Journal of Fundamental and Applied Sciences

ISSN 1112-9867

Available online at http://www.jfas.info

Research Article

Special Issue

FUZZY CONTROLLER FOR BETTER TENNIS BALL ROBOT

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Published online: 24 November 2017

ABSTRACT

This paper aims at designing a tennis ball robot as a training facility for tennis players. The robot is built with fuzzy controller which provides proper techniques for the players to gain practical experience as well as technical skills; thus, it can effectively serve the community and train athletes in the high-performance sport. It is found that it is more economically efficient by using the sensorless fuzzy control algorithm to replace the high-resolution optical encoders traditionally used in two main servo motors. From our simulation and practical experiment, the tennis ball robot can provide accurate speed and various directions as expected.

1. INTRODUCTION

Almost everyone who plays a sport in general and tennis in particular would always desire to become a good player; thus, they need to be trained and frequently practice to gain practical experience and playing skills [1]. However, many players, especially beginners, sometimes [illegible] anism called ball machine/ robot has been considered as a promissory alternative [2,3].

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doi: http://dx.doi.org/10.4314/jfas.v9i7s.62

Literally, the dynamics of a ball launched by a wheel-rotating machine cannot be explained exactly [3] as it contains a purely defined friction. Moreover, the surface roughness of the wheel as well as the elasticity and the remaining nap of the ball also significantly affect the performance [4]. Thus, several researchers, such as Alam et al. [5,6] and Goodwill [7], investigated the aerodynamic behavior of tennis balls. Kovacs & Hosszu [3] also claimed that placing the launching machine into different positions of the court and the ball elasticity may lead to some unexpected results of its performance.

Currently, there are several brands for the tennis ball robots available on the sport market as shown on the website of Oncourt-Offcourt. They can effectively not only serve balls to different places on the opponent court but also create interesting trajectories such as high-up ball, net-close ball, whirling ball, etc. by selecting appropriate training functions expected by the player or a remote controller. Yet, the selling price for a ball robot is normally too expensive compared to the average income of most players in several countries, including Vietnam. Therefore, this paper focuses on designing a better robot with intelligent control algorithms to enhance its accuracy and making it cheaper by using a speed estimation package instead of high-resolution optical encoder. Our proposed robot, briefly demonstrated in Fig. 1, consists of six major components, including: (1) ball-supply complex; (2) ball container; (3) ball conduit; (4) ball-serve complex; (5) angle-control complex; and (6) robot frame.

2. MECHANICAL DESIGN

The operational principle of the robot is described as: First, ball container is filled up with tennis balls which are then loaded into revolving salver and ball-supply complex before they are delivered to the ball conduit and ball-serve complex. The ball-serve complex consists of two flywheels directly connected with two coaxial motors to provide critical moment for kicking the ball. The two motors are in reverse rotating direction so that their joint force is strong enough to kick the ball off. The motors are controlled with fuzzy logic algorithm. Besides, the kicking-angles α for high-up balls and β for two touchlines can be easily adjusted with a control package to accurately serve the balls to expected places on the opponent court, as shown in Fig. 2.

