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AUTOMATIC INVERTED PENDULUM CONTROL SYSTEM

MOHD SYAZWI HELMI BIN JASHARI

Thesis submitted in fulfilment of the requirements for the award of the degree of Bachelor of Mechatronics Engineering

Faculty of Manufacturing Engineering UNIVERSITI MALAYSIA PAHANG

JUNE 2013

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis, which written by Mohd Syazwi Helmi Bin Jashari, and in my opinion, this thesis is adequate in terms of scopes and quality for the award of the degree of Bachelor of Mechatronic Engineering.

Signature Name of Supervisor: Mr. Ismail Bin Mohd Khairuddin Position: Date:

STUDENT'S DECLARATION

I hereby declare that the work in this report is my own, except for quotations and summaries which have been duly acknowledged. The report has not been accepted for any other Degree and is not concurrently submitted for award of other degree.

Signature Name: Mohd Syazwi Helmi Bin Jashari ID Number: FB09020 Date: Specially dedicated to

my beloved family, friends and those who have guided and inspired me throughout my journey of learning.

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ABSTRACT

This project is about developing of an Inverted Pendulum that been control by PID controller. The Inverted Pendulum is a classical control system problem due its nonlinear characteristic and unstable behavior. It is have same concept like the hand (broom) to maintain the stick upright. An inverted pendulum is a pendulum attach directly with the sensor (potentiometer) at pivot point. The cart mounted directly on the tire to move horizontal either forward or backward. The movement of mechanical part can be determining using PID controller and implement to microcontroller. Microcontroller used in this project is Arduino UNO. PID controller is obtained using MATLAB through Simulink. Lastly, the performances of PID controller are test on hardware to maintain the pendulum upright. Based on the result, the inverted pendulum manages to reach stability.

ABSTRAK

Projek ini tentang pemantul songsang yang dikawal menggunakan kawalan PID. Pemantul songsang adalah masalah kawalan sistem klasik disebabkan ciri-ciri dan keadan yang tidak stabil. Konsepnya adalah sama seperti tangan yang mengimbangi batang untuk kekal stabil keatas. Pemantul songsang adalah pemantul yang berhubung secara terus kepada pengesan yang digunakan iaitu potentiometer. Kereta melekat terus dengan tayar untuk bergerak melintang sama ada kedepan atau kebelakang. Pergerakan bahagian mekanikal dapat ditentukan menggunakan kawalan PID dan mengaplikasikan kepada kawalan mikro. Kawalan mikro yang digunakan dalam projek ini adalah Arduino UNO. Kawalan PID diperolehi daripada MATLAB melalui simulasi. Akhirnya, tindakbalas kawalan PID diuji kepada perkakas untuk mengetahui mengimbang pemantul keatas. Keputusan menunjukkan pemantul songsang berjaya mencapai kestabilan.

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LIST OF SYMBOLS

$Output_P$	Controller output due to proportional control (i.e., the corrective force)
$Output_D$	Controller output due to derivative control
$Output_{PID}$	Output of the PID controller
$Output_t$	Controller output due to integral control
K_P	Proportional constant for the system called gain
K _I	Integral gain constant (sometimes expressed as I/T_I)
K _D	Derivative gain constant (sometimes expresses as T_D , unit is time)
Ε	Error, the difference between where the controlled variable should be and where it is
$\sum (E\Delta t)$	Sum of all past errors (multiplied by the time they existed)
$rac{\Delta E}{\Delta t}$	Error rate of change (slope of error curve)

LIST OF ABBREVIATIONS

IP	Inverted pendulum		
DSP	Digital signal processor		
SP	Set points		
PV	Process variable		
PD	Proportional derivative		
CV	Control variable		
RP	Reference point		

CHAPTER 1

INTRODUCTION

1.1 Background

The inverted pendulum is the classical control system problem. It has some concept like a hand as a cart and stick as a pendulum which is hand try balance the stick. In addition, the inverted pendulum have limited motion that only can move right and left meanwhile the hand which try to balance the stick has advantage can moving upward and downward. An inverted pendulum does basically the same thing. Just like the broom-stick, an inverted pendulum is an inherently unstable system. Force must be properly applied to keep the system intact. To achieve this, proper control theory is required.

The inverted pendulum is essential in the evaluating and comparing of various control theories. The inverted pendulum (IP) is among the most difficult systems to control in the field of control engineering. Due to its importance in the field of control engineering, it has been choose for final year project to analyze its model and propose a linear compensator according to the PID control law.

In new era, the concept of inverted pendulum is become important in daily life especially in field control system. The concept stability that show in inverted pendulum can be apply in real life application for example the helicopter already use concept stability to reject windup disturbance and also the missile that moving faster without have problem due to the concept stability.

1.2 Project Synopsis

Broadly speaking, the inverted pendulum is the classical control system. Due to unstable system (non-linear) this project interesting to explore and do some research. This project involves two main parts which is hardware and software. First of all, the hardware includes the mechanical part, driver motor circuit and microcontroller. On the others hand, the PID controller is the part of controller that used to control the movement of pendulum cart during disturbances. The calibration between hardware and software will make this project challenging for undergraduate student.

1.3 Objective

- To develop a mathematical modeling of PID control system.
- To design and build cart automatic inverted pendulum control system using PID controller.
- To analysis the stability of pendulum during movement of the cart.

1.4 Problem Statement

The problem of this project is to maintain the pendulum upright when the cart is moving forward and backward or when the disturbance is approach to the pendulum. A PID controller should be design to provide good control around the unstable equilibrium (180 degree). There are two general control objectives which is quick rejection of low frequency disturbances and quick tracking of step reference inputs.

1.5 Project Scopes

This project involves the developing of hardware and software. Hardware have a few part need to design and the fabricate according the actual plan. The hardware use is mechanical part made myself using the steel plate. Others equipment is a potentiometer and DC motor. Meanwhile, the software use is MATLAB to simulate and analyze the behavior of pendulum or cart to maintain the pendulum and calculate the maximum angle for the cart during disturbances force. A PID controller use as the whole program for the reaction of the cart during disturbances and control the dc motor to move the cart forward and backward. A potentiometer functions as a sensor to detect inclination of angle on pendulum to maintain upright.

1.6 Project Organization

In general, this report consist of 5 chapters where chapter one is introduction of this report. **Chapter 1** explain briefly about the inverted pendulum system which are include introduction, project objective, problem statement, project scope and lastly the project organization.

Chapter 2 is discussing about the literature review which explains the details of the research on the inverted pendulum system background. In this chapter, theory and concept is explained briefly to relate the project in real life.

Chapter 3 is methodology which describes about the method that being used to solve the problems. The methods used in this topic are flowchart, process and analysis data, model and data collecting.

On the other hands, **Chapter 4** will discuss about the experimental and the result obtained from the project. The result included the project limitation, result analysis and suggestion for the project enhancement.

Lastly, **chapter 5** will discuss about the discussion and conclusion of this project. This chapter will state some recommendation about model, circuit and controller.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter will discuss about the research findings of literature reviews from past researches. This chapter discussing about the modeling of the inverted pendulum and others mechanism that used to design control system for inverted pendulum. A PID controller problem is used widely nowadays rather than others type of controller, especially neural network controller. In addition, PID controller much more practical and allows for much better adjustments to be made in the system. This literature review will also evaluate the sources and some information will be used as references to build real inverted pendulum.

2.2 Definition of Control

Control is defined the power to make decisions about something or decide what should happen.

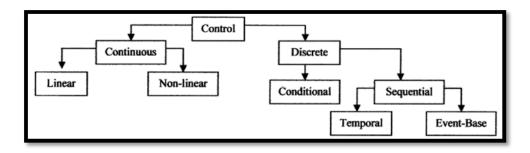


Figure 2.1 Types of control [10]

2.2.1 Control System

In most systems there will be an input and an output. A control system consists of subsystem and processes (or plant) assembled for the purpose of controlling the output of the processes. In the simplest form, a control system provides an output or response for a given input or stimulus .For example, the automobile steering which desired course of travel is known as input and actual course of travel known as output. In this system the others subsystem are driver, steering mechanism, and automobile. The Figure 2.2 shows the example of block diagram for control system.

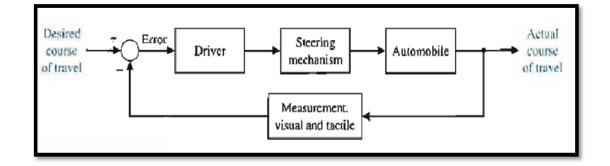


Figure 2.2 Block diagram automobile steering control system [10]

2.2.2 Open–Loop Control Systems

Open-Loop Systems start with a subsystem called an input transducer which convert the form of the input to the used by controller. The controller drives a process of plant. The input is sometimes called the reference, while the output can be called the controlled variable. Others signal such as disturbances, are shown added to controller and process outputs with summing junctions, which yield the algebraic sum of their inputs signal using associated sign.

Open–Loop System is the system does not use feedback. That's mean the controller must independently determine the signal to send the actuator. The disadvantage with this approach is the controller never knows either the actuator do the right thing according the plan. (Feedback control principles)

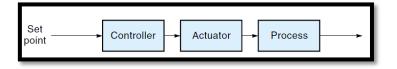


Figure 2.3 Open-loop control systems [1]

2.2.3 Closed-Loop Control Systems

Closed- loop system also known as a feedback control system. On the other hands, the output of process is constantly monitored by a sensor Figure 2.4. The sensor samples the output and passes this information back to controller due to the controller knows what actually system doing. In addition, the controller can make any adjustment necessary to keep the output where it belongs. This self-correcting feature of closedloop control makes it preferable over open-loop control in application nowadays.(Feedback control principles)

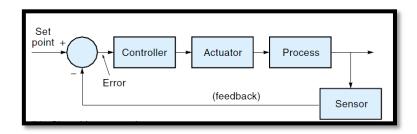


Figure 2.4 Closed-loop control systems [1]

2.3 Concept Model

Inverted pendulums have variety of model design nowadays. The pendulum cart concept will be discussed in aspect of modeling and dynamics. This pendulum cart inverted pendulum system same as seesaw system.

2.3.1 Pendulum Cart System

(Najihah, 2008) has presented the switching control for inverted pendulum system based on Energy Modification. To maintain the pendulum upright after disturbances the potential energy should be minimize. Broadly speaking, the approach to control the inverted pendulum system is accumulated by paying attention to the energy of pendulum. The model design is proposed where there is a mass situated at the centre of inverted pendulum. The equation derived using lagrangian dynamic analysis.

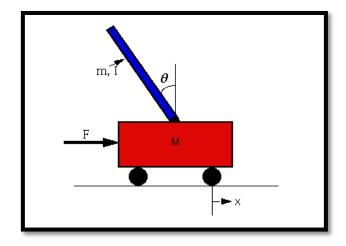


Figure 2.5 Model of pendulum cart system [2]

Table 2.1 Explanation	the symbols
-----------------------	-------------

Quantity	Symbol
Mass of the cart	М
Mass of the pendulum	m
Friction of the cart	b
Length of the pendulum	1
Inertia of pendulum	Ι
Force applied to the cart	F
Cart position coordinate	Х
Pendulum angle from vertical	θ

The Figure 2.6 below show the two free of body diagram (Hasan, Saha, Rahman, Sarker & Aditya, 2011):

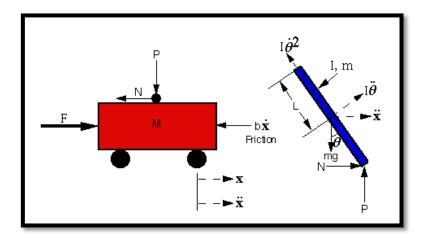


Figure 2.6 Free body diagram for cart and pendulum [3]

This system is difficult to design in Simulink because of the physical constraint (the pin joint) between the cart and pendulum which reduces the degrees of freedom in the system. Both the cart and the pendulum have one degree of freedom (X and θ , respectively). Then model Newton's equation for these two degrees of freedom.

$$\frac{d^2t}{dx^2} = \frac{l}{M} \sum_{cart} F_X = \frac{l}{M} \left(F - N - b \frac{dx}{dt} \right)$$
(2.1)

$$\frac{d^2\theta}{dx^2} = \frac{l}{I} \sum_{pent} \tau = \frac{l}{I} (NL \cos\theta + PL \sin\theta)$$
(2.2)

It is necessary, however, to include the interaction forces N and P between the cart and the pendulum in order to model the dynamics.

2.4 Mechanism

There are three main motor that can be used for this pendulum cart system. Firstly, a DC motor, second a stepper motor and lastly a servo motor. High torque and high speed is the main consideration for choosing the motor to fabricate in pendulum cart system. The torque is needed to change the direction and stabilize the pendulum in vertical. Meanwhile, the high speed is necessary so that the movement of cart can react faster to maintain pendulum. (Lund, Aaen, Juliusson, Thorbergsson, Madsen & Kristensen, 2010) has presented the dc motor used is to develop torque on the pendulum. (Stang, 2005) state the DC motor could have high torque and high speed but it comes at a cost. In addition, the DC motor required more power to run when the speed and torque increase. DC motors also are operated closed loop that give faster response for feedback control. Hbridge control circuitry is used to control the direction of the DC motor either clockwise or vice versa based on the directional signal.

