Design and PID Control of Two Wheeled Autonomous Balance Robot

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ABSTRACT

In this study, a two-wheeled autonomous balance robot has been designed and implemented practically. A visual computer interface based on Qt-Creator has been created. Thanks to the computer interface, different control algorithms can be performed on the robot easily, control parameters can be set up online, filter algorithms in various structures can be tried and the reaction of these changeable values to the system can be observed. The effects of some controllers such as Proportional (P), Proportional-Integral (PI), Proportional-Integral-Derivative (PID) on developed robot have been viewed successfully. Kalman Filters have been used for a stable control of the system and it has seen that the system can balance itself for a long time with optimum PID control parameters obtained.

Index Terms— Two-wheels Balancing Robot, PID Controller, Kalman Filter, Qt Creator User Interface, Feedback Control

1. INTRODUCTION

The research on a two-wheel inverted pendulum, which is commonly known as the self-balancing robot, has gained momentum over the last decade in a number of robotic laboratories [1-4]. The dynamics of such a system are quite complex, so its motion planning presents a challenge [5-6].

Various control strategies had been proposed by numerous researchers to control the two-wheeled balancing robot such that the robot is able to balance itself [7]. Therefore, a two wheeled balancing robot needs a good controller to control itself in upright position without the needs from outside. Nowadays various types of controllers were implemented on two wheeled balancing robot for example Linear Quadratic Regulator (LQR), Pole-Placement Controller, Fuzzy Logic Controller (FLC), PID Controller [8].

These capabilities have the potential to solve a number of challenges in industry and society. For example, a motorized wheelchair utilizing this technology would give the operator greater maneuverability and thus access to places most able- bodied people take for granted [9]. Two-wheeled carries (Segway) used by ground staff can be seen generally in the markets, car parks and airports.

In this study, a two-wheeled autonomous balance robot has been designed, having an interface by which different control algorithms can be performed easily. To maintain itself in upright position, various controller algorithms have been carried out on the robot and their effectiveness has been researched. The details about mechanical and mathematical modelling of designed balance robot are given in section 2; electronic equipment and interface software are given in section 3. The results of the study and outcomes obtained are given in the last section.

2. MECHANICAL DESIGN AND MATHEMATICAL MODELLING

2.1. Mechanical Design

Being a non-linear system, the robot's mechanic design is rather important. Thus very smooth light and durable materials have been preferred for mechanical design of the robot and a suitable center of gravity has been created. Balance robot has an interconnecting two boards made up of fibreglass material. As shown in Fig. 1 bottom board contains Direct Current (DC) motors which drive wheels directly, DC motor driver board and lithium polymer battery providing system's energy. On the top board there are STM32F103RB control board which has 32-bit Acorn Reduced Instruction Set Computing (RISC) Machine (ARM) based microprocessor, interface adaptor and Motion Processing Unit (MPU) 6050 balance sensor. General view of the balance robot is shown in Fig. 1.

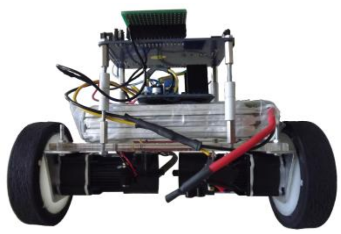

Fig. 1. General view of the balance robot

2.2. Mathematical Modelling

Dynamic performance of the balance robot depends on system's dynamic model and control algorithm's efficiency [10]. There are lots of studies about getting dynamic equations of some system like that. In this study, we dealt with the balance robot's dynamic model in reference [4].

$$\sum F_x = 0: m_k\ddot{x} = -\frac{1}{2}F_H + F_{pH} - b\dot{x} \qquad (1)$$

$$\sum F_y = 0: m_k\ddot{y} = F_{pV} - \frac{1}{2}F_V - m_k g \qquad (2)$$

$$\sum M_T = 0: J_k\ddot{\theta_k} = M_M - F_{pH}r \qquad (3)$$

Which describe the dynamics of the wheel, and

$$\sum F_x = 0: m_n\ddot{x_n} = F_H \qquad (4)$$

$$\sum F_y = 0: m_n\ddot{y_n} = F_V - m_n g \qquad (5)$$

Which describe the dynamics of the inverted pendulum. After combining equations 1-5, two equations of motions of are obtained:

$$(J_n + L^2 m_n)\ddot{\theta}_n = -Lm_n\ddot{x}\cos\theta + gLm_n\sin\theta - 2M_M \quad (6)$$

$$\left(m_k + \frac{J_k}{R^2} + \frac{1}{2}m_n\right)\ddot{x} = \frac{M_M}{R} - \frac{1}{2}m_n L\cos\theta\,\ddot{\theta} + \frac{1}{2}m_n L\sin\theta\,\dot{\theta}^2 - b\dot{x} \qquad (7)$$

In Fig. 2, there are forces and torques which act on the wheel and inverted pendulum.

