Fabrication, Balancing and Analysis of Two Wheeled Robot

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Fabrication, Balancing and Analysis of Two Wheeled Robot

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Of

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By

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Declaration

I do, hereby, declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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Date:

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Certificate

*This is to certify that the thesis entitled, **"Fabrication, Balancing and Analysis of Two Wheeled Robot",** being submitted by **Mr. Manas Kumar Padhan** to the Department of Mechanical Engineering, National Institute of Technology, Rourkela, for the partial fulfilment of award of the degree of **Master of Technology** with specialization in **Machine Design & Analysis**, is a record of bonafide research work carried out by him under our supervision and guidance.*

This thesis in our opinion, is worthy of consideration for award of the degree of Master of Technology in accordance with the regulation of the institute. To the best of our knowledge, the results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

Prof. Dayal R. Parhi
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AREA OF RESEARCH CERTIFICATE

This is to certify that the thesis entitled **"Fabrication, Balancing and Analysis of Two Wheeled Robot"** submitted for the award of Master of Technology in Mechanical Engineering of National Institute of Technology, Rourkela has been prepared by Manas Kumar Padhan under my guidance and is original.

Prof. Dayal R. Parhi
Supervisor

Dedicated to

My guide

Parents

And

Friends

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

Manas Kumar Padhan

ABSTRACT

Two wheeled self balancing robot is based on the concept of inverted pendulum, which center of mass is above the pivot point. Generally the pendulum is an unstable system on its horizontal plane and must be balanced to remain upright. This can be achieved by applying require amount of torque to the pivot point. Similarly here in two wheeled balancing robot being unstable will deflect from its vertical position and try to fall down. The angle of tilt is calculated by IMU sensor and sends to the microcontroller, which further gives a command to the motor through the motor controller to move in the same direction where the robot has been tilted. When the motor will rotate, it will give an opposite torque to the robot through the pivot point which will counter the angle of deflection and the robot will be stable. This will happen for both the direction of the deflection and hence the robot will move forward and backward and finally it will be balanced. So it require both mechanical and electronics equipments for the robot to achieve the goal.

Key words: Segway, Motor Controller, Inverted Pendulum, Kalman Filter, PID controller

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NOMENCLATURE

M	= Mass Of The Cart
m	= Mass Of The Pendulum
b	= Coefficient Of Friction For The Cart
l	= Length To Pendulum Center Of Mass
I	= Mass Moment Of Inertia Of The Pendulum
F	= Force Applied To The Cart
x	= Cart Position Coordinate
ϴ	= Pendulum Angle From Vertical
ϕ	= Deviation Of The Pendulum From The Vertical Axis

CHAPTER 01

INTRODUCTION

1.1. THEME OF THESIS

1.2. OBJECTIVE OF THESIS

1.3. LAYOUT OF THESIS

1.1. THEME OF THESIS

Robotics is currently a rapid growing branch of technology due to the high demand for seamless and automatic system. During recent year robotics has also made a breakthrough in personal transportation with the segway. Two wheeled robot is flexible vehicle that balance on two wheels and can be controlled through the motion of tilting in the direction on which to travel. Conceptually, it can be considered a modern adaptation of the inverted pendulum, which is an upside down pendulum with its centre of mass located above its pivoted point. The goal of the classical inverted pendulum is to keep the pendulum stable by applying correct amount of force or torque to its base, cancelling out any downward acceleration that the gravitational force has o the pendulum. However, unlike the classical pendulum, the segway personal transporter, with the help of an embedded control system and a movable base, is also able to freely drive and turn in all directions and maintains balance at all speed, this is achieved with the help of responsive sensor and advance control algorithm.

Two wheeled robot is very popular, because of its instability. Stability of two wheel robot holds a milestone among the researchers. This project covers the experimental setup, mathematical modelling, simulation model, control technique to balance the robot and its real world applications.

1.2. OBJECTIVE OF THESIS

Objective of the thesis is to make a low cost self balancing robot, which will balance itself in its mean position with the help of two wheels. Generally at least 3 wheels are required for the stability of any vehicle, but balancing with 2 wheels is a challenge here. We have seen number of two wheeled vehicles in daily life like motor bikes, but the difference between our robot and regular seen vehicle is, in motor bike one wheel is placed front and another is on rear, so that vehicle is constraint on forward and backward direction, but here in our robot wheels are placed sidewise (left and right). So the robot is not constraint on forward and backward direction rather on the each side. That means general vehicles are constraint on the driving directions so that they become automatically stable while in motion, but in the case of two wheeled robot it is not true.

The balancing principle of the robot is same as the inverted pendulum. Inverted pendulum is pivoted on a movable cart as shown in the figure 1.1, which centre of mass is above its pivot point. The pendulum can oscillate about the pivoted point and try to fall down on any one side of it. At that time the cart moves on that side and give an upward reaction to the pendulum which counters the unbalance created by the pendulum and make it stable. There must be a proper relation between the angle of tilt of the pendulum (about the vertical while unbalance) and the speed of the cart. If the speed of the cart is more, then it will give more amount of reaction to the pendulum, so that the pendulum will vibrate with high amplitude. If the speed of the cart is less, then it can't give the proper amount of the reaction to the pendulum and the pendulum will fall.

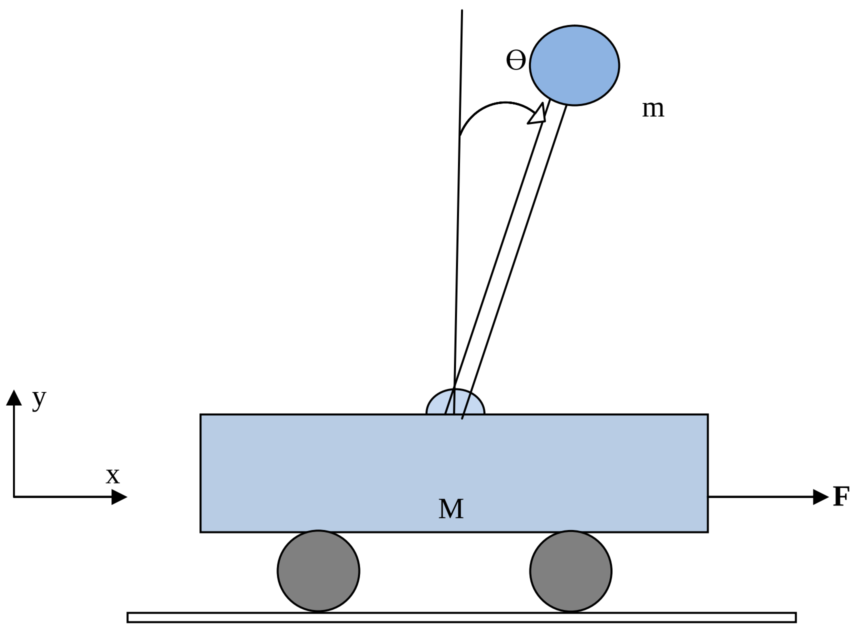

Fig 1.1 Inverted Pendulum

1.3. LAYOUT OF THESIS

The content of the thesis is as follows,

Chapter 1 deals about the introduction of the thesis, which includes the thesis theme, objective and layout. Here we discuss about the requirement of the robot in recent world, and what is the advantage of the two wheeled robot.

Chapter 2 deals with the literature survey. Many literature have reviewed and they have discuss briefly about their approach

Chapter 3 gives an idea about the selection of the equipments required for the robot and the manufacturing of the robot. Here specification of all the parts has been given. The Catia model is shown at the last.

Chapter 4 gives the mathematical modelling of the inverted pendulum. The detail derivation starting from the basic has been given. At last the simulation detail also described.

Chapter 5 says about the working detail and the concept of the balancing of the robot. Here the PID controller and its tuning procedure have been discussed

Chapter 6 gives the result by plotting the graphs for both simulated model and the physical model. Here the simulated model and the experimental model have been compared and the error have been discussed between their performance

Chapter 7 gives the conclusion of the thesis and recommended the future works

CHAPTER 02

LITERATURE SURVEY

2.1. INTRODUCTION

2.2. OVERVIEW OF LITERATURE

2.3. MATHEMATICAL MODELLING

2.4. CONTROLLER USED FOR BALANCING

2.5. SENSORS USED ON DIFFERENT ROBOT

2.1. INTRODUCTION

Many people are researching about the two wheeled self balancing robot now a days and their main area is becoming the balancing concept of the robot rather the robotics platform or the path simulation of the robot. The first two wheeled robot popularly known as the segway Human Transporter is inverted by the Dean Kamen an American entrepreneur. It is a commercial vehicle where one person can drive the vehicle with maximum of 20 km per hours. Now a day's people are using it as roaming purpose in different shopping mall and in Small Park. It is also being used by the police for patrolling purpose in many counties. As it is a commercial product, the safety and performance has taken into deep concentration.

These two wheeled robots are classified as two groups like manual control and automatic control. In manual control operator has to drive the vehicle or give command via remote controller or via Bluetooth controller. Fully automatic control are done by some predefine instructions to the robot. Robot catches the environment by a camera fitted to it and does the necessary work by path planning control. As the two wheeled robot is the semi autonomous robot, the driver determines the speed and direction of the robot by leaning forward and backward. The driver can stand on the platform to feel comfort and for easy steering. In some cases steering mechanism also implemented for better turning experience of the robot.

2.2. OVERVIEW OF LITERATURE

Miranda [1] has studied about the stabilization of the self-balancing robot by implementing PID Controller with Kalman filter in order to remove the noise from sensors. Chee et al. [2] have designed a two wheeled robot using PID controller for balancing and stabilizing. One of the PID control systems is used to control the tilt and angle of the robot and the other two PID control systems are used to control the speed of both left and right DC motors. Taylor et al. [3] have designed and fabricated a Segway with lower centre of mass and used 9 Volts battery. The system is capable of carrying mass up to 2kgs and line following using three photo-resistors as sensors. Ha et al. [4] have used sensor fusion algorithm between multiple sensors to calculate the real-time angle. They implemented Median filter and EKF (Extended Kalman filter) to reduce the noise of the accelerometer signal. Smith et al. [5] have made a self-balancing Segway which follow a line and also have mass carrying capability. PID Control is implemented to balance it. Zhou [6] has designed modelled and controlled the Segway. Project uses two electric scooter motors, two 12V car batteries, Brushed Direct Current (BDC) motor driver (350W 40A), one accelerometer and microprocessors. Modelling of system is also done and PID control is implemented but Segway can move in forward and backward direction only at very low speed and response time is too slow. Lam [7] has focused on balancing the inverted pendulum by moving a cart in horizontal direction. Non-linear heuristic controller and an energy controller successfully balanced the pendulum from downward to upright position and concluded that Energy controller is faster than the other. Mokonop [8] has derived the mathematical model (excluding the model of motors), analysed the system model on Matlab and fabricated it. It used belt system, 24 V DC motors (rated speed of 2500 rpm and a rated current of 6A), sensors (accelerometer, gyroscope and inclinometer) and Motorola HC12 microcontroller. According to mathematical modelling it's settling time is 3.5sec for step input and 4sec using feed forward gain method. It was capable of balancing without falling over. Tsai et al. [9] have used 2 DOF joy stick for the balancing of two wheeled cart by implementation of state feedback technique to stabilize it. The electronic differential steering algorithm was find out using real time modelling and verified experimentally. Ahmad et al. [10] have developed the modular fuzzy control approach for lifting and stabilizing a two-wheeled wheelchair. In the presence of noise and uncertainties, control system is quite robust and managed to stabilize in less than 4sec. Seet et al. [11] have designed a control design technique for the elimination of external disturbance by using techniques of the nested saturation and back stepping control design. Ren et al. [12] have applied the neutral-network like self-tuning PID for stability of two wheeled vehicle. The theoretical and experimentation shows the improvement in system response and have a short recovery time. Ooi [13] has implemented a Linear Quadratic Regulator (LQR) and a Pole-placement controller in balancing the system. The LQR controller uses several weighting matrix to obtain the appropriate control force to be applied to the system while the Pole placement requires the poles of the system to be placed to guarantee stability. As the robot will be moving about on a surface, a PID controller is implemented to control the trajectory of the robot. Ho [14] has uses the concept of inverted pendulum to analyse the two wheeled robot. He has uses two types of semiconductor sensors to provide tilt information. His main focus is on non-linear control strategy and analyses its effectiveness. Li et al. [15] have design and develops the dynamic model and balance control strategy of the robot. A Gibbs-Appell equation is applied to build the dynamic model of two-wheeled robot in this paper. The virtual prototype model of the robot and the state space model with feedback are obtained. They show that the state feedback controller carried on the robot model in the posture and the speed is effective and the dynamical balance process is stable. Laubli et al. [16] have uses Root Locus of Control System for balancing of the robot. Fang [17] has uses PD controller and compare with fuzzy immune PD controller. To make the robotics system more robust, people are attaching many necessary components to satisfy the requirements or enhance the applications. Jeong et al. [18] have design an arm and waist to the two wheeled robot. Similarly Acar [19] have used the manipulator for picking and placing of thing with the two wheeled robot. Besides two wheeled system Haung [20] and Nagarajan et al. [21] have studied about one wheel robot called as unicycle robot. Balancing of ball system are also there in the literature which is studied by Kumaga et al. [22].

