DC Motor Speed Controller Design using Pulse Width Modulation

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Abstract. DC Motor is an electric motor that requires a direct current voltage supply on the field coil to be converted into mechanical energy motion. In this study, a control system automation is made to control the rotation speed of motor DC in order to maintain the speed with load changes. PWM (Pulse Width Modulation) principle is used as speed stability control system for loaded DC motor with PID (Proportional Integral Derivative) method. PID is one of the controllers used for improving the performance of a system, including DC motor rotation control system. The speed of the response and error steady state are the parameters measured to evaluate the performance of the proposed control system PID control in this study is implemented through personalized software (PC) where the values obtained are copied into program or C source code to run DC motor. The best condition with PID tuning method in Matrix Laboratory software is obtained at the value of control constant $K_p=0.53$, $K_i=0.63$, $K_d=0.07$ with 5.61% over shoot, and average travel time when lifting weights with a distance of 1 meter=5.54 seconds, 2 meters=9.60 meters, 3 meters=11.50 seconds, 4 meters=16.48 seconds, and 5 meters=19.71 seconds.

1. Introduction

Technology tool is made to improve the quality of human life [1], one of the technology tools that can be used to help the effectiveness and efficiency of business processes in industries field is DC Motor [2]. DC Motor has an advantage in terms of smoothness of speed change, ease of control, and rapid dynamic response to changes in load torque [3]. To improve the effectiveness and efficiency of a task or work, an automation system can be applied. The conveyor system used in a car tire production is one of the examples of the use of robots in the car manufacturing process in industries [4].

The optimization of DC motor uses requires speed control that can be done using Pulse Width Modulation (PWM) [5]. A mechanism that can be used as a guideline in DC motor control is the longer the duration of time delay of the resulting PWM signal, the faster the motor rotation, and vice versa [6]. In addition to using a comparator in the generation of PWM signals, DC motor control can also be performed using control devices such as programmable logic or microcontroller, that allow PWM signals to be formed by programs in the controller.

Furthermore, it is necessary to design a DC motor controller, which, in this article, refers to a design of motor rotation speed control using PWM method generated by Arduino. DC motor used here is DC
motor with motor with 100kgs torque and 19-volt 6-Ampere operating voltage. Meanwhile, a rotary encoder is required to control constant speed requires.

2. Methodology

2.1. Design procedure
The design procedure consists of DC motor controller design including the design of DC motor and motor driver; meanwhile the design of PID control software is done in Matrix Laboratory. The design method of DC motor speed control follows the flowchart presented in Figure 1.

![Figure 1. Research flowchart.](image)

2.2. Tools and materials
The hardware used in the design includes:
- Arduino Uno.
- Toshiba DGM-3520-2A DC motor (19V-6 A).
- BTS 7960 Motor Driver
- Rotary Encoder
- Motor chain and gear
- Three Dry cell batteries 6V-4.5A.
- Cable.
- Notebook.
- Male and female sockets.
- Jumper.
- PCB.
- 7 meters Iron frame
- 2 Wheels
- Nuts and bolts
- Multi-meter.

The software used in the design includes:
- C Compiler of Arduino language.
- Matrix Laboratory (MATLAB)

In the methodology of DC motor speed control design, the material principles applied in the design consist of:
- Proportional Integral Derivative (PID), a controller to determine the precision of an instrumentation system with characteristics of feedback on the system[7]. PID control system consists of three control actions, namely: P (Proportional), D (Derivative) and I (Integral) controls with each advantage and disadvantage. In its implementation, each control action can work individually or simultaneously. In designing PID control system, it is essential to set the parameter of P, I or D so that the response of the system output signal to a particular input can be obtained as desired (Figure 2).

![Figure 2. PID Control System[7].](image)

- DC (Direct Current) motor. DC motor is used in industries requiring a movement with high precision for setting speed at constant torque (Figure 3.). DC motor converts electrical power into mechanical power through the motion of its motor rotation. The basic principle of DC motor is that if a wire is placed between two magnetic poles (N-S), there will be a resultant force acting on it to move.

![Figure 3. DC motor[8].](image)

The direction of the wire movement can be determined using the left-hand rule, namely: “if the open left hand is placed between the N and S poles, the force lines coming out of the north pole penetrate the left palm, and the current in the wire flows. In line with the direction of the four fingers, the wire will get a force whose direction corresponds to the direction of the thumb”. The working principle of DC motor can be seen on Figure 4.
Figure 4. Working principle of DC motor[8].

