Fuzzy-PID controller for Two Wheels Balancing Robot Based on STM32 Microcontroller

Mai The Anh, Dang Thai Son
Institute of Technique and Technology
Vinh University
Vinh, Vietnam
theanh@vinhuni.edu.vn
sondtbk@gmail.com

Anisimov D.N, Fedorova Ekaterina
Department of Control and Informatics
Moscow Power Engineering Institute
Moscow, Russia
AnisimovDN@mpei.ru
f.kat.public@gmail.com

***Abstract*— In this paper, a fuzzy-PID controller is proposed to regulate the movement of two wheels balancing robot. The fuzzy-PID controller is a combination of a fuzzy controller and PID controllers for the balancing and movement or distance of the two wheels balancing robot. The fuzzy controller is designed based on relation models for the robot's balancing. The PID controllers are proposed to control the robot's position. The whole fuzzy-PID is ported and run on a real-time operating system using an STM32F4 Discovery Kit. The received results showed advantages of the fuzzy-PID controller.**

Keywords*— *system control, fuzzy control, PID control, two wheels balancing robot, STM32 microcontroller.

I. INTRODUCTION

In recent years, two-wheeled inverted pendulum robot has been developed quickly. Self-balancing robot like the Segway has been absolutely recognized and used as a human transporter especially for policeman [1]. It is an ideal object of mechatronics, which includes electronic device and embedded control, which includes electronic device and embedded control. The two-wheeled robot is the combination of wheeled mobile robot and inverted pendulum system [2,3]. It also brings the concept of creating a transporter for human. Advantages as light weight, small footprint, rapid rotation, high maneuverability make it to really efficient for use in different areas.

A balancing robot is a common demonstration of controls in a dynamic system [4-7]. Due to the inherent instability of the equilibrium point, appropriate controllability and observability measures must be undertaken to stabilize the system about the desired equilibrium point. Two wheels balancing robot is a multivariable uncertain nonlinear system [8]. Many researchers and engineers are working on that because of its unstable nature, high order multivariable, nonlinear and strong coupling properties and mobility. The number of researches on fuzzy control for a two wheels balancing robot has increased in recent years [9-14]. The fuzzy controller provides a powerful tool for design of nonlinear system [15, 16]. This paper proposes a comprehensive design for the two wheels balancing robot based on STM32 microcontroller. A combination between a fuzzy controller and PID controllers provides more stable control method and algorithm for the robot.

II. SYSTEM DESCRIPTION

A. *Hardware description of robot*

A two wheels robot platform was designed by the authors (Fig. 1). It has a chassis that is consisted of two platforms to place electronic equipments. Our robot consists from a two wheels and a chassis that hides the inverted pendulum system. The chassis holds two motors each drives a wheel. The motors are mounted on the chassis. The chassis also holds the circuits that drive the motors, read sensors, and do the actual balancing and motion control.

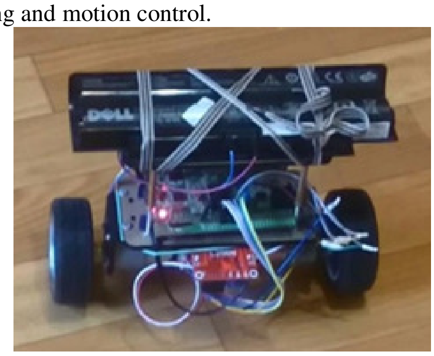

Fig. 1 The two wheels robot platform

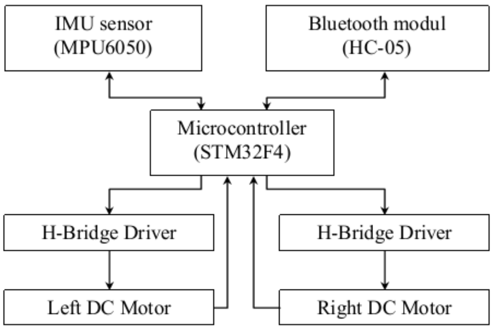

Fig. 2 Two wheels general system block diagram.

The main components in the circuit of the balancing robot are the Inertial Measurement Unit (IMU), the STM32F4 Discovery KIT and the DC servo motor. Fig. 2 shows the overall block diagram of the electronic system for a two wheels balancing robot. The IMU is used to measure the acceleration and the angular rate of the robot and the output is processed into digital form. The raw inputs from the IMU are further processed to obtain the tilt angle of the robot. This tilt angle is then fed into the fuzzy controller algorithm to generate the appropriate speed to the DC motor in order to balance the robot. The lithium polymer (LiPo) batteries of 11V which is located on the top of the robot to provide voltage for the robot. The robot is connected to computer or an android mobile phone through a Bluetooth module HC-05 for data transmission and control signal.

