Addis Ababa University

Addis Ababa Institute of Technology

Department of Electrical and Computer Engineering

DESIGN OF BATTERY POWERED TEF SEED ROW PLANTING ROBOT

A thesis submitted to Addis Ababa Institute of Technology in partial fulfillment of the requirement for the Degree of Master of Science in Electrical Engineering (**Control Engineering).**

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DECLARATION

I, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Advisor Name Signature

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List of Abbreviation

ADLI	Agriculture Development Led Industrialization
GDP	Gross Domestic Production
MoA	Ministry of Agriculture
ATA	Agricultural Transformation Agency
PMDC	Permanent Magnet Direct Current
ADC	Analogue Digital Convertor
WMR	Wheeled Mobile Robot
PWM	Pulse Width Modulation
AC	Alternate Current
DDMR	Differential Drive Mobile Robot
DC	Direct Current
Emf	electro motive force
$\dot{\xi}_a^I$	DDMR velocity vector as seen from global reference frame
$\dot{\xi}_a^r$	DDMR velocity vector as seen from moving reference frame
$\dot{\varphi}_R$	Angular velocity of right wheel
$\dot{\varphi}_L$	Angular velocity of left wheel
ω_L	Angular velocity of a robot due to right wheel
ω_L	Angular velocity of a robot due to left wheel
ω	Angular velocity of a robot due to both wheel
C_r	Coefficient of rolling resistance
ρ	density of air
C_d	aerodynamic drag coefficient
M_{total}	Total mass of vehicle chassis and differentially derived wheel mass only
M_{tot}	Total mass of the vehicle including motor, battery and seed mass

Abstract

This paper presents design of battery powered tef seed row planting differential drive mobile robot which can help farmers to increase productivity and efficiency of farming industries. Forward kinematics of a differential drive mobile robot is done by considering non-holonomic constraint and no lateral slip conditions. Lagrange equation is used to analyze dynamic behavior of the vehicle and its model has also been developed. Mechanical and electrical characteristic of a permanent magnet DC motor is also discussed. To select suitable motor and battery, load distribution of the vehicle is discussed by considering all resistance factors.

Appropriate object oriented programing is developed in Arduino environment and uploaded to the Arduino Uno ATmega328. And also Proteus software is used to develop the schematic capture of the system from input to output. PID controller is designed to control speed of differential drive motors and simulation is done on MATLAB Simulink environment.

Results of transient and steady state response of right and left wheel motors' controllers are shown using MATLAB scope graphs. Effects of chassis parameters and contribution of right and left motors on motion of the vehicle are simulated and there results in MATLAB scope graphs are compared.

Simulation of hardware interfacing of the system components with the Controller (Arduino UNO) is done using Proteus Software. The robot platform is well-ordered by controlling speed and position of the two PMDC motors using the driver L293D. LCD is interfaced for displaying statues of the battery, seed box and general information of the robot. Literatures are reviewed and compared with this thesis and significant of the work is clearly stated.

Keywords: *Permanent magnet dc motor, Arduino Uno ATmega328, non-holonomic constraint, differential drive mobile robot, Lagrange equation, Forward kinematics, dynamic behavior*.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Agriculture is the backbone of the Ethiopian economy and the people. It contributes about 50% of gross domestic production (GDP), employs 80% of the population and the main income generating sector for the majority of the rural population [1]. It also serves as the main source of food and generates 90% of the foreign exchange earnings.

Furthermore, Ethiopia's development strategy is Agriculture Development-Led Industrialization (ADLI) because its economy is predominantly agrarian in nature. It supplies about 70% of the country's raw material requirement for large and medium sized industries that are agro-based [2]

ADLI's broad objectives are to modernize agriculture and improve its efficiency and productivity, ensure food security and enhance the country's foreign exchange earnings with the aim to promoting the development of a vibrant industrial sector and accelerate overall economic growth. But food security is still the basic question of many Ethiopians and the sector has remained at subsistence level. In general, low productivity characterizes Ethiopian agriculture.

To increase agricultural productivity and improved food security at both national and household level in Ethiopia, no efforts have been started to use agricultural robots for soil preparation, pesticide spraying, seed sawing and for many other applications. But in modern globalization, many technologies are trying to update a new development based on automation which works very rigidly, high effectively and within short period.

Now a day, the progressive invention in agriculture system is becoming an important task because of rising demand on quality of agriculture products and declining labor availability in rural farming areas. Autonomous agricultural robots are an alternative to the tractors found on fields today. Cultivation tasks like seeding, spraying, fertilizing and harvesting and soil preparation may be performed by these robots.

For instance, tef which is one of the staple food crops of Ethiopians is believed to be originated, domesticated and diversified in the country. Researches prove that tef is a hugely important crop to Ethiopia, both in terms of production and consumption and it accounts for about 15% of all calories consumed in Ethiopia. In a country of over 80 million people, approximately 6 million households grow tef and it is the dominant cereal crop in over 30 of the 83 high-potential agricultural woredas [3]. And now a day Ethiopian farmers are trying to increase the product of tef by planting in a row. Though it increases the product, the way farmers are practicing to sow tef seed in a row is very tedious, time taking and inefficient. The approach of this thesis is therefore to develop a machine which place tef seed at right place at right time with right amount in the process of farming.

1.2 Statement of the Problem

In Ethiopia, tef is a highly valued crop and is primarily grown for its grain that is used for preparing injera, kitta (unleavened bread), anebaberro (double layered injera), porridge and alcoholic beverage such as tella and katikala. Especially, teff injera which is one of the exported agricultural products is becoming the main source of Ethiopian economy. It contains many nutritional values and minerals like calcium, magnesium, iron, carbohydrate, fiber, protein and is gluten free. Ethiopia as the origin of Tef and the rightful owner of the traditional knowledge that is associated with the production of Tef, should get patent for the crop itself and farmers should be beneficiaries [4].

However, the traditional way of sowing tef seed which is practiced in Ethiopia is hand broadcasting after cattle trampling the field. This method has many disadvantages such as more seed wastage, make weeding process difficult and uneven distribution of the seeds which increases competition with weeds and other tef plants itself. This competition leads lower nutrient uptake by the individual Tef plant. Furthermore, the seeds are left uncovered which are disposed to erosion (water and wind) and bird attack. This results in the reduction of Tef yield at the harvesting time.

To overcome the above mentioned problems, currently there are some works made in partnerships of Ministry of Agriculture (MoA) and Agricultural Transformation Agency (ATA). For examples farmers in all regions of Ethiopia are being introduced to modern technologies of row planting of Tef with reduced seed rate and application of other agronomic technologies. Some research from this partner assessed the achievements made by modern technologies in the improvement of Tef yield and farmers' level of perception towards the application of modern Tef production technologies. Some other also assessed the challenges that farmers faced with the application of row planting of Tef seed with reduced seed rate. But farmers are still straggling to place a desired amount of tef seed in the desired place (line). They use very traditional materials like rope to make line, wood to tie the rope on it and plastic bottle to sow the seed. First they fill plastic bottle with tef seed after they make line with wood and rope. Then they press the plastic bottle and flow the line which is very tidies, inefficient and large time consuming approach. Besides being wasteful, planting is very imprecise and lead to a poor distribution of seeds.

We can expect the robots to perform row planting of this tef seed autonomously. This thesis is also to design battery powered tef seed row planting robot which can actually solve the aforementioned problems and is very advantageous in several ways. For example, the seed can be distributed in appropriate way using this device. It can also perform repetitive task accurately without retirement.

1.3 Objectives of the Study

1.3.1 General objectives

The general objective of this thesis is to design battery powered tef seed row planting agricultural robot which can solve many problems in agricultural industry and improve productivities of tef crop in Ethiopia.

1.3.2 Specific objectives

The specific objectives of this thesis are the following:-

i. To design a differential derive wheel mobile robot which can actually plant tef seed in rows so that it decrease tef seed rate and make the weeding process easy.
ii. To apply robots for agricultural mechanization in Ethiopia.
iii. To mechanize agriculture in Ethiopia so that productivity increases.

1.4 Contribution of the Study

Ethiopia is repeatedly affected by food security problems due to lack of modern agricultural technologies and repetitive occurrence of drought. Farmers are also unable to store food crops and a like material which can be used for hazardous and unconditional time. Tef is a source of daily consumption for more than 50 million inhabitants of Ethiopia. Farmers mainly produce Tef through traditional broadcasting method with high seed rate of 25-50 kg per hectare, this cause yield reduction and lodging problem of the grain [5], [3]. Row planting method with reduced seed rate to 2.5-3kg per hectare allows minimum competition between seedling and increase growth of Tef grain [6] , [7].

Many experiments have been conducted by researchers in order to evaluate the potential of row planting with reduced seed rate technologies. The results of the experiments have proved large and positive impacts on Tef yields. Consequently, the Ethiopian government started deploying these new technologies on a very large scale. This study helps Ethiopian farmers to increases tef yields and they can secure food needs and save crops (tef in this case) to their store for unconditional time.

Other benefits of battery powered tef seed row planting robot are:

i. Reduce man power in the field so that farmers can let their children to go to school.
ii. It can distribute tef seed in a desired place and cover the seed with soil so that the seed will not be attacked by erosion (wind and water) and birds.
iii. Decreases seed rate and make the wedding proses easy.
iv. Increases yield of tef crop at the harvesting period.

Due to these and other benefit which are listed above on the problem statement, this study can contribute a lot for farmers in Ethiopia.

1.5 Organization of the Study

Chapter I present the background of the thesis, problem statement and the objective as well as the contribution of the thesis. General overviews of the thesis and literature survey are the focus point of the second chapter. Description of basic concepts and mathematical modeling of mechanical system and electrical system of the thesis are presented in chapter III. This chapter is also dedicated to the design of the system and controller of the system. In this chapter, Arduino as a controller is programed using Arduino environment and interfacing of input and output devices with the controller is discussed briefly. Chapter IV is all about performance evaluation of the designed system with different software. Conclusions, recommendations and suggestions for future work are all presented in Chapter V.

CHAPTER TWO

WHEELED MOBILE ROBOT

2.1 Introduction

A mobile robot is an automatic machine that is capable of locomotion. They are able to move around in their environment and are not fixed to one physical location. Mobile robots which are capable of navigating an uncontrolled environment without the need for physical or electromechanical guidance devices are autonomous mobile robot whereas mobile robots which rely on guidance devices that allow them to travel a pre-defined navigation route in relatively controlled space are called autonomous guided vehicle.

Autonomous mobile robots have been used in Hospitals to move materials for many years. This systems are also available in Storerooms to efficiently move materials from stocking shelves to order fulfillment zones. They are also found in industrial, military and security applications and actually in agricultural applications such as seeding or fertilizers sowing, weeding, pesticide spraying, collecting products etc.

This thesis mainly focus on wheeled mobile robot for seeding of tef in a row which will help Ethiopian farmers to save their time, seed and energy and increases productivity too. The Autonomous robots which are developed in this thesis for the aforementioned agricultural application is a differential drive wheeled mobile robot.

A differential drive wheeled robot is a mobile robot whose movement is based on two separately driven wheels placed on either side of the robot body. It can thus change its direction by varying the relative rate of rotation of its wheels and hence does not require an additional steering motion. If both the wheels are driven in the same direction and speed, the robot will go in a straight line. If both wheels are turned with equal speed in opposite directions, the platform spins in place. If the robot wheels movies at different speeds, the robot turns or moves along a curve. Since the direction of the robot is dependent on the rate and direction of rotation of the two driven wheels, these quantities should be sensed and controlled precisely.

2.2 General Overview and Literature Review

2.2.1 Overall principal concepts

Depending on the variety of activities needed in the farming fields, agricultural wheel mobile robots have been built and are also under modification in different fashion accordingly. The control mechanism of these kinds of device is also different which mainly focus on the types of activities that the robot supposed to perform and actually depends on the designer of the robot. Some Examples of activities which are performed by these kinds of robots are:

Weeding

For this activity, an autonomous agricultural vehicle with sensors for weed detection is bullet [8]. It has high precision GPS (RTK), encoders, compass, and tilt sensors, to position it and follow waypoints. It is also possible to avoid the use of pesticides and its effect on productivity with this autonomies vehicle. *Karina Dühring* [9] has also demonstrated the key aspects concerning the possibility to energize an autonomously running machine with photovoltaic energy. The aim was to incorporate renewable energy in daily use of agriculture machines. The machine is operated as a robot which had to take care of 3 different tasks: navigation, scouting and weeding. The goal was to provide power to the robot only with energy from the sun. This project examined how many solar modules needed or how long time the robot can operate with the 3 different tasks

Irrigation

This is watering of the farming land to foster plant growth. Autonomies device is used to do so. Humidity in the soil (farming field) is detected first by the help of sensors and water is supplied to the field which has water requirement. There are also sensors in the field which are not activated till water is supplied which send information (presence of water on the field which actually makes them active) to the controller. The Microcontroller (controller) then is used to control the water supply to the field accordingly. Once again if the field gets dry, sensors sense the requirement of water and send signals to the microcontroller and the process continue in the same manner [10].

Seed sowing

Exposure of seeds to rats, birds and snails which increases seed rating, time lose and energy loss to replace the wasted seed have been considered as a big problem in agriculture before autonomies mobile robots are introduced. This device uses for placing of different crops seed on a very precise place which actually overcomes this problems of direct seeding. For example Authors in [11] have demonstrated command based self-guided digging and seed sowing rover. In this demonstration, a sensor guided rover for digging, precise seed positioning and sowing has been proposed to reduce the human effort and also to increase the yield. The rover's navigation is performed by remote guiding devices fortified with the positioning system. Ultrasonic sensors are used to detect obstacles present in the pathway and it maps alternative route for smoother navigation. The rover is steered by high torque DC motor fitted with the available rotating seed storage hopper and digging tool. Figure 2.1 b) below shows its demonstration. Author in [12] have also demonstrated Robotic Agricultural Machine for cultivating ploughed land automatically. The project consists of two different mechanisms. The first one contains making an assembly of vehicle and its motion, and the second mechanism is preparing a seed bed on ploughed land. The microcontroller is used to control and monitor the process of system motion of vehicle.

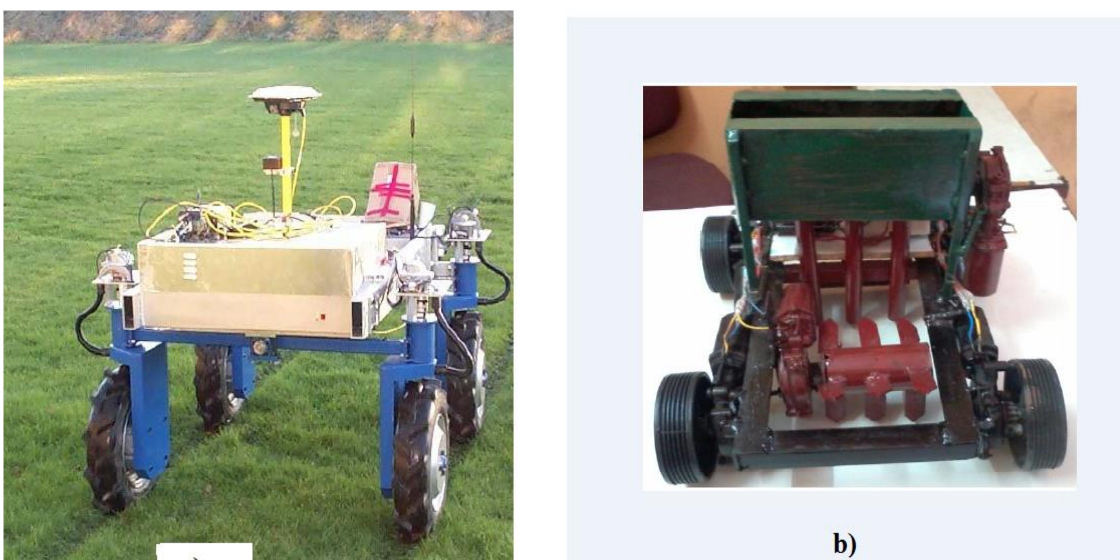


Figure 2.1 Autonomies wheeled mobile robot for: - a) weeding [8] and b) Self-guided digging and seed sowing [11]

Plowing

Tilling of farming land needs more energy than the rest agricultural activities. But plowing with engine tractors can be considered as a series cause of environmental pollution besides its energy consumption and man power need. Unlike the above listed activities, there are no verities of autonomies wheel robots which can till the farming field as needed due to its high intake of energy. But researchers are working on the improvement of this system. For example Indian Students, Mr. I.Vetrivel, Mr.V.K.Arun, Mr. K.Sivaraman and Mr. V.Premnath developed Remote powered solar plowing machine which is an autonomies wheeled mobile robot [13].

Harvesting

Autonomies mobile robots are also applicable in agricultural products such as fruits and crops when the farming is ready to harvest. Especially fruits which are ready to use are gathered selectively by this device with the help of high quality sensors. For example, autonomies vehicle with a five link robotic arm is shown in the figure 2-1 d) below. It is a modular design utilizing interchangeable 'fingers', which allows the harvesting of different kinds (or sizes) of fruits. The gripper was designed and its prototype was constructed and tested for its effectiveness in collecting fruits of size suitable to the fingertips used without damaging them. Electronic circuit board were constructed with appropriate control and there initial programming was successfully implemented for the gripper's operation [14].

Figure 2.2 Autonomies wheeled mobile robot prototype models for c) plowing [13] and d) Suitable gripper for harvesting sensitive agricultural products [14].

In this thesis, autonomies differential drive wheel mobile robot is demonstrated which is used for placing tef seed in rows with 20 c.m. distances on a well prepared seed bed [7].

2.2.2 General Block Diagram Representation of the System

The complete diagram of the system is consists of dc power supply (battery), Arduino Uno (controller of the system), sensor units (feed necessary information to the controller), motor driving units (PMDC motors), actuators (control seed valve accordingly), motor driver circuits (feed desired power for drives based on the information from the controller), ADC (analog to digital converters, control keyboard and voltage regulator.

This all are shown in the flowing figure and are explained latter.