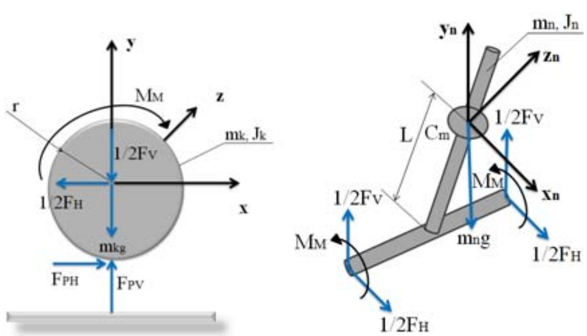

Fig. 2. Forces and torques acting on the wheel and inverted pendulum

In order to simplificate controller design, the nonlinear equations of motion have to be linearized. The desired state of the system is the one in which the angle is small and close to 0 degrees. Therefore, assuming $\sin\theta = \theta$, $\cos\theta = 1$ and $\dot{\theta}^2 = 0$ we get the following linearized equations

$$(J_n + L^2 m_n)\ddot{\theta}_n = -Lm_n\ddot{x} + gLm_n\theta - 2M_M \qquad (8)$$

$$\left(m_k + \frac{J_k}{R^2} + \frac{1}{2}m_n\right)\ddot{x} = \frac{M_M}{R} - \frac{1}{2}m_n L\ddot{\theta} - b\dot{x} \qquad (9)$$

Using the linear equation system gained in this paper, state-space form has been obtained and dynamic equations of the balance robot have been created.

3. ELECTRONICS AND SOFTWARE

3.1. Electronics

In order that two-wheeled autonomous balance robots stand in upright position, it's necessary to measure the tilt angle between balance robot and horizontal plant. In applications, various sensors are used to measure this angle. For this aim, Light Dependent Resistor (LDR), infrared, variable resistors and Inertial Measurement Unit (IMU) sensors are used commonly.

At the same time, some information such as torque on axis of oscillation, force component of acceleration of gravity on vertical and horizontal axis need to be known to be used for control algorithms.

In this study, MPU 6050 inertial measurement sensor in Fig. 3 has been used. In this integrated circuit, three-axis gyroscope and acceleration sensor exist as a whole. The sensor we used can give torque data and acceleration data. Integrated sensor has been connected to ARM based processor via Inter-Integrated Circuit (I2C) interface software. Acceleration sensor is ±2g sensitive and moment sensor is 250 degree/second sensitive.

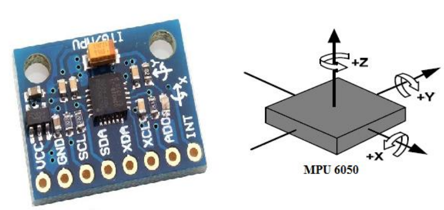

Fig. 3. MPU 6050 structure of inertial moment sensor

ARM based STM32F103RB development board has been used in the designed balance robot control system in order to get data from sensors and process it. The development board contains an ARM based processor operating at 72 Mega Hertz (MHz) frequency, having high-speed embedded memories (Flash memory up to 128 Kbytes and Synchronous Dynamic Random Access Memory) up to 20

Kbytes) and 32-bit RISC architecture. There are 12-bit Analog Digital Converters (ADCs), three general purpose 16-bit timers and also one Pulse With Modulation (PWM) timer. In addition, it has standard and advanced communication interfaces: up to two I2Cs and Serial Peripheral Interface (SPIs), three Universal Synchronous Receiver/Transmitter (USARTs), an Universal Serial Bus (USB) and a Controller Area Network (CAN). In Fig. 4 the development board is shown in detail.

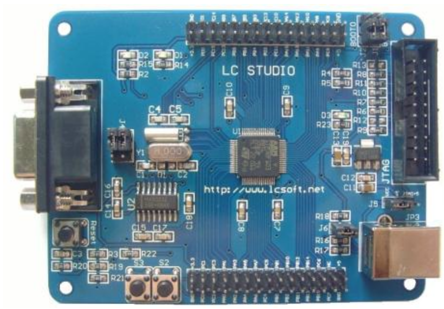

Fig. 4. STM32F103RB development board

The development board imports sensor, filters data via Kalman Filter and sends PWM signal to motor driving circuit calculating controller outputs of P, PI, PID control algorithms. Principle structure of the control system aforementioned has been summarized in Fig. 5.

