Advance in the efficiency of type 2 fuzzy controller in embedded systems and application for control two-wheel self-balancing robot

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Abstract: Type-2 Fuzzy Logic Controllers do not have the disadvantages of Conventional Fuzzy Logic Controllers, and are widely used in many control areas. However, using it to build embedded systems is accompanied by a large number of rules that increase the processing time and sometimes confusion, reducing the efficiency of the operating system in real time. To eliminate this disadvantage in the paper proposed the new structure of Type- 2 Fuzzy Logic Controller is proposed block based fuzzy controller to reduce the number of rules, and reduce the complexity and increase the reliability of the system control. The proposed controller is based on a fuzzy mass with a small number of fuzzy rules, due to the reduced number of input and output variables. The advantages of the new fuzzy controller are illustrated by the example of the embedded control system of the Self-Balancing Robot. The performance comparison of the proposed block based fuzzy controller shows that the rules of Type-2 Fuzzy Controller is less than twice the number rule of the conventional Type-2 Fuzzy Controller. This increases the yield by 45%, proving the feasibility of the actual application of the proposed controller.
Keywords: fuzzy controller, type-2 fuzzy logic system, embedded system, self-balancing robot.

1. Introduction

In some recent studies, the study [1] that demonstrates how to build a effective traditional fuzzy controller based on fuzzy blockes, but traditional fuzzy control has limitations [2]. To overcome these limitations, the studies [3-6] have build a Type-2 Fuzzy Controller, but the number of large components and the large expenses of practical application that stop the result at the simulation. In the studies [7-13], the control law of intelligent and advanced controllers for Two-wheel Self-balancing Robots is highly nonlinear, requiring the mathematical model of the object and the accurate observer.

This study focuses on the design of Type-2 Fuzzy Controller based on stable fuzzy block to balance two wheels robot, which is realized on a low profile embedded system. The controller is simple to use, it ensures the quality of the Type-2 Fuzzy Controller and ensures real time performance on embedded systems.

The rest of the article is organized as follows: In part 2 is the physics modeling of balanced two wheels robot and an overview of Type-2 Fuzzy

Controller based on fuzzy blockes. In part 3, presenting the design and construction of embedded balanced angle control systems for two wheels robot. In part 4, shows the simulation results on matlab and runs the embedded controller on the real model. The results were evaluated and compared with the Type 2 fuzzy controller. Finally, in part 5,the main contributions of the paper are summarized and future research will be conducted.

2. Mathematical model of two-wheel self-balancing robot

Qualitatively, the principle for keeping balance in two-wheeled robots is as follows. A robot in the equilibrium position is titled with an angle φ when subjected to a force. For the robot to regain its equilibrium, a force F is needed to applied to it so that its center of gravity is located in the middle of two wheels as shown in Figure 1.

The mathermatical model of Two-wheel Self-balancing Robot is described by the equations:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\varphi} \\ \ddot{\varphi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \dfrac{k_m k_e (M_p lr - I_p - M_p l^2)}{Rr^2\alpha} & \dfrac{M_p{}^2 g l^2}{\alpha} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \dfrac{2k_m k_e (r\beta - M_p l)}{Rr^2\alpha} & \dfrac{M_p{}^2 g l^2 \beta}{\alpha} & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \varphi \\ \dot{\varphi} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{2k_m (I_p + M_p l^2 - M_p lr)}{Rr\alpha} \\ 0 \\ \dfrac{2k_m (M_p l - r\beta)}{Rr\alpha} \end{bmatrix} U_a \qquad (1)$$

Where $\beta = (2M_\omega + \frac{2I_\omega}{r^2} + M_p)$; $\alpha = (I_p\beta + 2M_p l^2 (M_\omega + \frac{I_\omega}{r^2}))$; x - moving distance (m); $\dot{x}$ - velocity of the robot (m/s); $\ddot{x}$ - acceleration of the robot (m/s^2); φ - inclined angle of the robot's body (rad); $\dot{\varphi}$ - angular velocity of the robot's body (rad/s); $\ddot{\varphi}$ - angular acceleration of the robot's body (rad/s^2); U_a - control voltage (V); k_m - torque constant (Nm/A); k_e - voltage constant (Vs/rad); R - the terminal resistant (Ω); l - distance between the center of the wheel and the center of the robot (m); g - gravity acceleration (m/s^2); M_p - mass of robot frame (kg); r - radius of the wheel (m); I_p - moment of inertia of the frame (Nm); I_ω - moment of inertia of the wheel (Nm); M_ω - mass of the wheel (kg).