2.3. MATHEMATICAL MODELLING

Mathematical modelling is also an important part of the research to analyse the system to its depth. Although the system is highly nonlinear, it is applied after Linearizing it, because of it less complexity. Salerno et al. [23] and Pathak et al. [24] have studied about the Lagrange equation to study the models of two wheeled robot. Lin et al. [25] have applied Newton's law to study the behaviour of the system. Mathematical model is represented by the real system, where inertia is the important factor, which is studied by Chi et al. [26]

2.4. CONTROLLER USED FOR BALANCING

Most of the researchers studied about auto balancing of the robot which includes PID, LQR and different IR technique like fuzzy, neural etc. Oryschuk et al. [27] and Ruan et al. [28] have studied about the LQR control system for analysis. Nasir et al. [29] have used both PID and LQR controller and compare the performance between them. Tirmant et al. [30] have developed fuzzy controller in there robot and Lin et al. [31] have used Adaptive Neural Network for analysis of their robot.

2.5. SENSORS USED ON DIFFERENT ROBOT

Here the sensor what we are using have to give stabilized pitch angle. Sensors what we are using here are the accelerometer and gyroscope sensors which measure angle and the angular rate. Grepl et al. [32] and Jeong et al. [33] have used the accelerometer and gyroscope separately. As the both the sensors are inaccurate in their performance, Choi et al. [34] have uses both the sensor in one unit called IMU and applied Kalman filter for the better performance of the sensors. Tsai et al. [35] have used the IMU sensors which having inbuilt DMP filter for sensors fusion. There are some other angle measurement sensors people have used like Pannil et al. [36] have used the inclinometer and Burdette et al. [37] have used infrared range sensors to measure the pitch angle.

CHAPTER 03

EXPERIMENTAL SETUP

3.1. MICROCONTROLLER (ARDUINO UNO)

- **3.1.1 Overview of Arduino Uno**
- **3.1.2 Power supply of arduino**
- **3.1.3 Arduino pins details**
  - **3.1.4.1 Power pin**
  - **3.1.4.2 Digital pins**
- **3.1.4 Communication facility**

3.2. IMU SENSOR

- **3.2.1 Three Axis MEMS Gyroscope**
- **3.2.2 Three Axis MEMS Accelerometer**
- **3.2.3 Digital Motion Processor**

3.3. MOTOR CONTROLLER

- **3.3.1 Pulse Width Modulation**
- **3.3.2 The H-Bridge Amplifier**

3.4. MOTOR

3.5. FRAME

3.6. WHEEL

3.7. POWER TRANSMISSION

3.8. POWER SOURCE

Table 3.1 Equipments required and their specifications

Sl. no	Equipments	Specification	Nos.
1	Frame	Made of mild steel angle	-
2	Wheel	Small cycle wheel	2
3	Motor	DC motor (wiper motor)	2
4	Motor controller	6-16V, single motor controller	2
5	Microcontroller	Arduino Uno	1
6	Sensor	IMU	1
7	Battery	12V Rechargeable Battery	4

3.1. MICROCONTROLLER (ARDUINO UNO)

3.1.1 Overview of Arduino Uno

Arduino is a single-board microcontroller. The hardware consists of 8-bit Atmel AVR microcontroller, or a 32-bit Atmel ARM. It contain 14 digital pins where 6 are use as PWM, 6 analog pins, one USB port, one power jack and one reset button. For starting, we give the power supply through USB from computer or through power jack. To read the input and output we required to connect the pins to the respective devices. Arduino Uno, Due, Leonardo, Mega 2560, Mega ADK, Micro, Mini, Nano, Ethernet, Esplora etc are the different arduino board. An arduino Uno is shown as Figure 3.1

Arduino is the brain of our robot. It has an ability to sense the data from different sensors, analyse it through program, get the require output and send it to controller. The arduino application is written in java which understands the language like c and c++ for coding.

The arduino Uno has an inbuilt fuse that protects USB port from shorts and overcurrent. Fuse provides an external layer of protection over the computer's internal protection. If higher amount of current (i.e. more than 500 mA) is applied to the USB port, the fuse will automatically break the connection until the short or overload is removed.

Table 3.2 Specification of Arduino Uno

Sl. No.	**Parameters**	**Specifications**
1	Microcontroller	AT mega 328
2	Operating voltage	5V
3	Input voltage(recommended)	7-12V
4	Input voltage(limit)	6-20 V
5	Digital I/O Pins	14(for which 6 provides PWM output)
6	Analog Input Pins	6
7	DC Current per I/O Pin	400 Ma
8	DC Current for 3.3V Pin	50 mA
9	Flash Memory	32 KB(AT mega 328) of which 0.5 KB used by bootloader
10	SRAM	2 KB(AT mega 328)
11	EEPROM	1 KB(ATmega328)
12	Clock Speed	16 MHz
13	Length	68.6
14	Width	53.4
15	Weight	25 g

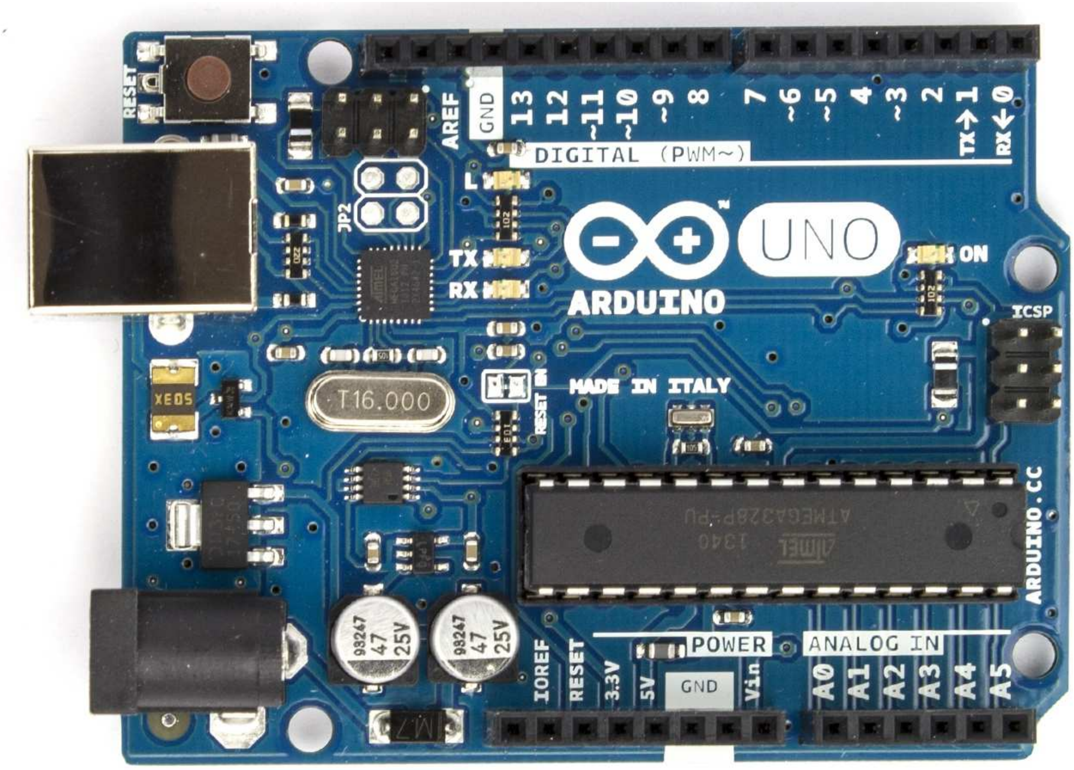

Fig 3.1 View of Arduino Uno

3.1.2 Power supply of arduino

The Arduino Uno required a 5V of input power supply for which, it has a USB port and a power jack. Arduino is connected to the computer through USB port via USB cable which gives a supply of 5V power. Through this USB port we can upload the program to the arduino and can connect to the serial monitor. The power jack is used for supply power from the battery. As normally we used the 12V battery, we need a voltage regulator circuit to drop the voltage from 12V to 5V, as the arduino required a 5V input supply.

The operating voltage of arduino board is 6 to 20 volts. If the supply is less than 7V the board may be unstable, and more than 12V may damage the board. So the recommended voltage range is 7 to 12 volts.

3.1.3 Arduino pins details

3.1.4.1 Power pins

- VIN- For external power supply, this pin gives the supply to the board. This pin is accessed when the supply is given by the power jack.
- 5V- Power to the arduino board is given by the USB or VIN and when 5v power is required by the other device, it is given by the 5v pin.
- 3V3- This pin is same as the 5v pin.
- GND. Ground pins.
- IOREF. This pin on the Arduino board provides the voltage reference with which the microcontroller operates. A properly configured shield can read the IOREF pin voltage and select the appropriate power source or enable voltage translators on the outputs for working with the 5V or 3.3V.

3.1.4.2 Digital pins

Arduino have 14 digital pins and each one can be used as an input or output by using the commands like pinMode (), digital Read (), digital Write (). All the pins operated with 5V supply. All pins have internal pull-up resistor which can receive current up to 40 mA.

- Serial- 0 (RX) and 1 (TX) denotes receive and transmit, which are used to receive and transmit data.
- External Interrupts- For low values and change in the required value, this pin trigger the interrupts.
- PWM- These pins are responsible for the speed variations with analogWrite () function
- SPI- By the help of SPI library, to support SPI communication these pins are used.

- LED- Pin 13 is connected with a LED light. If this pin is declared it will be ON when it receive HIGH value and OFF when receive LOW value.
- The Uno has 6 analog inputs named A0 to A5, used for analog inputs. A4 is called SDA pin and A5 called SCL pin
- AREF. Reference voltage for the analog inputs.
- Reset- Used to reset.

3.1.4 Communication facility

Arduino Uno can be connected with the computers via USB cable. After installing the software of arduino we have to define the type of arduino we are using i.e. Uno, Mega etc and also have to define the port we are using. For different device the port connected is different. Then we can connect it to the sensors and data can be read by the arduino. We can show the required data on opening serial monitor.

3.2. IMU SENSOR

Inertia Measurement Unit called is IMU sensor is an electronics device that measure velocity, orientation and gravitational forces by using combination of accelerometers and gyroscopes. The MPU-6050 which is an IMU sensor contains a MEMS accelerometer and a MEMS gyro and a digital motion processor (DMP) in a single chip. It is very accurate in measurement. The sensor uses the I2C-bus to interface with the Arduino. MPU 6050 is shown in the Figure 3.2.

The gyro sensor measures the angular velocity and orientation. Unfortunately, the gyro drifts over time. That means if it runs for long period, it gives error. But it is very precise for a short time. The accelerometer measures the acceleration in three dimensions but it is quite unstable and gives noisy data.

Table 3.3 Specification of IMU sensor

Sl. No	Parameters	Specification
1	Power supply	3-5 V
2	Mounting type	Surface mount
3	Operating temperature	40-150 ^{0}c
4	DOF	3(yaw, pitch, roll)
5	Sensor	3 axis accelerometer and gyro sensor
6	DMP	Inbuilt

Fig 3.2 View of IMU sensor

3.2.1 Three Axis MEMS Gyroscope

The MPU 6050 contain 3 axis gyroscopes for x, y and z axis. When the gyro senses the angular rotation about any of this axis, a vibration is observed by capacitive pickoff due to the Coriolis Effect. After amplifying, demodulating and filtering these signal gives a voltage output which is proportional to the angular rate. This voltage output is digitalized and shown as angular deviation.