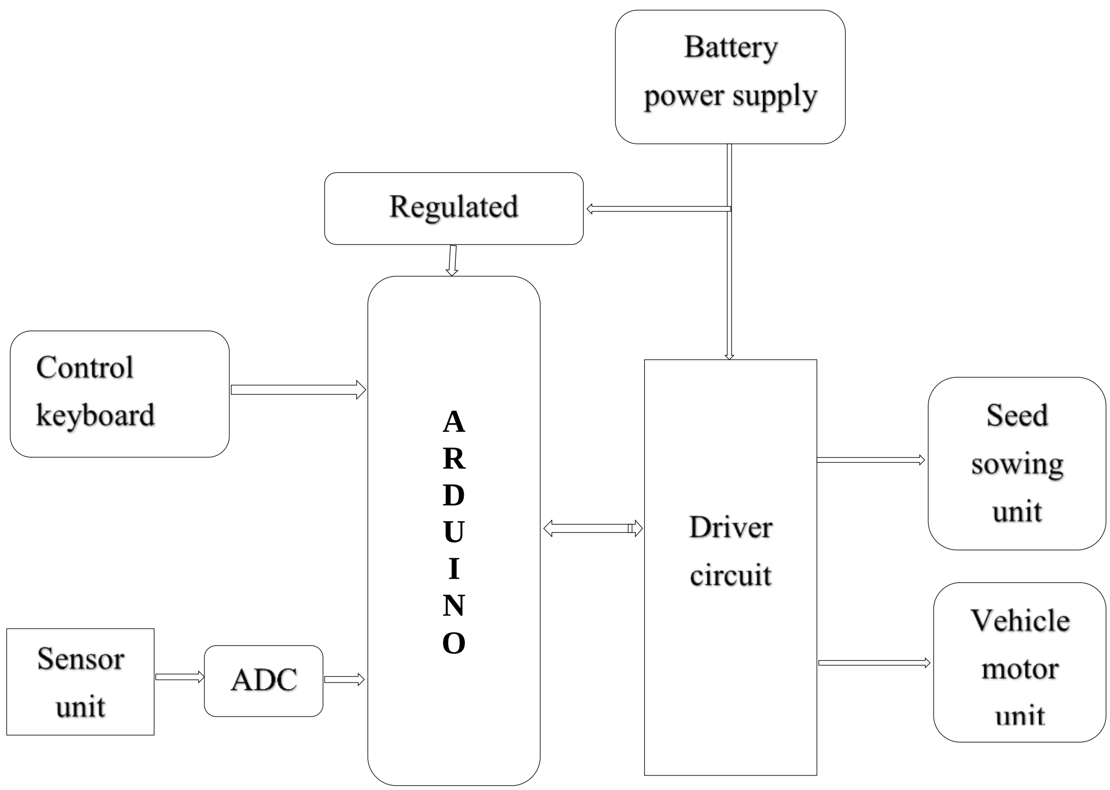


Figure 2.3 Block diagram of Seed sowing WMR

Power supply

A dc power supply is given to the two driving motors (identical PMDC motors to drive right and left wheels separately) and seed sowing units (two identical Servo Motors to control seed valves) through the driver circuits. The Arduino and sensors gets regulated power supply to prevent them from damage. The amount of power needed the whole system depends on the physical parameters of the vehicle such as weight (including seeds), height and width of the mobile platform, friction of the well prepared seed bed, types of material of the platform and the types of electrical drives used in the system. The total input power needed for this specific application is therefore calculated accordingly in the next chapter and the proper battery pack is selected.

Voltage regulator

It is needed to feed a well regulated input power for the controller (Arduino Uno). There is also a voltage regulator mounted in the Arduino Uno which actually limit input voltage of the microcontroller.

Arduino Uno

The Arduino Uno is a microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz ceramic resonator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with AC-to-DC adapter or battery to get started.

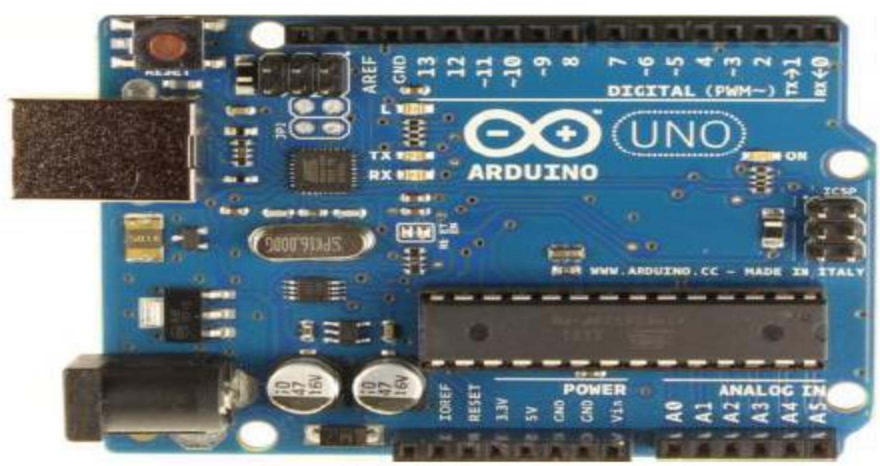


Figure 2.4 Arduino Uno

The Uno differs from all preceding boards in that it does not use the FTDI USB-to-serial driver chip. Instead, it features the Atmega16U2 (Atmega8U2 up to version R2) programmed as a USB-to-serial converter.

Table 2-1 Arduino Specifications

Feature	Specification
Microcontroller	ATmega328P
Operation voltage	5 v
Input voltage (recommended)	7-12 v
Digital input output pin	14(of which 6 provide PWM output)
PWM digital I/O pins	6
Analog input pins	6
DC current per I/O pin	20 mA
DC current for 3.3v pin	50 mA
Flash memory	32 KB (ATmega328P)of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	2 KB (ATmega328P)
Clock speed	16 MHz
LED_BUILTIN	13
Length	68.8 mm
Width	53.4 mm
Wight	25 g

The Arduino Uno can be powered via the USB connection or with an external power supply. The power source is selected automatically. External (non-USB) power can come either from an AC-to-DC adapter (wall-wart) or battery. The adapter can be connected by plugging a 2.1mm center-positive plug into the board's power jack. Leads from a battery can be inserted in the ground and V_{in} pin headers of the POWER connector. The board can operate on an external supply of 6 to 20 volts. If supplied with less than 7V, however, the 5V pin may supply less than five volts and the board may be unstable. If using more than

12V, the voltage regulator may overheat and damage the board. The recommended range is 7 to 12 volts.

The ATmega328 on the Arduino Uno comes pre burned with a boot loader that allows to upload new code to it without the use of an external hardware programmer. It communicates using the original STK500 protocol (reference, C header files).We can also bypass the boot loader and programs the microcontroller through the ICSP (In-Circuit Serial Programming) header.

2.3 Literature Review

Authors in reference [10] stated that the automatic irrigation machine is a key component of agriculture field. Sensors can detect the humidity in the soil (agricultural field) and supply water to the field which has water requirement. Microcontroller is used to control the water supply and the field to be irrigated which is a great thing. The author contributes a very good idea for agricultural technology development.

V.A.Kulkarni and Mr. Ajit G Deshmukh [15] conclude that the requirements and progress made towards achieving a future precision autonomous farming system. The assembly is developed for weed control system in ploughed land automatically i.e. no man power required. The project has consists of two different mechanism. The first mechanism contains making an assembly of vehicle and its motion, whereas second mechanism is cutting the weed in between to crop lines. The microcontroller is used to control and monitor the process of system motion of vehicle. It is controlled with help of DC motor and servo motor. This system also detect obstacle present in path of the vehicle by infrared sensor. It is also used for sensing turning position of vehicle at the end of land.

P.Usha, V.Maheswari and Dr.V.Nandagopal [16] implemented an agrobot which is mainly based on minimizing man power and cost of the equipment, which can be affordable to all farmers. This project is developed to automatically cultivating the land.

CHAPTER THREE

DIFFERENTIAL DRIVE MOBILE ROBOT SYSTEM DESIGN

3.1 Introduction

Mechatronics is defined as a cooperate integration of sensors, actuators, signal conditioning power electronics, decision control algorithms, computer hardware and software to manage complexity, uncertainty and communication in engineering systems. In other word, the accurate control of motion is a fundamental concern in mechatronics applications where placing an object in the exact desired location with the exact possible amount of force and torque at the correct time is essential for efficient system operation. The accurate control of motion depends on many factors including the accuracy of applied control strategy design, the accuracy of derived mathematical model, the accuracy of interpreting simulation and analysis results.

Therefore, understanding of mathematical representation and computer-aided simulations of mechanical, electrical and control subsystems are the main characteristic features of the mechatronic approach to the design of a wheeled mobile robot. These subsystems are integrated in the simulation model and information about mutual interactions among the individual subsystem can be obtained by using kinematic analysis and dynamic modeling of the WMR.

3.2 Design of the Mobile Robotic Platform

When deriving mathematical model for the mobile platform system, for maximum accuracy it is important to study and analyses dynamics between the field (The well prepared seed bed in which the robot vehicle pass over it to put tef seed in appropriate place), wheel and platform and to consider all the forces applied upon the mobile platform system. Therefore, in this section a mathematical description of a DDMR moving on a planar surface is formulated. To facilitate the analysis and subsequent control development, the vehicle is divided into three parts including kinematics, dynamics and drive subsystems.

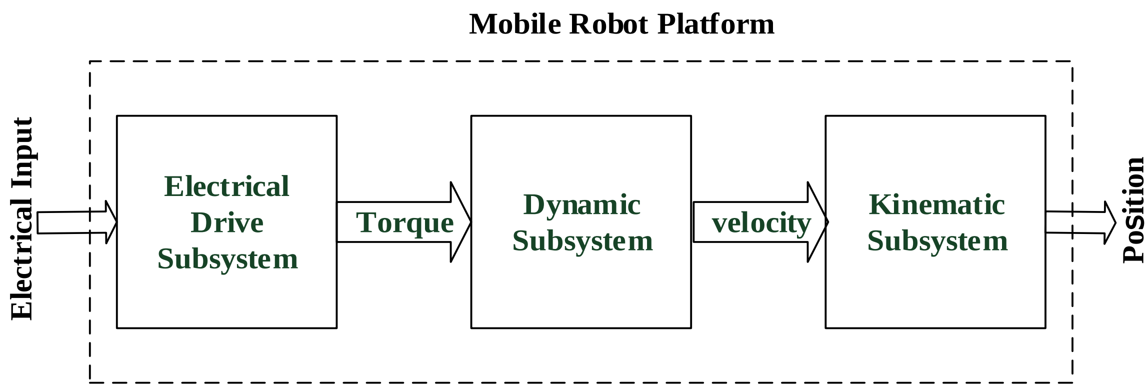


Figure 3.1 Decomposition of an electrically driven mobile robot.

3.2.1 Kinematics Modeling of Differential Drive Mobile robot

Kinematics is the most basic study of how mechanical systems behave. In mobile robotics, we need to understand the mechanical behavior of the robot both in order to design appropriate mobile robots for tasks and to understand how to create control software for an instance of mobile robot hardware.

In recent years, the robotics community has achieved a fairly complete understanding of the kinematics and even the dynamics (i.e., relating to force and mass) of robot manipulators. A mobile robot's workspace is equally important because it defines the range of possible poses that the mobile robot can achieve in its environment.

Mobile robot is a self-contained automation that can entirely move with respect to its environment. There is no direct way to measure a mobile robot's position instantaneously. Instead, one must integrate the motion of the robot over time. Furthermore, an inaccuracy of motion estimation due to slippage and it is clear that measuring a mobile robot's position precisely is a challenging task.

The process of understanding the motions of a robot begins with the process of describing the contribution each wheel provides for motion. Each wheel has a role in enabling the whole robot to move. In a similar way, each wheel also imposes constraints on the robot's motion. In the following section, notation that allows expression of robot motion in a global reference frame as well as the robot's local reference frame is introduced first. Then, using this notation, the construction of simple forward kinematic models of motion, describing how the robot as a whole moves as a function of its geometry and individual wheel behavior is demonstrated. Next, the kinematic constraints of individual wheels are described formally, and then combination of these kinematic constraints is done to express the whole robot's kinematic constraints. With these tools, one can evaluate the paths and trajectories that define the robot's maneuverability.

3.2.1.1 Representing robot position

In order to describe the position of the WMR in this environment, two different coordinate systems (frames) need to be defined first.

I. Inertial Coordinate System: - This coordinate system is a global frame which is fixed in the environment or plane in which the WMR moves in. Moreover, this frame is considered as the reference frame and is denoted as $\{X_I, YI\}$.

II. Robot Coordinate System: - This coordinate system is a local frame attached to the WMR, and thus, moving with it. This frame is denoted as $\{X_R, Y_R\}$.

The two defined frames are shown in Figure 3.2. The origin of the robot frame is defined to be the mid-point P_o on the axis between the wheels. The center of mass P_c of the robot is assumed to be on the axis of symmetry, at a distance d from the origin P_o.

As shown in the figure, the robot position and orientation in the inertial reference frame can be described mathematically as:

$$\xi^I = \begin{bmatrix} x_a \\ y_a \\ \theta \end{bmatrix} \tag{3-1}$$

Where ξ^I is the notation for position and orientation in the inertial reference frame, (x_a, y_a) is a point at the origin of robot reference frame coordinate system and θ is the angle between the two coordinates (Global reference frame and mobile reference frame coordinates.)

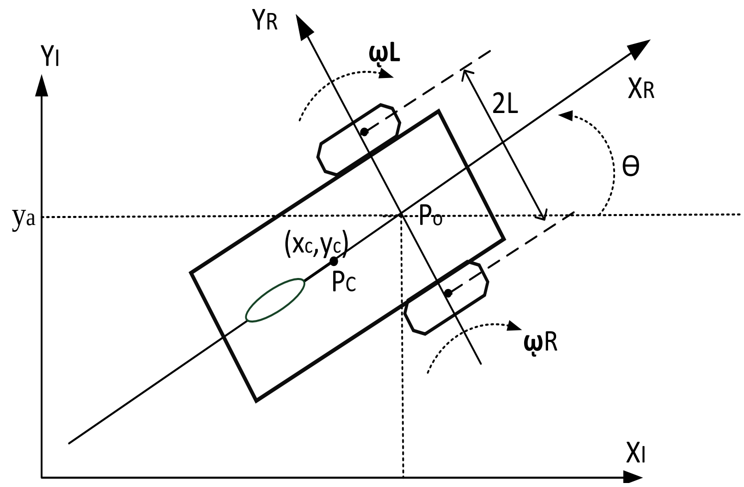


Figure 3.2 the two frame of references of Differential Drive Mobile Robot.

The essential thing that needs to be explained more at this step is the mapping between these inertial frame and robot frame. The position of any point on the robot can be defined in the two frames as follows.

Let $P^r = \begin{bmatrix} x^r \\ y^r \\ \theta^r \end{bmatrix}$, and $P^I = \begin{bmatrix} x^I \\ y^I \\ \theta^I \end{bmatrix}$ be the coordinates of a given point in a robot frame and inertial frame respectively.

The two coordinates are related by the following transformation.

$$P^I = R(\theta).P^r \tag{3-2}$$

Where R(θ) is the orthogonal rotational and translational matrix about z axis.

$$R(\theta) = \begin{bmatrix} \cos\theta & \sin\theta & x_c \\ -\sin\theta & \cos\theta & y_c \\ 0 & 0 & 1 \end{bmatrix} \tag{3-3}$$

This transformation will enable also the handling of motion between frames.

$$\dot{P}^I = R(\theta).\dot{P}^r \tag{3-4}$$

It will be seen in the next section that equation (3-4) is very important in deriving the DDMR kinematic and dynamic models as it describes the relationship between the velocities in the Inertial Frame and the Robot Frame.

3.2.1.2 Kinematic Constraints of the Differential-Drive Robot

Differential Drive

Differential Drive is the most common types of wheeled mobile robot. It is one of the least complicated with respect to programing and locomotion [17]. It has two wheels driven independently on a common axis and one or two caster wheels. In this modeling there is only one caster wheel which is just for support and do not affect mobile kinematics model. The configuration allows the robot to drive straight, spin and turn. If the drive wheels run at the same speed, the robot moves forward or in reverse. If the wheels run in opposite direction at the same speed, the robot spins in place. If the robot wheels movies at different speeds, the robot turns or moves along a curve.

Kinematic Constraints

The motion of a differential-drive mobile robot is characterized by two non-holonomic constraint equations, which are obtained by two main assumptions.

I. *No lateral slip motion:* **-** This constraint simply means that the robot can move only in a curved motion (forward and backward) but not sideward. In the robot frame, this condition means that the velocity of the center-point P_o is zero along the lateral axis.

$$\dot{y}_a^r = 0 \tag{3-5}$$

Using the orthogonal rotation and translational matrix $R(\theta)$, the velocity in the inertial frame gives.

$$\dot{\xi}_a^r = R(\theta)\ \dot{\xi}_a^I \tag{3-6}$$

This yields the following velocity equation in the y-axis.

$$\dot{y}_a^r = -\dot{x}_a \sin\theta + \dot{y}_a \cos\theta = 0 \tag{3-7}$$

II. *Pure rolling constraint***:** - We also assume that the plane of the wheel always remains vertical and that there is in all cases one single point of contact between the wheel and the ground plane. The pure rolling constraint therefore represents the fact that each wheel maintains a one contact point P with the ground as shown in Figure 3.3. There is no slipping of the wheel in its longitudinal axis (x_r) and no skidding in its orthogonal axis (y_r).

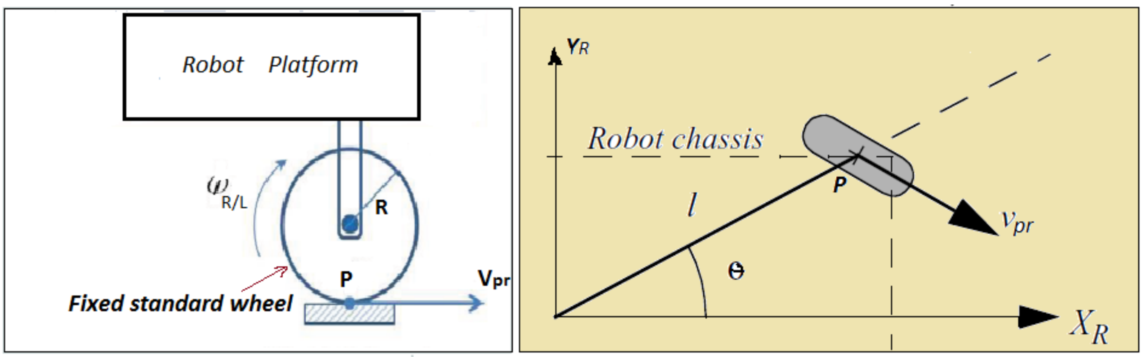


Figure 3.3 Pure Rolling Motion of Differential Drive Mobile Robot wheel constraint.

The velocities of the contact points in the robot reference frame are related to the wheel velocities by the following equation.

$$V_{PR} = R\dot{\varphi}_R$$
$$V_{PL} = R\dot{\varphi}_L \qquad (3\text{-}8)$$

Where $\dot{\varphi}_R$ and $\dot{\varphi}_L$ are spinning speed of right and left wheels respectively. In inertial (global) reference frame, this velocity can be calculated as a function of the velocity of the robot center point P_o as shown in figure 3.2. Position of the right wheel can be expressed as:

$$\left.\begin{aligned} X_{PR} &= x_a + L\sin\theta \\ Y_{PR} &= y_a - L\cos\theta \end{aligned}\right\} \qquad (3\text{-}9)$$

Motion of the right wheel (velocity of the point p) as a function of point P_o of the robot can be expressed as:

$$\left.\begin{aligned} \dot{X}_{PR} &= \dot{x_a} + L\dot{\theta}\cos\theta \\ \dot{Y}_{PR} &= \dot{y_a} + L\dot{\theta}\sin\theta \end{aligned}\right\} \tag{3-10}$$

Similarly the left wheel position and velocity can be expressed as follows.

Position:-

$$\left.\begin{aligned} X_{PL} &= x_a - L\sin\theta \\ Y_{PR} &= y_a + L\cos\theta \end{aligned}\right\} \tag{3-11}$$

And velocity: -

$$\left.\begin{aligned} \dot{X}_{PL} &= \dot{x_a} - L\dot{\theta}\cos\theta \\ \dot{Y}_{PL} &= \dot{y_a} - L\dot{\theta}\sin\theta \end{aligned}\right\} \tag{3-12}$$

Using the rotation matrix R(θ), the rolling constraint equations are formulated as follows: [18]

$$\left.\begin{aligned} \dot{X}_{PR}\cos\theta + \dot{Y}_{PR}\sin\theta &= R\dot{\varphi}_R \\ \dot{X}_{PL}\cos\theta + \dot{Y}_{PL}\sin\theta &= R\dot{\varphi}_L \end{aligned}\right\} \tag{3-13}$$

Forward kinematic models

In the simplest cases, the mapping described by equation (3-6) is sufficient to generate a formula that captures the forward kinematics of the mobile robot. It gives answer for how does the robot moves, given its geometry and the speeds of its wheels.