A stepper motor is electromechanical device which converts electrical pulses into discrete mechanical movements. On the other hand, the stepper motor have high torque but it problem with the speed in other words lack sufficient speed and resonances can occur if not properly controlled. It is also normally operated open loop and a stepper motor has two types of basic winding arrangement which is uni-polar and bi-polar.

In addition, a servo motor is the last choice to drive the cart but it is problem with the torque although could supply high speed. For the information, the servo motor has the ability to turn 360 degree only. This is problem for the cart to maintain the pendulum upright because over disturbances not cause by force but motor itself. Other problem is the voltage level applied to the motor tells the motor to be where and this is difficult to control it. In terms of controlling this part of motor less consideration to use for pendulum cart.

2.5 Sensor Feedback

There are 3 types of sensor common used in variety condition which is used in control system. Firstly are tilt sensor, second gyro sensor and lastly potentiometer. Three of them have their characteristic and different benefit. All types of sensor will be comparing to show their advantages and disadvantages.

Tilt sensor is the simple way to detect orientation or inclination. It is usually use in toys, gadgets and appliances. This sensor is small, inexpensive, low power and easy to use. (Hovingh & Roon, 2007) state the function of tilt sensor is to measure sideway acceleration of the pendulum due to gravity but the problem is this sensor can only detect acceleration and not position or velocity. Tilt sensor also can calibration with Arduino. The Figure 2.7 below shows the simplest circuit connection with Arduino or microcontroller.

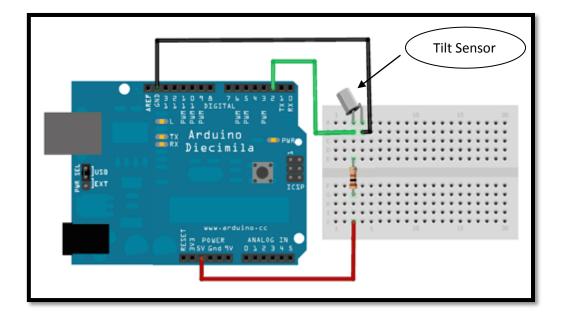


Figure 2.7 A simple circuit connection of tilt sensor with Arduino [9]

A Gyro sensor contains a single axis gyroscopic sensor that detects rotation and returns a value representing the number of degrees per second of rotation. In addition, this sensor can measure up \pm 360 degree per rotation. A rotation rate can be read up to approximately 300 times per second is the other benefit of this sensor. According (Dexter, 1999-2004) the disadvantages of this sensor is expensive and noise when function.

Potentiometer is voltage regulator that can be used as sensor. (Hovingh & Roon, 2007) state the potentiometer is the suitable sensor that can be used due to inexpensiveness and simplistic nature. This sensor is sticking with the single axis for the forcing function maintains linearity for controlling the system. ("Position sensor,") state potentiometers come in a wide range of designs and sizes such as the commonly available round rotational type or the longer and flat linear slider types. When used as a positional sensor the moveable object is connected directly to the shaft or slider of the potentiometer and a DC reference voltage is applied across the two outer fixed connections forming the resistive element.

2.6 Controller Design

PID is the combination of Proportional, Integral and Derivative. This combination can be used to design the control system. In new era, more intelligence controller prefer designed that use op-amps or a microprocessor. Proportional control is the first and most basic that can be preferred. (Feedback control principles) said with proportional control, the actuator applies a corrective force that is proportional to the amount of error, as expressed in Equation 2.3:

$$Output_P = K_P E \tag{2.3}$$

In addition, the other controller is integral control. Integral control can reduce the steady-state error to zero in control system. The sum of all past errors multiplied by time is proportional to the integral control that creates restoring force, as expressed in Equation 2.4:

$$Output_t = K_I K_P \sum (E\Delta t)$$
(2.4)

The value of $\sum (E\Delta t)$ will increase with time, causing the restoring force to get larger in result for a constant value of error. Finally, the restoring force will get large enough to overcome friction and move the controlled variable in a direction to eliminate the error.

An analogy showing the power of integral control is a person who sits down in a comfortable chair to read a book. After a short time, the reader notices the dripping sound of a leaky faucet (steady-state error). The first response of the reader is to do nothing, but as time goes on the sink starts to fill up and spill over, which gets the reader's attention and he or she gets up and turns it off. The point is that the dripping (error) was not increasing, but the effect of the steady-state error was increasing with time until finally the reader (system) was motivated to do something about it (Feedback control principles).

The others control PID is derivative control that only solution to overshoot problem in control system. Derivative control functional "*applies the brake*" to slow

down the controlled variable before it reaches destination. The equation below shows the contribution from derivative control in mathematical:

$$Output_D = K_D K_P \frac{\Delta E}{\Delta t}$$
(2.5)

On the other hand, the three combination control which is proportional + integral + derivative will be discussed on details. This combination as known as PID control and the foundation of the system is proportional control. Adding integral control may increase overshoot but a means to eliminate steady-state error. Meanwhile, derivative control is good to reduce the tendency to overshoot and also getting sluggish systems moving faster. Mathematically the combination of the PID control expressed in the Equation 2.6 below,

$$Output_{PID} = K_P E + K_I K_P \sum (E\Delta t) + K_D K_P \frac{\Delta E}{\Delta t}$$
(2.6)

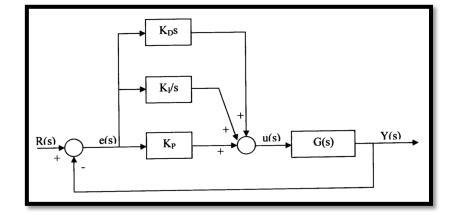


Figure 2.8 A PID controller system [1]

The comparison between proportional, integral and derivative summarize in the Table 2.2, in terms rise time, overshoot, settling time, and steady-state error.

Closed Loop Response	Rise Time	Overshoot	Settling Time	Steady-State Error
K _P	Decrease	Increase	Small change	Decrease
K _I	Decrease	Decrease	Increase	Eliminate
K _D	Small change	Decrease	Decrease	Small change

Table 2.2 The comparison between K_P , K_I and K_D

2.6.1 Analog PID

PID Equation 2.6 can be implementation either analog or digital. Unfortunately, all new installation used nowadays is digital control. (Aggarwal, Mao & O'Reilly) said the model using analog PID for self-tuning have several advantages over the digital PID system. Firstly, an analog system provides larger bandwidth, higher speed, and eliminates quantization noise. An analog controller must use a reconfigurable analog array instead of digital signal processor (DSP). The power consumption of a DSP halves every 18 months, as postulated by Gene's Law. Using a reconfigurable analog array can decrease power consumed by five orders of magnitude as compared to a DSP, implying by Gene's Law a 20 year leap in power reduction.

The next one, the analog controller save power, space and cost in addition it's also eliminates the need for ADCs and DACs. Figure 2.9 is the example of analog PID controller that uses five differential amplifiers in straightforward version. (Feedback control principles) state the first differential amplifier (U_1) subtracts the feedback from the set point to produce the error signal. Op-amps U_2, U_3 , and U_4 are known as unit gain, integrator and differential amplifiers, respectively. Other side, (U_5) sum all three terms which are U_2 , U_3 , U_4 and multiplies the sum by K_P to get output. The capacitor C_1 function to collect the error in form of charge meanwhile the capacitor C_D of the differentiator passes only the change in error. Besides, the constant K_P , K_I , and K_D are selected by adjusting R_1 , R_2 and R_3 . The circuits in Figure 2.9 can exactly implementation the PID equation.

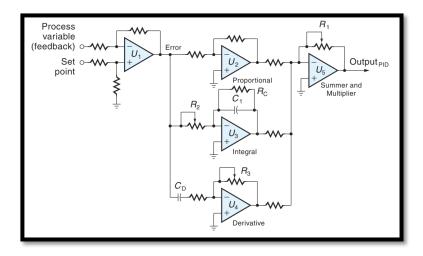


Figure 2.9 An analog PID controller [1]

2.6.2 Digital PID

A PID digital controller is broadly speaking a computer tend likely microprocessor-based. (Feedback Control Principles) state the controller executes a program that performs the same series of operations over and over again. Firstly, the computer key in value of set points (SP) and process variable (PV). Then to solve the system equation 2.4 these data is used and lastly it output the result to the actuator or the actuator drive circuit. The control strategies and parameter can be changed or fined tune by simply modifying the software is the one clear advantages of digital system. Mathematically, the Equation 2.7 below is the PID control system for digital which is can be implemented with a microprocessor-based controller and also knows as difference equation.

$$K_{I}\sum(E\Delta t) = K_{I}E_{1}T + K_{I}E_{2}T + K_{I}E_{3}T$$
(2.7)

2.6.3 PI and PD controller

The PI controller is combination of integrator with a proportional gain. This controller use for first order plant and it will produce a second order response for the system. Generally, if the disturbance or reference inputs either unchanging or have steps change there will be the zero steady-state error.

The Proportional Derivative (PD) is a type of feedback controller whose output, a Control Variable (CV) is generally based on the error (e) between some user-defined Reference Point (RP) and some measured Process Variable (PV)[controller 1]. (Najihah, 2008) state from the PD controller, it can be seen that the derivative controller (K_D) reduces both the overshoot and the settling time. Meanwhile for PI controller, the rise of time is decreased by the integral controller (K_I), both the overshoot and settling time is increased and the steady-state error is eliminated.

The problem for PD controller is to control pendulum's position back to original position which is vertical after some disturbances and therefore the reference signal should be zero. (Hasan, Saha, Rahman, Sarker & Aditya, 2011) said the force applied to the cart was considered as an impulse disturbance. The basic structure of the feedback control system is shown below:

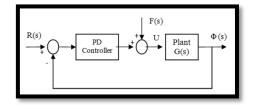


Figure 2.10 Control block diagram (closed loop)

2.6.4 Tuning PID Controller

(Feedback Control Principles) state the method of arriving at numerical values for the constants K_P , K_I and K_D depends on the application. Basically, PID control was applied to process control systems. However nowadays, PID control is being applied to position control systems (such as robots) as well. First, the constants K_P , K_I and K_D are set to initial values, and the controller is connected to the system. The system could consist of the actual hardware or a computer simulation of same. Then the system is operated, and the response is observed. Although many methods of tuning PID controllers exist, two of the most common were developed by Ziegler and Nichols and are called the continuous-cycle method and the reaction-curve method.

The continuous-cycle method (closed-loop method) can be used if the system goes into oscillation. This method will yield a system with a quick response, which means a step-function input will cause a slight overshoot that settles out very quickly. There are 4 steps to tuning PID Controller. First, Set $K_P = 1$, $K_I = 0$, and $K_D = 0$ and connect the controller to the system. Next, using manual control, adjust the system until it is operating in the middle of its range. Then increase the proportional gain (K'_P) while forcing small disturbances to the set point (or the process) until the system oscillates with a constant amplitude. Record the (K'_P) and T_C for this condition. In addition, Based on the values of (K'_P) and T_C from step 2, calculate the initial settings of K_P , K_I^* and K_D^* as follows:

$$K_P = 0.6K'_P$$
 (2.8)

$$K_I = \frac{2}{T_C} \tag{2.9}$$

$$K_D = \frac{T_C}{8} \tag{2.10}$$

Using the settings from step 3, operate the system, note the response, and make adjustments as called for. Increasing K_P will produce a stiffer and quicker response, increasing K_I will reduce the time it takes to settle out to zero error, and increasing K_D will decrease overshoot. Of course, K_P , K_I and K_D do not act independently, so changing one constant will have an effect across the board on system response. Tuning the system is an iterative process of making smaller and smaller adjustments until the desired response is achieved.

The reaction-curve method (open-loop method) is another way of determining initial settings of the PID parameters. This method does not require driving the system to oscillation. Instead, the feedback loop is opened, and the controller is manually directed to output a small step function to the actuator. The system response, as reported by the sensor, is used to calculate K_P , K_I and K_D . Note that the actuator, the process itself, and the sensor are operational in this test, so their individual characteristics are accounted for. Because the loop is open, this procedure will work only for systems that are inherently stable. There are 3 steps to tuning using this method. Figure 2.11 shows the steps tuning using the reaction-curve method.