3.2.2 Three Axis MEMS Accelerometer

The MPU 6050 also contain 3 axis Accelerometer on three axis by separate proof mass. Acceleration on any axis causes displacement on that particular proof mass, which is detected by the capacitive sensor.

3.2.3 Digital Motion Processor

The MPU 6050 contain inbuilt DMP filter to filter the data from the accelerometer and gyro sensor. DMP algorithm fuse both the data get a desire angle of tilt as output.

3.3. MOTOR CONTROLLER

Motor controller is always required when versatility in the motor performance is needed. Direct current supply can obvious to run the motor but only in one direction and at a single speed. When there is a requirement of speed and direction variation it is necessary to have a motor controller with addition to a motor. It can also have the ability to start and stop the motor automatically. The speed variation is done by PWM (Pulse Width Modulation) by regulating the voltage supply. We are using a 6 to 16 volts operating motor controller. It can drive a single motor at a time.

3.3.1 Pulse Width Modulation

By changing the duty cycle of the signal PWM produces a analog output. The PWM changes the speed of the by adjusting these duty cycle by varying the voltage supply to the motor.

3.3.2 The H-Bridge Amplifier

It amplifies the PWM signal to produce a proportional voltage output which is sufficient to drive the motor. To get the different speed the motor terminals are swapped by this H-Bridge. It has got two logic input and two different voltage sources for control of motor on both directions.

Table 3.4 Specification of the Motor Controller

Sl. No	Parameters	Specifications
1	Operating voltage	6V to 16 V
2	Continuous O/P current	20Amp
3	Peak O/P current	30Amp
4	Maximum PWM Frequency	20 KHz
5	Current sense	0.13V per Amp
6	Size	84.7× 44.7 mm

Fig 3.3 View of motor controller

3.4. MOTOR

Motor is taken as per the rpm and torque requirement. Here we require a low rpm with high torque capacity motor, as the speed is not so high. A 12V DC double speeds wiper motor has taken.

Table 3.5 Specifications of Motor

Sl. no	Parameters	Specification
1	Type	DC motor
2	Voltage	12 V
3	Power rated	60W
4	No load current	2.5 Amp
5	Load current	6.5 Amp
6	Load speed	65 RPM
7	Weight	2.5 kg

Fig 3.4 View of motor

3.5. FRAME

The major constraints on the frame design were high strength to weight ratio, availability, and versatility in joining. For this L shaped channel of mild steel is preferable, because L shaped is better in resisting bending and mild steel is easily available. Making of frame is easy with simple fabrication like welding, drilling, and cutting. Channel is cut with appropriate length and joined with require parts by welding or bolting as per the requirement. Strength of the frame should be high, so that it can sustain the weight of the operator and the accessories like battery, motor without bending.

3.6. WHEEL

The wheel are designed to carry the load of the robot itself and mass placed on it. For this purpose simple and easily available cheapest small cycle wheel has taken. Larger wheel is more preferable. The reason for the large wheel is, more of the components were able to place under the axle, thereby lowering the centre of mass of the cart. With a lower centre of mass balancing of cart would occur more naturally.

Table 3.6 Specification of wheel

Sl. No	Parameters	Specifications
1	Wheel outer diameter	19cm
2	Wheel inner diameter	15cm
3	Hub outer diameter	4cm
4	Hub inner diameter	3cm

Fig 3.5 View of wheel

3.7. POWER TRANSMISSION

Transmission of power from motor to wheel should be taken carefully, so that power loss will be less and operate safely at differential speed. Chain drive is the simplest, cheapest and easily available in the market but alignment of motor gear with wheel gear should be taken care separately. Misalignment may stuck the wheel rotation or may create jumping of the chain from the gear.

3.8. POWER SOURCE

12V rechargeable battery gives the require amount of power supply to run the robot, which is connected to the motor through the motor controller and is the only power source to the motor. We have used 4 nos. of battery having parallel connection with each other. More number of batteries gives more power, but simultaneously increases the weight of the robot. Batteries are placed under the base of the robot, so that the centre of gravity will go down and increase the stability of the robot.

Table 3.7 Specification of Battery

Sl. No	Parameters	Specifications
1	Nominal voltage	12V
2	Nominal capacity	7 Amp
3	Discharge current	350mA
4	Size	150.1x65 x94 mm
5	Weight	2.7 kg

Fig 3.6 View of battery

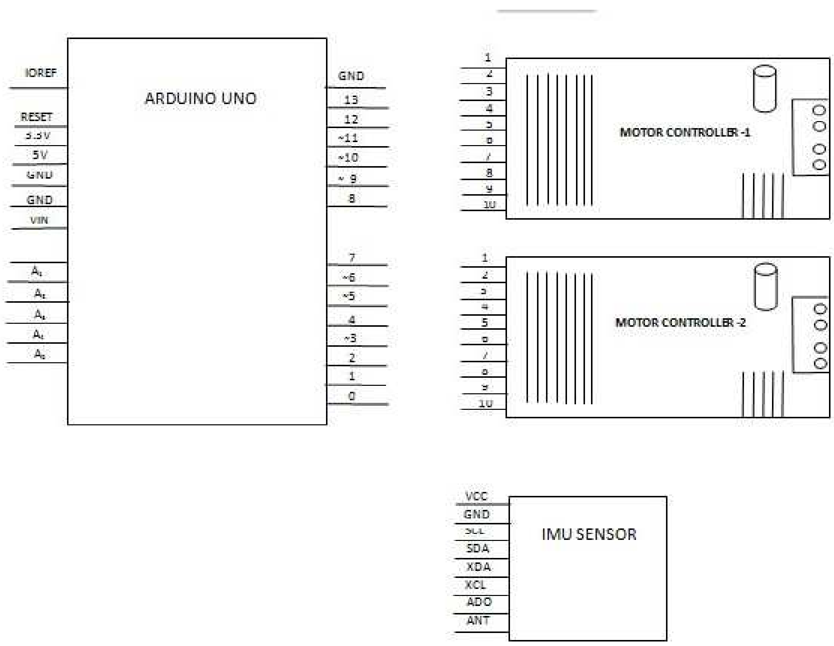

Fig 3.7 Line diagram of Arduino, Controller and IMU

After selecting the equipments, the 3D model has been made by using the Catia software. The 3D model gives the proper guidance to make the real model. Catia model made have shown below.

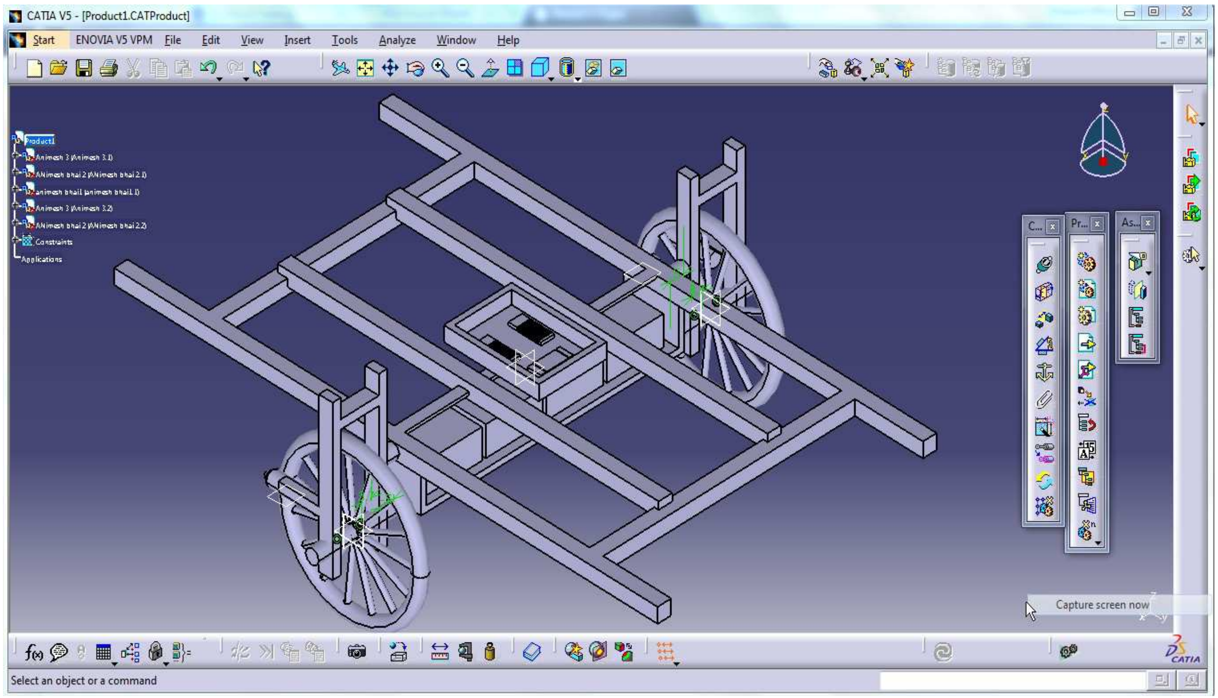

Fig 3.8 Catia Model of the Robot

CHAPTER 04

MATHEMATICAL MODELING
AND
SIMULATION

4.1. MATHEMATICAL MODELING

The robot has made by taking the principle of inverted pendulum. So by the free body diagram of the inverted pendulum we can analyse the forces induced and can deduce the transfer function for the robot. The fig 3 and fig 4 shows the inverted pendulum and its free body diagram respectively.

4.1.1 Specifications

M= mass of the cart

m= mass of the pendulum

b= coefficient of friction for the cart

l= length to pendulum center of mass

I= mass moment of inertia of the pendulum

F= force applied to the cart

x = cart position coordinate

ϴ= pendulum angle from vertical

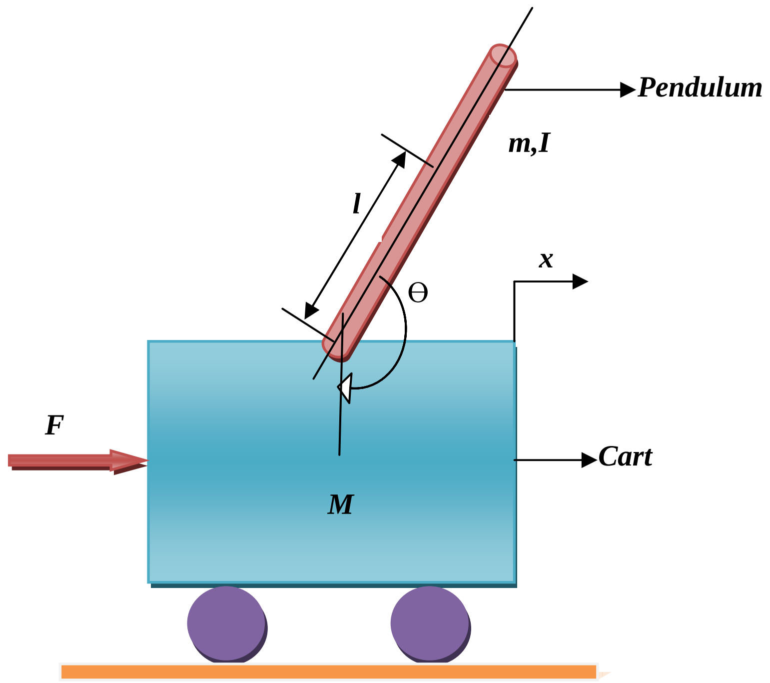

Fig 4.1 View of Inverted Pendulum on cart

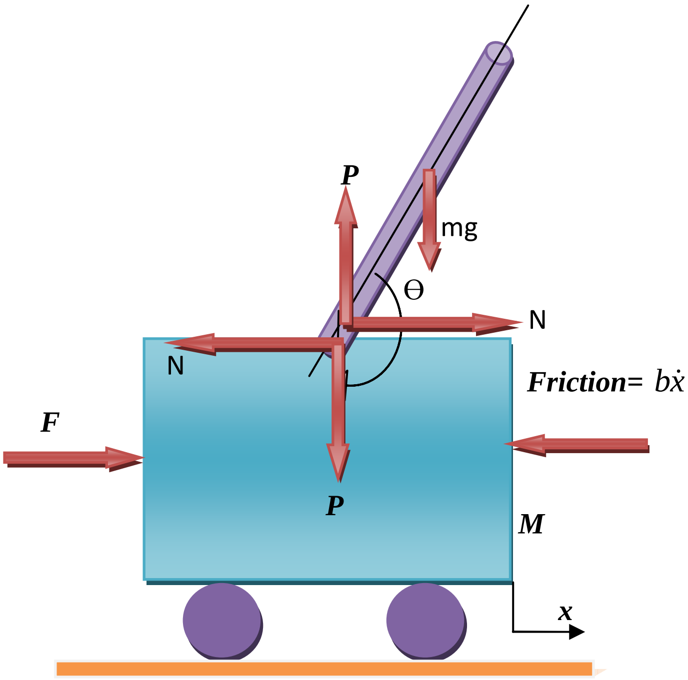

Fig 4.2 Free Body Diagram of Inverted Pendulum

From the free body diagram of then cart, we resolve forces in the x-direction and in y-direction and by adding we can deduce the equations of motion as follows,