More formally, consider the robot shown in figure 3-2 above with three wheels. This differential drive robot has two driving wheels, each with radios R and one caster wheel. Given a point P_o centered between the two drive wheels, each wheel is a distance L from point P_o. Given, L, R, angle of rotation, and the spinning speed of each right and left wheels, $\dot{\varphi}_R$ and $\dot{\varphi}_L$. A forward kinematic model would predict the robot's overall speed in the global reference frame:

$$\dot{\xi}^{I} = \begin{bmatrix} \dot{x_a} \\ \dot{y_a} \\ \dot{\theta} \end{bmatrix} = \boldsymbol{f}(\boldsymbol{L}, \boldsymbol{R}, \theta, \dot{\varphi}_R, \dot{\varphi}_L) \qquad \textit{(3-14)}$$

We can compute the robot's motion in the global reference frame from motion in its local reference frame.

$$\dot{\xi}_a^I = R(\theta)^{-1}.\ \dot{\xi}_a^r \qquad \textit{(3-15)}$$

Therefore, the strategy will be to first compute the contribution of each of the two wheels in the local reference frame $\dot{\xi}_a^r$.

Suppose that the robot's local reference frame is aligned such that the robot moves forward along $+X_r$, as shown in figure 3.2. First as stated above consider the contribution of each wheel's spinning speed to the translation speed at point P_o in the direction of $+X_r$. If one wheel spins while the other wheel contributes nothing and is stationary, since P_o is halfway between the two wheels, it will move instantaneously with half the speed.

$$\left.\begin{aligned} \dot{X}_R^r &= \frac{1}{2} R\dot{\varphi}_R \\ \dot{X}_L^r &= \frac{1}{2} R\dot{\varphi}_L \end{aligned}\right\} \qquad \textit{(3-16)}$$

In a differential drive robot, these two contributions can simply be added to calculate the $\dot{x_r}$ component of $\dot{\xi}_a^r$. Consider, for example, a differential robot in which each wheel spins with equal speed but in opposite directions. The result is a stationary spinning robot. As expected, $\dot{x_r}$ will be zero in this case. The value of $\dot{y_r}$ is even simpler to calculate. Neither right wheel nor left wheel can contribute to sideways motion in the robot's reference frame and is always zero. Finally, we must compute the rotational component $\dot{\theta}\boldsymbol{r}$ of $\dot{\xi}_a^r$. Once again, the contributions of each wheel can be computed independently and just added. Consider the right wheel (let right wheel be assigned as wheel R and the left one as wheel L). Forward spin of this wheel results in counterclockwise rotation at point P_o. Recall that if wheel R spins alone, the robot pivots around wheel L. The rotation velocity ω_R at P_o can be computed because the wheel is instantaneously moving along the arc of a circle of radius 2L.

$$\omega_R = \frac{R\dot{\varphi}_R}{2L} \tag{3-17}$$

The same calculation applies to the left wheel, with the exception that forward spin results in clockwise rotation at point P_o.

$$\omega_L = \frac{-R\dot{\varphi}_L}{2L} \tag{3-18}$$

Combining these individual formulas yields a kinematic model for the differential-drive mobile robot.

$$\dot{\xi}_a^I = R(\theta)^{-1}.\begin{bmatrix} \frac{R\dot{\varphi}_R}{2} + \frac{R\dot{\varphi}_L}{2} \\ 0 \\ \frac{R\dot{\varphi}_R}{2L} + \frac{-R\dot{\varphi}_L}{2L} \end{bmatrix} \tag{3-19}$$

This is the kinematic representation of the designed WMR. However, inverse of the rotational and translational matrix $R(\theta)$ has to be computed first. In general, calculating the inverse of a matrix may be challenging. In this case, conversely, it is easy because it is simply a transform from $\dot{\xi}_a^r$ to $\dot{\xi}_a^I$.

$$R(\theta)^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta & x_c \\ \sin\theta & \cos\theta & y_c \\ 0 & 0 & 1 \end{bmatrix} \tag{3-20}$$

The DDMR velocities can be obtained also in the inertial frame as follows:

$$\dot{\xi}_a^I = \begin{bmatrix} \frac{R}{2}.\left(\cos\theta + \frac{x_c}{L}\right) & \frac{R}{2}.\left(\cos\theta - \frac{x_c}{L}\right) \\ \frac{R}{2}.\left(\sin\theta + \frac{y_c}{L}\right) & \frac{R}{2}.\left(\sin\theta - \frac{y_c}{L}\right) \\ \frac{R}{2L} & \frac{-R}{2L} \end{bmatrix}.\begin{bmatrix} \dot{\varphi}_R \\ \dot{\varphi}_L \end{bmatrix} \tag{3-21}$$

Equation 3.21 is therefore, representation of the forward kinematic model of the differential drive mobile robot with two driving wheels and one caster wheel.

Having desired robot velocity, it is possible to determine rotational and angular velocity of both right and left wheels. This procedure is what we call inverse kinematics.

3.2.2 Dynamics Modeling of Differential Drive System

The motion of a mechanical system is related through a set of dynamic equations, and the forces or torques that the system subjected to. The study of this subject is important due to the problem of the control of the system, which is in contact with its environment. Indeed, for a model-based controller, the synthesis of the controller of such system depends heavily on the mathematical model of the physical structure of the system, which is basically nonlinear. Thus, the goal here is to develop a model that can describe the dynamics of the system as close to the real system so that we can have a better chance to develop a controller for the system that is effective in real-world situation.

In the case of a differential drive WMR, the contact with the environment occurs at the contact point between the wheel outer surface and the ground surface. The interaction between these two surfaces has a significant influence over the dynamic motion of the system, and hence, need to be properly modeled.

In general, there are two major methods for deriving the dynamic equations of mechanical systems. These are Newton's method and Lagrange's method. Newton’s method is directly related to Newton's second law and the second method has root in the classical work of Alembert and Lagrange on analytical mechanics. The main difference between the two methods is in dealing with constraint equations. While Newton's method treats each rigid body separately and explicitly model the constraints through the reactive force required to enforce them. Lagrange's provides systematic procedures for eliminating the constraints from the dynamic equations, typically yielding simpler system equations.

3.2.2.1 Dynamic System of a DDMR constraint Description

Unlike kinematics Dynamics is the study of the motion of a mechanical system which consider the different forces that affect its motion. The dynamic model of the DDMR is therefore very important for simulation analysis of the platform motion and for the design of various motion control algorithms.

To determine the dynamic model of this system, we need to identify mechanical system of the robot. These systems can be classified into linear and nonlinear systems. Holonomic and nonholonomic systems are also classes of nonlinear mechanical system of mobile robot. A differential drive wheel mobile robot is an example of nonholonomic mechanical system. Holonomy and nonholonomy are fundamental concepts that describe the constraints of the systems, which play the essential part in governing the motion of those systems [18]

Dynamic modeling of this platform, beyond a purely kinematic analysis is needed to consider how dynamic variables (the magnitudes of masses and inertias), as well as the geometric parameters, affect vehicle performance. In this section our goal is to develop expressions that relate the vehicle's acceleration to the motor torques and other design parameters. To do this, equations that govern the vehicle's motion must be developed. We can either take a Lagrangian or Newtonian approach. In this thesis Lagrangian method is implemented but the same results can be derived either way.

3.2.2.2 Noneholonomic Constraint Description

In figure 3.4 below, L is the distance measured from the origin of the robot platform to the center of the wheel along the y-axis of the body reference frame. The distance between point P_o and the COM (center of mass of the platform) along the x-axis of a robot reference frame is denoted by d. The location of the hubs points (the point that defines the center of the wheel's rotation) on left and right wheels are also denoted by H_L and H_R respectively.

Idealizing that the hub points are rigidly affixed to the main vehicle body and thus the velocity of the hub points (denoted by V_{HL} and V_{HR}) can be calculated from the vehicle's velocity via application of velocity transformation which gives the following equations.

$$\left.\begin{aligned} \vec{V}_{\mathrm{HL}} &= \vec{V}_{mr} + [\vec{\omega}_{mr}]\, X\, [R(\theta)\vec{r}_{\mathrm{HL}}] \\ \vec{V}_{\mathrm{HR}} &= \vec{V}_{mr} + [\vec{\omega}_{mr}]\, X\, [R(\theta)\vec{r}_{\mathrm{HR}}] \end{aligned}\right\} \tag{3-22}$$

Where

- $\vec{V}_{mr} = [\ \dot{x} \quad \dot{y} \quad 0]^T$ and $\vec{\omega}_{mr} = \begin{bmatrix} 0 & 0 & \dot{\theta} \end{bmatrix}^T$ are linear and angular velocity of the mobile robot respectively.
- $R(\theta)$ is orientation of the body fixe reference frame with respect to fixed observer and is described in equation 3.3.

- $\vec{r}_{\text{HR}} = [\,0 \quad -L \quad 0]^T$ and $\vec{r}_{\text{HL}} = [\,0 \quad L \quad 0]^T$ are vectors from origin of the body fixed frame to the right and left hub points respectively.

Substituting and simplifying equation 3.22 right wheel hub point velocity becomes

$$\vec{V}_{HR} = \begin{bmatrix} \dot{x} + L\dot{\theta}\,cos\,\theta \\ \dot{y} + L\dot{\theta}\,sin\,\theta \\ 0 \end{bmatrix} \tag{3-23}$$

Similarly, left wheel hub point velocity is simplified to

$$\vec{V}_{HL} = \begin{bmatrix} \dot{x} - L\dot{\theta}\,cos\,\theta \\ \dot{y} - L\dot{\theta}\,sin\,\theta \\ 0 \end{bmatrix} \tag{3-24}$$

To calculate the velocity of each wheel contact points to the ground, let as assume point C_L and C_R are the contact points of left and right wheel and V_{CL} and V_{CR} represent linear velocity of these points. Using velocity transformation concepts once again we get contact point velocity of each wheel as follows.

$$\left.\begin{aligned} \vec{V}_{\text{CR}} &= \vec{V}_{HR} + [\vec{\omega}_{Rw}]\,X\,[\vec{r}_{\text{hrcr}}] \\ \vec{V}_{\text{CL}} &= \vec{V}_{HL} + [\vec{\omega}_{Lw}]\,X\,[\vec{r}_{\text{hlcl}}] \end{aligned}\right\} \tag{3-25}$$

Where

- $\vec{\omega}_{Rw} = \dot{\psi}_R[\sin\theta \quad -\cos\theta \quad 0]^T$ and $\vec{\omega}_{Lw} = \dot{\psi}_L[\sin\theta \quad \cos\theta \quad 0]^T$ are angular velocity of right and left wheels with angular displacement of ψ_R and ψ_L respectively.
- $\vec{r}_{\text{hrcr}} = \vec{r}_{\text{hlcl}} = [\,0 \;\; 0 \;\; R]^T$ are the same vectors from origin of each hub points to each contact points of the wheel to the ground.

Substituting the above vector values in equation 3.25 and simplifying, the following expiration can be obtained to describe velocity of wheel contact point of right wheel.

$$\vec{V}_{CR} = \begin{bmatrix} \dot{x} + L\dot{\theta}\,cos\,\theta + R\,\dot{\psi}_R(cos\,\theta) \\ \dot{y} + L\dot{\theta}\,sin\,\theta + R\,\dot{\psi}_R(sin\,\theta) \\ 0 \end{bmatrix} \tag{3-26}$$

Using similar derivation, contact point velocity of left wheel is

$$\vec{V}_{CL} = \begin{bmatrix} \dot{x} - L\dot{\theta}\cos\theta - R\,\dot{\psi}_L(\cos\theta) \\ \dot{y} - L\dot{\theta}\sin\theta - R\,\dot{\psi}_L(\sin\theta) \\ 0 \end{bmatrix} \tag{3-27}$$

In nonholonomic mechanical system, the points on the wheel in contact with the ground must have zero velocity. Therefore, nonholonomic constraint equation can be written in the form of the following equation.

$$C(q)\dot{\vec{q}} = 0 \tag{3-28}$$

Where q is generalized coordinates of DDMR which can be actually described as

$\mathbf{q} = (x, y, \Theta, \psi L, \psi R)$ and $C(q)$ is the 3x5 matric which is a nonholonomic constraint.

Writing equation 3-26 and 2-27 in equation 3-28 form we get C(q) and can be expressed as the following matric form.

$$C(q) = \begin{bmatrix} \cos\Theta & \sin\Theta & 0 & \frac{R}{2} & -\frac{R}{2} \\ -\sin\Theta & \cos\Theta & 0 & 0 & 0 \\ 0 & 0 & 1 & \frac{R}{2L} & \frac{R}{2L} \end{bmatrix} \tag{3-29}$$

3.2.3 Lagrange dynamic approach

The DDMR shown in figure 3.4 below is a standard platform of a nonholonomic two wheeled mobile robot which has two differential driving wheels and a castor wheel used for balancing. The differential driving wheels has two degrees of freedom. These are the rotation around the motor-powered wheel axle and the contact point. The castor wheel is located at the back of the DDWM robot and has three degrees of freedom which are the rotation around the wheel axle, the contact point and the castor wheel.

The two driving wheels are powered by permanent magnet DC motors and have the same wheel radius R. The intersection of the longitudinal x-axis and the lateral y-axis Point P_o is the origin of robot axis. The center of mass (COM) is located at point P_c which cannot be located at the intersection point of axis of symmetry of the platform P_o to ensure no singularity in the control solution [19].

The Lagrange approach to deriving the equations of motion of a given system is based on the definition of Lagrange [20]

$$L(\vec{q},\dot{\vec{q}}) = K.E - P.E \qquad (3\text{-}30)$$

Where *K.E.* is the total kinetic energy of the dynamic system and P.E. is its potential energy.

The variable **q** denotes the configuration of the system (generalized coordinate system), which is the set of variables that can uniquely describe the position of the system at a fixed time.

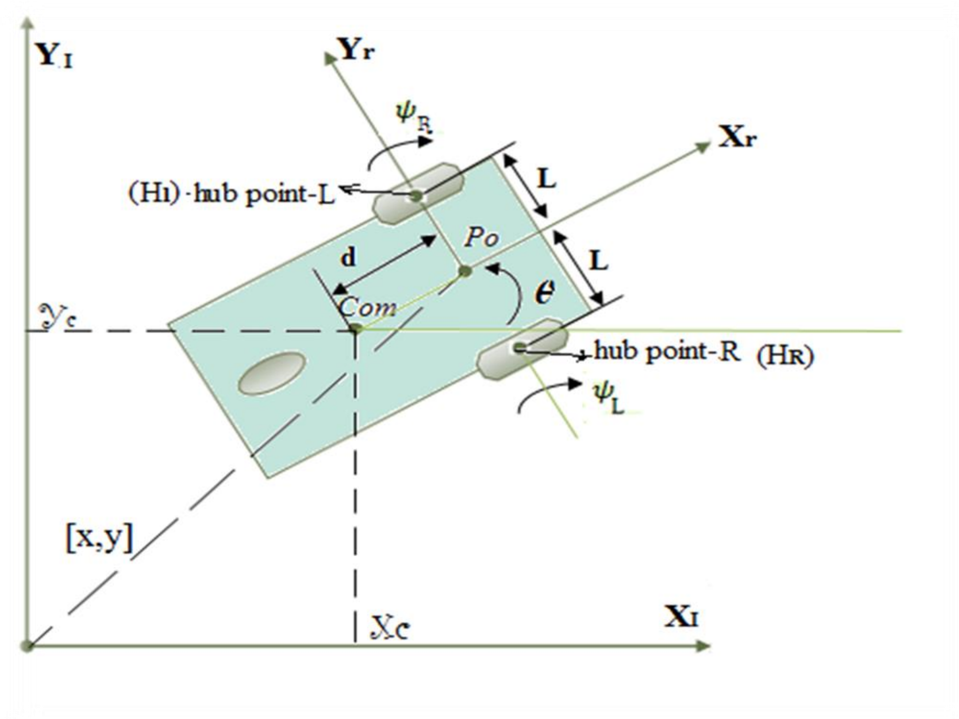


Figure 3.4 A differential drive mobile robot platform

Let as first define the generalized coordinates of DDMR which can be actually selected as

$$\boldsymbol{q} = (x_c, y_c, \Theta, \psi_L, \psi_R) \qquad (3\text{-}31)$$

Where X_c and Y_c are the coordinate of the COM, Ѳ represents the orientation of the robot frame from the inertial frame and $[\psi_L, \psi_R]$ is the angular displacement vector for the DDMR driving left wheel and right wheel respectively.

For an unconstrained system, Lagrange's equations of motion are derived from the Lagrangian as follows:

$$\frac{d}{dt}\left[\frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial \dot{\vec{q}}}\right] - \frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial \vec{q}} = \vec{T} \qquad (3\text{-}32)$$

Where $\vec{T}$ are the generalized forces acting on the system. However, when constraints are at work, the Lagrangian approach must be adapted to include the influence of the constraints. This is formally done using the method of undetermined Lagrange Multipliers.

Due to the nonholonomy of the system and by following the ideal no-slip assumption, its constraints use the form of Equation 3-28 and Lagrange's equations take the form:

$$\frac{d}{dt}\left[\frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial \dot{\vec{q}}}\right] - \frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial \vec{q}} - C^{T}(\vec{q})\vec{\lambda} = \vec{T} \qquad (3\text{-}33)$$

Where $\vec{\lambda}$ is the vector of undetermined Lagrange multipliers. The multipliers represent the forces which are necessary to maintain the constraints. For the differential drive vehicle, these multipliers are the reaction forces at the wheel-ground contact which are necessary to enforce the no-slip wheel constraints.

The main thing we should do is to find the kinetic and potential energies that govern the motion of the DDMR. But here in this thesis, since the WMR is moving in the X_I-Y_I plane, the potential energy of the DDMR is considered to be zero. So the Lagrangian is comprised solely of kinetic energy terms only and can be expressed as.

$$L(\vec{q},\dot{\vec{q}}) = \sum K.E = K.E_{body} + K.E_{RW} + K.E_{LW} \qquad (3\text{-}34)$$

To find kinetic energy mathematical expression of the system, the WMR platform can be partitioned into three parts namely the body of the platform and its two wheels (i.e. left wheel and right wheel).

a) Kinetic energy of the WMR body

The expression of the kinetic energy of the WMR body is given as

$$K.E_{body} = \frac{1}{2}M_{body}\left\|\vec{V}_{body}\right\|^{2} + \frac{1}{2}(\vec{\omega}_{body})^{T} I_{body}\vec{\omega}_{body} \qquad (3\text{-}35)$$

Where M_{body}, $\vec{V}_{body}$ and $\vec{\omega}_{body}$ are mass, linear velocity and angular velocity of WMR body platform respectively and I_{body} is Moment of inertia of robot body without wheels about a vertical axis through COM.