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B. Mathematical model

The robot's behaviour can be influenced by disturbances as well as the torque from the motor, the mathematical model will have to accommodate for such forces. The coordinate system of the robot is shown in Fig. 3.

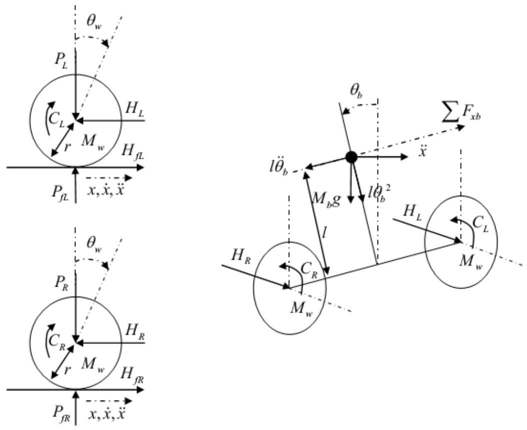

Fig. 3 Free-body diagram of the robot.

The linear movement of the robot is characterized by the position x and the speed $\dot{x}$; the chassis of the robot is also able rotate around the pitch axis which is described by the angle θ and the corresponding angular velocity $\dot{\theta}$. The rotation angles of the left wheel and the right wheel are described by the angle θ_w. The mathematical model of a two-wheeled balancing-robot was derived using Newtonian mechanics [1, 3], for the left wheel and the right wheel of the robot:

$$\begin{cases} M_w\ddot{x} = H_{fL} - H_L \\ I_w\ddot{\theta}_w = C_L - H_{fL}r \\ C_L = I_L\dfrac{d\omega}{dt} = \dfrac{-k_m k_e}{R}\dot{\theta}_w + \dfrac{k_m}{R}V_a \\ \ddot{\theta}_w r = \ddot{x} \\ \dot{\theta}_w r = \dot{x} \\ \theta_w = \dfrac{x}{r} \end{cases} \tag{1}$$

For the body of robot:

$$\begin{cases} (H_L + H_R) - M_b l\ddot{\theta}\cos\theta + M_b l\dot{\theta}^2\sin\theta \\ \qquad = M_b\ddot{x} \\ (H_L + H_R)\cos\theta + (P_L + P_R)\sin\theta \\ \qquad - M_b g\sin\theta - M_b l\ddot{\theta} = M_b\ddot{x}\cos\theta \\ (H_L + H_R)l\cos\theta + (P_L + P_R)l\sin\theta \\ \qquad - (C_L + C_R) = I_b\ddot{\theta} \\ \sum F_{xb} = M_b\ddot{x}\cos\theta \\ C_L + C_R = \dfrac{-2k_m k_e}{R}\dfrac{\dot{x}}{r} + \dfrac{2k_m}{R}V_a \end{cases} \tag{2}$$

Where $H_{fL}, H_{fR}, P_{fL}, P_{fR}$ are reaction forces between the wheels and the ground; H_L, H_R, P_L, P_R are reaction forces between the chassis and the wheels. The parameters of robot are defined by: Pitch angle of robot θ [rad]; mass of the wheels $M_w = 0.03\ [kg]$; mass of the body $M_b = 1.4[kg]$; length to the body's centre of mass $l = 0.02[m]$; radius of the wheels $r = 0.0325[m]$; input torque for the left and the right wheels $C_L, C_R\ [N/m]$; gravity constant $g = 9.81[m/s^2]$; inertia of the wheel $I_w = 39.10^{-6}\left[kg.m^2\right]$; inertia of the body $I_b = 41.10^{-4}\left[kg.m^2\right]$; motor torque constant $k_m = 0.006123[Nm/A]$; the back EMF constant of motors $k_e = 0.006087[Vs/rad]$; nominal terminal resistance $R = 3[\Omega]$; voltage applied to motors for controlling $V_a\ [V]$.