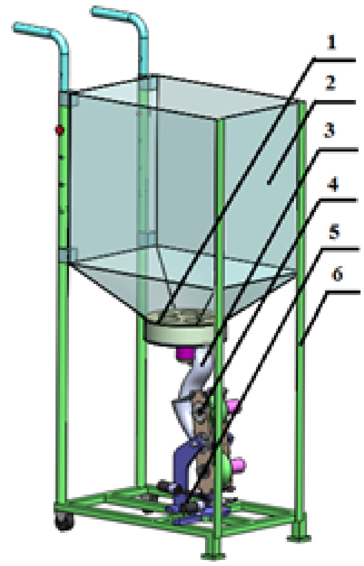

Fig.1. Our proposed robot

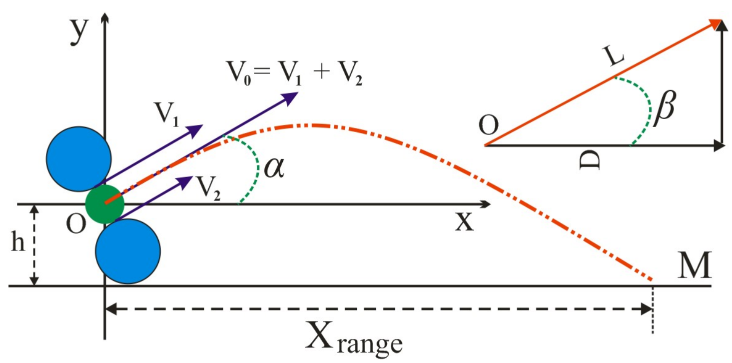

Fig.2. Adjustable kicking-angles α and β

2.1 Ball-supply complex

As shown in Fig. 3, this complex consists of: (1) a partition fixed on the container; (2) container bottom; (3) a motor; (4) a revolving salver with four orifices; and (5) joint spindle. Whenever there are some balls available in the container, they automatically fill up the orifices on the salver due to the Newton's law of universal gravitation; hence, when the salver spins, each ball falls into the conduit through the port on the bottom of the container. There is a partition working as a valve to prevent two consecutive balls on an orifice passing the port at the same time. The motor normally works at a fixed speed because the four orifices can efficiently supply enough balls for the ball-serve complex.

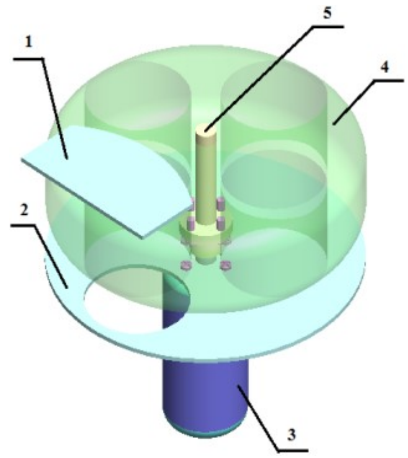

Fig.3. Structure of Ball-supply complex

2.2 Ball-serve complex

As a principle, we need to have a leading duct for an accurate kicking direction; and, the longer the duct, the more accurate the direction. However, too long duct makes it difficult in designing the robot. To overcome this shortcoming, we propose using larger flywheels that are properly concaved to have a maximum contact surface on the ball so that the ball can be efficiently gripped for a strong serve. Thus, this complex is designed as shown in Fig. 4 where we have six critical parts: (1) flywheel; (2) motor; (3) detailed frame; (4) rotating clutch; (5) moving pillow-block; and (6) fixed pillow-block. The main body of the complex is made with 6061 aluminum plate 4mm thick to provide steadfast stability and minimize its total weight. Besides, the flywheels are made of rubber pillar with good roughness and light weight.

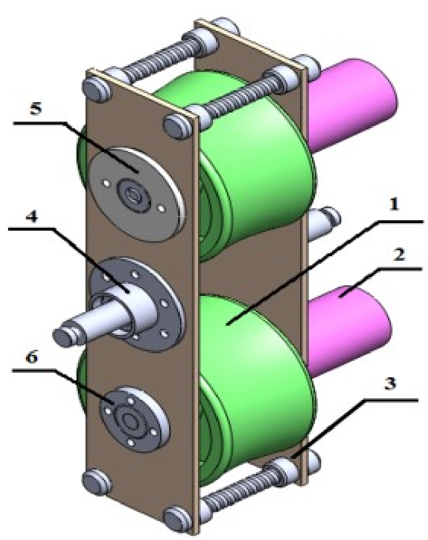

Fig.4. Structure of ball-serve complex

2.3 Angle-control complex

This complex uses nut lead screws as shown in Fig. 5 where we have: (1) transmitting crew to make the kicking-angle α; and (2) another crew for the kicking-angle β.

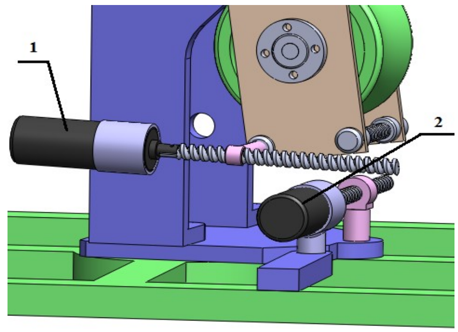

Fig.5. Structure of angle-control complex

3. DESIGNING OF CONTROLLER

Fig. 6 demonstrates the design of our proposed controller. Specifically, two main motors used in this ball robot are PSMS type, respectively named Ball-serve motor 1 (BSM1) and Ball-serve motor 2 (BSM2) which are controlled with fuzzy logic method in combination with vector control approach [8] to assure both accuracy and speed in kicking the ball to certain places on the opponent court. Moreover, in order to lower the cost price for the robot, we propose using sliding mode observers (SMOs) instead of high-resolution optical encoders. The SMOs can efficiently estimate and measure the motor speed. Meanwhile, other two motors are used to adjust the kicking-angles α and β to serve the balls better, either to touchlines or high-up direction. Mathematical equations for the control of BMS1 and BMS2 are respectively determined by:

$$\frac{di_{d_{1,2}}}{dt} = -\frac{r_{s_{1,2}}}{L_d} i_{d_{1,2}} + \omega_e \frac{L_{q_{1,2}}}{L_{d_{1,2}}} i_{q_{1,2}} + \frac{1}{L_{d_{1,2}}} \mathrm{v}_{d_{1,2}} \tag{1}$$

$$\frac{di_{q_{1,2}}}{dt} = -\omega_{e_{1,2}} \frac{L_{d_{1,2}}}{L_{q_{1,2}}} i_{d_{1,2}} - \frac{r_{s_{1,2}}}{L_{q_{1,2}}} i_{q_{1,2}} - \omega_{e_{1,2}} \frac{K_{E_{1,2}}}{L_{q_{1,2}}} + \frac{1}{L_{q_{1,2}}} \mathrm{v}_{q_{1,2}} \tag{2}$$

Vector control method is applied for both of the motors; particularly, the control current $i_{d1,2}$ is set at 0 so that the two motors are decoupled and the control of spindle moment only depends on the current $i^*_{q_{1,2}}$.

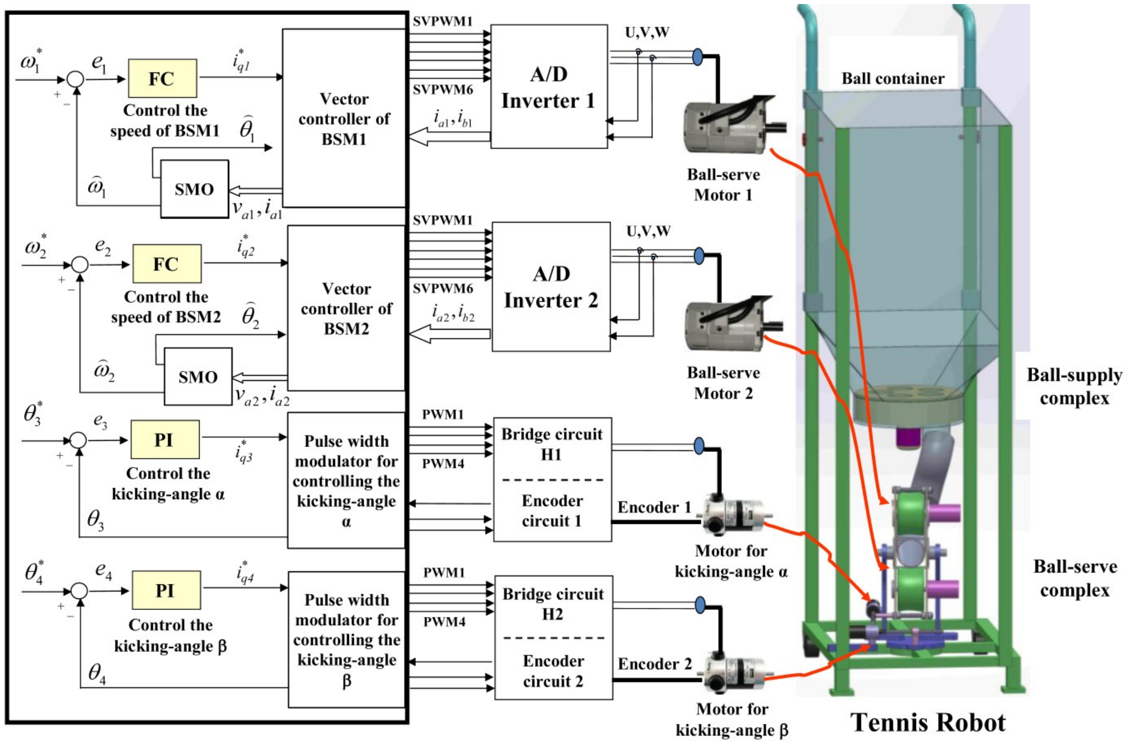

Fig.6. Structure of robot controller

The fuzzy logic controller uses singleton fuzzifier defuzzified with centroid average approach. The design of the fuzzy controller is typically based on the error analysis e(t) and its derivative. The reference inputs for the controllers are presented in Equation (3) and (4).