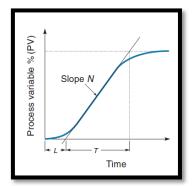


Figure 2.11 Graph of response to step input [1]

Firstly, draw a line tangent to the rising part of the response curve. This line defines the lag time (L) and rise time (T) values. Lag time is the time delay between the controller output and the controlled variable's response. Next, calculate the slope of the curve using the formula below:

$$N = \frac{\Delta PV}{T} \tag{2.11}$$

Where term N is a slope of the system-response curve. ΔPV is change in the process variable, as reported by the sensor (in percentage) and T is a rise time from response curve. Lastly, Calculate the PID constants using formula below:

$$K_P = \frac{1.2\Delta CV}{NL} \tag{2.12}$$

Where ΔCV is a percent step change the in control variable (output of controller), meanwhile N is a slope, as determined by Equation 2.11 and L is a lag time. K_I and K_D are obtained through the formula show in 2.13 and 2.14 below.

$$K_I = \frac{1}{2L} \tag{2.13}$$

$$K_D = 0.5L \tag{2.14}$$

CHAPTER 3

METHODOLOGY

3.1 Introduction

To fulfill requirement for this project, the method should be clear and this project ought to finish within the time. Firstly, the mathematical model of the system is calculated in order to determine the system behavior. These projects are involves hardware and software to completed the project. For the hardware parts, the mechanical part will be designed by using CATIA software and circuit part, driver motor with Arduino UNO used to complete the task. After the design complete, the model and circuit will be build and then software is been used in order to test their function according the plan. Meanwhile for the software, Simulink software had been used to model and simulate the PID controller. The last stage of this project is completed by integrated the hardware and software.

3.2 Mathematical Model

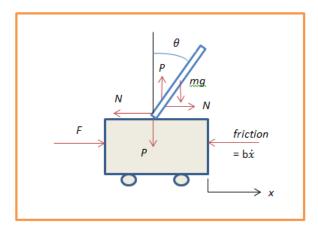


Figure 3.1 Two free-body diagrams of the system.

The mathematical modeling of inverted pendulum is desired by using the newton second law has shown in Equation (3.1) where F is force, m is mass and a for acceleration.

$$F = ma \tag{3.1}$$

The Equation 3.2 is obtained through Equation 3.1, which is in X- axis. The variables M represent the mass of the cart, b is representing the coefficient of friction and N is the force.

$$M\ddot{x} + b\dot{x} + N = F \tag{3.2}$$

In order to get value N, the Equation 3.3 is used. The variables m represent the mass of pendulum, and l is representing the half of length pendulum.

$$N = m\ddot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}\sin\theta \tag{3.3}$$

Next, the Equation 3.2 and 3.3 is combined in order to summarize the equation.

$$(M+m)\ddot{x} + b\dot{x} + ml\ddot{\theta}\cos\theta - ml\dot{\theta}^{2}\sin\theta = F$$
(3.4)

The equation through Y - axis is obtained and summarize in one equation which is shown on Equation 3.5 below.

$$P \sin \theta + N \cos \theta - mg \sin \theta = ml\ddot{\theta} + m\ddot{x} \cos \theta$$
(3.5)

P and N terms are combined together to get sum the moments about the centroid of the pendulum. The Equation 3.6 is obtained.

$$-Pl\sin\theta - Nl\cos\theta = I\ddot{\theta} \tag{3.6}$$

The Equation 3.5 and 3.6 is combined as the result the Equation 3.7 is obtained.

$$(I + ml^2)\ddot{\theta} + mgl\sin\theta = -ml\ddot{x}\cos\theta$$
(3.7)

The angle position for the pendulum is set, $\theta = \pi$, and assume that the system stays within a small neighborhood of this equilibrium. The maximum angle is valid within range 20 degree for pendulum to inclination. \emptyset is represent the deviation of the pedulum's position from equilibrium, that is, $\theta = \pi + \emptyset$. Again presuming a small deviation (\emptyset) from equilibrium, use the following small angle approximations of the nonlinear functions in the system equations:

$$\cos\theta = \cos(\pi + \phi) \approx -1 \tag{3.8}$$

$$\sin\theta = \sin(\pi + \phi) \approx -\phi \tag{3.9}$$

$$\dot{\theta}^2 = \dot{\phi}^2 \approx 0 \tag{3.10}$$

After substitute the above approximations into nonlinear equations, the two linearized equations of motion is obtained. The input F is substituted with the u.

$$(I+ml^2)\ddot{\varphi} - mgl\phi = ml\ddot{x} \tag{3.11}$$

$$(M+m)\ddot{x} + b\dot{x} - ml\ddot{\emptyset} = u \tag{3.12}$$

3.3 Transfer Function

Firstly assume zero initial condition for Laplace transform Due to get linearized system equation. The resulting Laplace transforms are shown below.

$$(I + ml^{2})\Phi(s)s^{2} - mgl\Phi(s) = mlX(s)s^{2}$$
(3.13)

$$(M+m)X(s)s^{2} + bX(s)s - ml\Phi(s)s^{2} = U(s)$$
(3.14)

Recall that a transfer function represents the relationship between a single input and a single output at a time. To find first transfer function for the output $\Phi(s)$ and an input of U(s) needed to eliminate X(s) from the above equations. Solve the first equation for X(s).

$$X(s) = \left[\frac{l+ml^2}{ml} - \frac{g}{s^2}\right]\Phi(s)$$
(3.15)

Then substitute the equation above into the equation 3.14 and the result shown below.

$$(M+m)\left[\frac{I+ml^2}{ml} - \frac{g}{s^2}\right]\Phi(s)s^2 + b\left[\frac{I+ml^2}{ml} - \frac{g}{s^2}\right]\Phi(s)s - ml\Phi(s)s^2 = U(s) \quad (3.16)$$

Rearranging, the transfer function is then the following,

$$\frac{\Phi(s)}{U(s)} = \frac{\frac{ml}{q}s^2}{s^4 + \frac{b(l+ml^2)}{q}s^3 - \frac{(M+m)mgl}{q}s^2 - \frac{bmgl}{q}s}$$
(3.17)

where,

$$q = [(M+m)(l+ml^2)]$$
(3.18)

From the transfer function above it can be seen that there is both a pole and a zero at the origin. These can be canceled and the transfer function becomes the following.

$$P_{pend}(s) = \frac{\Phi(s)}{U(s)} = \frac{\frac{ml}{q}s^2}{s^3 + \frac{b(l+ml^2)}{q}s^2 - \frac{(M+m)mgl}{q}s^1 - \frac{bmgl}{q}} \left[\frac{rad}{N}\right]$$
(3.19)

Second, the transfer function with the cart position X(s) as the output can be derived in a similar manner to arrive at the following.

$$P_{cart}(s) = \frac{X(s)}{U(s)} = \frac{\frac{(l+ml^2)s^2 - gml}{q}}{s^4 + \frac{b(l+ml^2)}{q}s^3 - \frac{(M+m)mgl}{q}s^2 - \frac{bmgl}{q}s} \begin{bmatrix} \frac{m}{N} \end{bmatrix}$$
(3.20)

3.4 State-Space

The linearized equations of motion can also be represented in state-space form if rearranged into a series of first order differential equations. Since the equations are linear, the standard matrix is formed as show below.

2 rows contained in a matrix due to both the cart's position and the pendulum's position are part of the output. Specifically, the cart's position is the first element of the output *y* and the pendulum's deviation from its equilibrium position is the second element of *y*.

3.5 Hardware

Part hardware in this project involves model and circuit. Firstly, the model was design by CATIA software. All the specification design will be discussed in **Chapter 4**. Figure 3.2 show the model design.

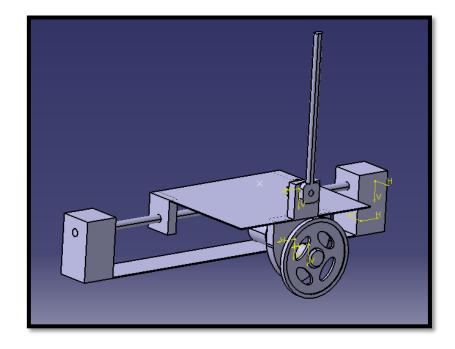


Figure 3.2 Model design by CATIA

The design inverted pendulum has 6 parts which are body (cart), pendulum, tire, rod and handler rod. Mechanical part is the main part to show the movement of the cart and the pendulum reaction either the cart can stabilize the pendulum when the PID controller implement. Figure 3.3 show the flow chart of model design.

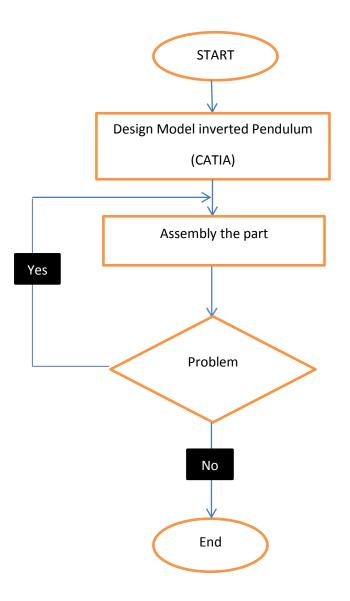


Figure 3.3 Flow chart of model

In addition, for the electrical part the sensor and driver motor will be design to calibrate with Arduino UNO. The sensor is the important part that should be discusses to detect the angle inclination. The sensor that be used in this project is potentiometer. Firstly, there are three state variables that need to be feed backed. All of them include the cart's position, velocity, and the pendulum's angle from the vertical. The cart's position and velocity is derived from the resistance potentiometer mounted to the pendulum. The pendulum's angle is measured and the give order to the microcontroller to maintain the position pendulum.

The resistance potentiometer is one of the simplest types of position sensor. A potentiometer is a three-terminal resistor with a sliding contact that forms an adjustable voltage divider. If only two terminals are used (one side and the wiper), it acts as a variable resistor. Potentiometers operated by a mechanism, in this case the cart and the rod, can be used as position transducer.

The potentiometer used in this project is 10k ohm. The Figure 4.4 shows the connections potentiometer with the microcontroller to detect the inclination during disturbance.

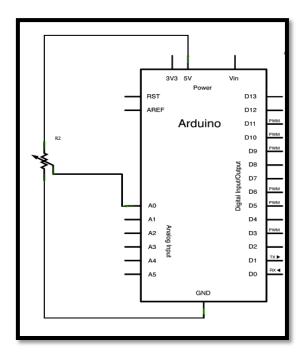


Figure 3.4 Potentiometer connections with Arduino UNO

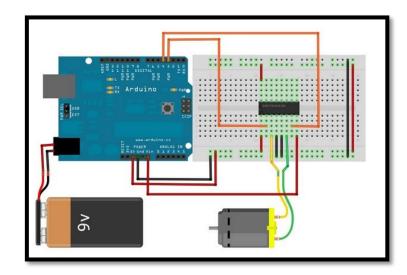


Figure 3.5 Motor driver connections with Arduino UNO

Meanwhile, the Figure 3.5 shows the motor driver connections with microcontroller. The component use for motor driver is L293D. The details about motor driver show in **Appendices A.** All the electrical parts will be design step by step according flow chart that show in Figure 3.6 below.

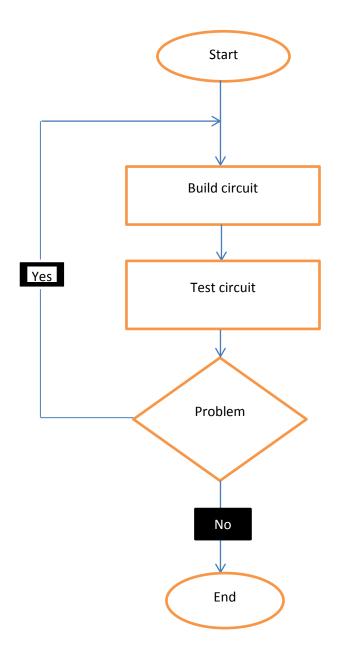


Figure 3.6 Flow chart of circuit

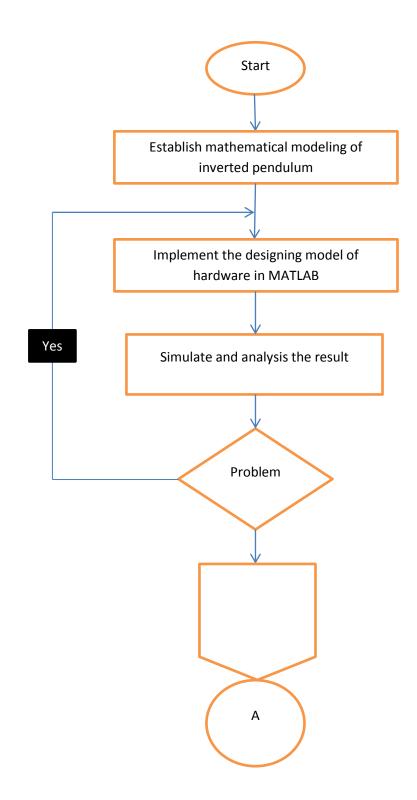
3.6 Software

First step before design controller, the mathematical model obtains for inverted pendulum system. The reason obtain mathematical model is to get the variable used in the system. The mathematical model obtains from the free body diagram which is for cart and pendulum itself.

Task continues with design the PID controller using MATLAB and the Simulation will be held to get the result for inverted pendulum system. There is open loop and closed loop systems are designed to get result. If there any problems occur during simulation, the controller will be design again to get result approximately.