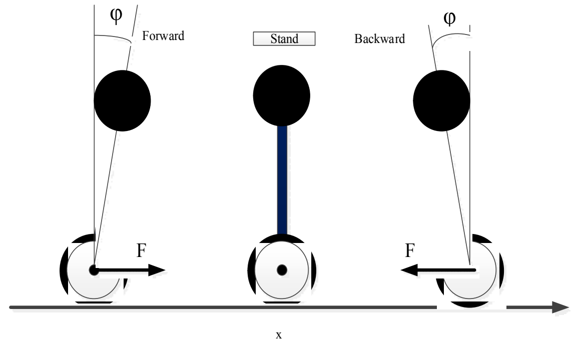


Figure 1. The qualitatively balancing principle

3. Block based type-2 fuzzy controllers

3.1. Type-2 Fuzzy Logic Controllers

Two-wheel Self-balancing Robot is a typical example of a SIMO system in which the number of actuators is less than the number of degrees of freedom of the system. So, in order to be able to control the robot at the same time as balance and position, we need to design two separate controllers. The balanced control voltage U_θ and the position control voltage U_x must be combined together into a control voltage U_a for both the system and the voltage U_θ , U_x are oppositely voltage on the same reference frame. The control structure diagram is illustrated in Figure 2.

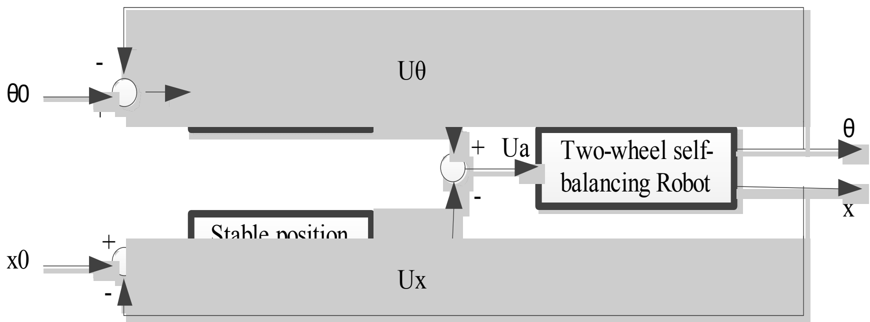


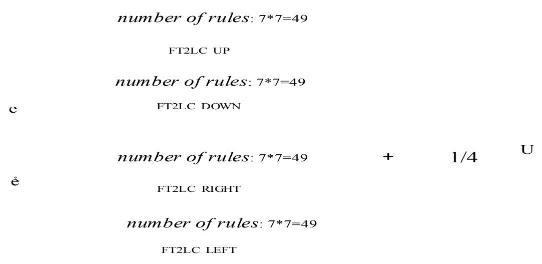
Figure 2: Control schematic diagram of Two-wheel Self-balancing Robot

When using a Type-2 Fuzzy Controller to control the balance of robot with the first input is the angular deviation (e) which is fuzzy by seven fuzzy sets {NB, NM, NS, ZE, PS, PM, PB}, and the second input is the angular velocity (e') is also fuzzy by seven sets {NB, NM, NS, ZE, PS, PM, PB}. The output of the fuzzy controller F is fuzzy by the seven fuzzy sets {NB, NM, NS, ZE, PS, PM, PB}. The fuzzy sets of input and output are denoted as follows: NB - Negative Big, NM - Negative Medium, NS - Negative Small, ZE - Zero, PS - Positive Small, PM - Positive Medium, PB - Positive Big. Type-2 Fuzzy Controller is performed based on fuzzy sets by distance and defuzzification fuzzy by the stage of conversion about kind of type 1. The dependent function of the input is changed to a period of uncertainty. This is done by defuzzificating the type-1 fuzzy sets [5,6,7], choosing to use uncertainty for all input functions is ± 0.03(Figure 3 (a)). Type-2 Fuzzy Controller structure is shown in Figure 3 (b). The method of defuzzification is based on the principle of average output of the four Type-2 Controllers:Fuzzy Type-2 Controller Top, Fuzzy Type-2 Controller Left, Fuzzy Type-2 Controller Right, Fuzzy Type-2 Controller Bottom [2]. The control rule of Type-2 Fuzzy Controller is designed according to figure 3 (c).