Here, the velocity of center of the mass (COM) can be taken as velocity of the body and is expressed as follows.

$$\vec{V}_{body} = \vec{V}_R + [\vec{\omega}_R]X[\vec{r}_{body}] \tag{3-36}$$

Where

- $\vec{V}_R = [\dot{x} \quad \dot{y} \quad 0]^T$ is linear velocity of the robot (the velocity of the origin of the body fixed reference frame).
- $\vec{\omega}_R = [0 \quad 0 \quad \dot{\Theta}]^T$ is angular velocity of the robot (the angular velocity of the origin of the body fixed reference frame).
- $\vec{r}_{body} = [d\cos\Theta \quad d\sin\Theta \quad 0]^T$ is vectors from origin of robot reference frame to center of mass (COM) of the vehicle.

Substituting the above expression in equation 3-36, velocity of the body is expressed as

$$\vec{V}_{body} = \begin{bmatrix} \dot{x} - d\,\dot{\Theta}\,sin\,\Theta \\ \dot{y} + d\,\dot{\Theta}\,cos\,\Theta \\ 0 \end{bmatrix} \tag{3-37}$$

Therefore, substituting velocity expression in kinetic energy equation, the total kinetic energy of the main body is written as follows.

$$K.E_{body} = \frac{1}{2}M_{body}[\dot{x}^2 + \dot{y}^2 + d^2\dot{\Theta}^2 + 2d\dot{\Theta}(\dot{y}\,cos\,\Theta - \dot{x}\,sin\,\Theta)] + \frac{1}{2}I_{body}\dot{\Theta}^2 \tag{3-38}$$

b) Kinetic energy of the WMR right and left wheels

Assuming that the wheel's center of mass lies exactly at the hub point as shown in figure 3-4, *Figure 3.4 A differential drive mobile robot platform*the velocity of the right wheel's center of mass point is:

$$\vec{V}_{CMR} = \vec{V}_{HR} = \begin{bmatrix} \dot{x} + L\dot{\theta}\cos\theta \\ \dot{y} + L\dot{\theta}\sin\theta \\ 0 \end{bmatrix} \tag{3-39}$$

Where L is the distance measured from the origin of the robot platform reference frame to the center of the wheel along the y-axis of the body reference frame. This wheel also rotates about an axis normal to the vertical plane and has an angular velocity which can be expressed as:

$$\vec{\omega}_{WR} = \dot{\psi}_R \begin{bmatrix} \sin\theta \\ \cos\theta \\ 0 \end{bmatrix} + \dot{\theta} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} \dot{\psi}_R \sin\theta \\ \dot{\psi}_R \cos\theta \\ \dot{\theta} \end{bmatrix} \tag{3-40}$$

And the expression of the kinetic energy for right wheel therefor is written as follows

$$K.E_{WR} = \frac{1}{2} M_{WR} \left\| \vec{V}_{HR} \right\|^2 + \frac{1}{2} (\vec{\omega}_{WR})^T I_W \vec{\omega}_{WR} \tag{3-41}$$

Where $I_{WR}=I_{WL}=I_W$ is inertia of a rotation wheel and this is because identical wheels are assumed for right and left wheels of the vehicle. $M_{WR} = M_w = M_{WL}$ is mass of a wheel (identical wheels for right and left wheel are used) and $\vec{V}_{HR}$, right wheel hub point velocity which is the same as velocity of its center of mass point is described in the previous section.

Rewriting kinetic energy of the right wheel using the above described angular velocity, linear velocity of the hub point expressions, the following new expression is developed.

$$K.E_{WR} = \frac{1}{2} M_W [\dot{x}^2 + \dot{y}^2 + L^2\dot{\Theta}^2 + 2L\dot{\Theta}(\dot{x}\cos\Theta + \dot{y}\sin\Theta)] + \frac{1}{2} I_W (\dot{\Theta}^2 + \dot{\psi}_R{}^2) \tag{3-42}$$

Using very similar procedure the left wheel kinetic energy expression becomes.

$$K.E_{WL} = \frac{1}{2} M_W [\dot{x}^2 + \dot{y}^2 + L^2\dot{\Theta}^2 - 2L\dot{\Theta}(\dot{x}\cos\Theta + \dot{y}\sin\Theta)] + \frac{1}{2} I_W (\dot{\Theta}^2 + \dot{\psi}_L{}^2) \tag{3-43}$$

Where $\dot{\psi}_R$ and $\dot{\psi}_L$ are right and left wheel angular velocity respectively.

Total Kinetic energy of the WMR

The total kinetic energy is simply the sum of the kinetic energies of each body.

$$K.E_{total} = K.E_{body} + K.E_{WR} + K.E_{WL} \tag{3-44}$$

Substituting the expressions derived above and then rearranging produces the desired kinetic energy expression which is also equals to the system Lagrangian under the assumption that the vehicle drives on the flat surface floor.

$$K.E_{total} = L(\vec{q},\dot{\vec{q}}) = \frac{1}{2}M_{total}.[\dot{x}^2+\dot{y}^2]+\frac{1}{2}I_{total}.\dot{\Theta}^2 + M_{body}.d\dot{\Theta}(\dot{y}\cos\Theta - \dot{x}\sin\Theta) + \frac{1}{2}I_W.\left(\dot{\psi_R}^2+\dot{\psi_L}^2\right) \quad (3\text{-}45)$$

Where $\mathrm{M_{total}}$(total vehicle mass) and I_{total} (total rotational inertial) are introduced as follows

$$M_{total} = M_{body} + 2M_W \quad (3\text{-}46)$$

$$I_{total} = I_{body} + M_{body}d^2 + 2M_WL^2 + 2I_w \quad (3\text{-}47)$$

Where all parameters are described above and are shown in figure 3-4, a differential drive mobile robot platform. And these newly introduced parameters are used in the following section.

Lagrange's Equations for the Differential Drive Vehicle

Recall equation 3-33, (Lagrange's equation)

$$\frac{d}{dt}\left[\frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial\dot{\vec{q}}}\right] - \frac{\partial L(\vec{q},\dot{\vec{q}})}{\partial\vec{q}} - C^T(\vec{q})\vec{\lambda} = \vec{T}$$

Substituting total kinetic energy equation in to equation 3-33 (Lagrange's equation) the following new expression is developed.

$$\frac{d}{dt}\begin{bmatrix} M_{total}\dot{x} - M_{body}d\dot{\Theta}\sin\Theta \\ M_{total}\dot{y} + M_{body}d\dot{\Theta}\sin\Theta \\ I_{total}\dot{\Theta} + M_{body}d(\dot{y}\cos\Theta - \dot{x}\sin\Theta) \\ I_w\dot{\psi}_R \\ I_w\dot{\psi}_L \end{bmatrix} + M_{body}d\dot{\Theta}\begin{bmatrix} 0 \\ 0 \\ \dot{y}\sin\Theta + \dot{x}\cos\Theta \\ 0 \\ 0 \end{bmatrix} - C^T(\vec{q})\vec{\lambda} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ T_R \\ T_L \end{bmatrix}$$

Where T_R and T_L are right and left wheels torques respectively, $C(\vec{q})$ is no sleep rolling nonholonomic constraint which is described in its respective section above and $\vec{\lambda}$ is Lagrange's multipliers.

Further mathematical manipulation of the above equation gives the following complete dynamic equation of the WMR.

$$M(\vec{q})\ddot{\vec{q}} + V(\vec{q},\dot{\vec{q}})\dot{\vec{q}} - C^T(\vec{q})\vec{\lambda} = \vec{T} \tag{3-48}$$

Where $$C^T(q) = \begin{bmatrix} cos\,\Theta & -sin\,\Theta & 0 \\ sin\,\Theta & cos\,\Theta & 0 \\ 0 & & 1 \\ \frac{R}{2} & 0 & \frac{R}{2L} \\ & 0 & \\ -\frac{R}{2} & 0 & \frac{R}{2L} \end{bmatrix},$$

$$\vec{q} = \begin{bmatrix} x \\ y \\ \Theta \\ \psi_R \\ \psi_L \end{bmatrix} \quad \text{and} \quad \vec{\lambda} = \begin{bmatrix} \vec{\lambda}_1 \\ \vec{\lambda}_2 \\ \vec{\lambda}_3 \end{bmatrix}$$

$$V(\vec{q},\dot{\vec{q}}) = \begin{bmatrix} 0 & 0 & -M_{body}d\dot{\Theta}\cos\Theta & 0 & 0 \\ 0 & 0 & -M_{body}d\dot{\Theta}\sin\Theta & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$M(\vec{q}) = \begin{bmatrix} M_{total} & 0 & -M_{body}d\sin\Theta & 0 & 0 \\ 0 & M_{total} & M_{body}d\cos\Theta & 0 & 0 \\ -M_{body}d\sin\Theta & M_{body}d\cos\Theta & I_{total} & 0 & 0 \\ 0 & 0 & 0 & I_W & 0 \\ 0 & 0 & 0 & 0 & I_W \end{bmatrix},$$ and $\vec{T}$ was defined above.

Finding the Lagrange Multipliers $\vec{\lambda}$

To eliminate the constant term $C^T(\vec{q}).\vec{\lambda}$, let us define the reduced vector

$$\vec{\eta} = \begin{bmatrix} \dot{\psi}_R \\ \dot{\psi}_L \end{bmatrix} \tag{3-49}$$

Recall the forward kinematics modeling and rearranging it gives.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\Theta} \\ \dot{\psi}_R \\ \dot{\psi}_L \end{bmatrix} = \frac{1}{2}\begin{bmatrix} R\,.\,(cos\,\theta + \frac{x_c}{L}) & R\,.\,(cos\,\theta - \frac{x_c}{L}) \\ R\,.\,(sin\,\theta + \frac{y_c}{L}) & R\,.\,(sin\,\theta - \frac{y_c}{L}) \\ \frac{R}{L} & \frac{-R}{L} \\ 2 & 0 \\ 0 & 2 \end{bmatrix} . \begin{bmatrix} \dot{\psi}_R \\ \dot{\psi}_L \end{bmatrix} \tag{3-50}$$

This can be rewritten as

$$\dot{\vec{q}} = S(\vec{q}).\vec{\eta} \tag{3-51}$$

Deviating this equation with time, we get new equation

$$\ddot{\vec{q}} = \dot{S}(\vec{q}).\vec{\eta} + S(\vec{q}).\dot{\vec{\eta}} \tag{3-52}$$

Substituting equation 3-51 and 3-52 in to equation 3-48 and multiplying by $S^T(\vec{q})$ and rearranging some terms

$$S^T(\vec{q}).\left[M(\vec{q}).S(\vec{q}).\dot{\vec{\eta}}\right] + S^T(\vec{q}).\left[M(\vec{q}).\dot{S}(\vec{q}) + V\left(\vec{q},\dot{\vec{q}}\right).S(\vec{q})\right].\vec{\eta}$$

$$= S^T(\vec{q}).B(\vec{q}).\vec{T} - S^T(\vec{q}).C^T(\vec{q}).\vec{\lambda} \tag{3-53}$$

Where $S(\vec{q}) = \frac{1}{2}\begin{bmatrix} R\,.\,(cos\,\theta + \frac{x_c}{L}) & R\,.\,(cos\,\theta - \frac{x_c}{L}) \\ R\,.\,(sin\,\theta + \frac{y_c}{L}) & R\,.\,(sin\,\theta - \frac{y_c}{L}) \\ \frac{R}{L} & \frac{-R}{L} \\ 2 & 0 \\ 0 & 2 \end{bmatrix}$ $and\ B(\vec{q}) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$

Here the last term i.e. $S^T.(\vec{q}).C^T(\vec{q}).\vec{\lambda}$ in equation 3-54 is identically zero and now introducing new terms

- $\bar{M}(\vec{q}) = S^T(\vec{q})M(\vec{q})S(\vec{q})$

$$= \begin{bmatrix} I_W + \frac{R^2}{4L^2}(M_{total}.(x_c{}^2 + y_c{}^2 + L^2) + I_{total}) & \frac{R^2}{4L^2}(M_{total}.(x_c{}^2 + y_c{}^2 + L^2) - I_{total}) \\ \frac{R^2}{4L^2}(M_{total}.(x_c{}^2 + y_c{}^2 + L^2) - I_{total}) & I_W + \frac{R^2}{4L^2}(M_{total}.(x_c{}^2 + y_c{}^2 + L^2) + I_{total}) \end{bmatrix}$$

- $\bar{V}(\vec{q}) = S^T(\vec{q})M(\vec{q})\dot{S}(\vec{q}) + S^T(\vec{q})V(\vec{q},\dot{\vec{q}})S(\vec{q}) = \frac{R^2}{4L^2}M_{body}d\dot{\Theta}\begin{bmatrix}-1 & 1\\ -1 & 1\end{bmatrix}$
- And $\bar{B}(\vec{q}) = S^T(\vec{q})B(\vec{q}) = \begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$

The dynamic equations are reduced to

$$\bar{M}(\vec{q})\dot{\vec{\eta}} + \bar{V}(\vec{q},\dot{\vec{q}})\vec{\eta} = \bar{B}(\vec{q})\vec{T} \qquad (3\text{-}54)$$

This equation can be represented by the following block diagram where $\bar{M}^{(-1)}(\vec{q})$ is the inverse of matric $\bar{M}(\vec{q})$. Detail block representation of this subsystem is developed in Simulink modeling of the entire system in chapter five.

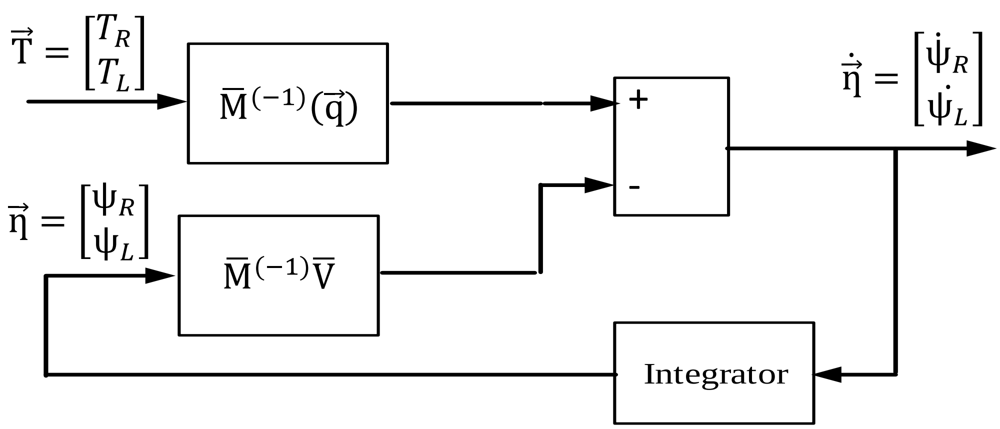


Figure 3.5 block diagram representation of dynamic equation of DDMR

3.3 Basic Electric Drive Modeling

The electric machines, considered in this paper are two PMDC motors to drive the front right and front left wheels respectively. For each machine mathematical models are derived, corresponding Simulink models are built and finally control solutions are proposed as follows.

3.3.1 Dynamic model of Permanent Magnet DC Motor

In modeling of a PMDC motor, two balance equations can be developed by considering the electrical and mechanical characteristic of the system.

3.3.1.1 Electrical characteristics

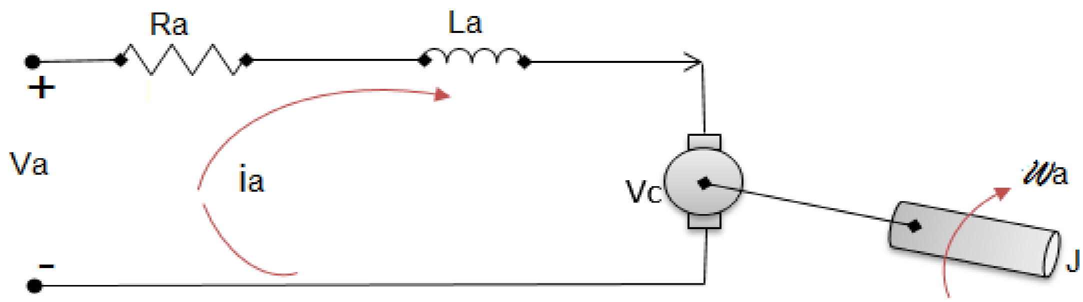


Figure 3.6 Equivalent circuit of DC motor

From the above figure, Electrical equivalent of armature coil is represented by inductance L_a in series with both resistance R_a and induced voltage V_c which opposes the voltage source V_a. The generated voltage by the rotation of electrical coil through the fixed flux lines of the permanent magnet is the induced voltage V_c which is also the buck emf(electro motive force).

Using Kirchhoff's voltage low around the loop we get:

$$V_a - V_{Ra} - V_{La} - V_c = 0 \qquad (3\text{-}55)$$

Where V_{Ra} and V_{La} are voltage drops across armature resistance R_a and Inductance L_a respectively.

Once again according to ohm's low of basic electrical circuit,

$$V_{Ra} = i_a R_a \qquad (3\text{-}56)$$

Where i_a is armature current of a PMDC motor.

The voltage across the inductor is proportional to the change of current through the coil with respect to time and can be expressed as:

$$V_{La} = L_a \frac{di_a}{dt} \tag{3-57}$$

The generated voltage in the armature of the motor which is called buck EMF can be

$$V_c = k_v \omega_a \tag{3-58}$$

Where, k_v is the velocity constant determined by flux density of the permanent magnet, reluctance of the iron core of the armature and number of turns of the armature coil, and ω_a is rotational angular velocity of the armature.

Substituting the above three equations in equation 3-55 gives

$$V_a - i_a R_a \; - L_a \frac{di_a}{dt} - k_v \omega_a \; = 0 \tag{3-59}$$

Taking Laplace transform of above equation and rearranging some terms gives

$$SI_a(s) - I_a(0) = -\frac{R_a}{L_a} I_a(s) - \frac{k_v}{L_a} \omega_a(s) + \frac{1}{L_a} V_a(s) \tag{3-60}$$

3.3.1.2 Mechanical characteristics

Energy balance of the mechanical system of figure 3.6 **Error! Reference source not ound.** is

$\sum \tau = 0$ I.e. summation of torque is zero.

$$\tau_e - \tau_\omega - \tau_{\dot{\omega}} - \tau_L = 0 \tag{3-61}$$

Where

- τ_e is electromagnetic torque of the PMDC motor
- τ_ω is torque produced from the velocity of the rotter.
- $\tau_{\dot{\omega}}$ is torque produced due to rotational angular acceleration of the rotter.
- τ_L is mechanical load torque which is actually considered as disturbance torque.

But, electromagnetic torque is due to the current through the armature winding and is proportional with this current. Mathematically we can write it as:

$$\tau_e = k_t i_a \tag{3-62}$$

Where k_t the torque constant which depends on flux density of fixed magnets, reluctance of the iron core and also on number of turns in the armature winding.

On the other hand $\tau_{\dot{\omega}}$ can be defined as:

$$\tau_{\dot{\omega}} = J_m \frac{d\omega_a}{dt} \qquad (3\text{-}63)$$

Where J_m inertia of the rotter and torque associated with angular velocity is expressed as:

$$\tau_{\omega} = B_m \omega_a \qquad (3\text{-}64)$$

Where, B_m is the dumping coefficient associated with a mechanical rotational system of the machine.