FOR CART:

Taking summation of the horizontal forces

$$\sum F_x = (F - N - b\dot{x}) \tag{4.1}$$

We know,

$$F = Ma = M\ddot{x}$$

$$\Rightarrow \ddot{x} = \frac{1}{M}\sum F_x = \frac{1}{M}(F - N - b\dot{x}) \tag{4.2}$$

Similarly,

$$\ddot{\theta} = \frac{l}{I}\sum \tau = \frac{l}{I}(-Nl\cos\theta - Pl\sin\theta) \tag{4.3}$$

FOR PENDULUM,

$$m\ddot{x}_p = \sum F_x = N \tag{4.4}$$

$$m\ddot{y}_p = \sum F_y = P - mg \tag{4.5}$$

$$\Rightarrow P = m(\ddot{y}_P + g) \tag{4.6}$$

DISPLACEMENTS

Position of the pendulum on x-axis will be,

$$x_p = x + l\sin\theta \tag{4.7}$$

Taking the first derivative w.r.t time 't',

$$\Rightarrow \dot{x}_p = \dot{x} + l\dot{\theta}\cos\theta \tag{4.8}$$

Taking the second derivative w.r.t time 't',

$$\Rightarrow \ddot{x}_p = \ddot{x} - l\dot{\theta}^2\sin\theta - l\ddot{\theta}\cos\theta \tag{4.9}$$

Similarly on y-axis

$$y_p = -l\cos\theta \tag{4.10}$$

Taking the first derivative w.r.t time 't',

$$\Rightarrow \dot{y}_p = l\dot{\theta}\sin\theta \tag{4.11}$$

Taking the second derivative w.r.t time 't',

$$\Rightarrow \ddot{y}_p = l\ddot{\theta}\sin\theta - l\dot{\theta}^2\cos\theta \tag{4.12}$$

We know, from equation no. (4.4)

$$N = m\ddot{x}_p \tag{4.13}$$

Putting the value of equation (4.9) on (4.13) we have,

$$\Rightarrow N = m(\ddot{x} - l\dot{\theta}^2\sin\theta - l\ddot{\theta}\cos\theta) \tag{4.14}$$

Similarly, putting the value of equation (4.6) on equation (4.12) and solving we get,

$$P = m(l\ddot{\theta}\sin\theta - l\dot{\theta}^2\cos\theta) \tag{4.15}$$

Taking the summation of horizontal forces of the cart

$$M\ddot{x} + b\dot{x} + N = F \tag{4.16}$$

Taking the summation of horizontal force of the pendulum

$$N = m\ddot{x}_p \tag{4.17}$$

$$\Rightarrow N = m(\ddot{x} - l\dot{\theta}^2\sin\theta - l\ddot{\theta}\cos\theta) \tag{4.18}$$

Putting the value of 'N' in the equation number (4.16) we get,

$$M\ddot{x} + b\dot{x} + m\ddot{x} - ml\dot{\theta}^2\sin\theta - ml\ddot{\theta}\cos\theta) = F \tag{4.19}$$

$$\Rightarrow (M+m)\ddot{x} + b\dot{x} - ml\dot{\theta}^2\sin\theta - ml\ddot{\theta}\cos\theta = F \tag{4.20}$$

This equation is called non-linearized governing equation

Taking the summation of vertical forces of the pendulum

$$P\sin(180-\theta)-mg\sin(180-\theta)-N\sin(\theta-90) \quad (4.21)$$

$$=P\sin\theta-mg\sin\theta+N\cos\theta \quad (4.22)$$

$$=m\ddot{x}\cos\theta+ml\ddot{\theta}\cos^2\theta-ml\dot{\theta}^2\sin\theta*\cos\theta+ml\ddot{\theta}\sin^2\theta+ml\dot{\theta}^2\sin\theta*\cos\theta \quad (4.23)$$

$$=m\ddot{x}\cos\theta+ml\ddot{\theta} \quad (4.24)$$

Taking the moment at the pivot point

$$-Pl\sin\theta-Nl\cos\theta=I\ddot{\theta} \quad (4.25)$$

We know from the equation, (4.25)

$$P\sin\theta+N\cos\theta-mg\sin\theta=ml\ddot{\theta}+mx\cos\theta \quad (4.26)$$

Multiplying ‘l’ in the above equation, we get

$$\Rightarrow Pl\sin\theta+Nl\cos\theta-mgl\sin\theta=ml^2\ddot{\theta}+mlx\cos\theta \quad (4.27)$$

Adding equation number (4.25) and (4.27), we will get

$$\Rightarrow -mgl\sin\theta=ml^2\ddot{\theta}+ml\ddot{x}\cos\theta+I\ddot{\theta} \quad (4.28)$$

$$\Rightarrow mgl\sin\theta+ml^2\ddot{\theta}+I\ddot{\theta}=-ml\ddot{x}\cos\theta \quad (4.29)$$

$$\Rightarrow mgl\sin\theta+(ml^2+I)\ddot{\theta}=-ml\ddot{x}\cos\theta \quad (4.30)$$

This equation is called non-linearized governing equation

4.1.2 Linearization of the equation

To analyse the control system, the set of equation need to be linearized, specifically on the vertical axis, so that the pendulum become equilibrium in the upward position. Let ϕ represent the angle of deviation from the vertical position so that,

$$\theta = \pi + \phi \tag{4.31}$$

$$\Rightarrow \cos\theta = \cos(\pi + \phi) = -\cos\phi \tag{4.32}$$

$$\Rightarrow \sin\theta = \sin(\pi + \phi) = -\sin\phi \tag{4.33}$$

Assuming for very small deviation, ϕ be very small so that,

$$\cos\theta = -\cos\phi = -1 \tag{4.34}$$

$$\sin\theta = -\sin\phi = -\phi \tag{4.35}$$

As derivative of small thing is negligible (to zero),

$$\dot{\theta}^2 = \dot{\phi}^2 = 0 \tag{4.36}$$

Putting these approximation values in the equation (4.20) and (4.30) we will have two linearized governing equations of motion,

$$mgl\phi + (ml^2 + I)\ddot{\phi} = -ml\ddot{x} \tag{4.37}$$

$$(M + m)\ddot{x} + b\dot{x} - ml\ddot{\phi} = U \tag{4.38}$$

Above equations (4.37) and (4.38) are called the linearized governing equations of motion,

4.1.3 Transfer function

Transfer function of the linearized equation taking Laplace transform of the system assuming zero initial condition,

$$(ml^2 + I)\phi(s)s^2 + mgl\phi(s)s = -mlx(s)s^2 \quad (4.39)$$

$$(M+m)x(s)s^2 + bx(s)s - ml\phi(s)s^2 = U(s) \quad (4.40)$$

Now from equation (4.39), we have

$$x(s) = \left[\frac{I+ml^2}{ml} - \frac{g}{s^2} \right] \phi(s) \quad (4.41)$$

Putting the value of 'x(s)' in the equation (4.40), we get

$$(M+m)\left[\frac{I+ml^2}{ml} - \frac{g}{s^2} \right] \phi(s)s^2 + b\left[\frac{I+ml^2}{ml} - \frac{g}{s^2} \right] \phi(s)s - ml\phi(s)s^2 = U(s) \quad (4.42)$$

$$\Rightarrow (M+m)\left[\frac{(I+ml^2)s^2 - gml}{mls^2} \right] \phi(s)s^2 + b\left[\frac{(I+ml^2)s^2 - gml}{mls^2} \right] \phi(s)s - ml\phi(s)s^2 = U(s) \quad (4.43)$$

$$\frac{U(s)}{\phi(s)} = \frac{(M+m)(I+ml^2)s^4 - (M+m)gmls^2}{mls^2} + \frac{b(I+ml^2)s^3 - gbmls}{mls^2} - mls^2 \quad (4.44)$$

$$\frac{U(s)}{\phi(s)} = \frac{(M+m)(I+ml^2)s^4 + b(I+ml^2)s^3 - (M+m)gmls^2 - gbmls - (ml)^2 s^4}{mls^2} \quad (4.45)$$

$$\frac{\phi(s)}{U(s)} = \frac{mls^2}{\left[(M+m)(I+ml^2) - (ml)^2 \right] s^4 + b(I+ml^2)s^3 - (M+m)gmls^2 - gbmls} \quad (4.46)$$

$$\frac{\phi(s)}{U(s)} = \frac{\frac{ml}{q} s^2}{s^4 + \frac{b(I+ml^2)}{q} s^3 - \frac{(M+m)gml}{q} s^2 - \frac{gbml}{q} s} \quad (4.47)$$

Where,

$$q = (M+m)(I+ml^2) - (ml)^2 \quad (4.48)$$

Both pole and zero at origin, so transfer function is given by the equation (4.49) and (4.50)

$$P_{pend}(s)=\frac{\phi(s)}{U(s)}=\frac{\frac{ml}{q}s}{s^3+\frac{b(I+ml^2)}{q}s^2-\frac{(M+m)gml}{q}s-\frac{gbml}{q}} \tag{4.49}$$

Similarly for cart,

$$P_{cart}(s)=\frac{x(s)}{U(s)}=\frac{\frac{(I+ml^2)s^2-gml}{q}}{s^4+\frac{b(I+ml^2)}{q}s^3-\frac{(M+m)gml}{q}s^2-\frac{gbml}{q}s} \tag{4.50}$$

4.1.4 State space

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dot{\theta}\\ \ddot{\theta}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0 & 0\\ 0 & \frac{\text{-(I+ml}^2)b}{\text{I(M+m)Mml}^2} & \frac{m^2gl^2}{\text{I(M+m)Mml}^2} & 0\\ 0 & 0 & 0 & 1\\ 0 & \frac{-mlb}{\text{I(M+m)Mml}^2} & \frac{mgl(M+m)}{\text{I(M+m)Mml}^2} & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}0\\ \frac{\text{-(I+ml}^2)b}{\text{I(M+m)Mml}^2}\\ 0\\ \frac{ml}{\text{I(M+m)Mml}^2}\end{bmatrix}u \tag{4.51}$$

$$y=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \theta\\ \dot{\theta}\end{bmatrix}+\begin{bmatrix}0\\ 0\end{bmatrix}u \tag{4.52}$$

4.2. SIMULATION MODEL

Simulation is done by MATLAB using Simulink library. Simulation model contain a plant model, PID controller, pulse generator to give the force and a scope to analyse the graph. All the data of the physical model like mass of the pendulum, mass of the cart and their centre of gravity distances etc are inserted to the Matlab command bar. The above derive transfer function also inserted to the function library of the plant model. PID controller is well tuned to get the satisfied result. The plant model is made by taking the equation of motion of inverted pendulum as reference. The PID controller block is added to the plant model to get the correct tilt angle. To balanced the robot at any critical condition we have to tune the PID controller, so that the overshot and settling time will less.