- PWM (Pulse Width Modulation) is a method to manipulate the width of signal in the form of pulse in a period, to obtain different average voltages (Figure 5). Some examples of PWM applications are data modulation for telecommunication, the control of the incoming power or voltage to load, voltage regulator, audio effect and amplification, and others[9].

Figure 5. PWM Signal[9].

- Arduino Uno R3, a microcontroller development-board based on the ATmega328P-20PU. This board has 14 digital pins to communicate (I/O, pins, input/output) of which 6 can used to modulate PWM output (pulse width modulation, to simulate the analog output), 6 analog inputs (digitalized using ADC/ Analog-to-Digital Converter internal), 16 MHz oscillator, a USB connector, power supply plug, ICSP header, and reset bottom[9].

Figure 6. Arduino uno[9].

- Rotary Encoder, an electro-mechanical device functioning to monitor the angular position on a rotating axis (Figure 7.). From the rotation of the object, the monitored data will be converted into digital data by the rotary encoder in the form of the pulse width then it will be connected to the controller (Microcontroller/ PLC). Furthermore, the data obtained in the form of angular position (angle) can be processed by the controller to get data in the form of speed, direction, and position of the rotation of the axis[10].

Figure 7. Optical Shaft encoder disk[10].
3. Design and implementation

3.1. DC motor design

DC motor is an electric actuator using input as its control variable. There are two types of DC motor control, namely field-controlled and armature-controlled[7]. DC motor used in this design is armature-controlled DC motor. The transformer of armature-controlled DC motor can be seen on Figure 8.

![Figure 8. The transformer of DC motor.](image)

\[ V_a = \text{Armature voltage} \]
\[ I_a = \text{Armature current} \]
\[ V_b = \text{Voltage of back} \]
\[ \omega = \text{Armature speed} \]
\[ R_a = \text{Armature resistance} \]
\[ T_m = \text{Motor torque} \]
\[ L_a = \text{Motor induction} \]
\[ J = \text{Inertia} \]
\[ K_m = \text{Motor constant} \]
\[ K_b = \text{Constant of back} \]
\[ B = \text{Motor load} \]

Armature controlled DC motor uses armature current \( i_a \) as its control variable. Stator field can be generated from a coil or a permanent magnet. When a constant field current flows in the field coil, motor torque is:

\[ T_m = (K_1K_f I_f)I_a = K_m I_a \]

If it uses permanent magnet, the torque is:

\[ T_m = K_m I_a \quad (1) \]

\( K_m \) is the permeability function of magnetic material, the anchor current is connected to the input voltage in the anchor circuit according to the following equation:

\[ V_a = (R_a + L_a)I_a + V_b \]
\[ V_b = K_b \omega \quad (2) \]

\( V_b \) is back electromotive force (EMF) proportional to motor speed. Therefore, we get the equation. Moreover, armature current is:

\[ I_a = \frac{V_a - K_b \omega}{(R_a + L_a)} \quad (3) \]

by considering motor output torque equation in terms of loading.

\[ \tau(t) = J_{eff} \theta + f_{eff} \quad (4) \]
In this study, from DC motor block diagram, we can find the equation as follows:

$$\frac{\theta(s)}{V_a(s)} = \frac{K_{tn}}{S^2L_f+SL_f+RS_f+RF_f+K_bK_{tn}} \quad (5)$$

The equation of the transfer function that has been obtained is then used to find the value of PID and to design the DC motor PID controller.

3.2. Motor driver design

The circuit of DC motor driver uses module BTS 7960B H-bridge 43A high-power motor driver as voltage, current and signal amplifier. BTS 7960B H-bridge is also used as motor drive with 5.5-27 Volt input voltage and capable of accommodating a very high current up to 43 Amperes. This motor driver is composed of several components i.e. IC BTS7960, mosfet, diode, header, 220 uF capacitor, heatsink.

![Module of BTS 7960B H-bridge 43A high-power motor driver.](image)

Motor driver used here can control two DC motors because there are two outputs in one IC BTS7960. Meanwhile, this study uses only one DC motor (single motor) (Figure 9). Furthermore, since DC motor requires a very high current and voltage, motor driver must be capable of accommodating the current and voltage coming out as well as the feedback from DC motors and accumulator.