Substituting equation 3-62, 3-63 and 3-64 in to equation 3-61 we get the following differential equation:

$$k_t i_a - B_m \omega_a - J_m \frac{d\omega_a}{dt} - \tau_L = 0 \qquad (3\text{-}65)$$

Taking Laplace transformation of equation 3-65 like we did for electrical characteristics of PMDC motor dynamic system and rearranging we get:

$$S\omega_a(s) - \omega_a(0) = \frac{k_t}{J_m} I_a(s) - \frac{B_m}{J_m} I_a(s) - \frac{1}{J_m} \tau_L(s) \qquad (3\text{-}66)$$

If perturbation around some steady state values are considered, the initial conditions goes to zero and all the variables become some changes around a reference state.

Then, armature current and angular speed can be solved as

$$\left.\begin{aligned} I_a(s) &= \frac{-k_v \omega_a(s) + V_a(s)}{L_a S + R_a} \\ \omega_a(s) &= \frac{-k_t I_a(s) - \tau_L(s)}{J_m S + B_m} \end{aligned}\right\} \qquad (3\text{-}67)$$

Finally the electrical and mechanical characteristics of permanent magnet DC motor are coupled to each other through an algebraic equation given by equation 3-67 have the following nature.

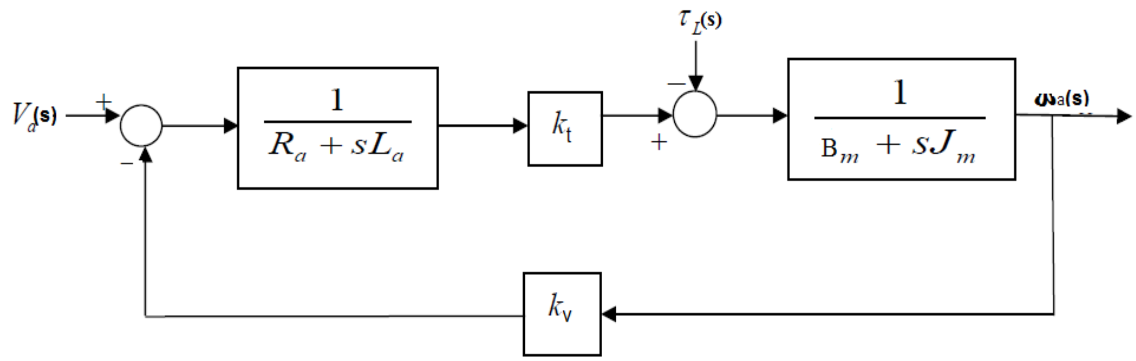


Figure 3.7 open loop characteristics of DC motor

3.3.2 Sensor modeling

Tachometer is a sensor used to measure the actual output angular speed of right and left wheels, ω_R and ω_L respectively.

Dynamics of tachometer and its transfer function for the right wheel can be represented using the following equation:

$$V_{out} = K_{tac}\frac{d\Theta}{dt} = K_{tac}\omega_R \qquad (3\text{-}68)$$

Where K_{tac} is tachometer constant which has to be modeled. So, rearranging the above expression gives.

$$K_{tac} = \frac{V_{out}}{\omega_R} \qquad (3\text{-}69)$$

Similarly, the left wheel tachometer constant can be expressed as follows

$$K_{tac} = \frac{V_{out}}{\omega_L} \qquad (3\text{-}70)$$

Where ω_L and ω_R are the actual angular speed of left and right wheels respectively.

3.4 Load Distribution to Determine Battery Power Needed

In this section, basic concepts in choosing appropriate battery to power the WMR's motors and to choice this motors required to drive right and left wheels intelligently is discussed.

Force components involved in mobile robot motion are therefore identified first and total torque (rotational force) needed is determined from this force components later. [21]

Several forces are acting on the designed wheeled mobile robot platform when it is in motion. Dynamics modelling of this kind of system also involves the balance between the acting forces on the moving platform. This forces actually categorized in to field-load and tractive force. The field-load force consists of the gravitational force, rolling resistance of the wheels, the aerodynamic drag force and the aerodynamic lift force. The sum of all these acting forces can be taken as the resultant force of the given system [22].

3.4.1 Load distribution

Consider the following figure to determine each force components.

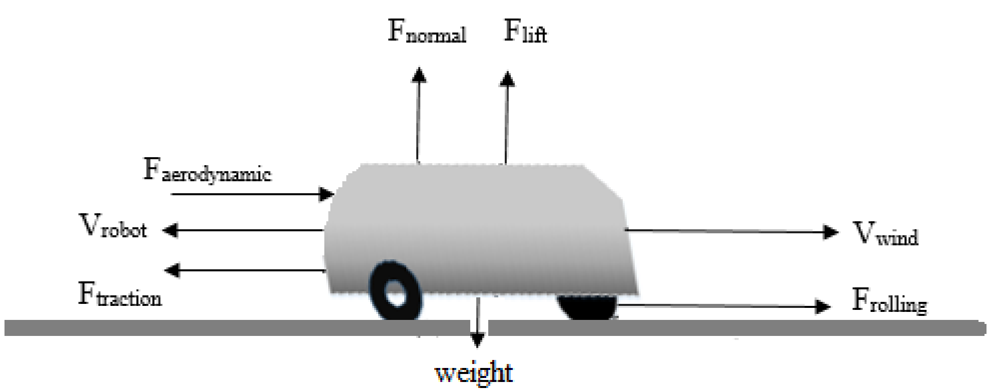


Figure 3.8 Forces acting on the moving WMR platform in a horizontal surface

This figure shows force components free body diagram of the moving robot platform in a horizontal surface. This is because tef seed bed is prepared on a labeled farming field.

The following assumptions are considered in determining the succeeding force expressions.

- The well prepared seed bed which the vehicle moves on to plant tef seed has no elevation which lets the mobile platform to not moving up or down the hill. Therefore, weight of the mobile robot will not create a hill climbing resistance force directed down ward.

- The robot platforms moves in a constant speed so that there will be a uniform distribution of seed through the line. But, to properly size the two needed motors, the situation where the robot accelerates from rest to full speed is considered. The torque required to get the robot moving is much greater than keeping it in motion. In this case, the summation of the forces acting on the robot platform is equal to the total mass multiplied by this acceleration.
- The WMR do its job in atmospheric temperature and pressure so that some constants are selected accordingly.

The disturbance torque to mobile platform is the total resultant torque generated by the acting forces. This acting force can be expressed as:

$$F_{tr} = F_{ard} + F_{rol} + F_{acc} \tag{3-71}$$

Where F_{ard} , F_{rol} and F_{acc} are aerodynamic drag force, rolling resistance force and force components due to linear acceleration respectively.

The driving force comes from the two battery powered PMDC motors with gear box shaft torque which can be written as the wheel torque

$$T_{wheel} = (N) * (ŋ) * \left(T_{shaft}\right) \tag{3-72}$$

Where N is the gearing ratio, ŋ is the transmission efficiency and T_{shaft} is the torque produced by the driving motor. This wheel torque provides the resultant driving tractive force F_t to the platform and can be written as follows.

$$F_{tr} = \frac{T_{wheel}}{r} \tag{3-73}$$

Where r is the wheel radius. The relationship between the resultant tractive force and the torque produced by the motor T_{shaft} can be obtained from the above two equations.

$$T_{shaft} = F_{tr} \frac{r}{Nŋ} \tag{3-74}$$

Expressions of each force components acting on the moving vehicle using physical parameters of the platform are determined as follows. [23]

Rolling resistance force

Rolling resistance force is produced by flattening of the tire at the contact surface of the field seed bed. It is conservative force with the possibility to partly recover. It mainly depends on the platform's speed and is proportional to the platform weight.

It is given by

$$F_{rol} = F_n C_r = M_{tot} g(C_r) \quad (3\text{-}75)$$

Where *M* is the mass of the platform, g is the gravity acceleration (m/s^2) and *Cr* is the rolling resistance coefficient.

*Cr (*the rolling resistance coefficient) is the force needed to push or tow a wheeled platform forward and can be calculated by the following expression.

$$C_r = 0.01(1 + \frac{3.6}{100} V) \quad (3\text{-}76)$$

Where V is linear velocity of the WMR. Having wheel radius r, the rolling resistance torque is given by:

$$T_r = (M_{tot} g\, C_r)r \quad (3\text{-}77)$$

Aerodynamic drag force

Aerodynamic drag force is the force opposing the motion of the platform due to air drag (wind resistance). It consists mainly of the shape drag and skin friction and is a function of the mobile platform linear velocity V.

$$F_{ard} = 0.5\, \rho\, A\, C_d V^2 \quad (3\text{-}78)$$

Where A is the effective cross-sectional area of the body, **ρ** [rho] is the density of air and V is the speed of the object. C_d is a dimensionless drag coefficient that depends on the shape of the object and whose value generally lies in the range between 0.5 and 1.0. The direction of the drag force is opposite to the direction of the velocity.

The aerodynamic torque is therefore,

$$T_{ard} = 0.5(\rho \, A \, C_d V^2)r \tag{3-79}$$

The hill climbing force deflate

The hill climbing force F_{clim} can be expressed as

$$F_{clim} = M_{tot} g \sin \beta \tag{3-80}$$

While the mobile platform is moving up or down the hill with inclination angle β, the weight of the mobile platform will create a hill-climbing resistance force directed downward. But in this particular case, the platform is assumed to go in a horizontal surface. Therefore there is no hill climbing force component.

The linear acceleration force F_{acc}

F_{acc} *is* the force required to increase the speed of the mobile platform and can be described as a linear motion given by:

$$F_{acc} = M_{tot} a = M_{tot} \frac{dV}{dt} = \left(M_{tot} + \frac{J_{wheel}}{R^2} \right) \frac{dV}{dt} \tag{3-81}$$

Where M_{total} is the mass of the mobile platform (mobile robot), *a* is acceleration experienced as a result of V is linear velocity of the platform.

Substituting and manipulating these mathematical equations of force components, Tractive force which pushes against the wheel (the force which produce contractive torque to the driving motor) becomes:

$$F_{tr} = \left(M_{tot} + \frac{J_{wheel}}{R^2} \right) \frac{dV}{dt} + M_{tot} g (\, C_r) + 0.5 \, \rho \, A \, C_d V^2 \tag{3-82}$$

3.4.2 Demand Power Determination

In this section, total power needed to make the mobile robot be able to move in a desired speed and location in the field is determined. In this case, it is important to study and analyze dynamics between the field, wheel and platform and to consider all the forces applied upon the mobile platform system.

Several forces are acting on the mobile platform when it is running. The modelling of the mobile platform system dynamics involves the balance between the acting on the running platform forces and forces categorized into field load and tractive force. The field load force consists of the gravitational force, rolling resistance of the tires, the aerodynamic drag force and the aerodynamic lift force. The resultant force is the sum of all these acting forces.

The needed power in kW that the mobile platform should develop at stabilized speed, can be determined by multiplying the total tractive force with the velocity of the platform. Mathematically, it can be written as:

$$P_{total} = (F_{tr}).V \tag{3-83}$$

Where V is the desired linear speed of the platform and (F_{tr}) is the tractive force component which can be described in the following mathematical expressions

Applying newton's second low of motion.

$$\sum Force = F_{total} = M_{tot}.(a) \tag{3-84}$$

But $$\sum Force = F_{tr} - F_{ard} - F_{rol} - F_{clim} = M_{tot}.(a) \tag{3-85}$$

Where each force components are discussed in the previous section and the hill climbing force component is zero. Tractive force equation therefore becomes.

$$F_{tr} = F_{ard} + F_{rol} + M_{tot}.(a) \tag{3-86}$$

The force which produces counteractive rotational force to the driving motor is tractive force and this toque can be determined from tractive force component as follows.

$$T = R * F_{tr} = [F_{ard} + F_{rol} + M_{tot}.(a)] * R \tag{3-87}$$

Where R is the radius of the wheel.

Power needed to generate this rotational force (torque) for both wheels is rewritten as:

$$P_{total} = 2 * T * \omega = 2 * [F_{ard} + F_{rol} + M_{tot}(a)] * R * \omega \tag{3-88}$$

Where, ω is angular velocity of a single wheel.

3.5 Parameter Specification of DDMR

There are two basic types of parameters that have to be determined first before designing the controller of a developed system. The first one is physical parameters of the platform which are mechanical parameters that affects electrical subsystem of the study. The second one is electrical parameters more specifically motor parameters which directly involves in controller design of the whole system.

3.5.1 Physical Parameter setting of DDMR platform

Physical parameters of the developed system includes total mass, width, length and height of the moving vehicle, distance between the two differentially derived wheels, distance between COM of the vehicle and origin of the moving reference frame, angle difference between the two reference frames (position of the robot), position of the right and left wheels, radius of the wheels, moment of inertia of the two wheels and seed lines distance.

Moment of inertia of the wheels

Moment of inertia is a quantity which varies as the axis rotation varies, or, more clearly, as the distance from the axis varies. The two differential drive Wheels in the left and right side of the platform are a special bicycle wheel type wheels with all futures. Moment of inertia of this type wheel is therefore measured experimentally and then checked the measured values with a theoretical measure. [24]

$$I_W = M_W R^2 \qquad \textit{3-89}$$

Where M_w is mass and R is radius of the wheel.

Substituting the values $I_w = 0.02304$ kg.m^2

Recalling equation 3-47, total moment of inertia with respect to center of gravity is described as

$$I_{total} = I_{body} + M_{body} d^2 + 2M_W L^2 + 2I_w$$

Substituting parameters value

$$I_{total} = \left[37.5\left(\frac{(0.5^2 + 0.45^2)}{12}\right) + 0.31608\right] kg\ m^2$$

$$I_{total} = 1.7301\ kg\ m^2$$

Other chassis parameters of mobile robot

The distance between lines on which tef seed is planted and frontal, top and side area of the plat form are considered in designing Vehicle cheese. Physical parameters are therefore seated accordingly in the following tabulation.

Table 3-1 Chassis parameters

Name of parameters	**Notation**	**Value seated**
Distance between hub point of wheel and origin of the moving reference frame	L	0.2 m
Distance between the two seed valve	d_v	0.2 m
Distance between COM of the vehicle and origin of the moving reference frame	d	0.1 m
Moment of inertia of the wheel	I_w	0.02304 kg.m^2
Width of the platform	w_p	0.5 m
Length of the platform	l_p	0.45 m
Height of the platform	h_p	0.35 m
Mass of differentially derived wheel	M_w	1.5 kg.
Mass of caster wheel	M_{cw}	1 kg.
Mass of chassis	M_{body}	20 kg.
Radius of the wheel	R	0.12 m
Moment of inertia of robot with respect to center of gravity	I_{total}	1.3907 kg.m^2

3.5.2 Motor parameters

Before determining DC motor parameters, motor requirements to drive the developed physical system should be specified using some basic physics. After the required power (motor power needed) is calculated from physical parameters of the platform, motors with realistic specifications are selected and an understanding of how they relate to robot's performance and capabilities is analyzed. In most cases, the perfect motors for any designed robot might not be available in the market and some tradeoffs is made in order to make final motor selection which can be the best sweats of the requirements.

Therefore, motor power needed is determined from load distributions calculation which has been discussed in dynamic modeling of the system.

Table 3-2 motion parameters, constants and coefficients of different parameters [26], [27]

Parameters	**Notation**	**Value**
Expected linear velocity of the platform	V	0.6 m/s
Linear acceleration of the platform to attain full load speed	A	0.3 m/s^2
Density of air at STP	**ρ**	1.2041 kg/m^3
Air drag coefficient	C_d	0.72
Tilled field rolling resistance coefficient	C_r	0.219
Frontal area of the platform	A_f	0.175 m^2
Angular velocity of the wheel	Ω	47.7 rpm
Inclination angle	β	0^o

Total torque needed from the output of the motor is calculated from equation 3-88 above.

$$T = R * F_{tr} = [F_{ard} + F_{rol} + F_{clim} + M_{tot}(a)] * R$$

Recalling force components equation from the preceding chapter, it can be calculated as follows one by one.

- Rolling resistance force

$$F_{rol} = F_n C_r = M_{tot} g(C_r)$$

$$F_{rol} = [(37.5)*(9.81)*(0.219)]N = 80.5646 \text{ N}$$

- Aerodynamic drug force

$$F_{ard} = 0.5 \rho A C_d V^2$$

$$F_{ard} = [(0.5) * (1.2041) * (0.175) * (0.82) * (0.6^2)]N = 0.0311 \text{ N}$$

- Hill climbing force

$$F_{clim} = M_{tot} g \sin \beta$$

$$F_{clim} = (37.5) * (9.81) * (\sin 0) N = 0\ N$$

- Linear acceleration force

$$F_{acc} = M_{total} a = (37.5) * (0.3) N = 11.25\ N$$

Total traction force therefore is $F_{tr} = F_{ard} + F_{rol} + F_{clim} + F_{acc} = 91.8467\ N$

So, two PMDC motors are needed to produce total torque of

$$T_{total} = R * F_{tr} = [(0.12) * 91.8467] Nm = 11.02\ Nm$$

Stall torque for each motor becomes $T_{stall} = \frac{1}{2} T_{total} = 5.51\ NM.$

But this is not the starting torque of the motor. It is the starting torque developed by the wheel. Therefore, recalling wheel torque expression in equation 3-72 from the previse section and rearranging, the following developed torque expression by individual motors is obtained.

$$T_{Shaft} = \frac{T_{wheel}}{(N) * (\eta)} \tag{3-90}$$

Assuming the gearing ratio N=3 and the transmission efficiency $\eta = 78\%$ and substituting

$$T_{Shaft} = \frac{5.51\ \text{NM}}{(3) * (0.78)} = 2.3547\ \text{NM}$$

The selected PMDC Motor for the aforementioned required torque has the following parameters.

Table 3-3 PMDC motor parameters *[28]*

Parameters	**Notation**	**Value**
Armature resistance	R_a	0.1557 ohm
Armature inductance	L_a	0.82 MH

Motor torque constant	K_t	1.1882 Nm/A
Geared motor inertia	J_m	0.271 kg. m^2
Geared motor viscous dumping	B_m	0.27 N.m.s
Motor back EMF constant	K_v	1.185 rad/s/V
Gear ratio	N	3

3.6 Energy Consumption Modeling and Analysis for DDMR

Though energy carried by robots in batteries is limited without solar panel or combustion engine generator and Recharging is difficult for autonomous robots in work, rechargeable battery powered robots is applied for most mobile robots in different applications. Similarly, powering a differential drive wheel mobile robot by using two simple rechargeable batteries is the scope of this research.

In overall, energy in a battery of the designed WMR is expended for the following two purposes:

I. Power for robotics functions like computing, sensing and communication.
II. Power for seed valve and motion of the vehicle platform.

The question which has to be addressed first to determine the demanded energy are, how far robot goes and how fast it gets there. However, total energy for driving is primarily independent on speed since driving energy is related to total mass of the vehicle including battery mass and tef seed in a seed box, gravity, distance traveled and all type of motion resistances. On the other hand, the energy for robotics functions like sensing, computing and communication utilizes considerable power whether driving or sitting. This is small when compared to the first one (needed power for seed valve and for the two motors).

Generally, Energies of watt hours are required and the total energy expended during whole mission time could be quantified as: [29]

$$\text{Total Energy} = \text{Robotics Energy} + \text{Mobility Energy}$$
$$= (\text{Robotics power})\text{x}(\text{mission time}) + (\text{constant})\text{x}(\text{total mass})\text{x}(\text{distance})$$

Here robotic power depends on the soil type and the vehicle geometry which actually affects energy consumption for a specified field coverage. The rolling resistance constant of the soil (field) and other parameters which affect energy are discussed in the above section.