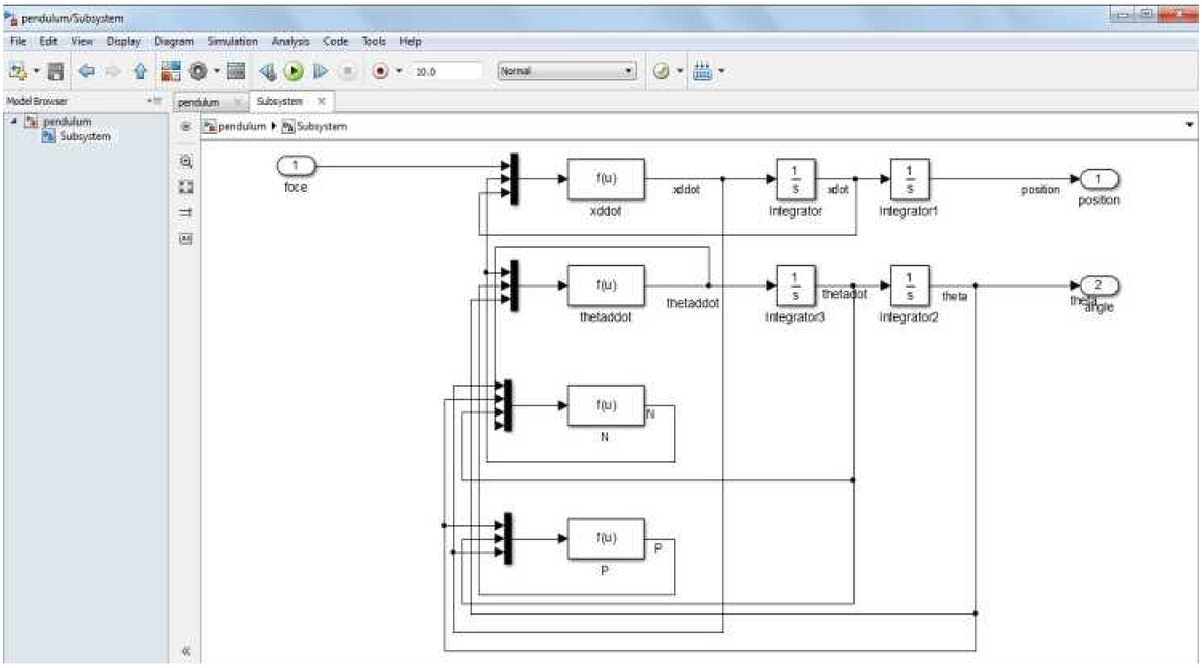

Fig 4.3 Plant Model for Simulation

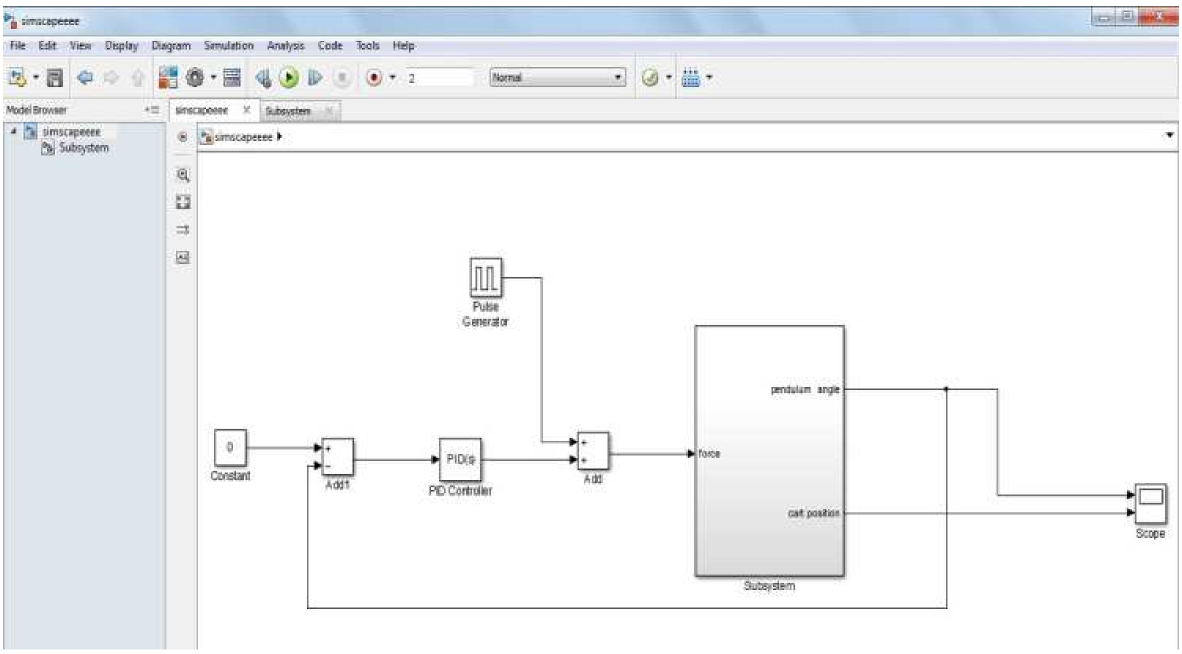

Fig 4.4 Simulink block Diagram

CHAPTER 05

WORKING DETAILS AND BALANCING CONCEPT OF THE ROBOT

5.1. WORKING DETAILS OF THE ROBOT

The robot is consists of 6 numbers of equipments namely,

- Battery
- Sensor
- Microcontroller
- Motor controller
- Motors
- Wheels

Objective of the project is to rotate the wheels in required direction (clockwise or anticlockwise) depending on the angle tilt of the base of the robot. We require to change the direction and speed of the robot at any time as required, which is carried out by the motor controllers.

➢ Battery

Battery is the only power source which give power supply to the motor, motor controller and the arduino as per their voltage requirements.

➢ Sensor

Sensor sends the amount of deviation to the arduino as every fraction of seconds when the power supply is turn on. Here in IMU sensor three angles of tilts are generated such as yaw, pitch and roll about z, y and x axis respectively. As our robot have required only deviations about y-axis, so among the three data sends by the sensor only the pitch is the required data for us.

➢ Microcontroller

By connecting the arduino board to the computer and installing its software and adjusting the ports on the arduino, we can upload the sensor code to the arduino board and also see the data coming out from the sensor by clicking the serial monitor. The serial monitor data is shown in the figure 5.1. As our robot has one degree of freedom only the pitch value date among the yaw, pitch and roll is required. Taking into consideration to this angle of tilt, the user decides the motor output (i.e. the direction and speed of the motor) through the motor controllers. User has to write the code for the motor output on the basis of angle of tilt with in an if clause where it has to defined the range of the motor output for a range of the tilt angles. But this method will not work properly i.e. the balancing of the robot will not be up to mark. For better balancing of the robot, we can use different IR technique like fuzzy, neural network, genetic algorithm and Neuro-Fuzzy etc. We have used the PID controller in our robot.

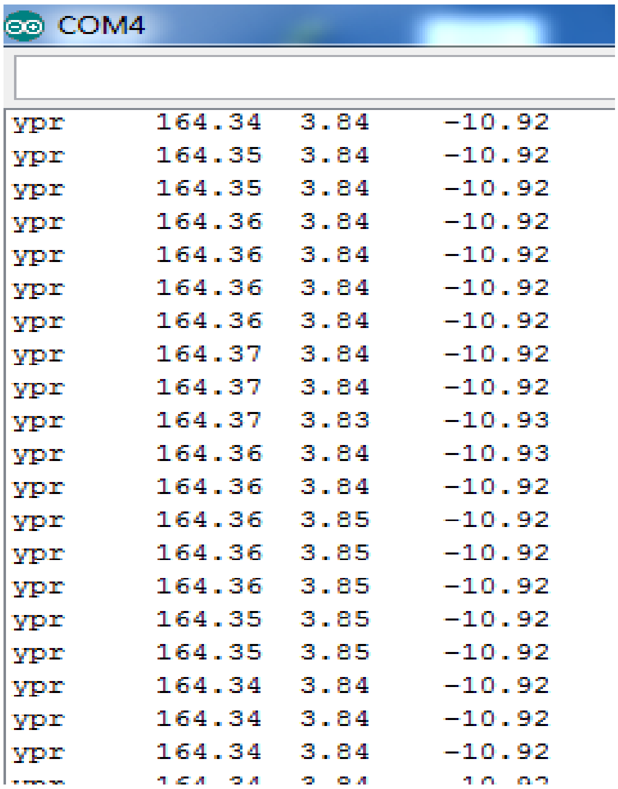

Fig 5.1 View of Serial Monitor Data

- Motor controller

Motor controller gets the data from microcontroller and sends it to its respective motors. The speed and direction can be varied by changing the voltage output of the controller. We have to vary the motor output from 0 to 255 (duty cycle) to vary the speed of the motor where

0 is called always off condition i.e. motor will stop spinning and 255 is called always on i.e. motor will spin with highest speed.

- Motor

By getting the voltage output the motor will start rotating with respective speed and direction, which further transfer the output to the rigidly connected wheels. Transfer of data from sensor to the wheel is shown in the figure 5.2.

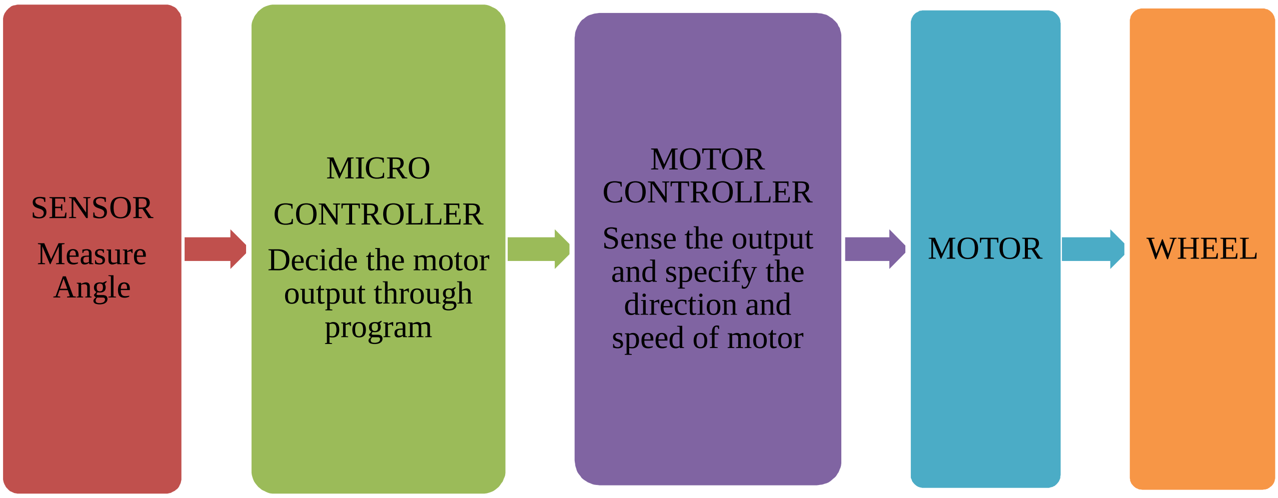

Fig 5.2 Line diagram of the control system

5.2. CONCEPT OF BALANCING

Balancing of the robot is a simple concept. It is same as the principle inverted pendulum and a rod on the palm. The only process of balancing is to move the base of the robot on that direction where it is falling by applying force to the base, as we are moving our hand to balance a rod on the palm. This action keep the centre of mass of the rod above the base of the rod like the robot has to keep its centre of mass above its axis of rotation.

So balancing of two wheeled robot implies keeping the robot upright in vertical position. It is obvious that being an unstable system the robot will try to fall down in any one side from its horizontal plane and this angle of tilt is measured by IMU sensor filtered by kalman or

DMP. As per the angle measured the speed of the motor is decided. So to achieve balance the motor start rotating in the same direction of tilt giving an opposite moment to the chassis of the robot which counter the instability of the system. The speed of the motor should be proportional to the angle of tilt of robot and the relation between them also should perfect to get better balancing. If the speed is very high, motor will give a high amount of moment which causes a high amplitude vibration causing the robot more unstable and if it is less it will not give the require amount of torque to the robot and the robot will unstable.

The simple procedure followed to make the robot balanced is, for less amount of angle tilt, the motor speed should be less and for high tilt angle motor speed should be high. But for this the torque of the motor should be high enough to pull the weight of the whole mass of the chassis. Anyway when the robot will start it will be unstable for some time and it will vibrate with large amplitude, but later on it will be balanced. The range for angle of tilt and respective motor's duty cycle for both forward and backward motion of the wheels are shown below in table. This data have shown only to know the concept of balancing of the robot i.e. at lower tilt the motor speed is less and high tilt motor speed is high, however the logic will not work properly without using PID controller.