$$e_{1,2}(k) = \omega^*_{1,2}(k) - \hat{\omega}_{1,2}(k) \quad (3)$$

$$de_{1,2}(k) = e_{1,2}(k) - e_{1,2}(k-1) \quad (4)$$

The rules for the fuzzy logic controllers consists of 49 statements in a form of "If $e_{1,2} = A_m$ and $de_{1,2} = B_n$, $U_{f1,f2} = C_{m,n}$",, which are briefly illustrated in Fig. 7.

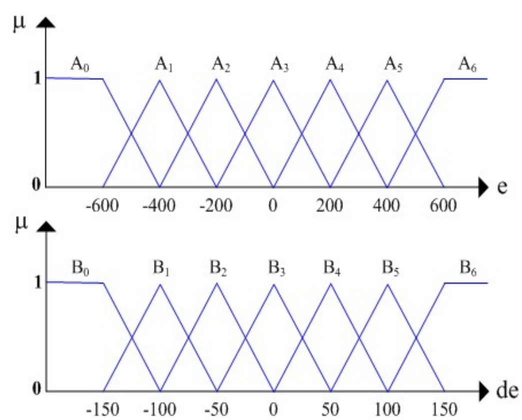

Fig.7. Fuzzy membership functions

As shown in Fig. 7 and Table 1, as the membership functions are equilateral triangles, Quynh et al. [9] found that the controlled outputs of the fuzzy controllers are determined by:

$$u_{f1,f2}(e_{1,2},de_{1,2}) = \frac{\sum_{n=i}^{i+1}\sum_{m=j}^{j+1} c_{m,n}[\mu_{A_n}(e_{1,2})*\mu_{B_n}(de_{1,2})]}{\sum_{n=i}^{i+1}\sum_{m=j}^{j+1}[\mu_{A_n}(e_{1,2})*\mu_{B_n}(de_{1,2})]} \square \sum_{n=i}^{i+1}\sum_{m=j}^{j+1} c_{m,n} * d_{n,m} \quad (5)$$

Table 1. Knowledge bases for fuzzy control rules

dE \ E	A0	A1	A2	A3	A4	A5	A6
B0	-600	-600	-600	-600	-400	-200	0
B1	-600	-600	-600	-400	-200	0	200
B2	-600	-600	-400	-200	0	200	400
B3	-600	-400	-200	0	200	400	600
B4	-400	-200	0	200	400	600	600
B5	-200	0	200	400	600	600	600
B6	0	200	400	600	600	600	600

Figure 8 demonstrates the operation of a block for estimating the motor speed, including sliding mode observer (SMO), bang-bang controller, three low pass filters, computing magnetic flux angle block, and speed estimation block [9,10]. As the ball-serve complex uses PSMS motors, the SMOs can be therefore described by Equations (6) and (7) while the bang-bang controller is constructed from Equation (8).

$$\frac{d}{dt}\hat{i}_a = \begin{bmatrix} -r_s/L & 0 \\ 0 & -r_s/L \end{bmatrix}\hat{i}_a + \frac{1}{L}(v_a - z_a) \quad (6)$$

$$\hat{i}_a(n+1) = \begin{bmatrix} \sigma & 0 \\ 0 & \sigma \end{bmatrix}\hat{i}_a(n) + \psi(v_a(n) - \hat{e}_a(n)) \quad (7)$$

$$Z = \begin{bmatrix} z_\alpha \\ z_\beta \end{bmatrix} \underline{\underline{\Delta}}\, k * sign\left(\begin{bmatrix} \hat{i}_\alpha - i_\alpha \\ \hat{i}_\beta - i_\beta \end{bmatrix}\right) \quad (8)$$

The difference between estimated current and measured one is defined as:

$$e_{cur}\,\underline{\underline{\Delta}}\left[\tilde{i}_\alpha \quad \tilde{i}_\beta\right]^T = \left[\hat{i}_\alpha - i_\alpha \quad \hat{i}_\beta - i_\beta\right]^T \quad (9)$$