3.2. Type-2 Fuzzy Controller based on block

The number of compound clauses in Type-2 Fuzzy Controllers is an important issue in Type-2 Fuzzy Controller design, especially for real-time applications. The number of compound clauses of the fuzzy type-2 basis increases exponentially as the number of controller inputs increases. Complete compound clauses for Type-2 Fuzzy Controllers with n inputs and each input with fuzzy sets will have $4m^n$ compound clauses. Thereby reducing the number of component clause is very important for Type-2 Fuzzy Controller in the real-time control applications. Accuracy of the fuzzy controller can be achieved by using 5, 7 or 9 fuzzy sets at each input. Increasing accuracy can increase the number of fuzzy sets, but this leads to an increase in the number of compound clauses and increased computational costs. The structure of Type-2 Fuzzy Controller based on block is shown in Figure 4 (b) with some fuzzy controllers having less compound clauses than Type-2 Fuzzy Controller.

(a)



(b)

e \ e'	NB	NM	NS	ZE	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	ZE
N M	PB	PB	PB	PM	PS	ZE	NS
NS	PB	PB	PM	PS	ZE	NS	NM
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	PM	PS	ZE	NS	NM	NB	NB
P M	PS	ZE	NS	NM	NB	NB	NB
PB	ZE	NS	NM	NB	NB	NB	NB

(c)

Figure 3: Selection of type-2 dependent function from type-1 dependent function

Type-2 Fuzzy Controller based on block proposed in this study includes the sum of three Type-2 Fuzzy Controllers with 36 composite clauses in each block of the controller. The fuzzy set input of is shown in Figure 4(a), Three Type-2 Fuzzy Controllers based on block with dependent functions are different base values. The output of each block also consists of three fuzzy sets with different bases, proportional to the input: [-7; 7], [-3.5; 3.5], [-1.5; 1.5]. The control rule of Type-2 Fuzzy Controller based on block is based on experiment is shown in Figure 4(c).

4. Simulation and experimental results

4.1 Simulation results with Type-2 Fuzzy Controller based on block

Parameters of the mathematical model (1) are determined by the real model with parameter values in Table 1. Simulations were performed on MATLAB Simulink software with initial conditions: robot standing still then moves to the position from 1 (m) and stood there. The simulation results are shown in Figure 5. In Figure 5(a) is the inclined angle of the robot's body, while Figure 5(b) is the moving distance by the robot. From the simulation results, the response of Type-2 Fuzzy Controller based on block has lower overshoot and higher stability.

FT2LC 1
number of rules:
4*3*3=36

e

FT2LC 2
number of rules:
4*3*3=36

+ U

ė

FT2LC 3
number of rules:
4*3*3=36

(b)

e \ e'	NB	ZE	PB
NB	PB	PB	ZE
ZE	PB	ZE	NB
PB	ZE	NB	NB

(c)

(a)