The robot can't be balanced if the angle of tilt is very high, because the gravity and weight of the robot will be more dominating over the thrust given by the motor. The angle of tilt should be in a particular zone for both positive and negative side of the vertical balanced position. If the robot is out of that zone than the user have to bring it to the balanced zone and after than the robot will try to balance it as quick as possible. So while keeping the robot in motion, robot must be on a small tilting position till the goal is reached by it. After getting the goal the rider has to take it to the balanced zone, than the robot will make the centre of mass of the robot vertically upward. As long as the robot is upright the robot stays stationery.

Table no. 5.1 Relation between angle of tilt and duty cycle of motor for forward direction

Sl. No	Angle of Tilt	Motor Duty Cycle	Wheel Direction
1	2.45-3.15	50	Forward
2	3.15-3.95	80	Forward
3	3.95-4.95	100	Forward
4	4.95-5.95	150	Forward
5	5.95-7.95	190	Forward
6	7.95-10.95	210	Forward
7	10.95-13.95	250	Forward

Table no. 5.2 Relation between angle of tilt and duty cycle of motor for backward direction

Sl. No	Angle of Tilt	Motor Duty Cycle	Wheel Direction
1	1.75	50	Backward
2	0.95	80	Backward
3	-0.5	100	Backward
4	-1.5	150	Backward
5	-3.5	190	Backward
6	-6.5	210	Backward
7	-9.5	250	Backward

By implementing the PID controller with proper tuning we can get the satisfactory result. Tuning involve the proper implementation of the proportional, integral and derivative constant so that the overshot and settling time will be less. With high overshot the robot will vibrate a lot and with high settling time and the balancing will be delayed which is not satisfactory.

5.3. PID CONTROLLER

5.3.1 Overview

Since 1939 the PID controller is being used by most of the industry worldwide. An investigation says that on 1989 about 90% of the process industry used the PID controller and also the advance version of the PID controller.

The popularity of the PID controller is due to its simple procedure and its performance. PID stands for proportional, integral and derivative gains, multiplied by a error value which is the difference between the desire value and the actual value. The error is denoted by ‘e’. This error is send to the controller where the integral of the error and derivative of the error is computed. The plant receive a signal which is the summation of the proportional times the magnitude of error with integral times the integral gain of the error and with derivative times the derivative gain of the error. These three gains are set properly to get the exact result, which is also called as PID tuning. After receiving the signal the plant gives an output feedback to find the new error after comparing. Then again the derivative and integral of error is calculated and process goes on till the final result. Proportional gain improve the rise time, derivative gain improve the overshoot and integral control improve the steady state error. PID controller equation is given by the equation 5.1 and the PID schematic diagram is shown by the figure number 5.3. By taking Laplace Transform of the equation 5.1 we can compute the Transfer function, which is shown by the equation 5.2.

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_p \frac{de}{dt} \tag{5.1}$$

$$K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \tag{5.2}$$

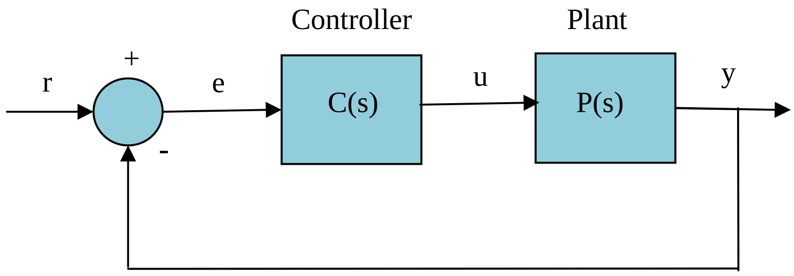

Fig 5.3 PID Controller Schematic Diagram

5.3.2 PID Tuning

Changing of the three gains value, so that the input to the plant will reach the desire value is called the PID tuning. These three values are denoted by Kp, Ki, Kd. We can manually change the values in the PID algorithm of arduino program and directly can observe the result on the physical model, but this process is quite risky as the physical model may get damage.

So we can use the Matlab to evaluate the proper gains. For this we should have one mathematical model of the system so that the gains are manually change to get the optimum value and the result can be observe by the simulation model, made by the Simulink library of the Matlab. Matlab also provides an inbuilt PID tuner, which can automatically tune the gain value.

CHAPTER 06

RESULT AND DISCUSSION

6.1. SIMULATION RESULT

6.2. EXPERIMENTAL RESULT

6.3. ERROR EVALUATION

6.1. SIMULATION RESULT

From the Matlab Simulink model, we can plot different responses by taking the time on x-axis and angle of tilt on y-axis, applying range of impulses. Here for all the iteration the responses will be same; the only difference between them is on the maximum overshoot and on the settling time. The only objective here in the discussion part is to analyse the feasibility of the settling time and maximum overshoot. Maximum overshoot is the maximum amplitude of vibration and the settling time denoted how much time the robot is taking to have vertical up ride position. Higher settling time and overshoot will make the result unsatisfactory. If anyone from these two data gets deviate more though having exact value of other, it will make the robot incorrect in its action. Here for robot we have designed should have maximum of plus or minus 10 degree of overshoot as per the capacity of motor used. The settling time must be less than 20 sec to have a quick response of the robot. The simulation plot is shown in the figure 6.1 to 6.8.