Lastly, Simulink result is performed on real inverted pendulum system. The result will show the performance of real inverted pendulum with PID controller either success or vice versa. If not satisfy the requirement, it will interface the system until satisfy result obtain.

Overall project shows on the flow chart below. Hardware and Software calibrate to finish the inverted pendulum project.



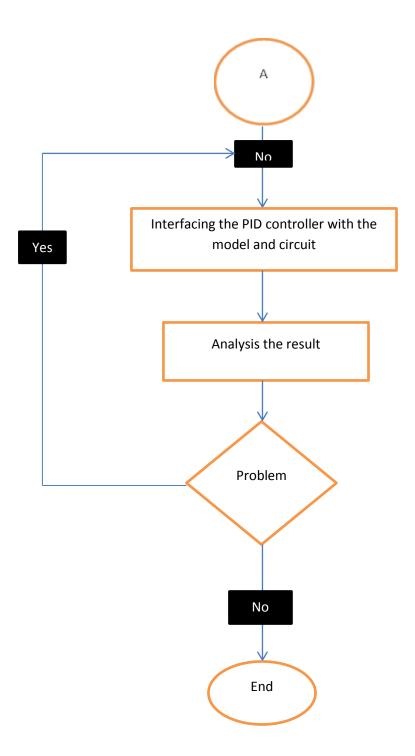


Figure 3.7 Flow chart of overall project

CHAPTER 4

RESULTS

4.4 Hardware Development

In this hardware development, overall mechanical parts and electrical parts will be explaining details from part by part. Mechanical parts divide by cart, pendulum, DC motor, rod and handler rod. Meanwhile in electrical part divide by motor driver and Arduino UNO only.

4.4.1 The Inverted Pendulum Setup

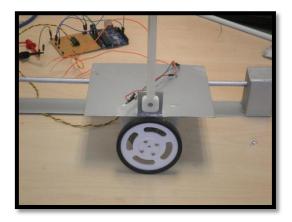


Figure 4.2 The cart pendulum

This setup is designed cart pendulum with one tire to balance the pendulum. The rod used as the track for the cart moving with tire. The cart is made using steel plate and thickness only 0.01m. Meanwhile, pendulum made using hollow steel and their length 0.5m stick together with potentiometer acts as sensor to detect inclination.

The total weight for the cart is 0.436 kg included cart steel plate, DC motor, sensor (potentiometer) and Tire. In addition, the sum weight pendulum is 0.044kg. On the other hands, the length of the rod is 0.45m. All details about mechanical parts will be shown on **Appendices B**.

4.4.2 DC Motor

A DC motor is built to convert electrical power into mechanical power. The interaction of two magnetic fields is converting the electrical energy to mechanical energy in a DC motor. A permanent magnet assembly on the stator is producing one field furthermore an electrical current flowing in the motor winding on the rotor is producing other field. As the result torque on these two fields concludes 21 tends to rotate the rotor. A continuous torque input produced as the current in the winding is commutated when the rotor turns. Some DC motors use coils, instead of using permanent magnets to produce permanent magnetic fields.

The cart is driven by DC motor which direct attach the tire with coupling. The motor has maximum speed 7000 rpm and maximum output torque of 0.0235 N.m. The rated voltage for the motor 12 V and the maximum current for this motor is 70 mA. In addition, the output power on this motor is 1.1 W.

The motor is geared with gear ratio 20 to 1 which mean the speed is larger than torque on this motor. The efficiency of the gear is 60 percent and with the gear the maximum speed is 185 rpm. The rated current is 410 mA and the rated torque is 0.00588 Nm.

4.4.2.1 DC Motor Control Using PWM

DC motor speed can be obtained by controlling its driving voltage. The larger value of voltage, the higher motor speed can be achieved. A pulse width modulation method is used in many DC motor-controlling applications due to in many application, a simple voltage regulation would cause lots of power loss in the control circuit. In the basic PWM method, the operating power to the motor is turned on and off to modulate the current to the motor. The speed of the motor can be determined depend on the ratio of on time to off time or as know the duty cycle.

The microcontroller (Arduino UNO) can be interfaced with a DC motor through a driver. This interface takes up only two I/O pins. The PWM module requires a steadily running oscillator to operate. For the microcontroller, a built in timer module is used as the oscillator. The duty cycle will be adjusted by the controller function in the microcontroller through coding programming.

4.4.2.2 Motor Driver

The fact, the microcontroller (Arduino UNO) cannot supply the necessary current to drive a motor directly although the DC motor can operate at 5V or less. The microcontroller only can supply a minimum current to any practical DC motor but it is not enough to operate by microcontroller. Depending on the size and rating of the motor, a suitable driver must be selected to take control signals from the microcontroller and deliver the necessary voltage and current to the motor.

The drive motor used in this project is L293D which a standard motor driver and available in many current and voltage rating. This motor driver maximum current is 1A and has four channels. The pin assignment and block diagram of L293D are shown in Figure 4.2. There are two supply voltages: V_{cc1} and V_c . V_{cc1} is the logic supply voltage, which can be from 4.5 to 36V. V_c is the analog supply voltage and can be as high as 36V.

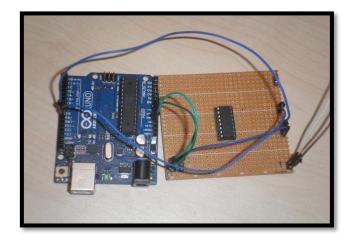


Figure 4.3 Connections L293D with Arduino UNO

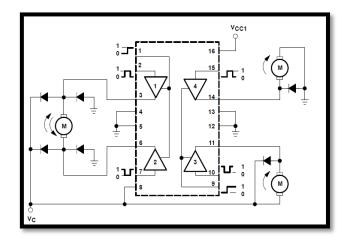


Figure 4.4 Block diagram of L293D

4.5 Simulation Result

The MATLAB is used as the software to analysis and get the data for the inverted pendulum. Firstly, the open loop system was created to know the amplitude of the inverted pendulum. Figure 4.5 show the graph open loop impulse response.

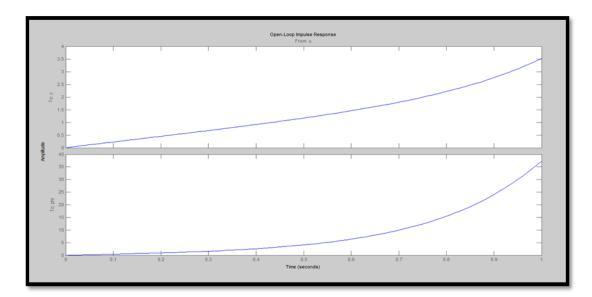


Figure 4.5 Open loop impulse responses

Next, the Figure 4.6 is show the graph distance and angle for pendulum characteristic. The response for the angle is faster than distance response due the pendulum face inertia momentum during the movement of DC motor to stabilize the pendulum.

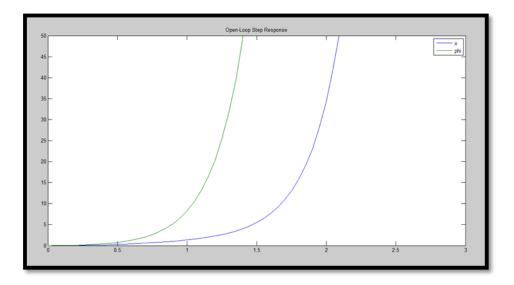


Figure 4.6 Open loop step responses

Meanwhile, next graph will show the characteristic for the close loop response from the inverted pendulum. Figure below shows the response when some PID applies on the system.

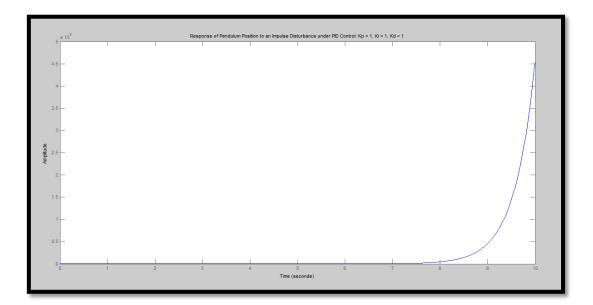


Figure 4.7 Response of pendulum position to an impulse disturbance under PID controller Kp = 1, Ki =1, Kd = 1

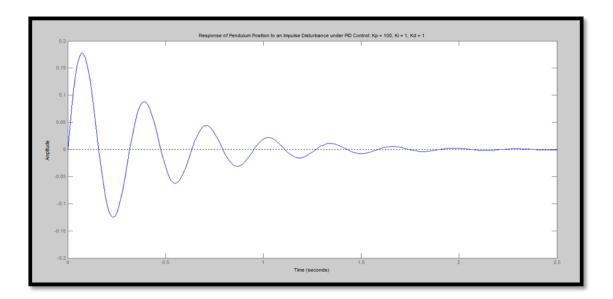


Figure 4.8 Response of pendulum position to an impulse disturbance under PID controller Kp = 100, Ki = 1, Kd = 1

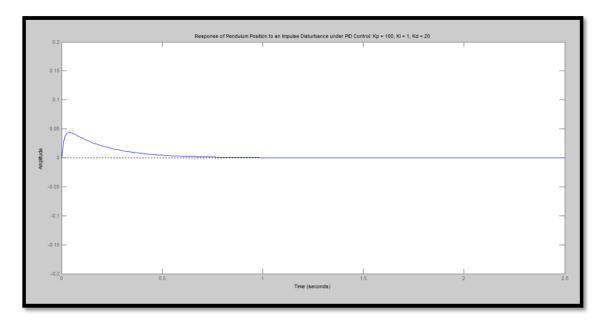


Figure 4.9 Response of pendulum position to an impulse disturbance under PID controller Kp = 100, Ki = 1, Kd = 20

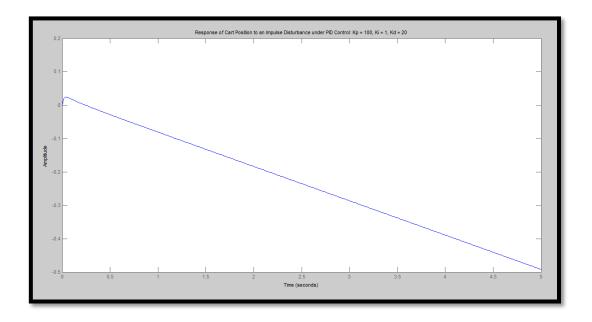


Figure 4.10 Response of cart position to an impulse disturbance under PID controller

$$Kp = 100, Ki = 1, Kd = 20$$

On the other hand, to get the PID controller block diagram was design and simulate through MATLAB. Figure 4.11 shows the block diagram use in MATLAB meanwhile, the Figure 4.12 show the graph response both of angle and position.

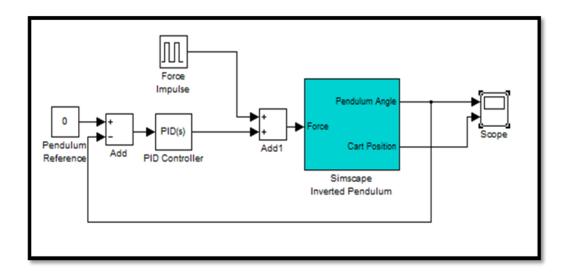


Figure 4.11 The block diagram simscape inverted pendulum

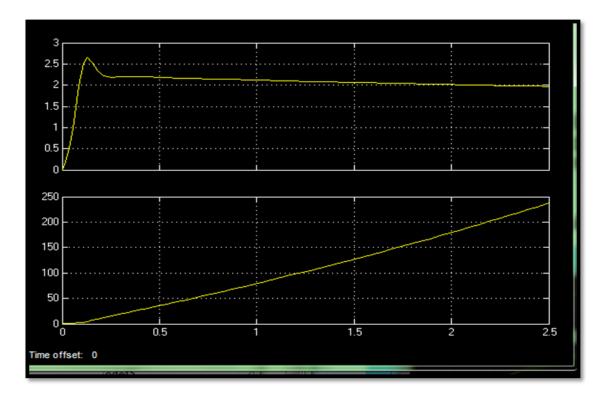


Figure 4.12 Response angle and position

4.5 Discussion and analysis

The results show the parameter PID controller that can be used to implement on the inverted pendulum. The Table below shows the parameter of PID controller that is implementing on inverted pendulum.

Terms	Parameter
Кр	100
Ki	1
Kd	20
Maximum angle response	2.5 rad
Time response	5.46 s

 Table 4.1 PID controller parameter

From the Table 4.1 is show the parameter that be used to apply on real inverted pendulum. The parameter obtained will be programming on microcontroller to show the

characteristic movement of inverted pendulum either cart can maintain pendulum upright or instead.