For a large enough value of k so as to $e_{cur}^{T}\dot{e}_{cur} < 0,$ the SMOs change to sliding states and result in $e_{cur}^{T} = \dot{e}_{cur} = 0.$ Back-EMF is then determined by:

$$z_a = e_a = \omega_e K_E \begin{bmatrix} -\sin\theta_e \\ \cos\theta_e \end{bmatrix} \quad (10)$$

This complex integrates two low pass filters, named LPF1 and LPF2, to eliminate the high-order waves caused by bang-bang controller. The two filters are respectively presented by $\widehat{e}_{a1} = \frac{2\pi f_0}{s + 2\pi f_0} z_a$ and $\widehat{e}_{a2} = \frac{2\pi f_0}{s + 2\pi f_0} \widehat{e}_a$. The angle of rotor magnetic flux is determined by $\hat{\theta}_e(n) = \tan^{-1}\left(-\frac{\hat{e}_{\alpha 2}(n)}{\hat{e}_{\beta 2}(n)}\right)$. A mechanism to compensate the loss of flux angle caused by the filters is defined by $\hat{\theta}_{out} = \theta_{filterd} + \hat{\theta}_{compensate}$; and the estimation of the motor speed is obtained by $\widehat{\omega} = k_{speed} * \sum_{0}^{4}\left[\widehat{\theta}_e(n) - \widehat{\theta}_e(n-1)\right]$. Moreover, in order to achieve an even speed, a third filter (LPF3) of the same type is used to provide feedback to the speed controllers.

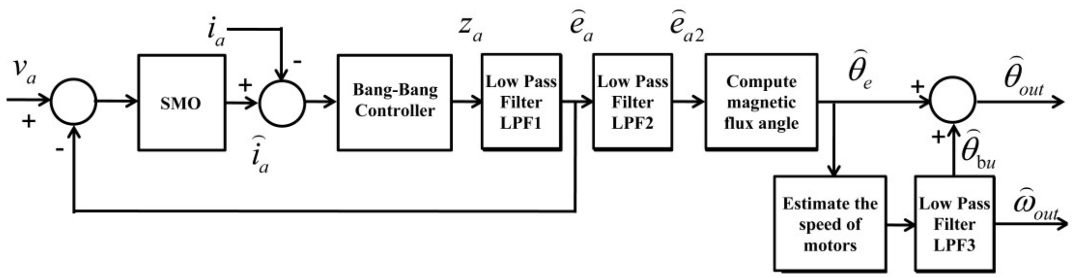

Fig.8. Block for estimating the motor speed based on the reference inputs of current and voltage