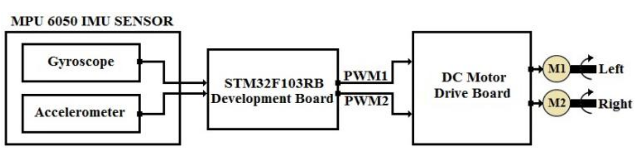

Fig. 5. Principle structure of the control system

Besides, there are two identical Faulhaber, 12 Volt 400 Revolutions Per Minute (RPM) DC motor and L298 integrated DC motor driving board to drive these motors via PWM. For system power supply 11.1 V lithium polymer battery has been used.

3.2. Software

In the designed balance robot control system, there is a visual computer interface which provides that designed control algorithms can be performed easily, system response can be observed online and control parameters can be changed online when the robot is working. Computer interface, its general view is given in Fig. 6, is written in Qt-Creator visual interface development environment. With the help of interface, PID control parameters can be changed in real time, system reaction against parameter changes can be observed online. So, various controllers such as P, PI, PID, FLC can be performed easily on the robot. Filtration algorithms can be operated and deactivated easily and algorithms can be compared easily in terms of system reaction.

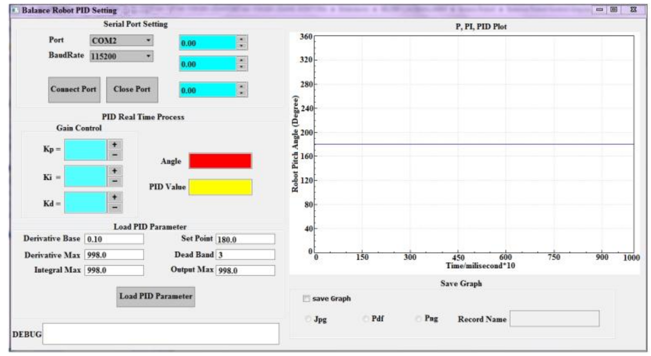

Fig. 6. Balance robot control interface

4. CONTROLLER DESIGN AND SIMULATION

In this part, the controller applied on the balance robot has been researched in detail and the implementation results of these control designs have been included in. Also, there is a constant bias drift in base of data of moment sensor and it has been seen that accelerometer sensor has been affected from noise. So it's necessary to unify two sensor data by filtering them (sensor fusion) to determine the right angle. Kalman Filters have been used to filter sensor data and make them more reliable.

As shown in Fig. 7, feedback control algorithm has been used for system control. In the system, P, PI, PID outputs have been turned into PWM value. Using the angle determined by Kalman Filter, and then it has been performed for motor drive circuit. After that, new angles obtained by means of feedback of system have been compared again via Kalman Filter and it has been aimed that the robot can stand in upright position.

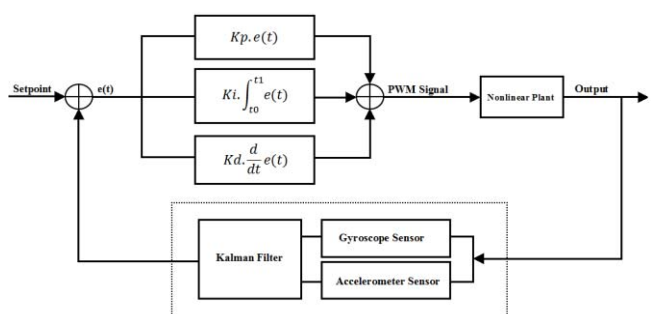

Fig. 7. Block diagram of the feedback control system

Firstly, in the system P controller has been used and balance robot's reaction to the controller has been viewed. As seen in Fig. 8, system reaction has been observed when Kp=77 by means of robot control interface. As seen in the figure, robot can balance itself just 1-2 second due to its inertial moment and frictional force applied by ground

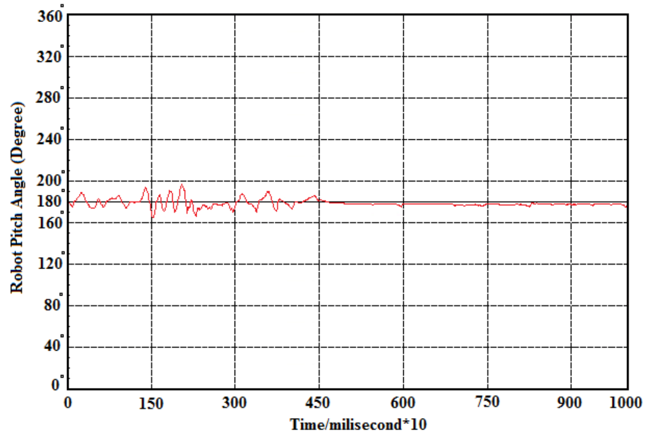

Fig. 8. When Kp=77, Ki=0 ve Kd=0 system response

Because these proportional controllers cannot get zero steady-state error inherently, the expected balance couldn't be realized in our system.