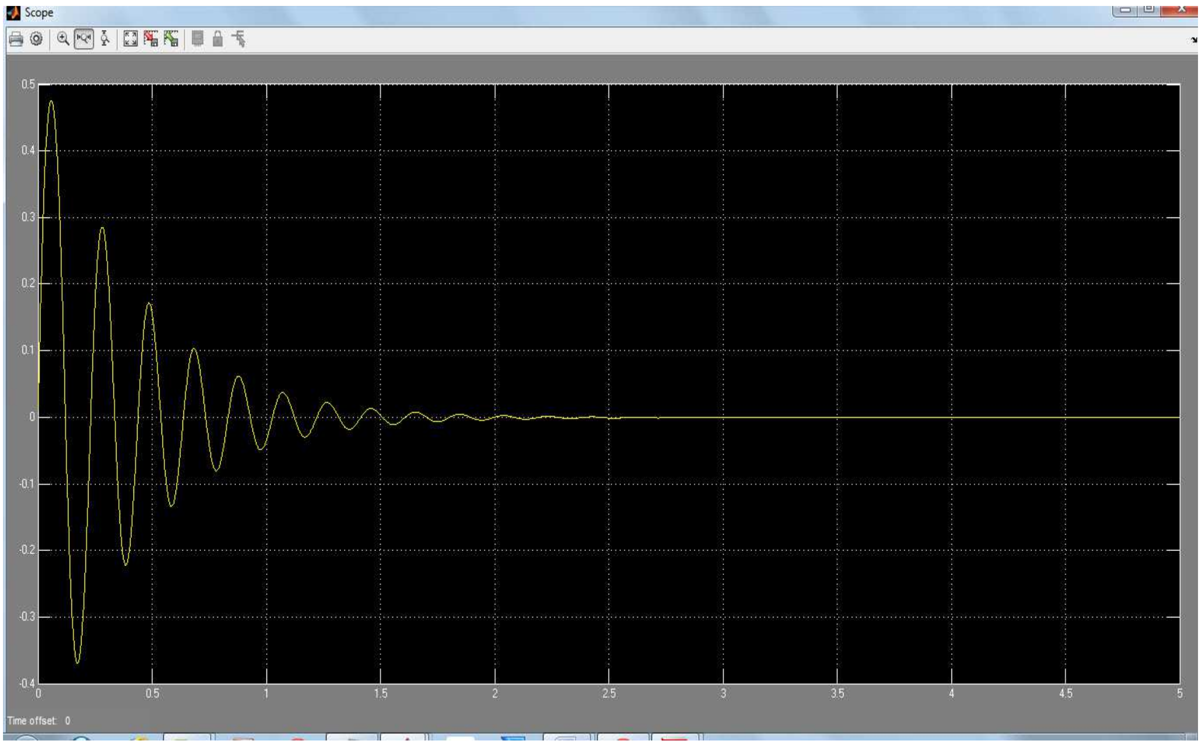

Fig 6.1 Simulation Result for first iteration

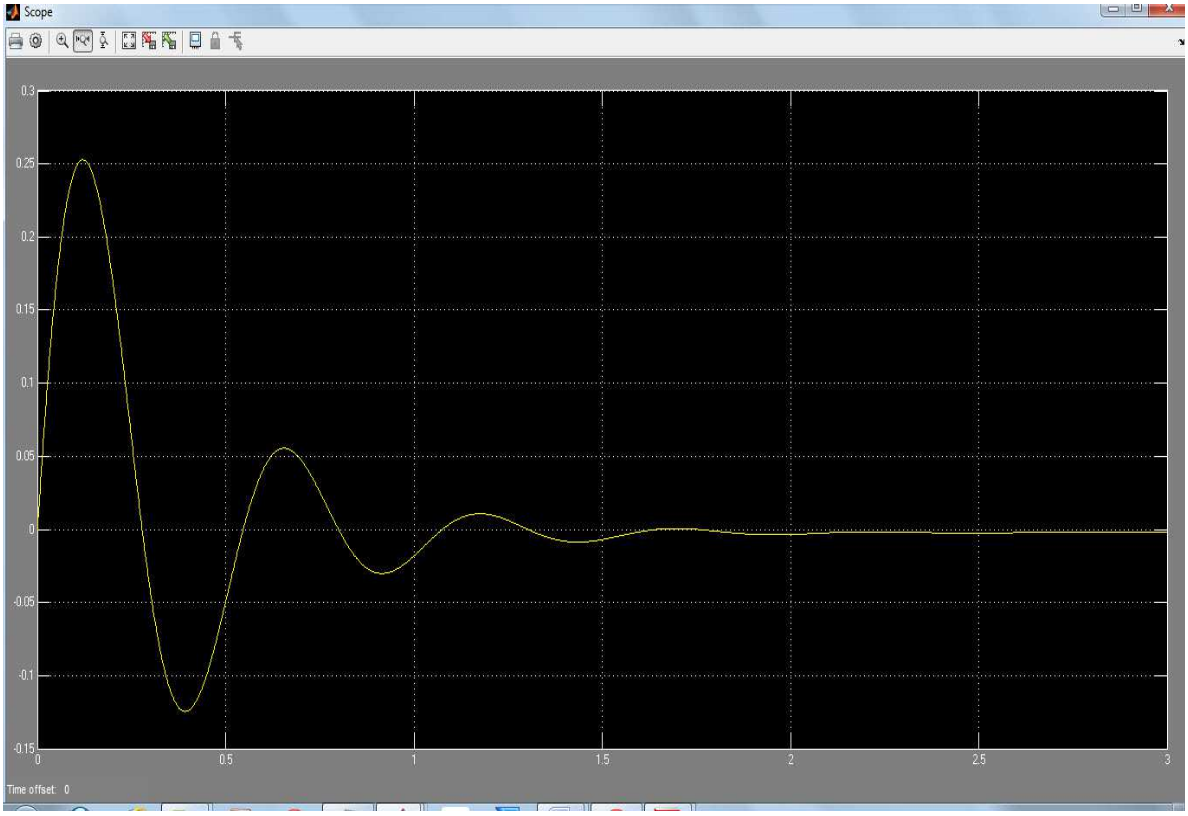

Fig 6.2 Simulation Result for second iteration

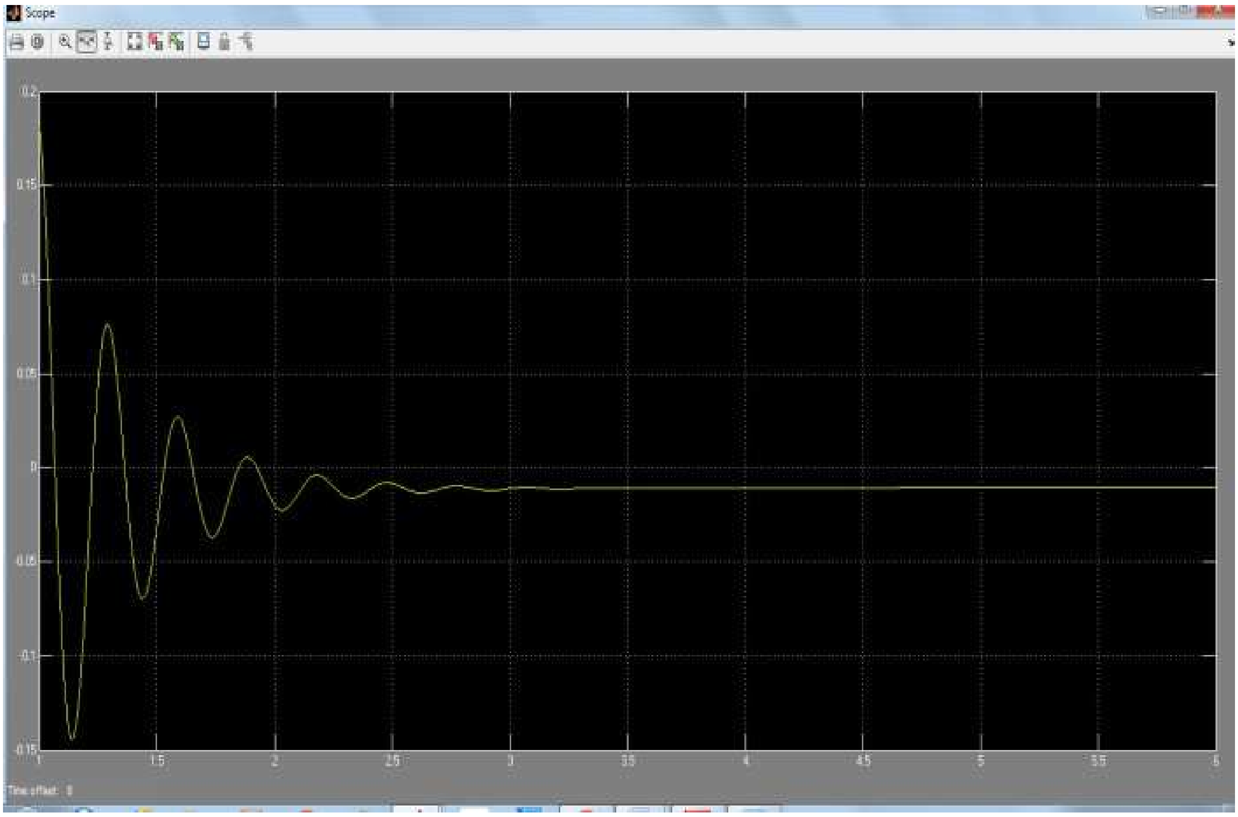

Fig 6.3 Simulation Result for third iteration

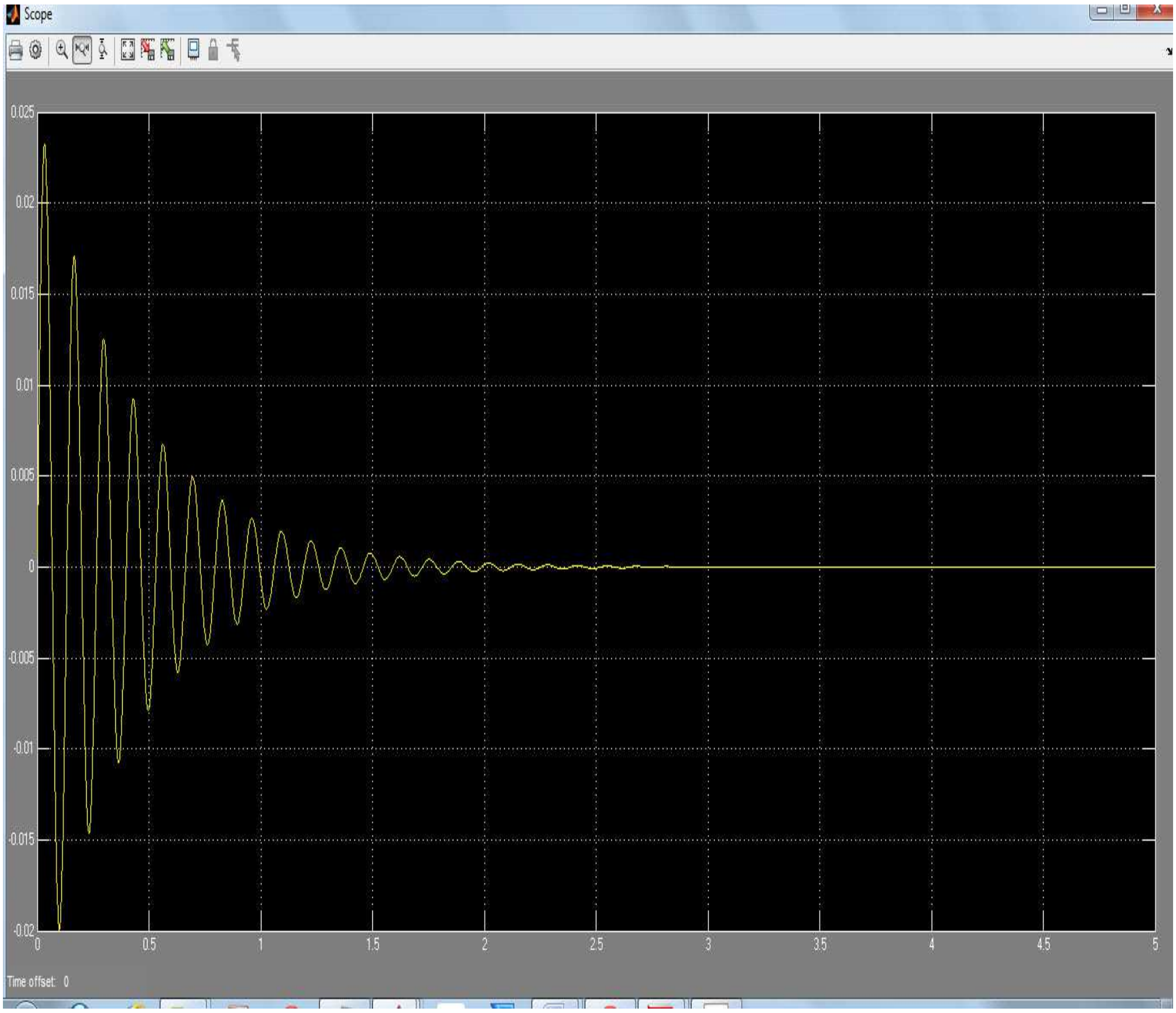

Fig 6.4 Simulation Result for forth iteration

6.2. EXPERIMENTAL RESULT

Getting experimental response is quite easy as compare to the simulation result. Here we have to connect the robot to the computer through the USB port of the Arduino and on Matlab we have to define the port of the Arduino we are using and also the Baud Rate. All the required data like the PID controller tuned values are given to the experimental setup through the arduino code. Then the serial monitor is opened by Matlab with command 'fopen' and the data from the sensor is plotted by taking robot running time on x-axis and angle of tilt on y-axis. When the robot will run the variation is shown by the serial monitor and sends to the Matlab to plot the require data. The Matlab data plotted are shown by the figure 6.5 to 6.8 for four different forces applied.