Figure 4: Composition of Type-2 Fuzzy Controller based on block

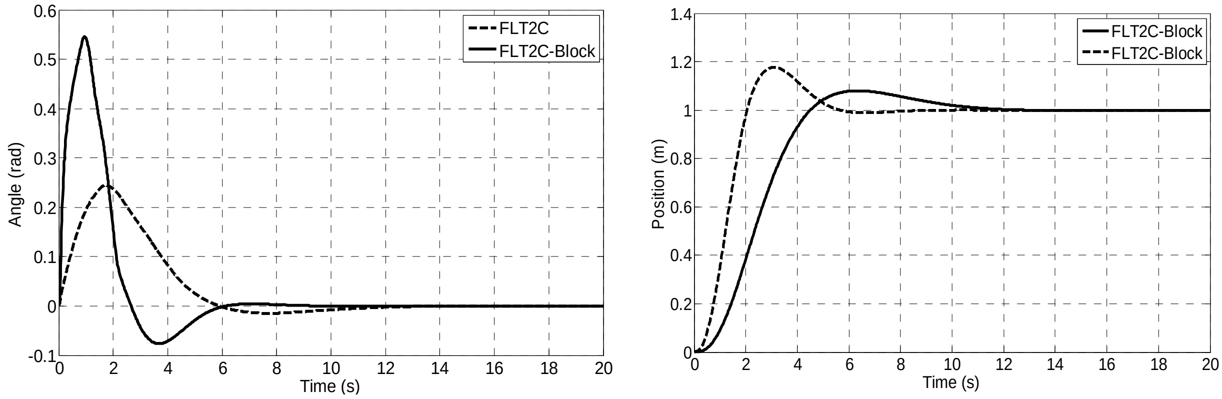
Table № 1

The parameter values of Two-wheel Self-balancing Robot

k_m	0.022 (N.m/A)	M_ω	0.03 (kg)
k_e	0.4 (Vs/rad)	I_p	0.0012 (kg.m^2)
R	1.7 (Ω)	I_ω	0.000016 (kg.m^2)
r	0.0325 (m)	l	0.05 (m)
M_p	1 (kg)	g	9.81 (m/s^2)

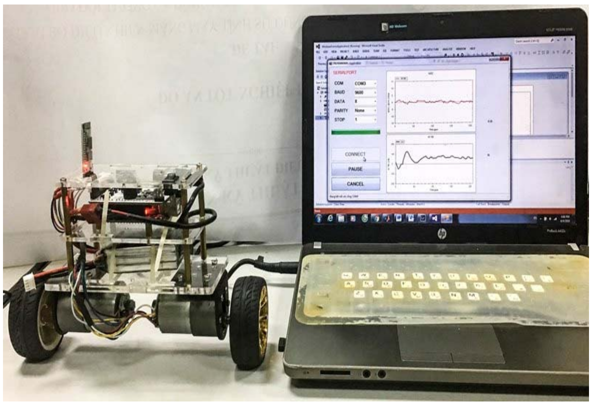
4.2 Design of an embedded controller for Two-wheel Self-balancing Robot

The control block diagram of Two-wheel Self-balancing Robot and the actual model are shown in Figure 6(a). In Figure 6(b), a model of Two-wheel Self-balancing Robot. Arduino Board has the embedded Arduino Uno 16MHz working frequency, the MPU6050 accelerometer and transmits data via Bluetooth HC-6 to the computer.



(a) (b)

Figure 5: Angle response, robot position using FLT2 based on block and FLT2

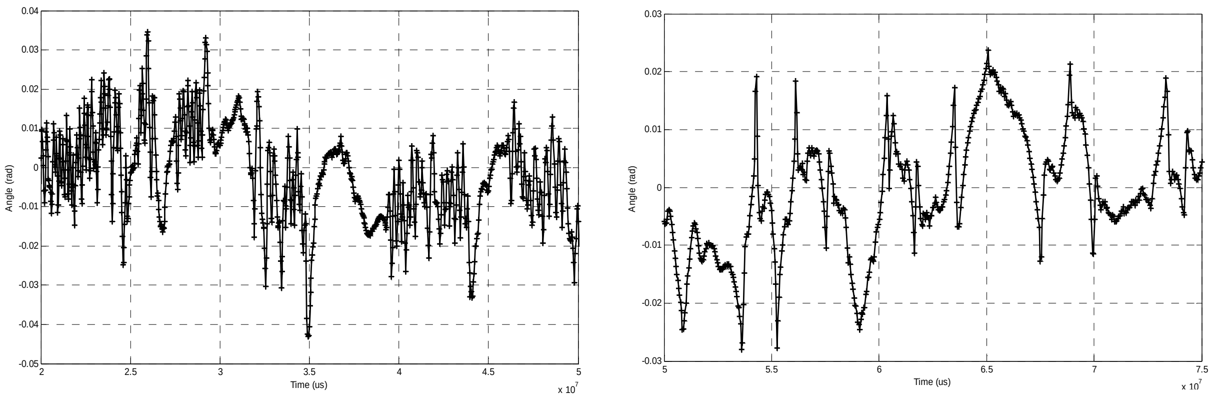


(a) (b)

Figure 6: The hardware block diagram of Two-wheel Self-balancing Robot

The difficulty of embedded programming of Type-2 Fuzzy Controllers is the number of multiple clauses and the construction of dependent functions. Thus, in the program the authors use the technique of constructing functions in programming.