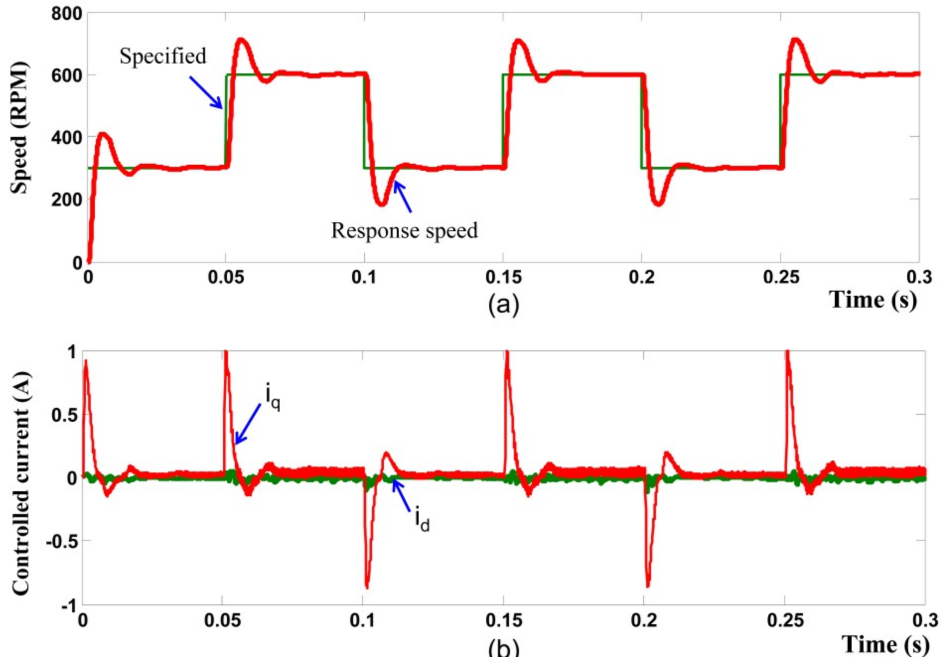

Fig.9. Feedback speed and controlled current using PI controller

Using PI controller results in the feedback speed and controlled current as shown in Fig. 9 while Fig. 10 illustrates the feedback speed and 3-phase current on motor stator obtained from the fuzzy logic controller (FC) proposed in this paper. These figures clearly show the significant difference between the PI and FC control methods. Specifically, the combination of PI controller with speed estimation package makes the percent of overshoot (POT) increased by about 30%; though the POT is reduced a lot after the Ki and Kp are refined, it is still more than 10% as shown in Fig. 9. However, with the FC controller, the POT totally disappears and the motor speed is asymptote with the designed parameters. Therefore, exactly controlling the motor speed makes the ball kicked in such an expected direction that can effectively train players to enhance their playing experience and practical skills.

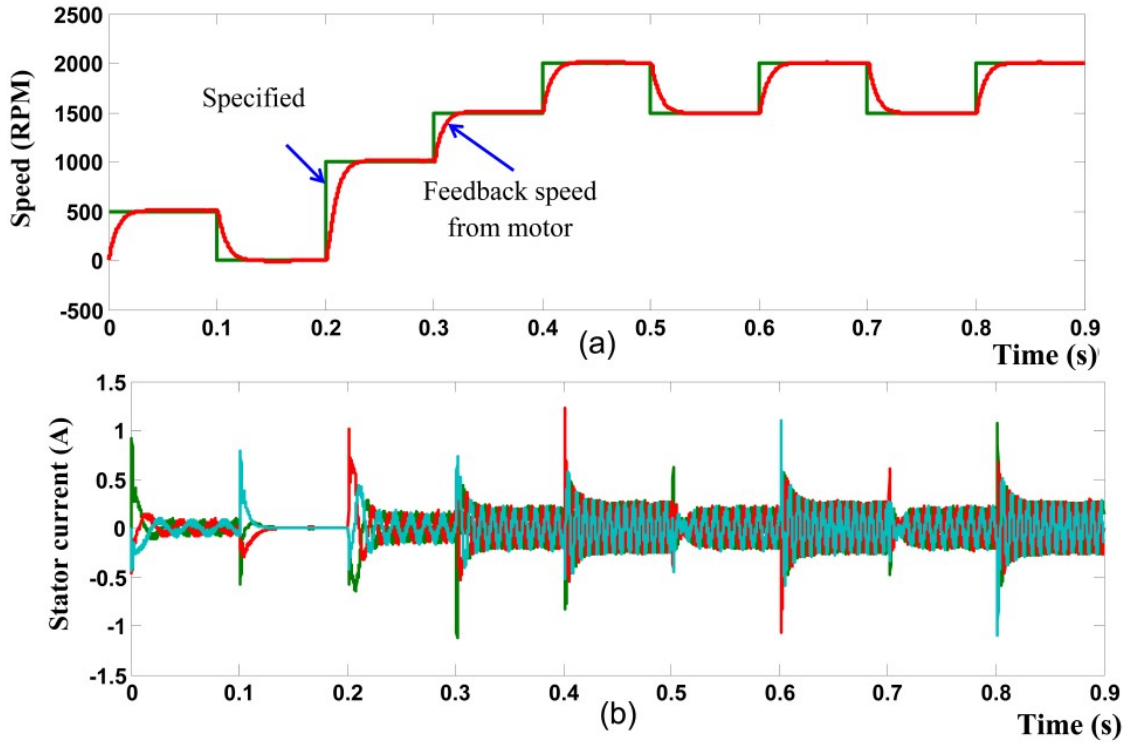

Fig.10. Feedback speed and controlled current using FC controller

4. CONCLUSION

This paper proposes an intelligent algorithm to accurately control the motors in tennis robot to serve balls in various directions so that players can enhance their playing experience and practical skills. The use of speed estimation algorithm not only lowers the cost price but also increases the technical performance of the robot, indicating that our proposed approach overcomes some certain drawbacks of the existing ones. Practically, the commercialization of the product is feasible.

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How to cite this article:
Nguyen V Q, Tran H T and Huynh D M T. Fuzzy Controller for Better Tennis Ball Robot. J. Fundam. Appl. Sci., 2017, *9(7S), 667-677.*