From (1) and (2), non-linear equations of motion of two-wheels balancing robot are written as:

$$\begin{cases} (I_b + M_b l^2)\ddot{\theta} - \dfrac{2k_m k_e}{Rr}\dot{x} + \dfrac{2k_m}{R}V_a + M_b gl\sin\theta \\ \qquad = -M_b l\ddot{x}\cos\theta \\ \dfrac{2k_m}{Rr}V_a = (2M_w + \dfrac{2I_w}{r^2} + M_b)\ddot{x} + \dfrac{2k_m k_e}{Rr^2}\dot{x} \\ \qquad + M_b l\ddot{\theta}\cos\theta - M_b l\dot{\theta}^2\sin\theta \end{cases} \tag{3}$$

III. CONTROL DESIGN

The function block diagram of the control system is shown in Fig. 4, it is constructed by four control loops: the first control loop uses a PID controller for orientation of the robot; the second loop uses a PD controller for position; the third loop uses a PI controller to provide a requested tilt of the robot; the fourth loop is the main loop that keeps the robot in equilibrium by using a fuzzy controller.

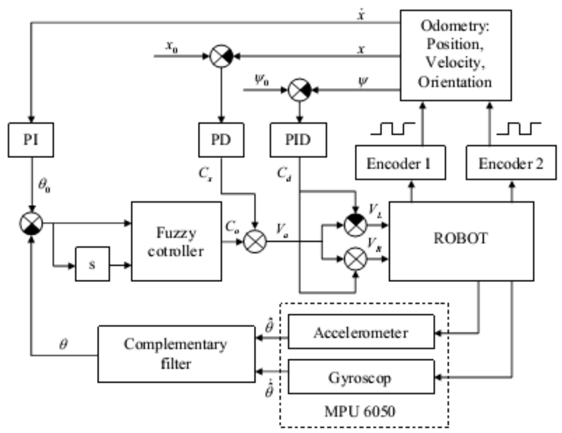

Fig. 4 The function block diagram of the control system

The two motor coaxial encoders will produce pulses, which will be converted to obtain the real-time speed of the two motors, calculating the average of real-time speed of the two motors gives the real-time speed of the robot. The real-time speed of the robot and the optimal estimate of the tilt that is obtained by the complementary filter will together constitute a closed-loop control system with four control loops as above. The closed-loop control system will output the stable and reliable PWM signal to the motor driver chip to control two motors, keeping the robot equilibrium in requested odometry.

A. Complementary filter

In order to obtain the tilt angle of the robot, we use a MPU-6050 module which consist of an accelerometer and a gyroscope. The angular of the robot can be obtain with a accelerometer by using trigonometry to calculate the angle of the gravity vectors which is always visible on the accelerometer. But all forces are working on the robot are also measured, it will disturb measurement completely. The title of the robot can be also defined simply by integration of angular velocity that is received form the gyroscope. The measurement data is not affected by the bobot's acceleration or external forces. But the integration over time make the measurement has tendency to drift, the measurement data has accumulated bias. So a complementary filter is used for sensor fusion. The complementary filter consists of both low and high pass filter and as it is easier to implement, block diagram of a complementary filter is shown in Fig 5.

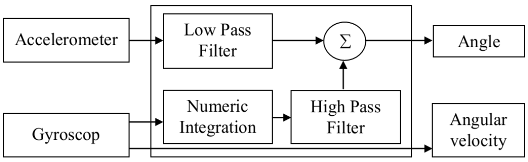

Fig. 5 Block diagram of the complementary filter

The equation of the complementary filter is shown in (4).

$$\theta = \alpha \cdot (\theta + gyroAngle * sampleTime) + (1-\alpha) \cdot accelerometerAngle \quad (4)$$

Where α is the filter coefficient which determines to which degree the final angle measurement will depend on each sensor.

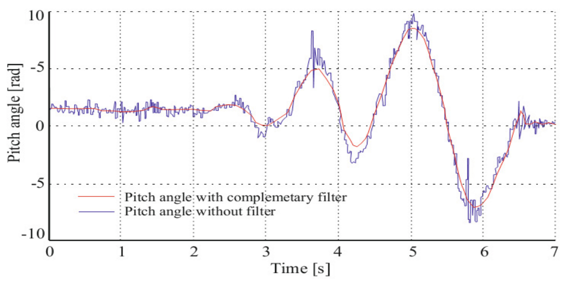

Fig. 6 Comparison of angle measurements.

The measurement data of the pitch angle is illustrated in Fig.6. The accuracy of the filter is tested with a wide range of pitch angle. We can see the signal of the pitch angle is better. The complementary filter is very easy and light to implement making it perfect for embedded systems..