The system has been searched for PI control by adding Ki parameters along with Kp parameters to the system. Experimentally, Kp and Ki parameters have been tried on balance robot system. For example, system reaction is more stable than previous one when Kp=51 and Ki=45 as seen in Fig. 9. The robot has tried to keep its balance and achieved that practically. It has given soft reaction to these chosen controller parameters and tried to maintain itself in vertically upright position. When appropriate Kp and Ki values are realized, it has seen that the robot keeps its balance.

However, the supervised system can't balance itself for a long time because the integral term in the system sums the accumulated error over time.

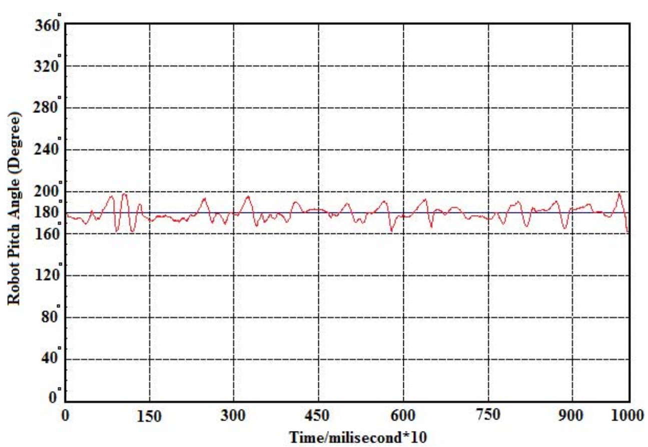

Fig. 9. When Kp=51, Ki=45 ve Kd=0 system response

As shown in Fig. 10, when Kp=51, Ki=45 and Kd=4.10 for PID control, the system has resisted to falling down and maintained itself in upright position, reacting to very small changes. When Kp=51 and Ki=45 are fixed and Kd parameters is over 4.10, it has seen that these reactions have become more speed. But, this high sensitivity has caused knocking and prevented the robot's balancing itself for a long time.

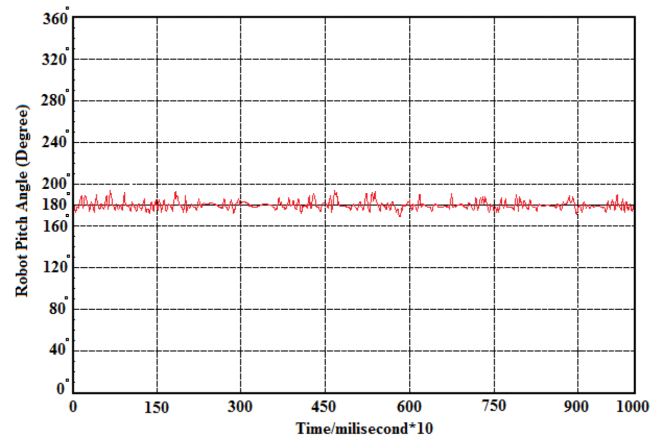

Fig. 10. When Kp=51, Ki=45 ve Kd=4.10 system response

5. CONCLUSIONS

In this paper, a two-wheeled autonomous mobile robot system has been designed and implemented. The system has flexibility, by means of that various control algorithms can be performed easily and it has Qt-Creator based computer interface when user-friendliness is taken into account. It has been aimed that robot can balance itself in upright position and to achieve that various controllers such as feedback P, PI, PID control have been implemented. Observing robot's reactions to these controllers, the best controller has been determined for robot's balance in upright position.

As a result of the study, it has seen that P controller is not enough for robot's balance. When appropriate Kp and Ki gain values are chosen for PI controller, it has seen that the robot can balance itself for a short time and try to maintain its balance in a certain area by swinging. As for PID controller, the robot can stand in upright position longer if the appropriate Kp, Ki and Kd gain values are chosen.

Finally, robot can balance itself best by using PID control method. Various controller parameters have been determined easily using the designed visual interface program and robot system has balanced itself successfully.

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