for the error angle 5 degrees extension. On the subject of 4 for the third trial, flexion angle is reached during the 3rd cycle, whereas the extension angle is reached during the 3rd cycle. While the largest flexion error angle is 5 degrees, and for the error angle 5 degrees extension.

There are some phenomena that need to be discussed. Oscillation response to the implementation of FES with T2-Fuzzy control method does not occur in every trial for each subject. Plot of sensitivity in each muscle that is stimulated vs. TB can make a reference to detect the presence of external factors affecting the performance of this T2-Fuzzy control. By calculating the correlation between sensitivity to the TB can be known whether there is a correlation between changes in sensitivity with changes in TB. If the correlation value is large, then there is a correlation between sensitivity to the TB, and this also means that indicate external factors that affect both muscle force potentiation, and muscle fatigue. When compared to the performance results of stimulation using T2-Fuzzy control with adaptive PID control with settling index, mean error, and error rate large parameter, T2-Fuzzy control has been a better results than a previously research [1]. The comparison between both using T2-fuzzy with adaptive PID control can be shown on Table 4.



(a) (b)

Figure 18. (a) Subject 1 trial 1. (b) Subject 4 trial 3.

Table 4. Performance evaluation vastus muscle of 3 normal subject.

		T2-Fuzzy control					Adaptive PID control		
Subject	Trial	Settling Index	Mean Error (deg)	Large Error Rate	Subject	Trial	Settling Index	Mean Error (deg)	Large Error Rate
1	1	3	2.4	3	1	1	6	10	7.7
	2	3	2.8	3.4		2	5	3.2	12.1
	3	3	2.7	2.8		3	6	3.3	14.1
2	1	3	4.2	3.5	2	1	6	0	7.2
	2	4	5.8	2.2		2	6	0	6.1
	3	4	5.6	2.3		3	6	6.7	9.2
3	1	4	4	2.9	3	1	6	14.3	16.2
	2	3	3.6	3.7		2	8	0	13.2
	3	3	3.2	3.5		3	9	12.9	21.4

5. Conclusion

By comparing the performance results of stimulation using T2-adaptive fuzzy control with PID control with settling index, mean error, and error rate large parameter, it can be make conclusion that using T2-Fuzzy, the angle of the target knee extension and knee flexion angle targets reached very fast than previosly research. This shows that by using T2-Fuzzy, quickly reached the target angle. The average value of absolute error is relatively small, and large errors caused by factors vatigue muscle not due to the oscillation factor. It can be concluded the error was not caused by the oscillation factor because when the target angle is achieved, control can be maintained within a few cycles without any oscillation. It can be shown in the performance evaluation of the value of settling control index. And also T2-Fuzzy with fast geometric defuzzification can be executed in real-time.

References

[1] Arifin A. A Computer Simulation Study on the Cycle-to-Cycle Control Method of Hemiplegic Gait Induced by Functional Electrical Stimulation. Doctoral Dissertation. Japan: Tohoku University; 2005.

[2] Borisoff JF, McPhail LT. Detection and Classification of Sensory Information from Acute Spinal Cord Recordings. *IEEE Trans. Biomed. Eng*. 2006; 53(8): 1715-1719.

[3] Ferrarin M, Pedotti A. The Relationship Between Electrical Stimulus and Joint Torque: A Dynamic Model. *IEEE Trans. Rehabl. Eng.* 2000; 8(3): 342-352.

[4] Kubo K, Fujita K, Itakura N, Iguchi Y, Minamitani H. Simultaneous Closed-Loop Control of Knee and Ankle Joints Using Functional Electrical Stimulation. *IEICE Trans. Inf. & Syst.* 1988; J71-D(10): 2197-2204.

[5] Hatwell MS, Oderkerk BJ, Sacher CA, Inbar GF. The Development of A Model Target Adaptive Controller To Control The Knee Joint of Paraplegic. *IEEE Trans Automatic Control.* 1991; 36(6): 683-690.

[6] Abbas JJ, Chizeck HJ. Neural Network Control of Functional Neuromuscular Stimulation System: Computer Simulation Studies. *IEEE Trans. Biomed. Eng.* 1995; 42(11): 1117-1127.

[7] Chang GW, Luh J, Liao G, Lai J, Cheng C, Kuo B, Kuo T. A Neuro-Control of System for The Knee Joint Position Control with Quadriceps Stimulation. *IEEE Trans. Rehabl. Eng.* 1997; 5(1): 2-11.

[8] Chen Y, Chen S, Chen W, Hsiao C, Kuo T, Lai J. Neural Network and Fuzzy Control in FES-assisted Locomotion for the Hemiplegic. *J. Med. Eng & Tech.* 2004; 28(1): 32-38.

[9] Castillo O, C´azarez N. Intelligent Control of Dynamic Systems Using Type-2 Fuzzy Logic And Stability Issues. *International Mathematical Forum*. 2006; 1(28): 1371-1382.

[10] Wicaksono H. Fuzzy Controller Type-2 Based on Cycle-to-Cycle Method for Swing Phase Gait Restoration with Functional Electrical Stimulation. Master Thesis. Surabaya, Indonesia: Institut of Technology Sepuluh Nopember (ITS); 2009.

[11] Mendel JM, John RIB. Type-2 Fuzzy Sets Made Simple. *IEEE Trans. on Fuzzy Systems*. 2002; 10(2): 117–127.

[12] Coupland S, John R. A Fast Geometric Method for Defuzzification of Type-2 Fuzzy Sets. *IEEE Trans on Fuzzy Systems.* 2008; 16(4): 929 - 941.