B. PID controllers

As mentioned above, the robot uses a PID controller in the aspect of its orientation. The robot's position is given by a PD controller. A PI controller is used to give the requested angular which need for velocity aspect of the robot. The best parameters of the PID, PD, PI controllers are chosen after a number of simulations and experiments, it is shown in Table 1.

TABLE I. PARAMETERS OF THE PID CONTROLLERS

Controllers	**Parameters**
PID	$K_P = 15.2;\ K_D = -9.4;\ K_I = 4.8$
PD	$K_P = -30.11;\ K_D = -25.3$
PI	$K_P = 3.7;\ K_I = 0.86$

C. Fuzzy controller

The fuzzy controller is used to regular the pitch angular of the robot. The fuzzy controller is designed to have two inputs and one output, where the inputs are the error (e) and the error rate (de) of the pitch angle, the output is the control signal (C_0). The inputs and the output membership functions are denoted as Negative (N), Zero (Z) and Positive (PS). The fuzzy membership functions for the inputs and the output are shown in Fig.7.

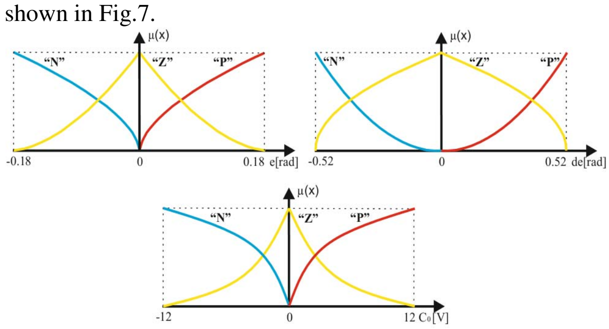

Fig. 7 The membership functions of the fuzzy controller.

The control rules are designed to achieve the best performance of the fuzzy controller, which are given by a relation matrix R. After a number of simulation experiments in Visual Studio C# environment, the parameters of the relation matrix R for the robot are given below:

$$R = \begin{array}{c} "--" \\ "-0" \\ "-+" \\ "0-" \\ "00" \\ "0+" \\ "+-" \\ "+0" \\ "++" \end{array} \overset{\begin{array}{ccc} "-" & "0" & "+" \end{array}}{\begin{bmatrix} 0,8 & 0,2 & 0 \\ 0,5 & 0,5 & 0 \\ 0,4 & 0,6 & 0,4 \\ 0,5 & 0,5 & 0 \\ 0,3 & 0,7 & 0,3 \\ 0 & 0,5 & 0,5 \\ 0,4 & 0,6 & 0,4 \\ 0 & 0,5 & 0,5 \\ 0 & 0,2 & 0,8 \end{bmatrix}} \quad (5)$$

The control surface of the fuzzy control is shown in Fig.8.

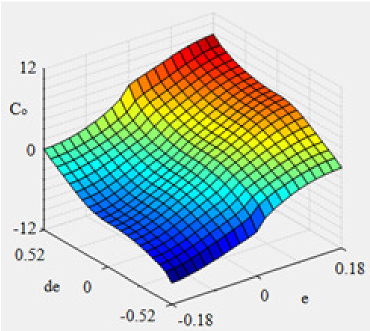

Fig. 8 The control surface of the fuzzy control

IV. MAIN RESULTS

A. Simulation results

The simulation results is conducted in Visual Studio C# environment with FuzzyLab program which is written by the authors.

In the first case, the robot is tested with maintains at equilibrium, doesn't move. The robot's balancing regulation is implemented with large initial angle ($\theta_0 = 0.1[rad]$) . The response of the robot is shown in Fig.9, both the angle and the position of robot converge to zero after 0.6s

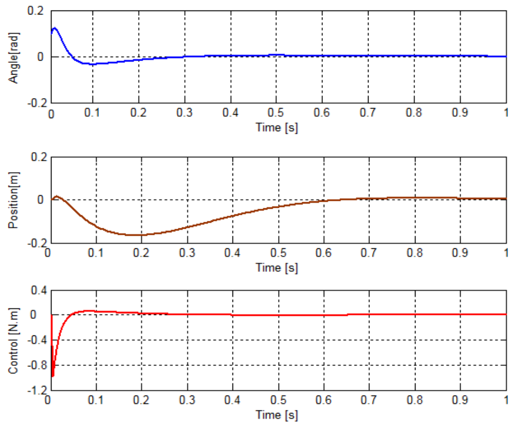

Fig. 9 Response of the system in simulation with initial condition $\theta_0 = 0.1[rad]$

In the second case, the robot moves to the set position $x_0 = 1[m]$ is shown in Fig.10. The robot can reach to the set position in 3.5[s].