3.3. Software design

3.3.1. PID controller design using MATLAB.

One of controllers widely used in industrial process controllers is PID controller. This controller has a transfer function as follows:

$$G_c(s) = K_p + \frac{K_i}{s} + K_ds \quad (6)$$

Where:

- $K_p$ = Proportional gain
- $K_i$ = Integral gain
- $K_ds$ = Differential gain

The equation for output in time domain is:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad (7)$$

If we set $K_D=0$, proportional controller and integral (PI).

$$G_c(s) = K_p + \frac{K_i}{s} \quad (8)$$

When $K_i=0$,

$$G_c(s) = K_p + K_ds \quad (9)$$
It is called proportional plus derivative (PD) controller. Furthermore, DC motor design will produce DC motor block diagram (Figure 10).

![DC motor block diagram](image)

**Figure 10.** DC motor block diagram.

From the block diagram above, we can find an equation as follows:

\[
\theta(s) = \frac{Ktn}{S^2J_{eff}+SLE_{eff}+RSE_{eff}+REF_{eff}+KbKtn}
\]

(10)

3.3.2. *Constant speed controller system design.* Figure 11 illustrates how a control system work from connecting the power supply to Arduino Uno and DC motor. Then Arduino turns on automatically that also directly turns on PID system to make DC motor rotate from zero to the constant speed, until it is back to zero again. Furthermore, the encoder that acts as a sensor reads the speed point set automatically to give the command to make the motor speed rotation constant. Sensor is a devise to detect the state of an observation object [11, 12]. The encoder will give the return command according to whether it is more than the desired speed or not? If it is not, Arduino will repeatedly re-command until the desired constant speed is reached, meanwhile, if it is constant, the encoder will continue to work so that when the speed suddenly changes, it will reset automatically to get the desired speed.

![Constant speed controller system design](image)

**Figure 11.** Constant speed controller system design.

3.4. *Electronic device design*

The design of block diagram is then applied to the design of electromagnetic devices to assemble each component into a hardware set as shown on Figure 12.
3.5. Toshiba DC motor DGM-3520-2A
DC motor used in this study is DC motor manufactured by Toshiba with serial number DGM-3520-2A. This motor has rating voltage of 19 Volt and current of 6 Amps (Figure 13).

3.6. Arduino Uno
Arduino Uno is used as control device. Arduino functions as PWM, input and output to deliver and receive commands from other components, and vice versa. For the power supply, USB power with a voltage of approximately 5 Volts is used.

3.7. Rotary encoder
Encoder used in this study is opto coupler opto optical groove coupler FC-03. The hardware of this encoder FC-03 can be seen on Figure 14. This encoder has 4 pins of which 2 are used for VCC and Ground, and the other 2 are used for output A and B. This encoder uses LM393 and requires voltages ranging from 3.3 to 5 volt.

3.8. BTS 7960 motor driver
The circuit of motor driver in this study includes optoisolator and H-Bridge. Optoisolator circuit is used to separate the microcontoleric voltage source with the DC motor voltage source, and produce the PWM. Meanwhile, H-Bridge circuit is used to control the forward and backward motion of the motor. The main component used is BTS 7960 (Figure 15).
3.9. **Robot framework**

In design stage, a robot frame is made on a manual sketch without software. Furthermore, the figures are implemented into a real form. The material used in implementing the robot framework design is iron elbow. The result of the implementation of the robot framework in the real form is on Figure 16-18.

**Figure 15.** BTS 7960 motor driver.

**Figure 16.** Implementation of the main frame.

Figure 16 is the implementation of the main frame made of iron elbow 40 cm length x 40 cm width x 20 cm height and 3 mm thick; and tire 17 cm diameter and 4.5 cm thick, ass motor retainer iron 50 cm length. Figure 17 is the implementation of robot frame leg support. After the main frame and frame leg support have been made, both parts are welded into one. Figure 18 and Figure 19 are the implementation of the board of electronic devices and control of robots. After all parts have been completely made, they will be assembled into a unit as on Figure 20.

**Figure 17.** Implementation of frame leg support.

**Figure 18.** Implementation of the main frame and leg support.
4. Conclusions

PID control designed on a DC motor is capable of maintaining speed automatically when carrying no load or carrying various loads using a rotary encoder sensor as feedback in accordance with the set point set that regulates the PWM of 125 in Arduino. The average steady state error of the tests done is 0%. Moreover, PID Parameter obtained is $K_p=0.532$, $K_i=0.6544$, $K_d=0.077$. DC motors are able to maintain a constant speed when tested without load and when carrying a load from 10 to 50 Kg even more than the maximum load. The average time of the DC motor speed when carrying loads varying from 10 to 50 kg in 1-5 meters is as follows: 1 meter=5.62 seconds, 2 meters=9.67 seconds, 3 meters=11.54 seconds, 4 meters=16.53 seconds, and 5 meters=19.82 seconds.

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