4.7 Problem Encountered

Problems Reasons		Solutions					
Mechanical limitations							
Vibration of handler rod	Handler rod moving with wheel	Handler rod should permanent on table or the change the heavy base					
The rod shorter	The rod shorter Movement of cart limited						
	Electrical limitations						
Low speed of DC motor	Cannot react faster to balance pendulum	Change another types of DC geared motor with high speed and high torque					

Table 4.2 Problems et	encountered	and	solutions

CHAPTER 5

CONCLUSION AND SUGGESTION

5.1 Conclusion

In this project, the PID controller has been successful implement on the inverted pendulum although some problem encountered. The cart is acting to maintain the pendulum upright which is vertical when the potentiometer detected some angle inclination. Therefore it can be concluded the objective is achieved to implement PID controller on the inverted pendulum control system although the pendulum can maintain a few seconds.

5.2 Further Development

Firstly, the mechanical part especially the handler rod should be permanently on the table to avoid itself move during movement of the cart. In addition, the rod also needs larger to give unlimited movement cart to maintain the pendulum.

Next, replace the sensor that has more sensitivity sensor to detect a small inclination angle from the pendulum. More sensitivity sensor will give accurate data and pendulum can maintain upright longer.

On the other hand, maybe in future try design a different type of inverted pendulum for examples rotary inverted pendulum, two wheels balance, and etc. Otherwise, use basic inverted pendulum to apply in real application such as helicopter Segway and etc.

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APPENDICES A

GANTT CHART

GANNT CHART / PROJECT SCHEDULE FOR FYP 1

FINAL YEAR PROJECT TITLE: AUTOMATIC INVERTED PENDULUM CONTROL SYSTEM

WEEKS PROJECT ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
	SEPT	SEPT	SEPT	ОСТ	ОСТ	ОСТ	ОСТ	NOV	NOV	NOV	NOV	DEC	DEC	DEC
Final Year Project Title Announcement & Briefing		JEFT	JEFT	001	001	001	001	NOV	NOV	NOV	NOV	DEC	DEC	DEC
Project Title Research		\rightarrow												
Project Objective & Project Scope Setting and With Supervisor														
Submission of Project Flow Chart & Gannt Chart for Supervisor Verification				^										
Project Introduction (Chapter 1) Writing & Submission					^									
Academic Research For Literature Review														
Literature Review (Chapter 2) Writing & Submission														
Project Components Identification									1					
Project Design														
Project Components Quotation														
Project Methodology (Chapter 3) Writing & Submission												\rightarrow		
Complete Log Book Submission												\rightarrow		
Final Year Project Mock Presentation													\rightarrow	
Final Year Project 1 Presentation & Progress Report Submission														\rightarrow

Important Submission & Presentation

Note : Final Year Project 1 Starts on 10th September 2012 as 1st Week.

GANNT CHART / PROJECT SCHEDULE FOR FYP 2

FINAL YEAR PROJECT TITLE: AUTOMATIC INVERTED PENDULUM CONTROL SYSTEM

WEEKS PROJECT ACTIVITIES	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
	FEB	FEB	MAR	MAR	MAR	MAR	APR	APR	APR	APR	MAY	MAY	MAY	MAY
Design and Assembly Mechanical Part		^												
Design and Build Circuit for PIC and PWM			\rightarrow											
Microcontroller Programming				\rightarrow										
Establish Mathematical Modeling														
Design PID Controller														
Implement the Designing Controller in MATLAB								\rightarrow						
Simulate and Analysis the Result									>					
Interfacing the controller (MATLAB) with mechanical part and Circuit														
Data Collection & Analysis														
Full Thesis Writing														
Complete Log Book Submission														
Final Year Project Mock Presentation														
Final Year Project 2 Presentation & Final Report Submission														—

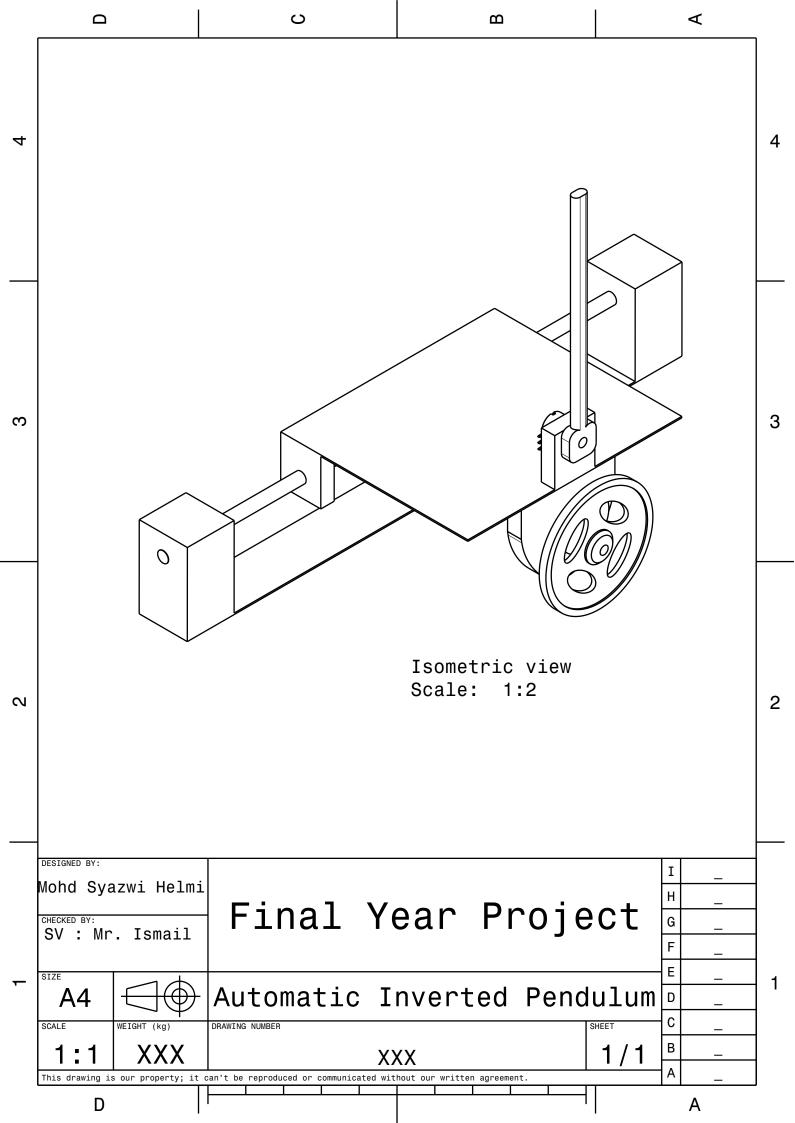


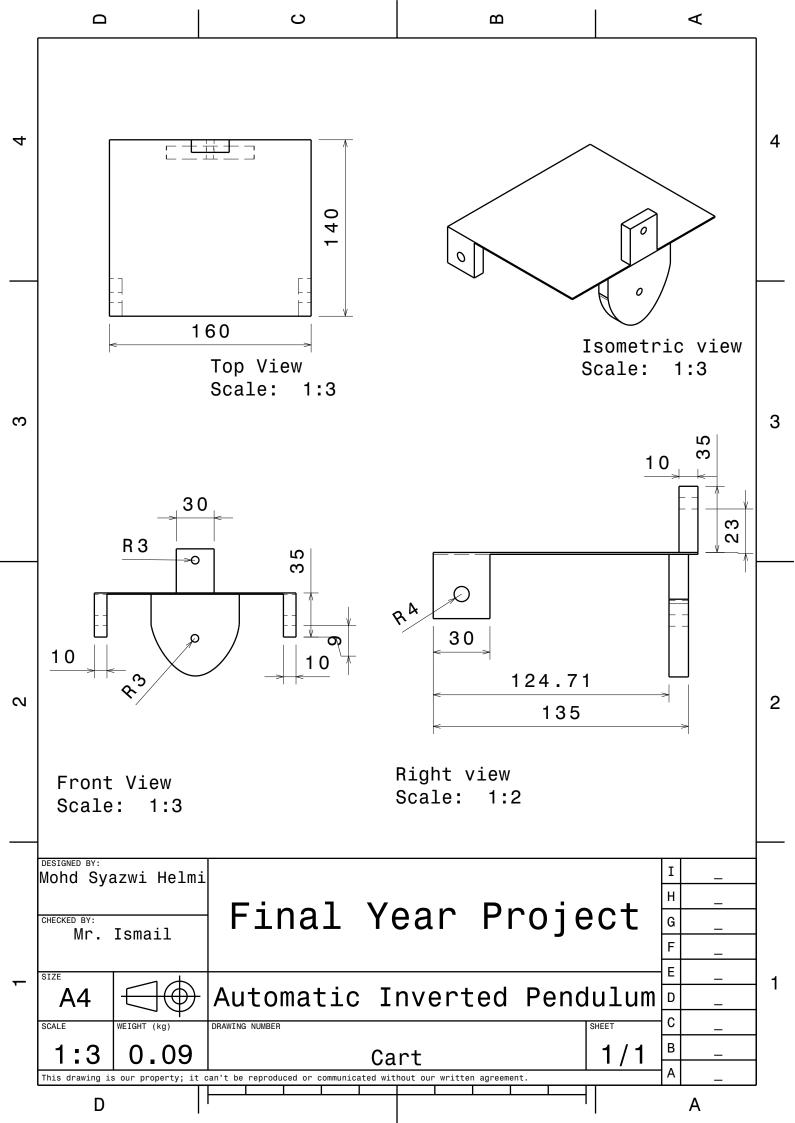
Important Submission & Presentation

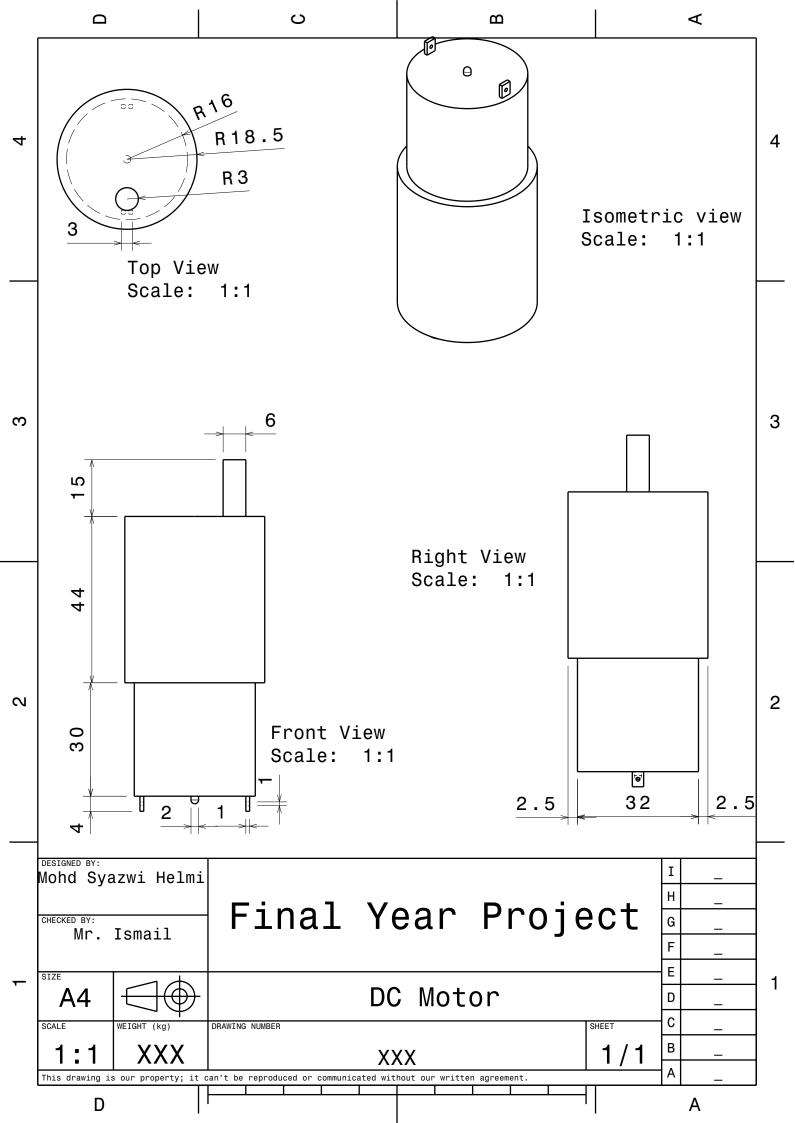
Note : Final Year Project 2 Starts on 18th February 2012 as 1st Week.