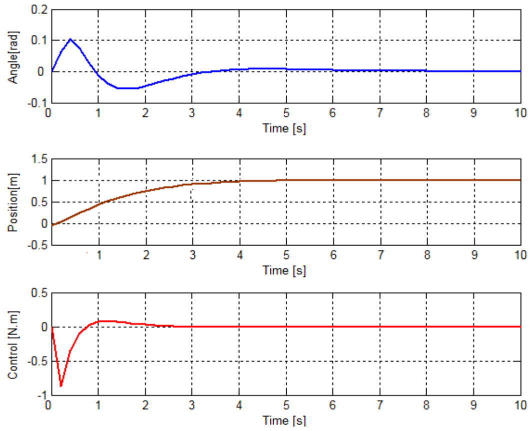

Fig. 10 The response of the robot in simulation with moving to the new position $x_0 = 1[m]$

B. Experimental results

The obtained parameters from the simulation are applied to the two wheels robot platform which is designed by the authors.

In the first experiment, the robot doesn't move. An external disturbance is applied to the robot to test capability of equilibrium of the robot. The disturbance is a slight push of the robot in backwards direction. The disturbance is introduced to the robot at $t = 3[s]$. The robot moves backward to regulate the pitch angle and returns to the equilibrium point in $\Delta t \approx 0.7[s]$ which is shown in Fig.11.

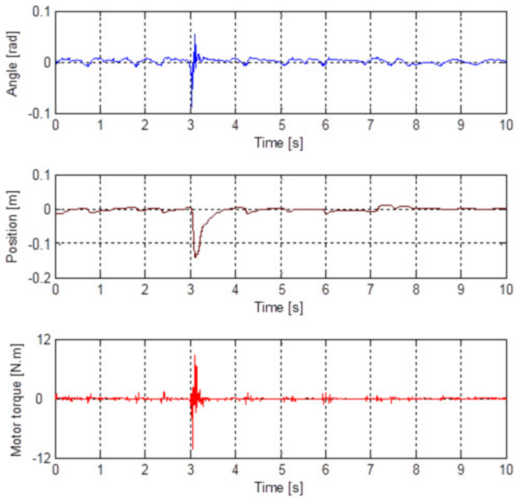

Fig. 11 Real-time curves of the designed robot with an external disturbance.

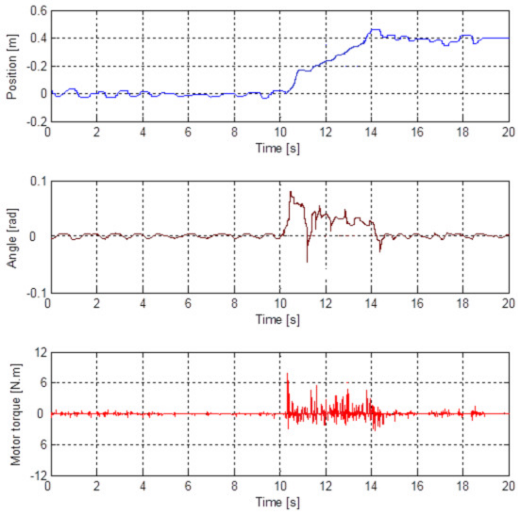

Fig. 12 Real-time curves of the designed robot with moving backward to the negative set position.

In the second experiment, the robot is tested with moving to the set position $(x_0 = 0.4[m])$. The response of the robot is shown in Fig.12, the robot can reach to the new set position in $\Delta t \approx 3.8[s]$

V. CONCLUSIONS

The paper presented an approach to design and implement a suitable controller for a two wheels balancing robot. Combination of conditional PID theory and fuzzy logic control theory provides a powerful tool for design of nonlinear systems such as the two wheels balancing robot. The proposed fuzzy-PID is implemented with real-time platform on STM32F4 DISCOVERY KIT, the simulation and experiment results show advantages of the fuzzy-PID controller. In the future, the fuzzy-PID controller will be optimized to improve quality of system. Beside, applications of the fuzzy-PID for other objects are also considered.

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