Total electrical energy (current and voltage coming out of the primary battery pack) and the energy needed to move the vehicle in a desired position and to sow tef seed in a row should be balanced. Therefore total demand energy of the robot for this particular application should be determined first so that appropriate battery capacity can be selected accordingly.

The following assumptions are taken to determine field demand energy of the robot.

- The robot moves with a constant linear velocity of 0.6 m/s on a seed bed and plants tef seed in a 20 c.m distance rows.
- Seed bed is assumed to be prepared on a 50m by 100m farming field as shown in the figure below.

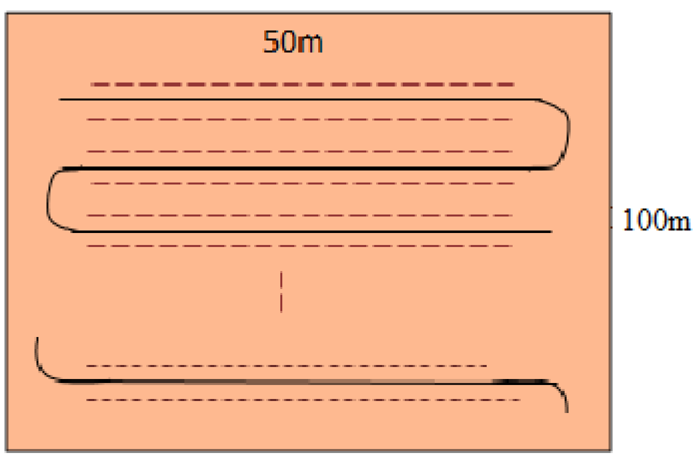


Figure 3.9 farming field and rows on it

The dotted lines in figure 3-9 shows rows on which tef seed is planted and the dashed line is the path of platforms center of mass (COM). Therefore as you can see from the figure, mobile robot is designed to sow two rows in a single move. Total energy needed to plant a certain specified filed can be determined from the following energy equsion.

$$total\ Enegry = (total\ Power\ ) * (time\ it\ takes\ to\ sow\ the\ field) \quad (3\text{-}91)$$

Total power can be determined from equation 3-83 as follows

$$\mathrm{P_{total}} = (\mathrm{F_{tr}}\ )\mathrm{V} = (91.8\mathrm{N}) * \left(\frac{0.6\mathrm{m}}{\mathrm{s}}\right) = 55.108\ \mathrm{W}$$

But to determine time that the robot will take to sow the whole filed, basic physics equation is used.

$$time\ = \frac{distance\ \ traveled}{\|velocity\|} \quad (3\text{-}92)$$

Total distance that the platform traveled is the sum of each single path including distance that the platform cover to make turns.

Consequently to determine total distance, number of turns that the robot makes has to be determined first. The distance between two rows is 0.2m and the platform plants two rows at a time. Therefore the distance between two paths of platforms center of mass is 0.4m.

And number of paths that the platform will make to plant the aforementioned field will be

$$Number\ of\ paths = \frac{width\ of\ the\ field}{distance\ between\ paths} = \frac{100m}{0.4m} = 250$$

A single path has 49.6m length. This is because the robot needs 0.2m from both sides to make turns. Total distance covered by the robot in moving street line is

$$S_{line} = Number\ of\ paths \times length\ of\ the\ path = 250 \times 99.6m = 24900m$$

Total distance covered by the robot in making turns is

$$S_{turns} = No.of\ turns\ \times length\ of\ a\ turn = (No.of\ paths - 1) \times curve\ distance$$

$$S_{turns} = (250 - 1) \times (3.14 \times 0.4m) = 312.7m$$

Total distance cover by the mobile robot is

$$S_{total} = S_{path} + S_{turns} = 24900m + 312.7m = 25212.7m$$

Substituting total distance and velocity of the vehicle in equation 3-92, we get how long the mobile robot takes to plant 50m x 100m area farming filed.

$$\text{time} = \frac{\text{distance traveled}}{\|\text{velocity}\|} = \frac{25212.7m}{0.6m/s} = \frac{25212.7m}{2160m/h} = 11.67h$$

Total demand field energy is therefore determined as follows:

$$Field\ demand\ energy = total\ pwor\ needed \times total\ time.$$

$$E_{demnd} = 55.108W \times 11.67h = 643.25Wh$$

Now, a 12V battery pack which can give this energy has to be selected for this specific robot. So, to determine battery specification total energy is divided by nominal voltage of the battery.

$$battery\ Ah = \frac{E_{demand}}{V_{nominal}} = \frac{643.25Wh}{12V} = 52.6Ah$$

Table 3-4 battery specification *[30]*

Nominal VOLTAGE	(20 hour) Nominal CAPACITY	DIMENSIONS				WEIGHT lbs.	TERMINAL Type
		Length	Width	Height	Total Height		
12V	26Ah	6.54"	6.89"	4.92"	4.92"	20.5	bolt
12V	33Ah	7.68"	5.12"	6.69"	7.09"	24	bolt
12V	40Ah	7.76"	6.50"	6.69"	6.69"	30	bolt
12V	55Ah	9.41"	5.20"	9.25"	9.25"	40	post/screw
12V	70Ah	10.16"	6.54"	9.25"	9.25"	53	bolt/post
12V	90Ah	12.05"	6.65"	9.09"	9.09"	66.1	flag/screw
12V	100Ah	12.99"	6.73"	8.43"	8.66"	70.5	flag/screw

Now from the listed battery specification of the above tabulation, 55Ah battery is selected for this particular study.

3.7 Controller Design

The most basic design requirements of a given electric DC motor are to rotate at desired angular speed and to achieve desired angular position at the minimum possible steady-state error. Different resources introduce different methodologies and approaches for mobile robot modelling and controller selection and design. In this thesis, the whole system is controlled using microcontroller (Arduino) and obviously some parameters like speed and position of right and left motors are controlled using PID controller which actually is included in the C-code for the main controller (Arduino). Before designing the controller, physical parameters of the mobile robot platform and electrical motor parameters must be introduced.

Speed controller design for DC motor

PID controller is used to control speed of the two motors used to drive right and left wheels. It contains both derivative and integral gain. The PD component improves transient and the PI component improves steady state and combination of two is used to improve overall time response of the system. Block diagram of the controller is shown below.

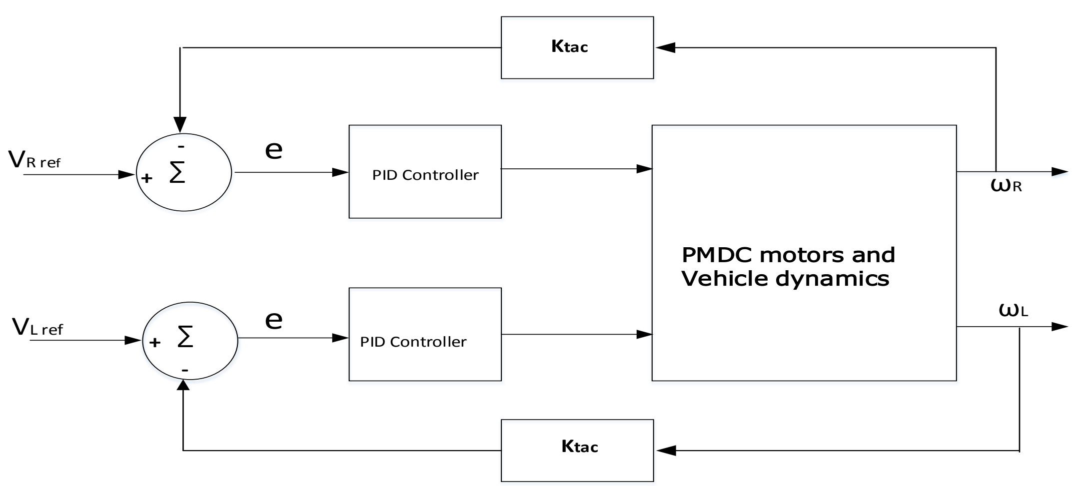


Figure 3.10 block diagram of overall PID feedback system

Tachogenerator senses the actual speed of the motor and its output voltage is compared with the input voltage to give the desired angular speed of the motor.

Recalling tachogenerator equation from the preceding chapter and subsisting

$$K_{tac} = \frac{V_{out}}{\omega} = \frac{12v}{5rad/sec} = 2.4\, V.s/rad$$

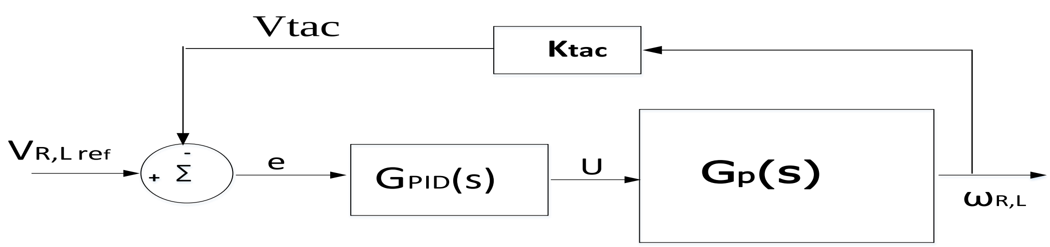


Figure 3.11 Block diagram of PID controller of PMDC motor for right or left wheel

Where V_{tac}, $V_{R,Lref}$, e and U are tachogeneretor output voltage, reference input voltage, error signal and controller output signal respectively.

The controller transfer function can be described as follows

$$G_{PID}(s) = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_P s + K_I}{s} \quad (3\text{-}93)$$

Where K_p, K_I and K_D are Modulating gain, integral gain and differential gain respectively. Recalling the equations that describe the DC motor, system dynamics and sensor modeling, the next open loop motor transfer function, relating the armature input terminal voltage, $V_{R,\ Lref}$ and output terminal voltage of the tachometer V_{tac} with most corresponding load torques applied is

$$G_{PM}(s) = \frac{K_v K_t}{(sL_a + R_a)(sJ_m + B_m) + (sL_a + R_a)T_L + K_t K_v} \quad (3\text{-}94)$$

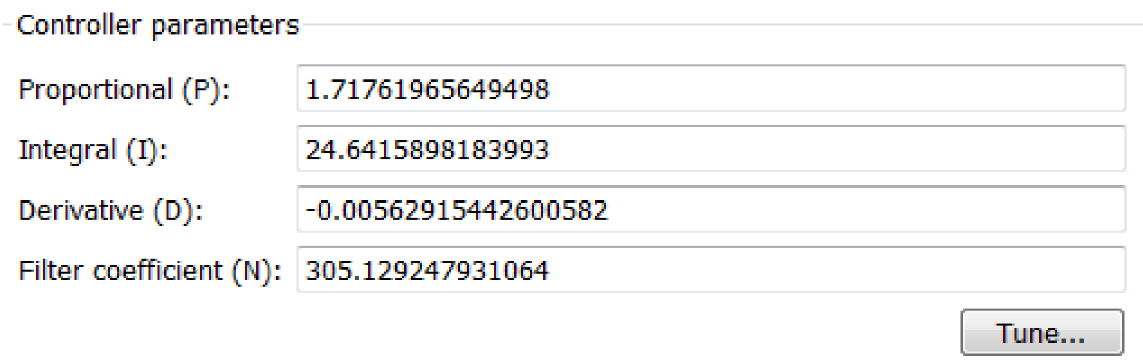
Where, K_v, K_t, J_m, B_m, L_a and R_a are motor parameters which are described in table 4-3 above and T_L is the load torque.

Substituting this parameters in equation 4-3, the following transfer function is found.

$$G_{PM}(s) = \frac{1.1408}{(0.22)s^2 + (0.2645)\text{s} + 1.1828 + (0.82 * \text{s} + 0.1557)T_L}$$

For the whole system dynamic i.e. motor dynamics and vehicle dynamics as a plant, PID tuning for both right and left motors speed control is done using MATLAB compensator editor and the following controller parameters are found.

Right wheel motor speed controller parameters



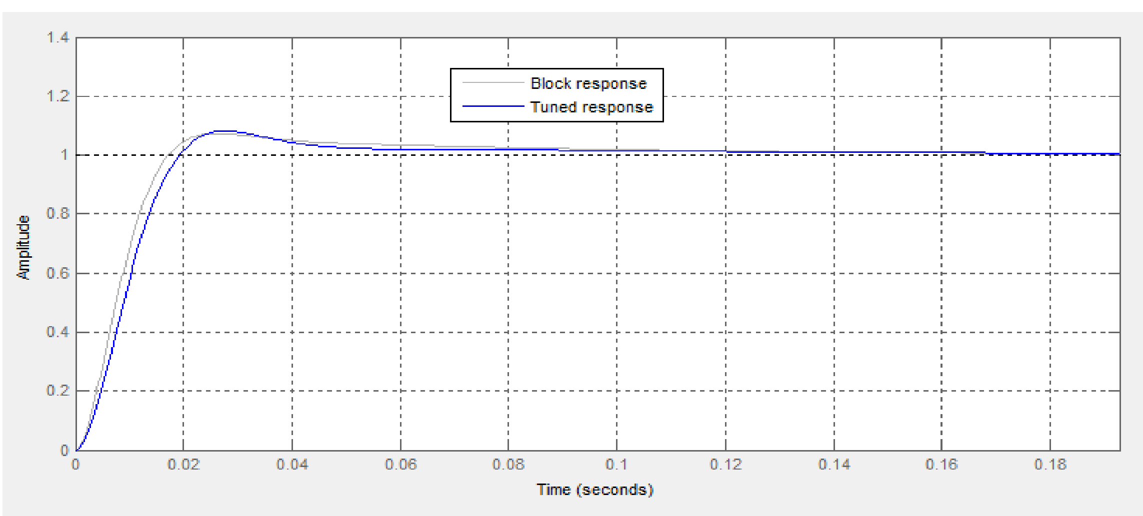


Figure 3.12 time response of right wheel motor speed controller.

Left wheel motor speed controller parameters

Controller parameters

Proportional (P):	1.79142454992024
Integral (I):	26.653095153047
Derivative (D):	-0.00566118408741837
Filter coefficient (N):	316.439904136234

Tune...

Step response of PID controllers for both right and left wheels are shown in Figure 3.12 and 3.13 respectively. Transient and steady state responses of the controllers can be observed from these graphs.

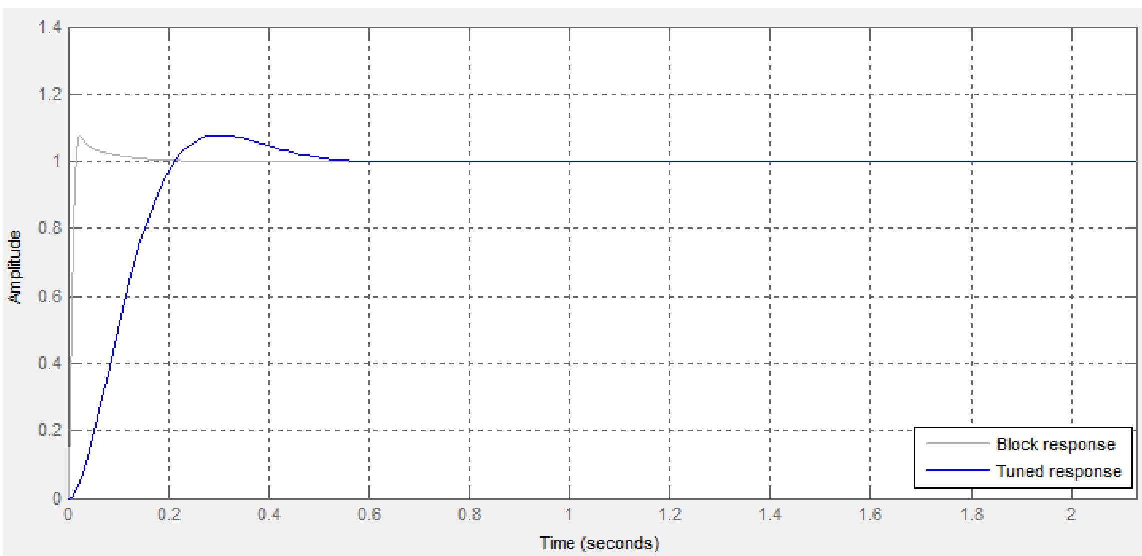


Figure 3.13 time response of left wheel motor speed controller.

CHAPTER FOUR

SIMULATION RESULT

4.1 Introduction

Two types of software are presented and discussed to show results of the proposed wheel mobile robot. This are MATLAB/Simulink model and Proteus software with Arduino environment to write C language. The first one is used to show and compare different results of the system and how the controller makes the output to truck the reference input. Proteus on the other hand, is used to testify how Arduino is used to control the whole system.

4.2 Matlab/Simulink result

Simulink model of the DDMR is developed as proposed (as figure 3.1) based on the mathematical description of the system.

Recalling kinematics modeling of the system the following Simulink model is developed.

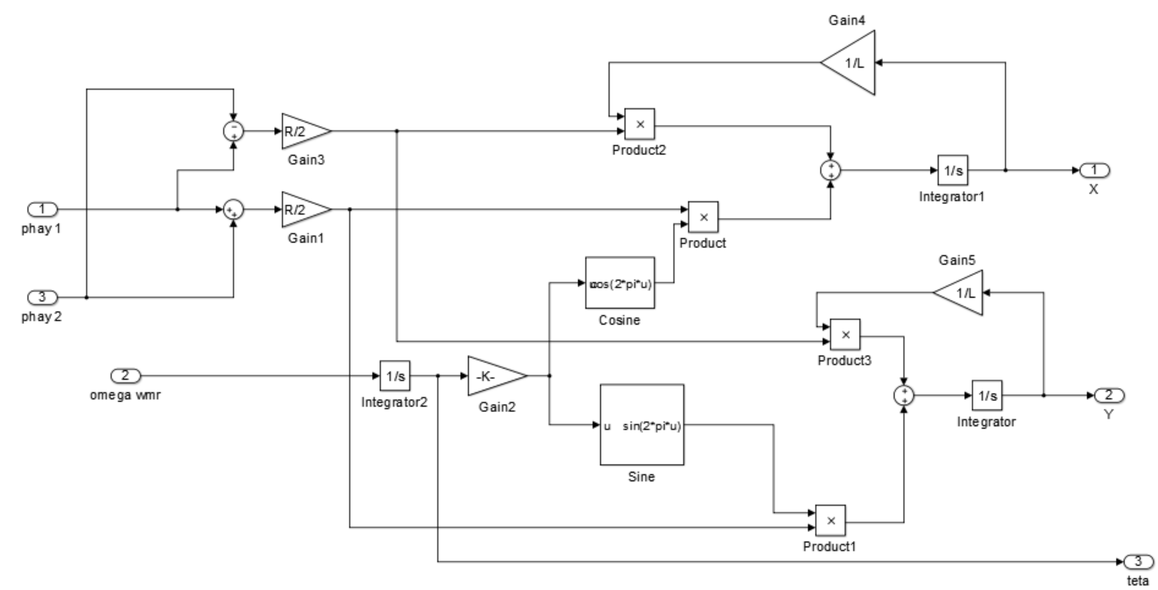


Figure 4.1 Simulink model of forward kinematics subsystem

Dynamic model of the system is developed in chapter three using Lagrange method. The following Simulink model is developed based on motor dynamic equation and system dynamic equation of differential drive mobile robot which are described in chapter three in detail.