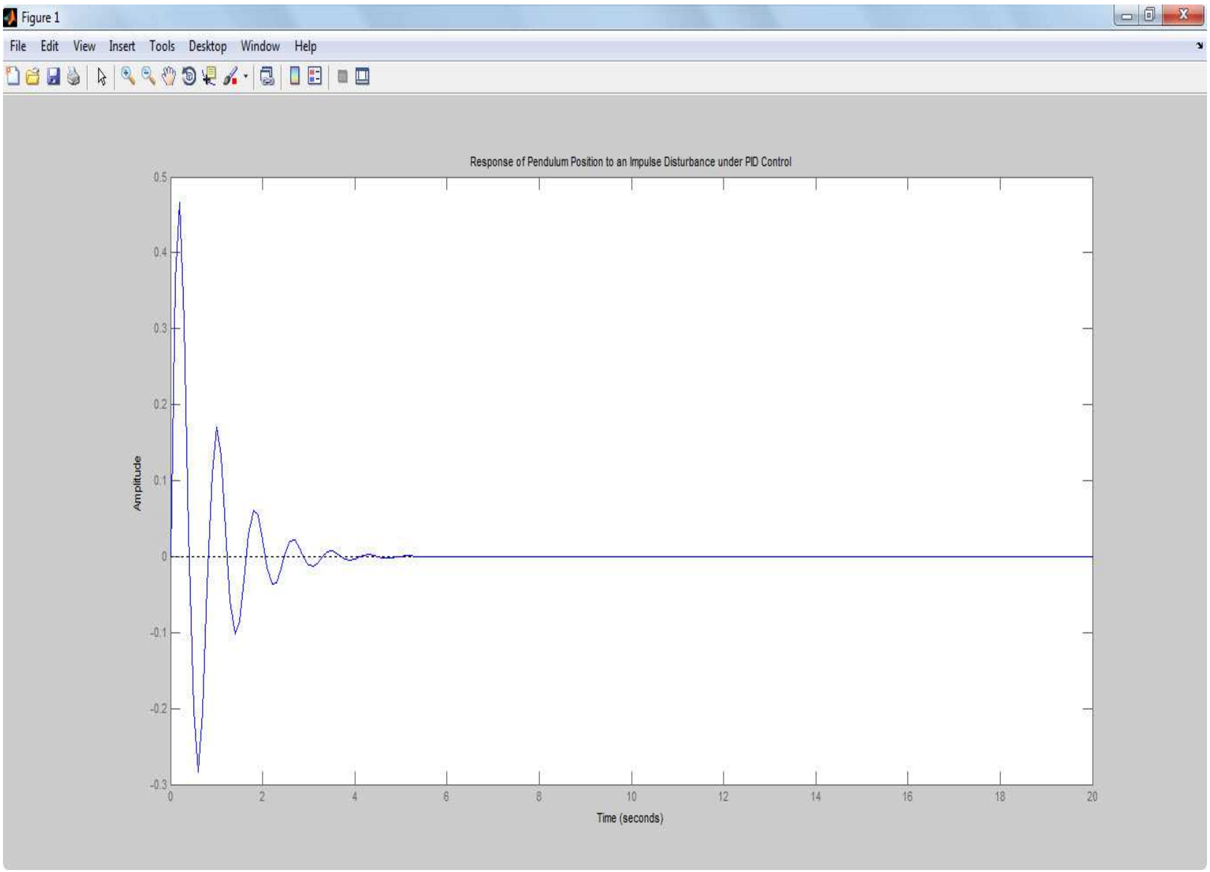

Fig 6.5 Experimental Result for first iteration

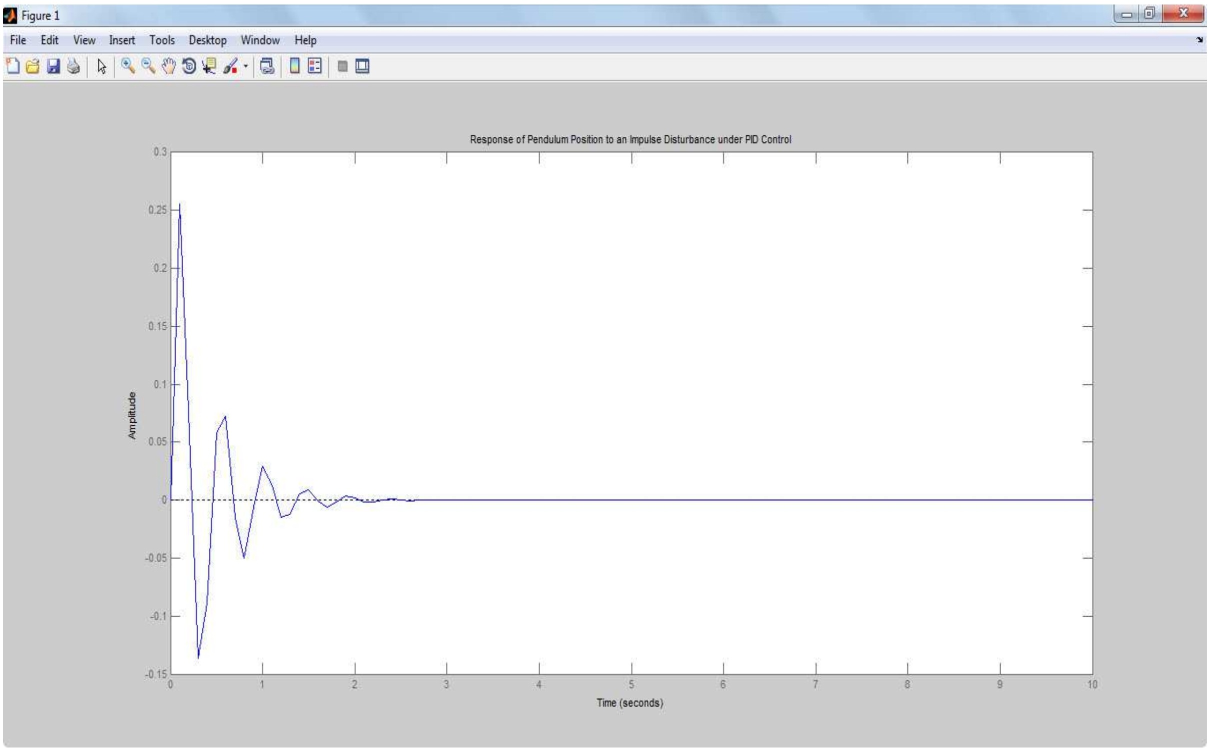

Fig 6.6 Experimental Result for second iteration

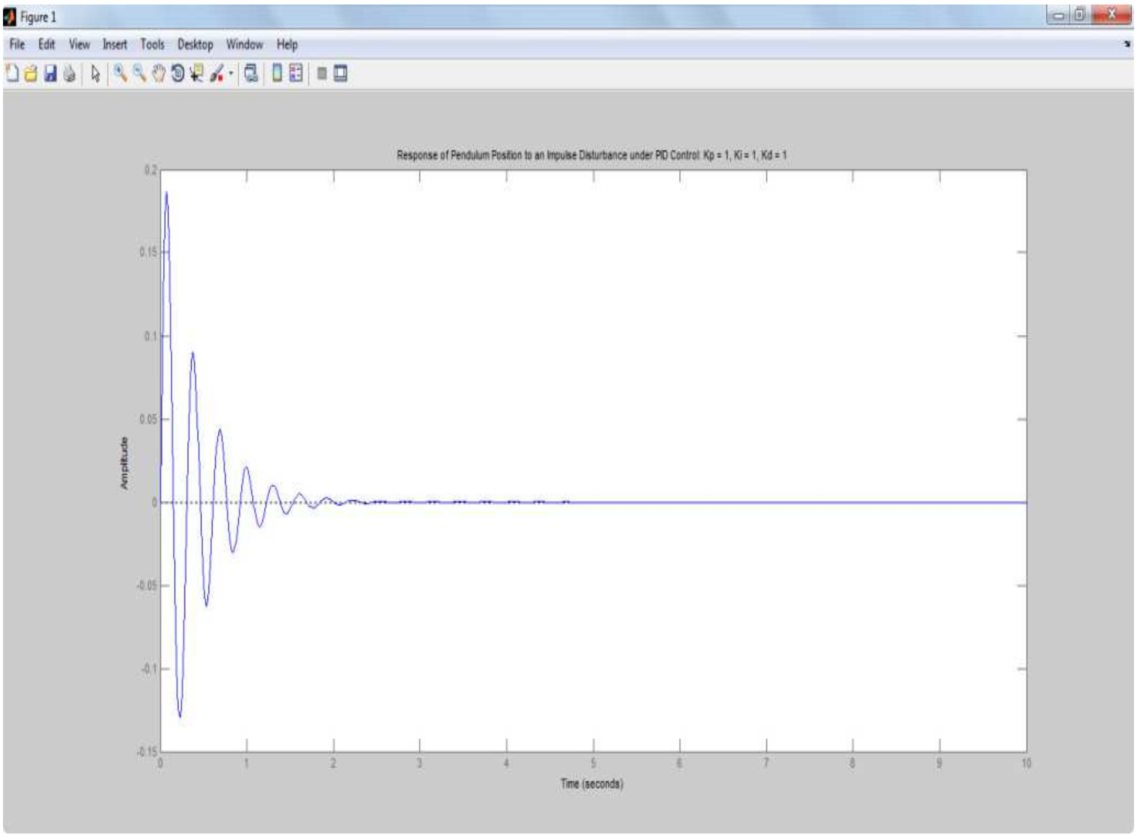

Fig 6.7 Experimental Result for third iteration

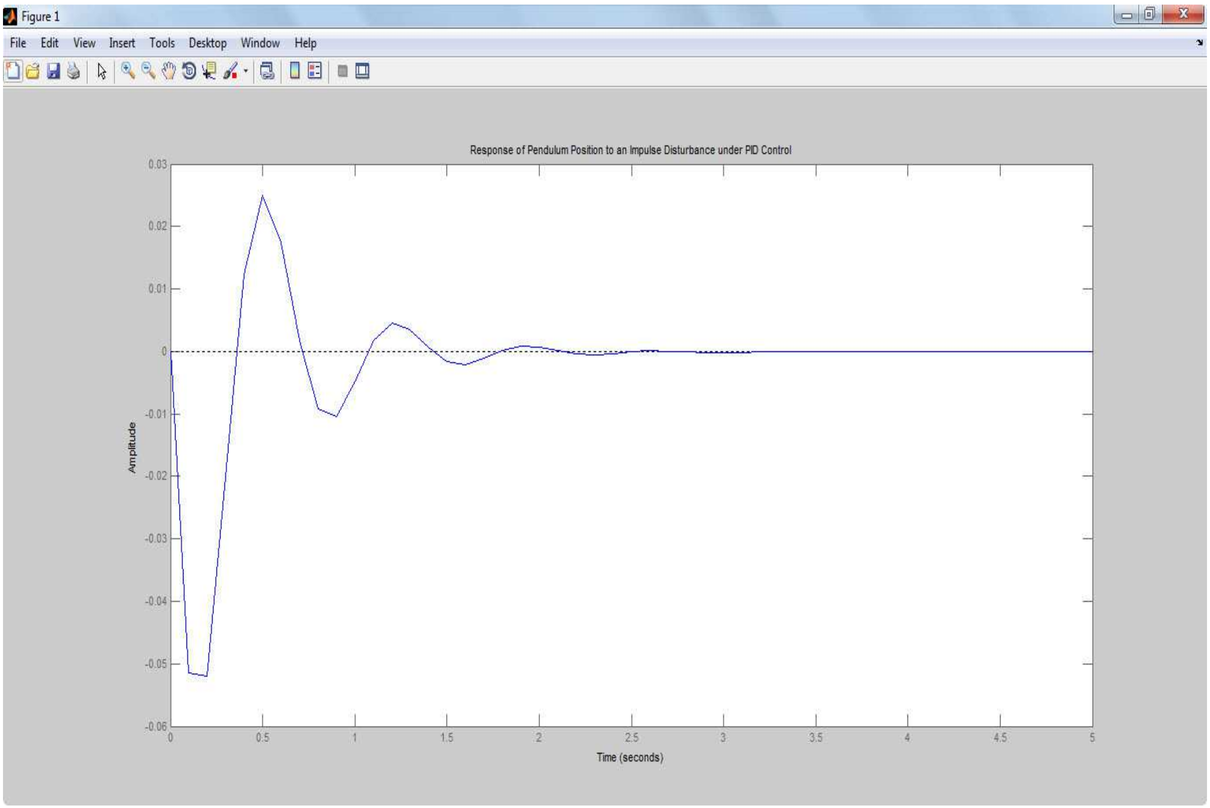

Fig 6.8 Experimental Result for forth iteration

6.3. ERROR EVALUATION

After getting the responses from simulation and the experimental, the maximum overshoot and settling time is compared and percentage of error is calculated by taking the simulation model is as the reference frame. It has been seen that for all the iteration the experimental data are deviating little bit from the simulation data for both the settling time and maximum overshoot cases. The errors found for settling time are in the range of 3 to 7 and for maximum overshoot it is between 2 to 8 percent. That means the physical model is satisfactory in its job. The maximum overshoot and the settling time including the error for all the iterations have been shown by the table number 6.1. The error graph is shown below in figure number 6.9 and 6.10 for settling time and maximum overshoot respectively.

Table 6.1 Error calculation between simulation model and physical model

No. Of iteration	Maximum Overshoot (in degree)		Settling Time (in sec)		Percentage Error	
	Simulated model	Physical Model	Simulated model	Physical Model	Maximum overshoot	Settling time
1st	0.47	0.48	4.6	4.8	2.1	3.9
2nd	0.25	0.26	2.67	2.8	4.0	4.2
3rd	0.17	0.18	3.1	3.25	5.88	4.83
4th	0.023	0.025	3.0	3.2	8.69	6.67

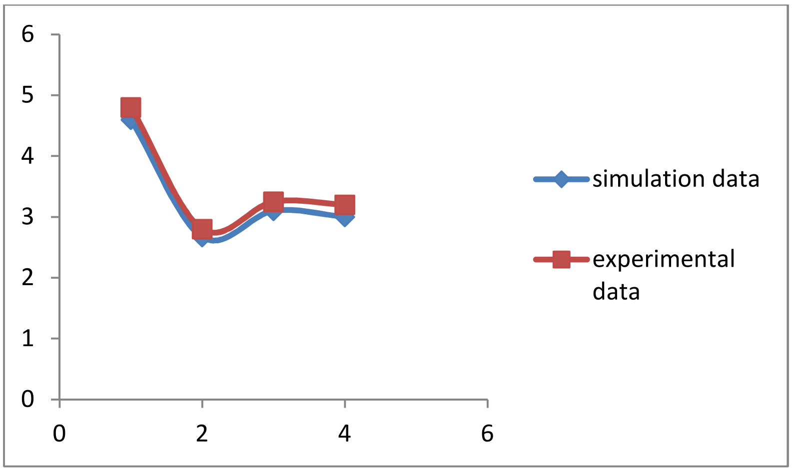

Fig 6.9 Error Graph of Maximum overshoot

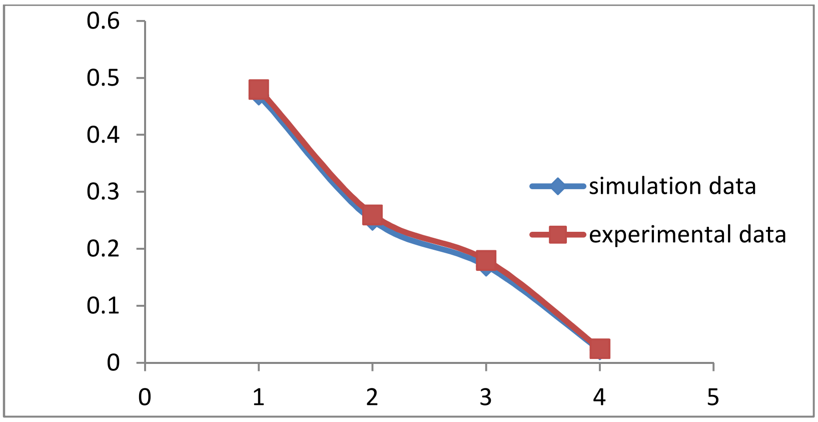

Fig 6.10 Error Graph of Settling Time

CHAPTER 07

CONCLUSIONS AND FUTURE WORK

6.1. CONCLUSIONS

- ❖ The design and fabrication of robot is correct with no failure of the joints even at maximum amplitude of vibration.
- ❖ The source of power transmission is sufficient enough to supply require amount of power and the chain drive used have proper alignment with no slippage and no loss in power transmission.
- ❖ From the graphs of simulation and experimental model it has been seen that, the maximum overshoot never exceed 5 degree for both the side of vertical axis, which is giving a satisfactory result. However the maximum overshoot for experimental model is slightly higher than the simulation model.
- ❖ It has also been seen that, the settling time of the robot is very fast all the time i.e. less than five percent. However for experimental setup it is slightly higher than the simulation model.
- ❖ From the error calculation table it has been seen that the error between the simulation model and the experimental model never exceed more than seven percent for both the maximum overshoot and settling time cases, which gives a very accurate result.

6.2. SCOPE OF FUTURE WORKS

- ➢ Operate the robot to move forward as well as to take right and left turn by using another IMU sensor
- ➢ Use of different IR technique for balancing and navigation
- ➢ Use of high torque motors to increasing the speed
- ➢ Modify the model and its analysis
- ➢ Attach some robot arm for pick and place

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