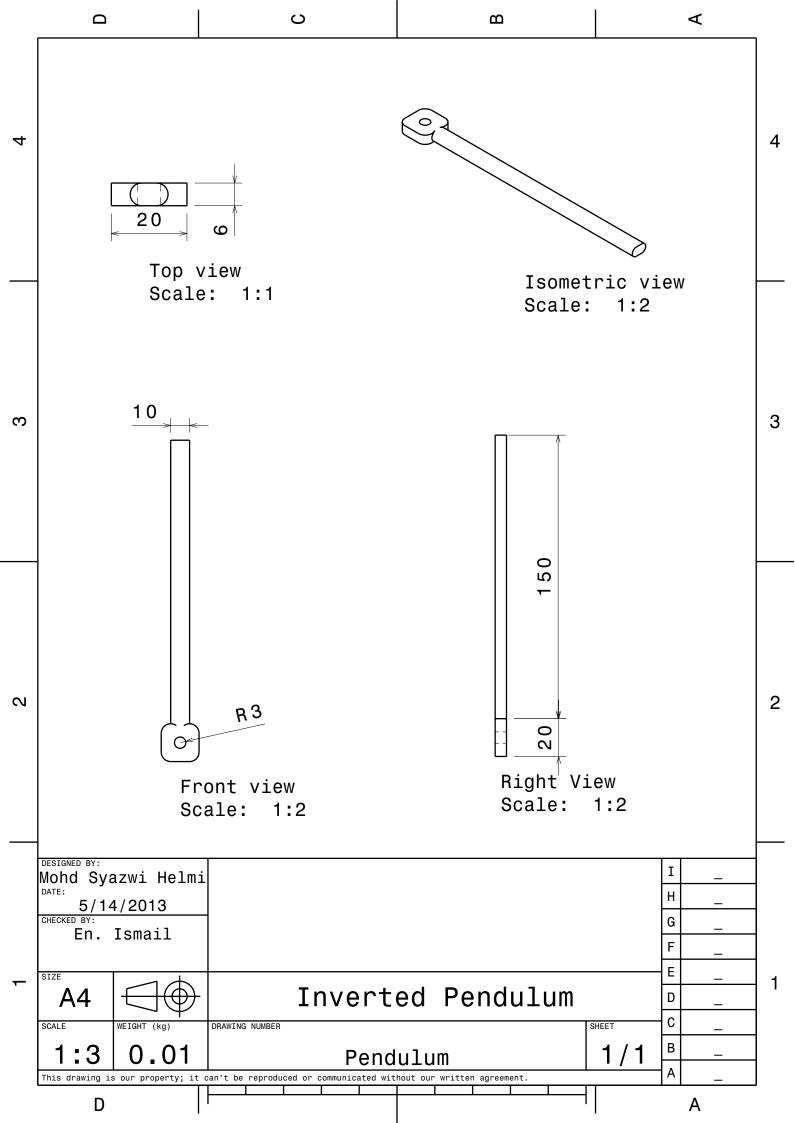
APPENDICES B

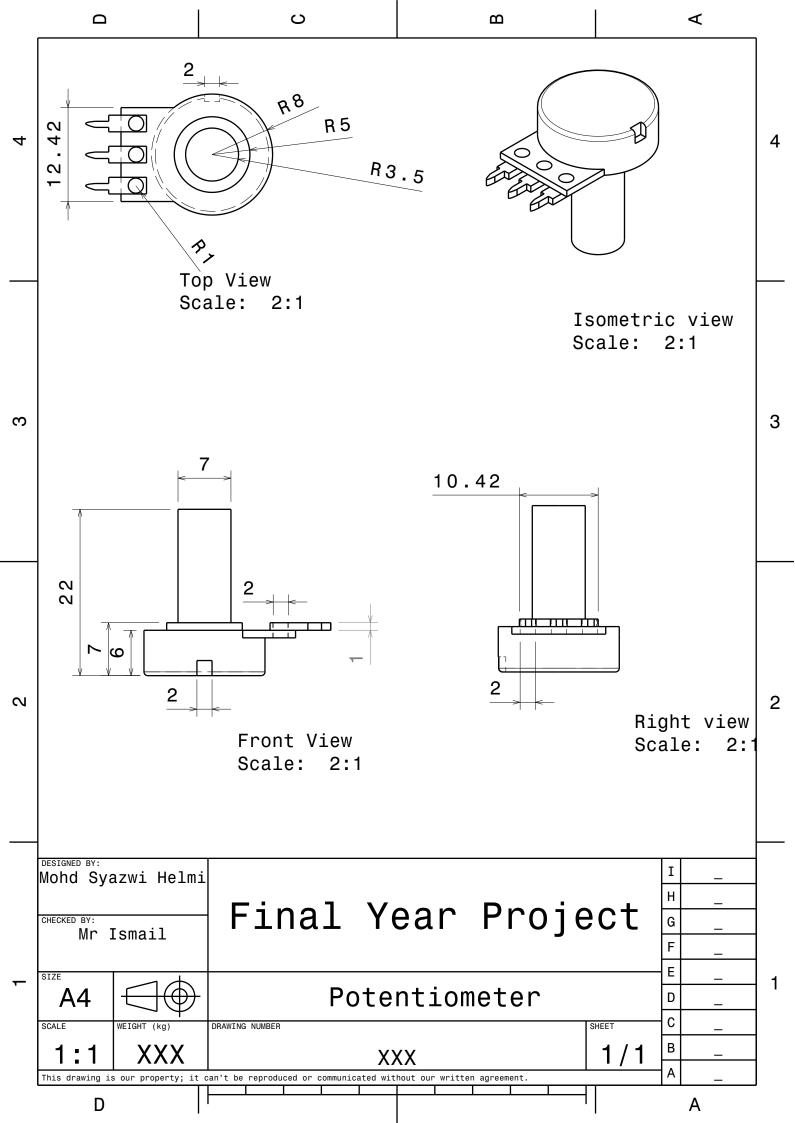
MECHANICAL PART DRAWING AND DATASHEET

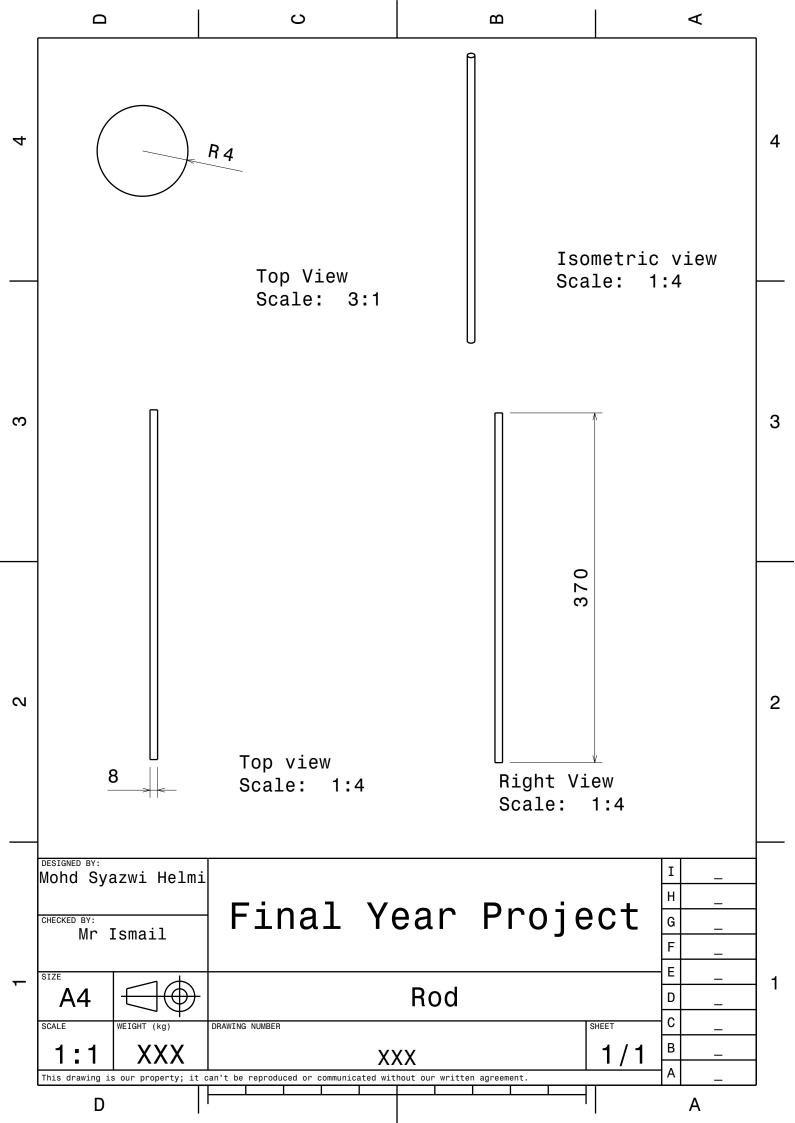


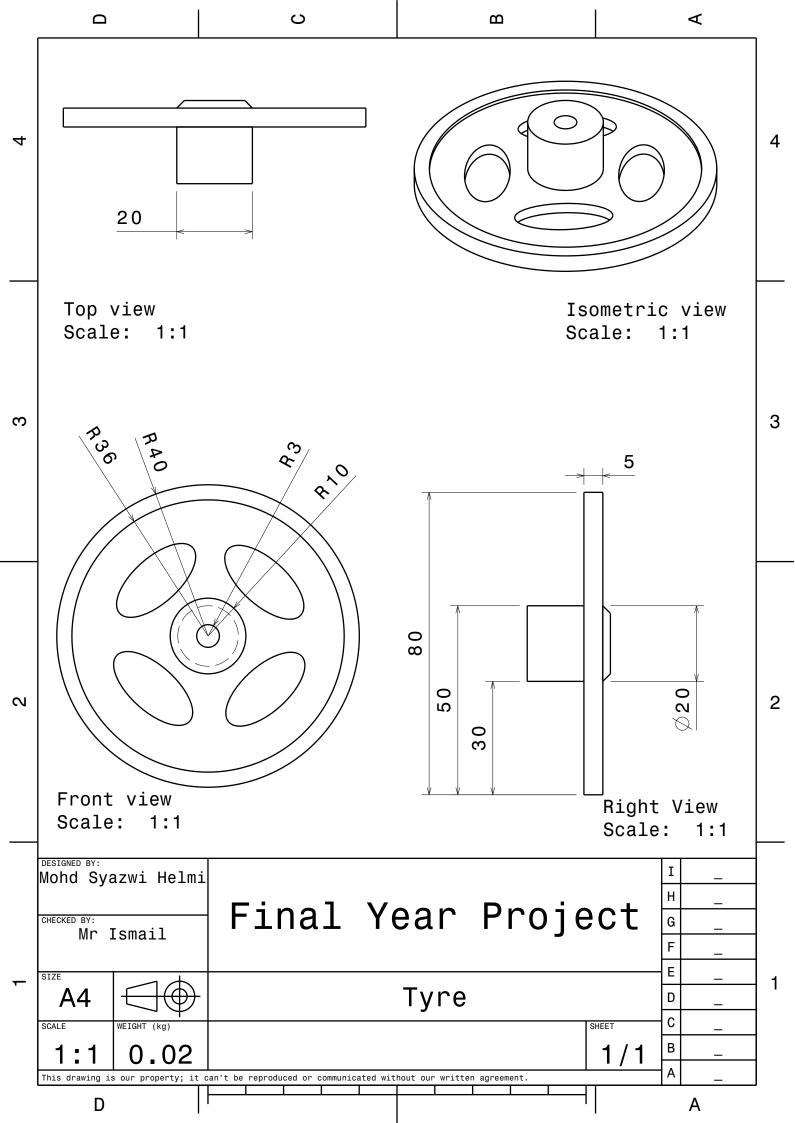














SPG30 Series



Output Power: 1.1W

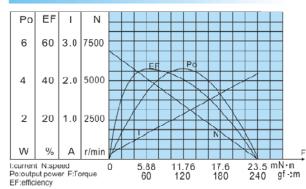
Weight: ~160g

CYTRON.COM.MY

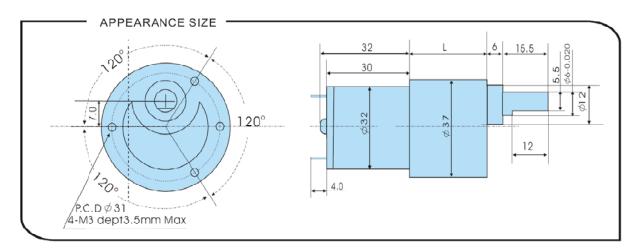
Typical applications: Labal printers, auto shutter, welding machines, water meter IC card, grill, oven, cleaning machine, garbage disposers, household appliances, slot machines, money detector, automatic actuator, coffee machine, towel disposal, lighting, coin refund devices, peristaltic pump.