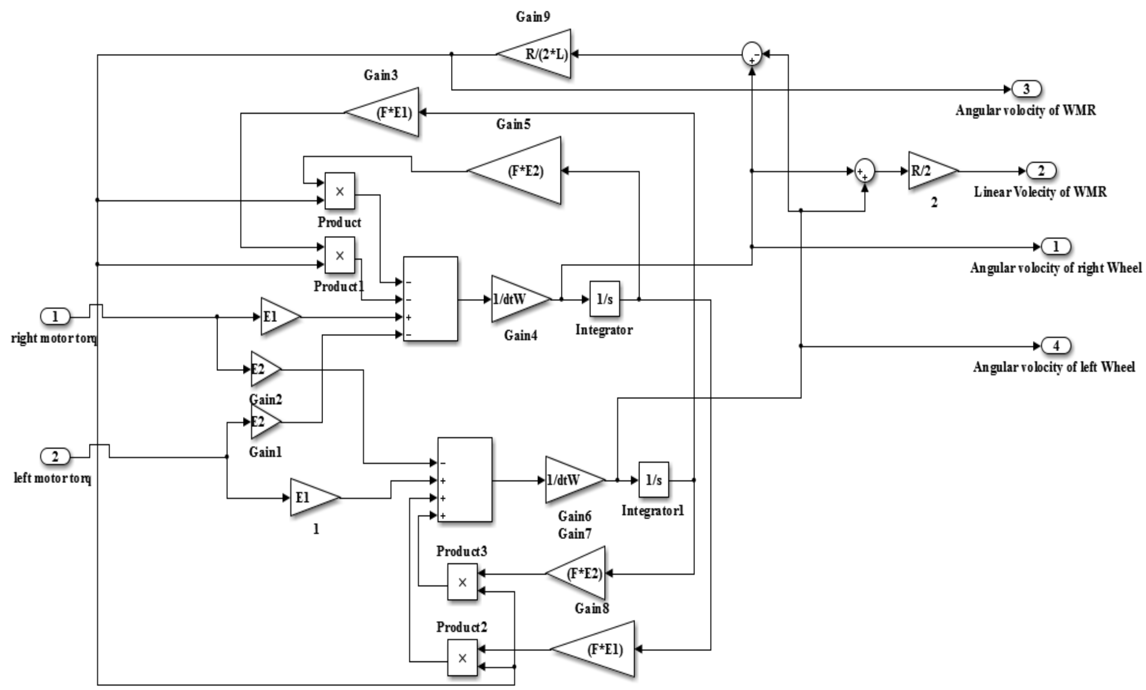


Figure 4.2 Simulink model of open loop system dynamic

In this model some long mathematical expressions are represented by a single gain for simplification of and equation describing the relationships are written in appendix of this report.

Similarly motor dynamics for right and left wheels are developed of the system

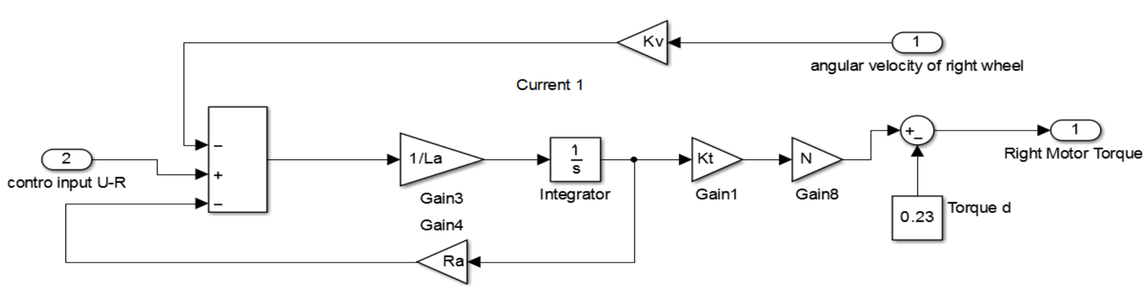


Figure 4.3 motor dynamic Simulink model for right wheel

Since similar motor specifications are used for both sides, Left motor dynamic Simulink model is very similar with the right motor Simulink modeling.

Combining these all Simulink models which are described in the above three figures in one, the following overall Simulink model is developed like proposed in figure 3.1.

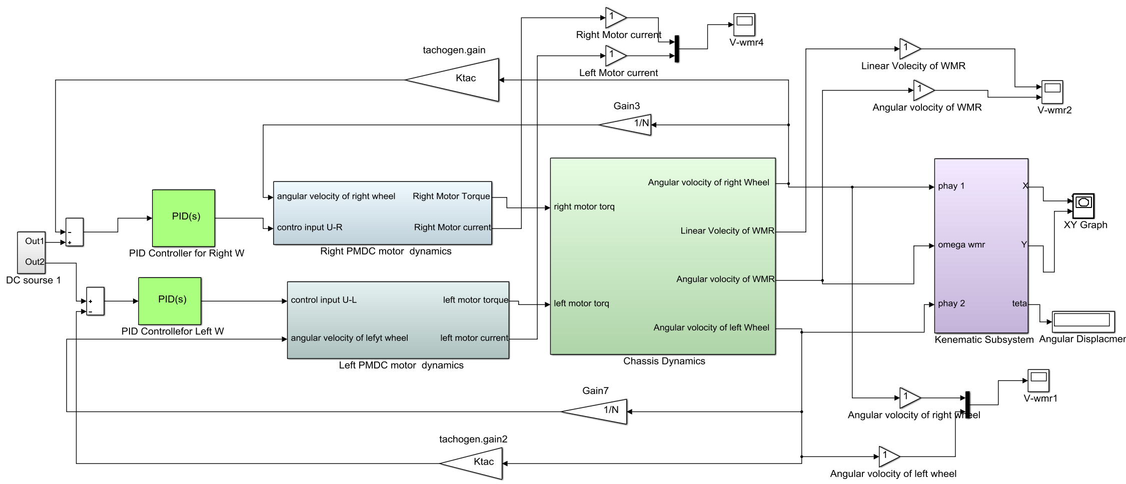


Figure 4.4 overall system Simulink model

As stated in figure 4-4 above, the overall system consists of three subsystems, Kinematic subsystem, dynamic subsystem and electrical drives subsystem. All subsystems description is shown in the preceding figures of this chapter.

Overall system modeling ware simulated based on the parameters defined in chapter four and the following results are recorded accordingly.

The system is a differential drive system which implies the two motors are powered according to the motion of the platform. For example if the platform is needed to make turn, one of the motor should stop running and the other one should run at full load. If the platform is needed to move in a straight line, the two motors should run at the same speed.

12 v dc source is given to the right or left motor when the vehicle is needed either to move in a street line or make turn to the other side. This input is taken as reference signal and actual output is measured using tachogenerator and compared with the output. The following two graph shows how PID controller lets the output to track the referred input.

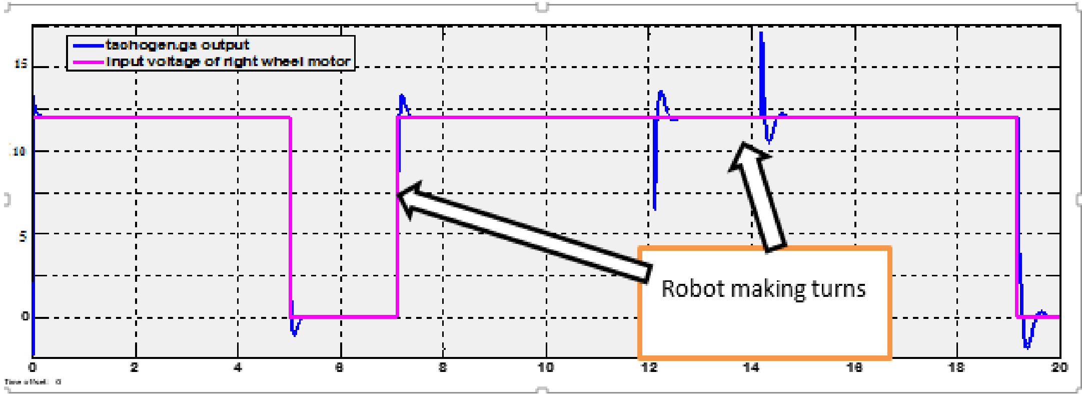


Figure 4.5 reference input and measured output for right wheel motor controller

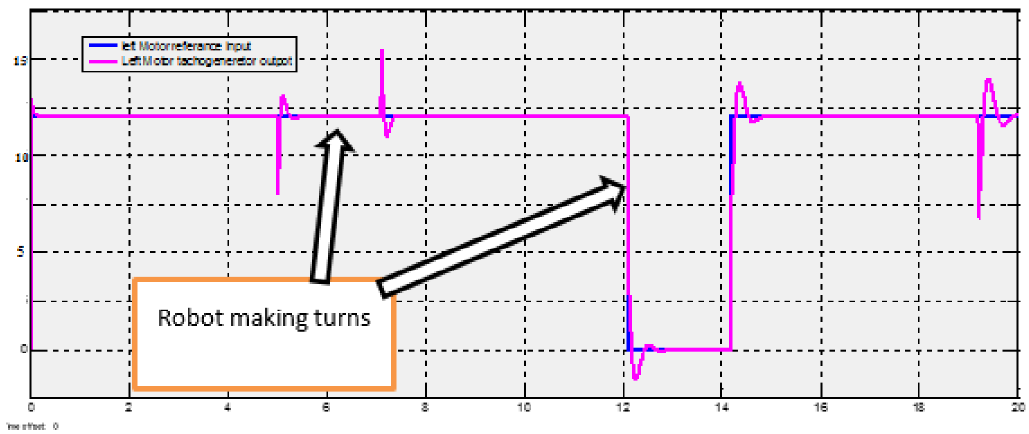


Figure 4.6 Reference input and measured output of left wheel motor

As stated in parameter determination section, the platform has 0.6 m/s linear velocity and doesn't have angular velocity when it moves in a straight line and has about 0.3 m/s and actually some value of angular velocity when it makes turn. This is because one motor run at 0.6 m/s and the other motor didn't move in making turns. For example in the figure below the vehicle made four turns. Angular and linear velocities of the WMR are shown below for those four turns.

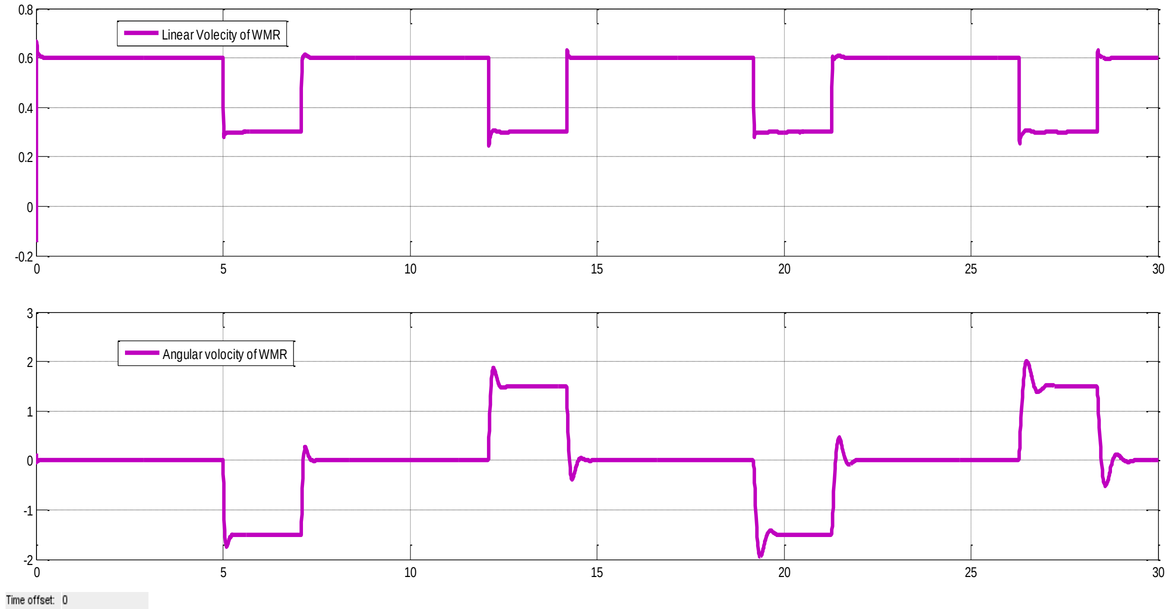


Figure 4.7 simulation result of Linear speed and Angular speed of the WMR

The two motors run alternatively in making turns. In need of a street line motion, the two wheel run at a speed of 5 rad/sec as calculated in chapter four. But, when the vehicle make turns, a single wheel run at 5 rad/sec and the other wheel stops on the point so that the platform makes turn accordingly. The following simulation result shows the two wheel angular speed relationships in mobile motion.

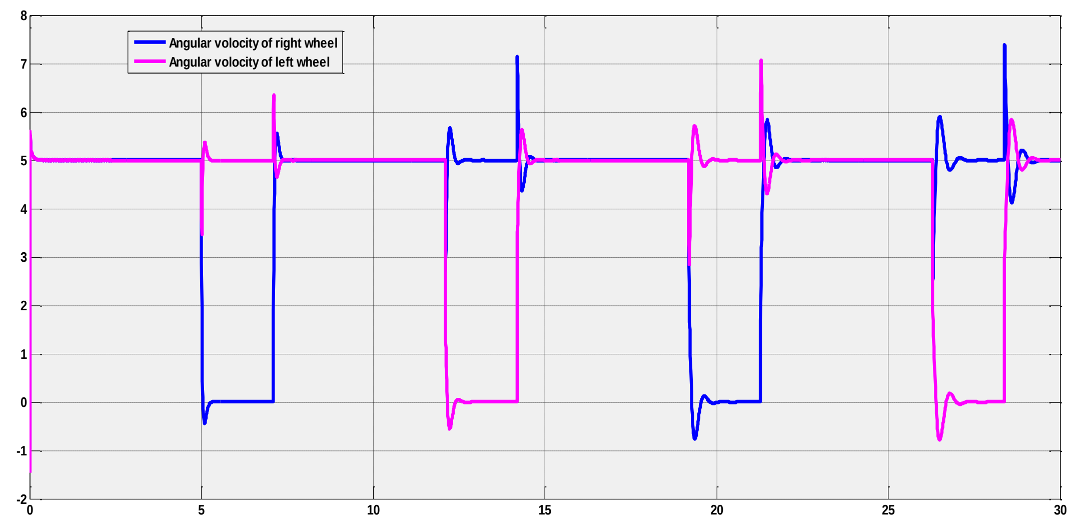


Figure 4.8 Right and left wheel angular speed of the mobile robot

The well prepared seed bed of the field is considered as x-y plane and simulation result where the platform moves and plant tef seed in line is shown below.

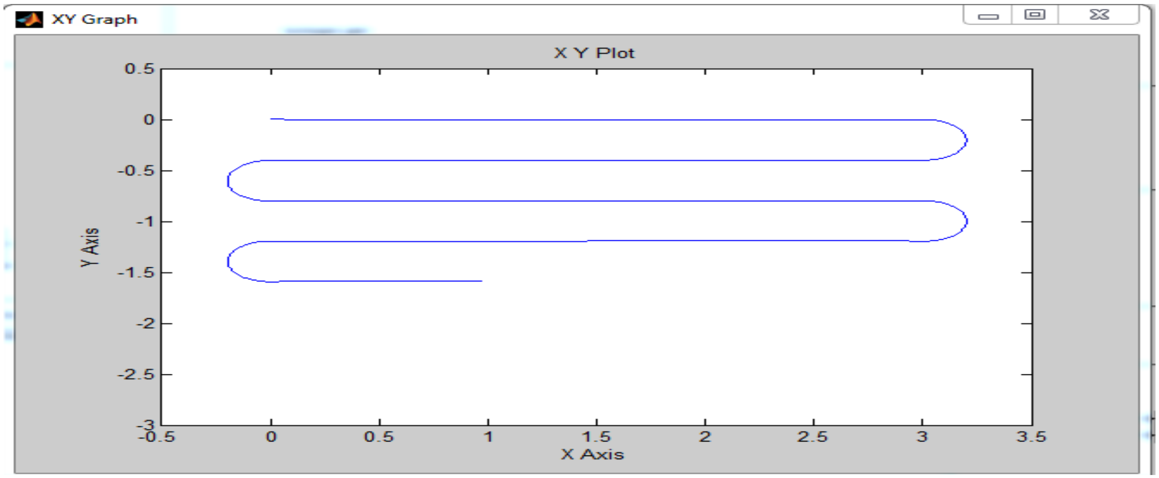


Figure 4.9 trajectory of WMR

4.3 Simulation result using Proteus

The most exciting and important future of Proteus simulator is its ability to simulate the interaction between software running on a microcontroller and any analogue or digital electronics and drives connected to it directly or indirectly. It simulates the execution of written object code (machine code) just like a real chip.

This thesis is also simulated by Proteus software to testify that the overall system of the project is controlled by Arduino (the controller) according to the object code loaded to it. Schematic capture of the overall system is shown in the figure below.

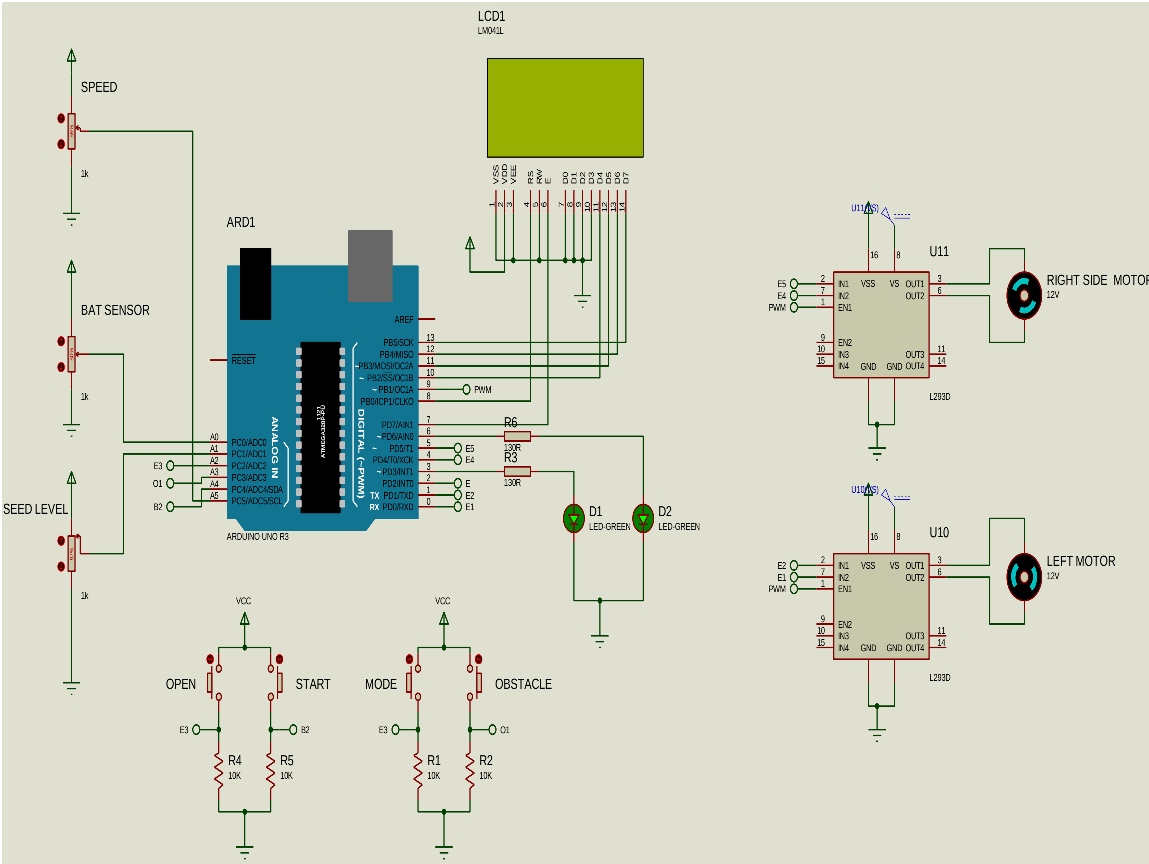


Figure 4.10 schematic capture of mobile robot on Proteus software

Object code was loaded and the following result is observed.