Experimental results of the inclined angle of the robot's body are shown in Figure 7. In particular, Figure 7(a) is the inclined angle φ of the robot's body for Type-2 Fuzzy Controller, and Type-2 Fuzzy Controller based on block is shown in Figure 7(b). From the experimental results, we can see that the efficiency of Type-2 Fuzzy Controller based on block as implemented on the embedded system.



(a) (b)

Figure 7: Robot's angle response on embedded systems

a: FLT2 controller; b: FLT2 based blocks.

5. Conclusion

Based on the type-2 fuzzy theory combined with the method of building a fuzzy controller and based on the block, the authors have developed a Type-2 Fuzzy Controller based on embedded blocks for Two-wheel Self-balancing Robot. Simulation and experiment results show that a method of building fuzzy controllers based on block is highly effective in real-time control applications. The method of building Type-2 Fuzzy Controllers based on block is possible to apply complex control systems to multiple inputs and outputs while still ensuring that the system works in real time.

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References

1. Mehmet Karakose, Erhan Akin, "Block based fuzzy controllers," International Journal of Research and Reviews in Applied Sciences 3 (1) (2010), pp. 100-110.

2. S. M. Abuelenin, "Decomposed Interval Type-2 Fuzzy Systems with Application to Inverted Pendulum," in Engineering and Technology (ICET), 2014 International Conference on, 2014, pp. 1–5.

3. J. Mendel, "Type-2 fuzzy sets and systems: an overview," IEEE Computational Intelligence Magazine, vol. 2, pp. 20-29, February 2007.

4. D. Wu and W. W. Tan, “A simplified architecture for type-2 FLSs and its application to nonlinear control,” in Proceedings. IEEE Conf. On Cybern. andIntell. Syst., Singapore, Dec. 2004, pp. 485–490.

5. J. M. Mendel and R. I. B. John, “Type-2 fuzzy sets made simple,” IEEE Trans. Fuzzy Syst., vol. 10, no. 2, pp. 117–127, Apr. 2002.

6. Hai N. Phan, Chiem X. Nguyen, “Building embedded quasi-time-optimal controller for twowheeled self-balancing robot,” MATEC Web Conf.Volume 132, 2017 XIII International Scientific-Technical Conference“Dynamic of Technical Systems” (DTS-2017). URL: doi.org/10.1051/matecconf/201713202005.

7. Nguyen Ngoc Son, Ho Pham HuyAnh, “Adaptive Backstepping Self-balancing Control of a Two-wheel Electric Scooter,” International Journal of Advanced Robotic Systems, 2014, 11:165. URL: journals.sagepub.com/doi/10.5772/59100.

8. S.C. Lin, C.C. Tsai, H.C. Huang, “Nonlinear Adaptive Sliding-Mode Control Design for Two-Wheeled Human Transportation Vehicle,” Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics, pp. 1965-1970 (2009).

9. H. Ohara and T. Murakami, “A stability control by active angle control of front-wheel in a vehicle system,” IEEE Trans. Ind. Electron. vol. 55, no. 3, pp. 1277-1285, Mar. 2008..

10. Vinodh Kumar E, Jovitha Jerome. Robust LQR Controller Design for Stabilizing and Trajectory Tracking of Inverted Pendulum. Procedia Engineering 64 (2013), pp. 169 – 178.

11. Koburneeva M.P., Klimanskaya E.V. Inženernyj vestnik Dona (Rus), 2017, №4. URL: ivdon.ru/ru/magazine/archive/n4y2017/4611.

12. Danilova M.G., Chernyshov C.Yu., Sidorov E.N., Osnovin M.S. Inženernyj vestnik Dona (Rus), 2014, №3. URL: ivdon.ru/ru/magazine/archive/n3y2014/2456.

13. Beloglazov D.A., Kosenko E.Yu., Solovyev V.V., Titov A.E., Shapovalov I.O. Inženernyj vestnik Dona (Rus), 2015, №4 URL: ivdon.ru/ru/magazine/archive/n4y2015/3387.