MOTOR CHARACTERISTICS

MOTOR TORQUE/SPEED/CURRENT



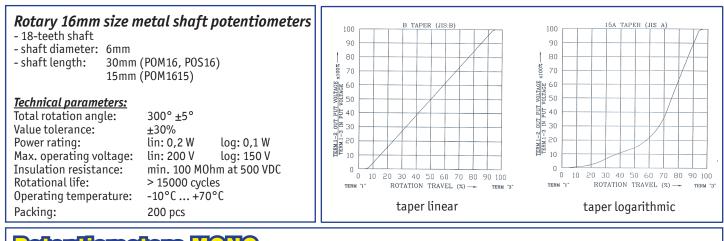
Rated voltage	12VDC
No load speed	7000r/min
No load current	70mA
Rated torque	60gf•cm 5.88mN•m
Rated current	410mA
Rated speed	5200r/min
Stall torque	240gf•cm 23.5mN•m
Stall current	1.8A



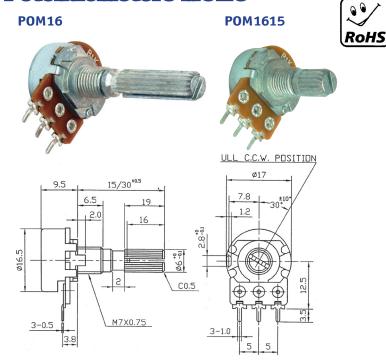
	Order Option								
Order Code	Input Voltage	Ra	ted	Weight (g)	Power (w)	Diameter (mm)	L (mm)		
Older code	input ronage	Speed (RPM)	Torque (mN.m)		100001(0)	Branneter (min)	2 ()		
SPG10-30K	6	440	29.4	10	-	12	24		
SPG10-150K	6	85	107.9	10	-	12	24		
SPG10-298K	6	45	176.5	10	-	12	24		
SPG20-50K	12	130	58.8	60	0.6	27.2	-		
SPG30-20K	12	185	78.4	160	1.1	37	22		
SPG30-30K	12	103	127.4	160	1.1	37	22		
SPG30-60K	12	58	254.8	160	1.1	37	25		
SPG30-150K	12	26	588	160	1.1	37	27		
SPG30-200K	12	17	784	160	1.1	37	27		
SPG30-300K	12	12	1176	160	1.1	37	27		
SPG50-20K	12	170	196	300	3.4	37	23		
SPG50-60K	12	56	588	300	3.4	37	26		
SPG50-100K	12	34	980	300	3.4	37	26		
SPG50-180K	12	17	1960	300	3.4	37	28		



16mm SIZE METAL SHAFT POTENTIOMETERS



Potentiometers MONO



Туре	Value	Taper
POM16 LIN 1K B	1 K	LIN
POM16 LIN 5K B	5 K	LIN
POM16 LIN 10K B	10 K	LIN
POM16 LIN 50K B	50 K	LIN
POM16 LIN 100K B	100 K	LIN
POM16 LIN 200K B	200 K	LIN
POM16 LIN 500K B	500 K	LIN
POM16 LIN 1M B	1 M	LIN
POM16 LOG 1K A	1 K	LOG
POM16 LOG 5K A	5 K	LOG
POM16 LOG 10K A	10 K	LOG
POM16 LOG 50K A	50 K	LOG
POM16 LOG 100K A	100 K	LOG
POM16 LOG 200K A	200 K	LOG
POM16 LOG 500K A	500 K	LOG
POM16 LOG 1M A	1 M	LOG
POM1615 LIN 1K B	1 K	LIN
POM1615 LIN 5K B	5 K	LIN
POM1615 LIN 10K B	10 K	LIN
POM1615 LIN 50K B	50 K	LIN
POM1615 LIN 100K B	100 K	LIN
POM1615 LIN 500K B	500 K	LIN

a

ALPHA

Potentiometers STEREO SHAFT SHOWN IN FULL C.C.W. POSITION 30^{±0.5} Ø17 11.5 19 6.5 7.8 30 16 2.0 C0.5 1.2 90 KNURL 18TEETH n N N M7X0.75 0.5 1.0 5.0 3.8 5

2	Туре	Value	Taper
	POS16 LIN 1K B	1 K	LIN
S	POS16 LIN 5K B	5 K	LIN
	POS16 LIN 10K B	10 K	LIN
	POS16 LIN 50K B	50 K	LIN
	POS16 LIN 100K B	100 K	LIN
	POS16 LIN 200K B	200 K	LIN
	POS16 LIN 500K B	500 K	LIN
	POS16 LIN 1M B	1 M	LIN
	POS16 LOG 1K A	1 K	LOG
	POS16 LOG 5K A	5 K	LOG
	POS16 LOG 10K A	10 K	LOG
	POS16 LOG 50K A	50 K	LOG
	POS16 LOG 100K A	100 K	LOG
	POS16 LOG 200K A	200 K	LOG
	POS16 LOG 500K A	500 K	LOG
	POS16 LOG 1M A	1 M	LOG

L293, L293D QUADRUPLE HALF-H DRIVERS

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17 🛛 3Y

16 3A

15 3,4EN

2Y 🛛 12

13

 Featuring Unitrode L293 and L293D Products Now From Texas Instruments 	N, NE PACKAGE (TOP VIEW)
 Wide Supply-Voltage Range: 4.5 V to 36 V 	1,2EN 1 16 V _{CC1}
 Separate Input-Logic Supply 	
Internal ESD Protection	1Y 🛛 3 14 🗍 4Y
Thermal Shutdown	HEAT SINK AND $\int \left[4 + 13 \right] $ HEAT SINK AND
High-Noise-Immunity Inputs	GROUND GROUND
• Functional Replacements for SGS L293 and	2Y [] 6 11 [] 3Y 2A [] 7 10 [] 3A
SGS L293D	V _{CC2} [8 9] 3,4EN
 Output Current 1 A Per Channel (600 mA for L293D) 	
 Peak Output Current 2 A Per Channel 	DWP PACKAGE (TOP VIEW)
(1.2 A for L293D)	
 Output Clamp Diodes for Inductive 	1,2EN 1 1 28 V _{CC1}
Transient Suppression (L293D)	
	1Y [] 3 26]] 4Y NC [] 4 25]] NC
description	NC [] 4 25 [] NC NC [] 5 24 [] NC
The L293 and L293D are quadruple high-current	
half-H drivers. The L293 is designed to provide	HEAT SINK AND $\int \frac{1}{2}^7 = 22 \frac{1}{2}$ HEAT SINK AND
bidirectional drive currents of up to 1 A at voltages	$\begin{array}{c c} \text{HEAT SINK AND} \\ \text{GROUND} \end{array} \begin{array}{c} 1 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\ 3 \\$
from 4.5 V to 36 V. The L293D is designed to	
provide bidirectional drive currents of up to	
600-mA at voltages from 4.5 V to 36 V. Both	NC 🛛 11 18 🗍 NC

All inputs are TTL compatible. Each output is a complete totem-pole drive circuit, with a Darlington transistor sink and a pseudo-Darlington source. Drivers are enabled in pairs, with drivers 1 and 2 enabled by 1,2EN and drivers 3 and 4 enabled by 3,4EN. When an enable input is high, the associated drivers are enabled and their outputs are active and in phase with their inputs. When the enable input is low, those drivers are disabled and their outputs are off and in the high-impedance state. With the proper data inputs, each pair of drivers forms a full-H (or bridge) reversible drive suitable for solenoid or motor applications.

On the L293, external high-speed output clamp diodes should be used for inductive transient suppression.

A V_{CC1} terminal, separate from V_{CC2}, is provided for the logic inputs to minimize device power dissipation.

The L293and L293D are characterized for operation from 0°C to 70°C.

devices are designed to drive inductive loads such

as relays, solenoids, dc and bipolar stepping

motors, as well as other high-current/high-voltage

loads in positive-supply applications.



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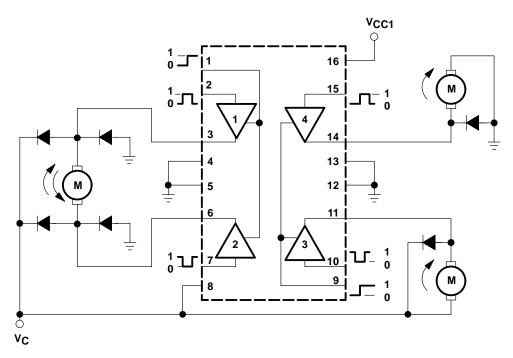


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L293, L293D QUADRUPLE HALF-H DRIVERS

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block diagram



NOTE: Output diodes are internal in L293D.

TEXAS INSTRUMENTS AVAILABLE OPTIONS

	PACKAGE
TA	PLASTIC DIP (NE)
0°C to 70°C	L293NE L293DNE

Unitrode Products from Texas Instruments AVAILABLE OPTIONS						
T _A T _A PACKAGED DEVICES SMALL OUTLINE (DWP) (N)						
0°C to 70°C	L293DWP L293N L293DDWP L293DN					

The DWP package is available taped and reeled. Add the suffix TR to device type (e.g., L293DWPTR).



L293, L293D QUADRUPLE HALF-H DRIVERS

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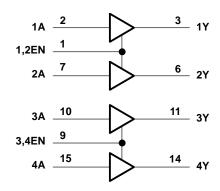
FUNCTION TABLE (each driver)

INPUTS [†]		OUTPUT
Α	EN	Y
Н	Н	Н
L	Н	L
Х	L	Z

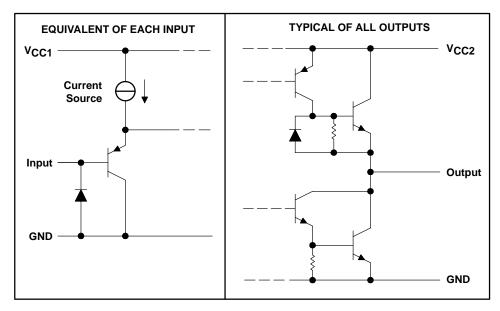
H = high level, L = low level, X = irrelevant, Z = high impedance (off)

[†] In the thermal shutdown mode, the output is in the high-impedance state, regardless of the input levels.

logic diagram



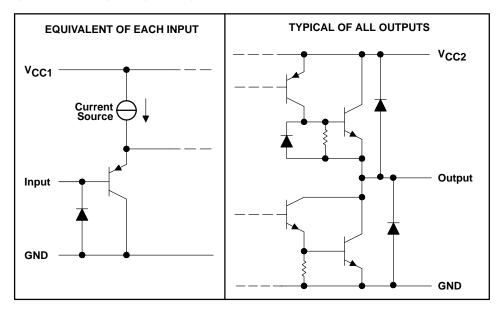
schematics of inputs and outputs (L293)





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schematics of inputs and outputs (L293D)



absolute maximum ratings over operating free-air temperature range (unless otherwise noted)[†]

Supply voltage, V _{CC1} (see Note 1)	
Output supply voltage, V _{CC2}	
Output voltage range, V _O	
Peak output current, I_{O} (nonrepetitive, t \leq 5 ms): L293	
Peak output current, I_O (nonrepetitive, t \leq 100 μ s): L293D	±1.2 A
Continuous output current, I _O : L293	±1 A
Continuous output current, Io: L293D	±600 mA
Continuous total dissipation at (or below) 25°C free-air temperature (see Notes 2 and 3)	2075 mW
Continuous total dissipation at 80°C case temperature (see Note 3)	5000 mW
Maximum junction temperature, T _J	150°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds	260°C
Storage temperature range, T _{stg}	–65°C to 150°C

[†] Stresses beyond those listed under "absolute maximum ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under "recommended operating conditions" is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTES: 1. All voltage values are with respect to the network ground terminal.

2. For operation above 25°C free-air temperature, derate linearly at the rate of 16.6 mW/°C.

3. For operation above 25°C case temperature, derate linearly at the rate of 71.4 mW/°C. Due to variations in individual device electrical characteristics and thermal resistance, the built-in thermal overload protection may be activated at power levels slightly above or below the rated dissipation.



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recommended operating conditions

		MIN	MAX	UNIT
	V _{CC1}	4.5	7	V
	Supply voltage V _{CC2}	VCC1	36	v
VIH	High-level input voltage $V_{CC1} \le 7 V$	2.3	V _{CC1}	V
	V _{CC1} \ge 7 V	2.3	7	V
V_{IL}	-0.3†	1.5	V	
ТĄ	0	70	°C	

[†] The algebraic convention, in which the least positive (most negative) designated minimum, is used in this data sheet for logic voltage levels.

electrical characteristics, V_{CC1} = 5 V, V_{CC2} = 24 V, T_A = 25°C

	PARAMETER			TEST CONDITIONS	MIN	TYP	MAX	UNIT
VOH	High-level output voltage		L293: I _{OH} : L293D: I _{OH}		V _{CC2} -1.8	V _{CC2} -1.4		V
V _{OL}	Low-level output voltage		L293: I _{OL} = L293D: I _{OL} =			1.2	1.8	V
Vокн	High-level output clamp v	oltage	L293D: IOK	= -0.6 A		V _{CC2} + 1.3		V
VOKL	Low-level output clamp vo	oltage	L293D: IOK	= 0.6 A		1.3		V
I			V _I = 7 V			0.2	100	
IIH High-level input current	EN				0.2	10	μA	
IIL Low-level input current A EN		А	N/- 0			-3	-10	
		EN	VI = 0			-2	-100	μA
				All outputs at high level		13	22	
ICC1 Logic supply current			IO = 0	All outputs at low level		35	60 m.	mA
				All outputs at high impedance		8	24	
				All outputs at high level		14	24	
ICC2 Output supply current	Output supply current		IO = 0	I _O = 0 All outputs at low level		2	6	mA
				All outputs at high impedance		2	4	

switching characteristics, V_{CC1} = 5 V, V_{CC2} = 24 V, T_A = 25°C

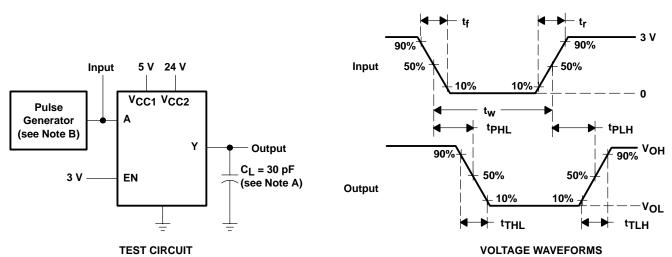
PARAMETER		TEST CONDITIONS	L293NE, L293DNE			UNIT
	PARAMETER	TEST CONDITIONS	MIN	TYP	MAX	UNIT
^t PLH	Propagation delay time, low-to-high-level output from A input			800		ns
^t PHL	Propagation delay time, high-to-low-level output from A input			400		ns
^t TLH	Transition time, low-to-high-level output	$C_L = 30 \text{ pF}$, See Figure 1		300		ns
^t THL	Transition time, high-to-low-level output		300		ns	

switching characteristics, V_{CC1} = 5 V, V_{CC2} = 24 V, T_A = 25°C

	PARAMETER	TEST CONDITIONS	L293DWP, L293N L293DDWP, L293DN			UNIT
			MIN	TYP	MAX	
^t PLH	Propagation delay time, low-to-high-level output from A input			750		ns
t _{PHL}	Propagation delay time, high-to-low-level output from A input	ne, high-to-low-level output from A input				ns
^t TLH	Transition time, low-to-high-level output	C _L = 30 pF, See Figure 1 100			ns	
^t THL	Transition time, high-to-low-level output			350		ns



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PARAMETER MEASUREMENT INFORMATION

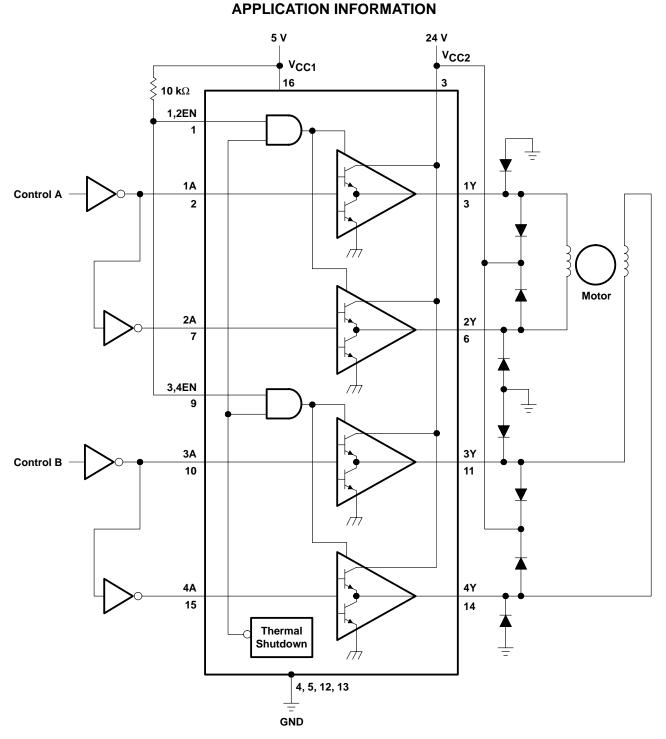
NOTES: A. CL includes probe and jig capacitance.

B. The pulse generator has the following characteristics: $t_f \le 10$ ns, $t_f \le 10$ ns, $t_w = 10 \ \mu$ s, PRR = 5 kHz, $Z_O = 50 \ \Omega$.

Figure 1. Test Circuit and Voltage Waveforms



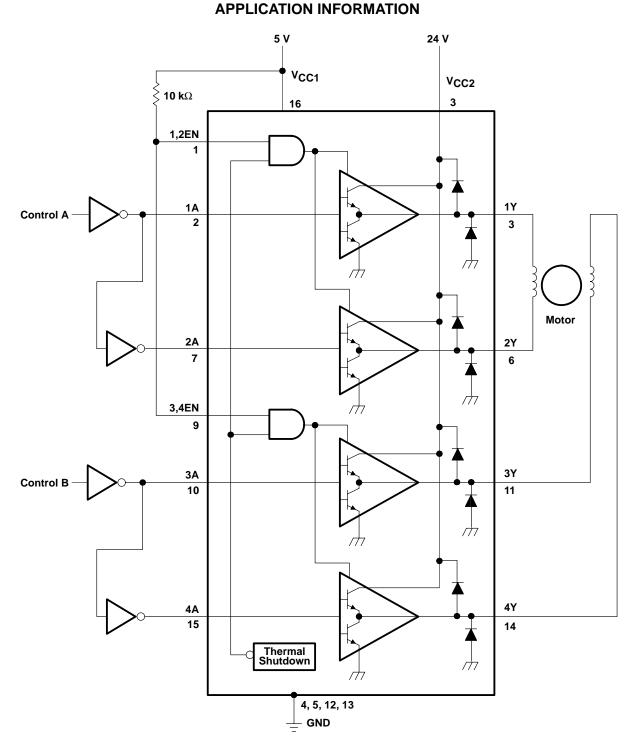
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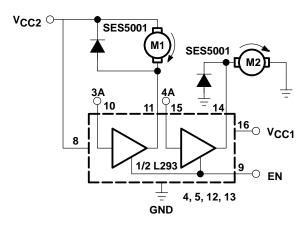


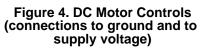




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APPLICATION INFORMATION





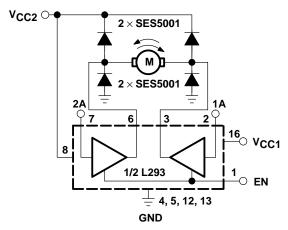


Figure 5. Bidirectional DC Motor Control

EN	3A	M1	4A	M2		
Н	Н	Fast motor stop	Н	Run		
Н	L	Run	L	Fast motor stop		
L	х	Free-running motor stop	х	Free-running motor stop		

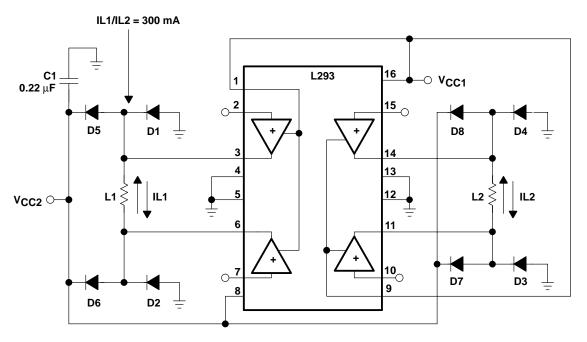
L = low, H = high, X = don't care

EN	1A	2A	FUNCTION
н	L	Н	Turn right
н	Н	L	Turn left
н	L	L	Fast motor stop
н	Н	Н	Fast motor stop
L	Х	Х	Fast motor stop

L = low, H = high, X = don't care



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APPLICATION INFORMATION

D1-D8 = SES5001

Figure 6. Bipolar Stepping-Motor Control

mounting instructions

The Rthj-amp of the L293 can be reduced by soldering the GND pins to a suitable copper area of the printed circuit board or to an external heatsink.

Figure 9 shows the maximum package power P_{TOT} and the θ_{JA} as a function of the side l of two equal square copper areas having a thickness of 35 μ m (see Figure 7). In addition, an external heat sink can be used (see Figure 8).

During soldering, the pin temperature must not exceed 260°C, and the soldering time must not be longer than 12 seconds.

The external heatsink or printed circuit copper area must be connected to electrical ground.



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APPLICATION INFORMATION

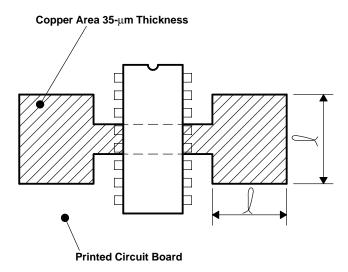
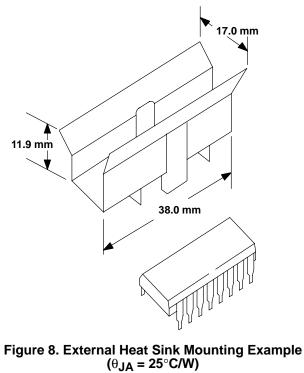


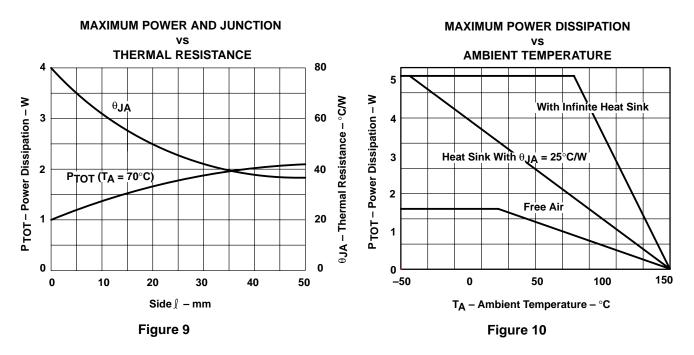
Figure 7. Example of Printed Circuit Board Copper Area (used as heat sink)





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APPLICATION INFORMATION





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APPENDICES C

CODING PROGRAMMING

Coding Programming

// These constants won't change. They're used to give names // to the pins used: const int analogInPin = A0; // Analog input pin that the potentiometer is attached to const int analogOutPin = 9;// Analog output pin that the LED is attached to const int analogOutPin_cw = 8; // value read from the pot int sensorValue = 0; int outputValue = 0; // value output to the PWM (analog out) void setup() { // initialize serial communications at 9600 bps: Serial.begin(9600); } void loop() { // read the analog in value: sensorValue = analogRead(analogInPin); // map it to the range of the analog out: outputValue = map(sensorValue, 0, 1023, 0, 255); // change the analog out value: if (sensorValue < 500) { digitalWrite (9, LOW); digitalWrite (8, HIGH); //analogWrite(analogOutPin, outputValue); } if ((sensorValue >=501)&&(sensorValue <=509))

{

```
digitalWrite (9, LOW);
  digitalWrite (8, LOW);
}
if (sensorValue >510)
{
  digitalWrite(8, LOW);
  digitalWrite(9, HIGH);
  //analogWrite(analogOutPin_cw, outputValue);
}
// print the results to the serial monitor:
Serial.print("sensor = " );
Serial.print(sensorValue);
Serial.print("\t output = ");
Serial.println(outputValue);
// wait 2 milliseconds before the next loop
// for the analog-to-digital converter to settle
// after the last reading:
delay(2);
```

```
}
```

Coding Programming

```
// These constants won't change. They're used to give names
// to the pins used:
const int analogInPin = A0; // Analog input pin that the potentiometer is attached to
const int analogOutPin = 9;// Analog output pin that the LED is attached to
const int analogOutPin_cw = 8;
int Actual, Error, IntThresh, ScaleFactor, Last;
float Integral;
float P,I,D;
                            // value read from the pot
int sensorValue = 0;
int outputValue = 0; // value output to the PWM (analog out)
void setup() {
  // initialize serial communications at 9600 bps:
  Serial.begin(9600);
}
void loop() {
  // read the analog in value:
  sensorValue = analogRead(analogInPin);
  // map it to the range of the analog out:
  outputValue = map(sensorValue, 0, 1023, 0, 255);
  // change the analog out value:
  Actual = analogRead(analogInPin);
  Error = 501 - Actual;
  if (abs(Error) < IntThresh){ // prevent integral 'windup'</pre>
      Integral = Integral + Error; // accumulate the error integral
```

```
}
```

```
else {
```

```
// zero it if out of bounds
     Integral=0;
}
P = Error*100;
                                      // calc proportional term
I = Integral*1;
                                 // integral term
D = (Last-Actual)*20; // derivative term
sensorValue = P + I + D;
                                        // Total drive = P+I+D
sensorValue = sensorValue*ScaleFactor; // scale Drive to be in the range 0-255
if (sensorValue < 500)
{
  digitalWrite (9, LOW);
  digitalWrite (8, HIGH);
  Last = Actual;
//analogWrite(analogOutPin, outputValue);
}
if (sensorValue >=501)
{
  digitalWrite (9, LOW);
  digitalWrite (8, LOW);
}
if (sensorValue >502)
{
  digitalWrite(8, LOW);
```

```
digitalWrite(9, HIGH);
Last = Actual;
//analogWrite(analogOutPin_cw, outputValue);
}
// print the results to the serial monitor:
Serial.print("sensor = " );
Serial.print(sensorValue);
Serial.print("\t output = ");
Serial.println(outputValue);
```

// wait 2 milliseconds before the next loop

// for the analog-to-digital converter to settle

// after the last reading:

delay(2);

}