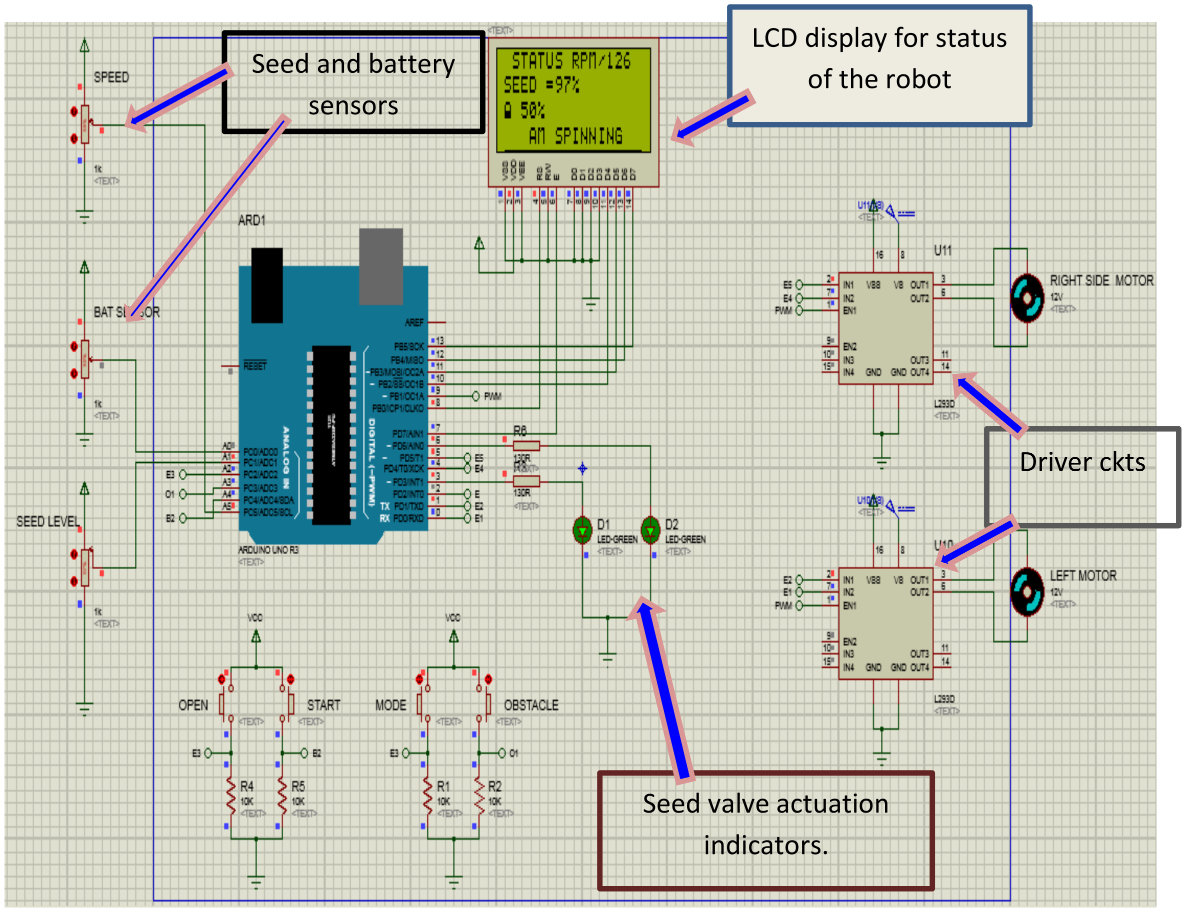


Figure 4.11 Proteus simulation result of WMR

When seed sensor senses there is no seed in the seed box, no seed will display and the robot stop moving. When the battery sensor senses less than 25% of a fully charged battery power, battery low will displayed and the two motors stop running and the vehicle stops on a place. The two seed servomotors close the valves when the vehicle make turns and open the valves if and only if the two motors run at the same speed. These all are observed from the above simulation result as shown in the figure above.

CHAPTER FIVE

CONCLUSION, RECOMMENDATION AND FUTURE WORK

In this section summarization of the major findings of the study, recommendations and future works are discussed. Section 5.1 is conclusion of major findings, Section 5.2 is recommendations and section 5.3 is future work of this study.

5.1 Summary of Major Findings

In this thesis, battery powered tef seed row planting differential drive agricultural mobile robot is designed. Considering no slipping and taking non holonomic constraint of the mobile robot, forward kinematic of a system is developed. Dynamic modeling of the system is also determined in Lagrange equation by using non holonomic constraint described in kinematic analysis.

Motion of the developed differential drive mobile robot (vehicle) is controlled by powering right and left wheel motors differentially. This means electric dc power is given to the motors according to the motion needed by the vehicle and speed of both motors are controlled accordingly. Chassis parameters for MATLAB simulation results of overall system models are chosen based on spacing of rows and other parameters are chosen considering power demand for the system and from load distribution of the system.

In addition to this, interfacing of system components with the Controller (Arduino UNO) is done using Proteus Software. The robot platform is well-ordered by controlling speed and position of the two PMDC motors using the driver L293D. LCD is interfaced for displaying statues of the battery and seed box and general information of the robot.

By implementing this project in the field of agriculture it can help Ethiopian farmers by seeding tef crop in rows of 0.2 meters distance so that tef seed wastage is reduced and weeding will be easier. I.e. row spacing is maintained and seed rate is controlled. Furthermore, implementing this project in the field is very useful for farmers who are intended to do agricultural activity but facing the labor problem and can save more time required for sowing process.

5.2 Recommendation

Ethiopian farmers use *Maresha*, an ox-drawn ard plough to prepare soil for cultivation. Most of the components of the plough are wooden except two pieces: the plough share and a tying unit. It is cheap and simple, but inefficient. This ploughing tool is pulled by animals which needs enough space for them to pass through and do the job. But the geographical settlement of the field is not comfortable for such activity. Due to this farmers are straggling to prepare the soil in all field for cultivation purpose. For examples the unreached field by the ox is dig by farmers using traditional tools like domma which is very tidies and inefficient.

On the other hand, the common practice method of sowing the seeds is by hand. This is a large time consuming approach. Besides being wasteful, planting was very imprecise and lead to a poor distribution of seeds.

The other methods for digging the fields is by using tractors. But the size of tractors is very big which makes it inapplicable for the aforementioned like fields. This is not the only drawback of using tractors in agriculture but environmental pollution and luck of man power can be taken as a serious problem and also Power supplying unit can be taken as a drawback to its reliability.

Therefore, to overcome this problems, designing solar based agricultural robots such as plowing robots, seed sowing robot and a like works are the recommended project areas.

5.3 Future work

The wheeled mobile robot is controlled to make a perfect turn by its input given with time. This means within a given angular speed of motor and chassis parameter, time the vehicle will take to make turn is calculated and power is given to both motors so that the vehicle will move in a street line. But if factures such as obstacles, delay of the response of the system and other factors which can possibly affect timing are existed, the vehicle will not make perfect turn. Therefore it's possible to use other mechanisms to make a perfect turn instead which has to be future work.

Nowadays renewable energy is a big bold research area. But battery is used in this work. Without solar panel or combustion engine generator, energy carried by robots in batteries is always limited. Recharging is also sometimes impossible for autonomous robots in work, especially in places and time periods lack of sunlight. Therefore designing solar based projects for this particular application has to be the future work.

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Appendixes

Appendix A: Matlab function for MATLAB Simulink modeling.

```
%Chassis parameters

R=0.12;             %radius of the wheel

L=0.2;    % distance b/n wheel center and origin of %the moving reference frame.

Mb=15;              % mass of chassis (Skeleton)

Msw=1.5;         % mass of standard wheel

Msd=1;              % mass of seed in a single seed box.

Mmotr=2.5;          % mass of motor

Mcw=0.5;            % mass of caster wheel

Mbtt=6.5;           % mass of battery

d=0.1;           %distance b/n COM and origin of (Xr,Yr)

It=1.3907;        %Moment of inertia of robot with respect to &center of gravity

Iw=0.02304;          %Moment of inertia of the wheel


% motor parameters

Kt=1.1882;          %Motor torque constant

Kv=1.185;           %Motor buck EMF constant

La=0.82;            %Armature inductance

Ra=0.1557;          %Armature resistance

Jm=0.271;           %Geared motor inertia
```

```
Bm=0.27;              %Geared motor viscous dumping

Td1=0;

Td2=0;

N=3;                  %Gear ratio

Ktac=2.4;             %tachogeneretor constant

%Kd=-0.0282245924021079;

%Ki=12.7351741665213;

%Kp=1.01200889980323;

%representation of complicated mathematical expressions for %simplification of dynamic models.

Mtr=tf(1,[La,Ra])

Mt=Mb+2*(Msw+Msd+Mmotr)+Mcw+Mbtt

F=[(R^2)*Mb*d]/(2*L)

E1=Iw+((R^2)/(4*(L^2)))*[Mt*(L^2)+It]

E2=(R^2)/(4*(L^2))*[Mt*(L^2)-It]

dtW=Iw^2+[(R^2)/(4*L^2)]*[2*Iw*(Mt*L^2+(It/2))+R^2*Mt*It]
```

Appendix B: Arduino programing

```
D #include <LiquidCrystal.h>

// initialize the library with the numbers of the interface pins

LiquidCrystal lcd(8, 7, 10, 11, 12, 13);// RS,EN,D4,D5,D6,D7

int motorone = 0;
```

```
int motoroneone= 1;

int motortwo = 5;

int motortwotwo = 4;

int seed = 6;

int seed2 = 3;

int battery = A0;

int powerbutton = A2;

int stateold =LOW;

int currentstate = LOW;

int stateoldup =LOW;

int loopit =1;

int seedweightpin = A1;

int start = A4;

int roundloop =0;

int obstacle =A3;

double drive = 0;

double duty = 0;

double error = 0;

double  ierror = 0;
```

```
double errorold = 0;

double edot =0;

double setpoint = 0;

double input = 0;

double kp =1;

double ki=0;

double kd = 0;

double dutycycle = 0;

int pmwout = 9;

byte rpmcount;

unsigned int rpm;

unsigned long timeold;

char ty[] = {'T','A','Y','E','*','R','O','B','B','O','T','I','C','S'};

byte bat[8]={

B01110,

B10001,

B10001,

B10001,

B10001,
```

```
B10001,

B11111,

B11111};

void setup() {

//attachInterrupt (0, rpm_fun, FALLING );

// put your setup code here, to run once:

pinMode(motorone ,OUTPUT);

pinMode(motoroneone ,OUTPUT);

pinMode(pmwout ,OUTPUT);

pinMode(motortwo,OUTPUT);

pinMode(motortwotwo,OUTPUT);

pinMode(seed,OUTPUT);

pinMode(seed2,OUTPUT);

pinMode(powerbutton,INPUT);

pinMode(seedweightpin,INPUT);

pinMode(seedweightpin,INPUT);

pinMode(start,INPUT);

pinMode(obstacle,INPUT);

// set up the LCD's number of columns and rows:
```

```
lcd.begin(16, 4);
lcd.setCursor(0,1);
lcd.print("  Press[OPEN]");}
void speedmes(int x){
// detachInterrupt (0);
delay (10);
rpm = 30*1000/( millis() - timeold)*x;
timeold = millis();
rpmcount = 0;
//Restart the interrupt processing
//attachInterrupt (0, rpm_fun, FALLING );}
void rpm_fun(){
rpmcount++;}
int powervar =0;
int bounce (int x){
int pinstate = digitalRead(powerbutton);
if(pinstate !=x){
delay(5);
pinstate = digitalRead(powerbutton);}
```

```
return pinstate;}

int startloop = 0;

int batteryvalue;

int seedvalue;

void loop() {

// speedmes(rpmcount);

int power = powerfun();

batteryvalue= analogRead(A0);

batteryvalue = map(batteryvalue,1,1023,1,100);

seedvalue= analogRead(A1);

seedvalue=map(seedvalue,1,1023,1,100);

rpm = map(analogRead(A5),1,1023,1,230);

if(power == 1 && startloop == 0){

lcd.setCursor(0, 0);//move courser to second line}

lcd.print(" STATUS ");//showing name

batterchar();

batterypattern();

lcd.setCursor(2, 3);//move courser to second line}

lcd.print("Press[START]  ");//showing name
```

```
loopit = 0;

if(digitalRead(start)==HIGH){

if(batteryvalue >=25 && seedvalue >=25){

startloop = 1-startloop;

lcd.setCursor(12,2);

lcd.print("   ");

lcd.setCursor(12,1);

lcd.print("   ");

lcd.setCursor(2, 3);//move courser to second line}

lcd.print(" AM SPINNING    ");//showing name

digitalWrite(seed,HIGH);

digitalWrite(seed2,HIGH);}

else {if(batteryvalue <25){

lcd.setCursor(12,2);

lcd.print("LOW");

batterypattern();}

else{ lcd.setCursor(12,2);

lcd.print("   ");}

if(seedvalue <25){
```

```
lcd.setCursor(12,1);
lcd.print("LOW");
batterypattern();}
else{
lcd.setCursor(12,1);
lcd.print("   ");}
}}}
if(startloop==1){
batterchar(); batterypattern();
if(digitalRead(obstacle)==HIGH && roundloop ==0){roundloop = 1;turntoleft();}
if(digitalRead(obstacle)==HIGH && roundloop ==1){roundloop = 0;turntowright();}
digitalWrite(motorone,LOW);
digitalWrite(motoroneone,HIGH);
digitalWrite(motortwo,HIGH);
digitalWrite(motortwotwo,LOW);
setpoint=230;
input= rpm;
dutycycle=pid_loop(kp,ki,kd,setpoint,input);
analogWrite(pmwout,dutycycle);
```

```
lcd.setCursor(2, 3);//move courser to second line}

lcd.print(" AM SPINNING    ");//showing name

digitalWrite(seed,HIGH);

digitalWrite(seed2,HIGH);

batterypattern();

if(batteryvalue <25 && seedvalue<25){

poweroff();

startloop = 0;

seedre();

battre();

} else{

if(batteryvalue<25){  battre();poweroff();

digitalWrite(seed,LOW);

digitalWrite(seed2,LOW);

startloop = 0;}

if(seedvalue <25){ seedre();poweroff();

digitalWrite(seed,LOW);

digitalWrite(seed2,LOW);

startloop = 0;}
```

```
}}
// put your main code here, to run repeatedly:
if(power == 0 && loopit== 0){
lcd.clear();
lcd.setCursor(0,1);
lcd.print(" GOOD BYE...... ");//showing name\
delay(1000);
poweroff();
for(int x = 0;x<=6;x++){
lcd.setCursor(15-x,1);
lcd.print(" ");
delay(1000);}
for(;;){
lcd.clear();
power = powerfun();
if(power ==1){
wellcome();
loopit = 1;
break;}
```

```
}}}
int  powerfun(){
currentstate = bounce(stateold);
if(currentstate == HIGH && stateold == LOW){
powervar = 1-powervar;
if(powervar ==1){
wellcome();
}}
stateold = currentstate;
return powervar; }
void wellcome(){
lcd.clear();
lcd.setCursor(0, 1);//move courser to second line}
lcd.print("    WELLCOME  ");//showing name
delay(500);
lcd.setCursor(0, 2);//move courser to second line}
lcd.print("      TO  ");//showing name
delay(500);
lcd.clear();
```

```
lcd.setCursor(1,1);

lcd.cursor();

for(int x = 0;x<=13;x++){

lcd.print(ty[x]);

delay(100);}

lcd.noCursor();

///lcd.print(" TAYE ROBBOTICS   ");//showing name

delay(500);

lcd.setCursor(0,3);

lcd.print("LOAD");

for(int x = 0;x<=8;x++){

//lcd.setCursor(5+x,1);

lcd.print(".");

delay(100); }

lcd.clear();

lcd.setCursor(0, 0);//move courser to second line}

lcd.print("STATUS  ");//showing name}

void batterchar(){

if(batteryvalue == 100){
```

```
for(int x = 1;x<=5;x++){
bat[x]=B11111;
}}
else{if(batteryvalue < 100&&batteryvalue>= 80){
bat[1]=B10001;
bat[2]=B11111;
bat[3]=B11111;
bat[4]=B11111;
bat[5]=B11111;
} else {
if(batteryvalue < 80&&batteryvalue>= 60){
bat[1]=B10001;
bat[2]=B10001;
bat[3]=B11111;
bat[4]=B11111;
bat[5]=B11111;
} else {
if(batteryvalue < 60&&batteryvalue> 40){
bat[1]=B10001;
```

```
bat[2]=B10001;

bat[3]=B10001;

bat[4]=B11111;

bat[5]=B11111;

} else{

if(batteryvalue < 40&&batteryvalue> 20){

bat[1]=B10001;

bat[2]=B10001;

bat[3]=B10001;

bat[4]=B10001;

bat[5]=B11111;

} else{

}}}}}}

void batterypattern(){

lcd.createChar(0,bat);

lcd.setCursor(8, 0);//move courser to second line}

lcd.print("RPM/");//showing name

lcd.print(rpm);//showing name

lcd.print(" ");//showing name
```

```
lcd.setCursor(0, 1);//move courser to second line}

lcd.print("SEED =");//showing name

lcd.print(seedvalue);//showing name

lcd.print("%");//showing name

lcd.setCursor(0, 2);//move courser to second line}

///lcd.print("BAT =");//showing name

for(int x = 0;x<5;x++){

lcd.setCursor(0, 2);//move courser to second line}

lcd.write(byte(0));

lcd.print(" ");//showing name

lcd.print( batteryvalue);//showing name

lcd.print("%");//showing name

lcd.print(" ");//showing name

delay(10);

}}

void poweroff(){

digitalWrite(motorone,LOW);

digitalWrite(motoroneone,LOW);

digitalWrite(motortwo,LOW);}
```

```
void seedre(){ lcd.setCursor(12,1);

lcd.print("LOW");}

void battre(){lcd.setCursor(12,2);

lcd.print("LOW");}

void turntoleft(){ digitalWrite(motoroneone,HIGH);

digitalWrite(motortwo,LOW);lcd.setCursor(2, 3);//move courser to second line}

lcd.print("TURN TO RIGHT ");//showing name}

digitalWrite(seed,LOW);

digitalWrite(seed2,LOW);

delay(7000);}

void turntowright(){ digitalWrite(motoroneone,LOW);

digitalWrite(motortwo,HIGH);lcd.setCursor(2, 3);//move courser to second line}

lcd.print(" TRUN TO LEFT ");//showing name}

digitalWrite(seed,LOW);

digitalWrite(seed2,LOW);

delay(7000);}

double pid_loop(double kp, double ki, double  kd, double setpoint, double in){

error=setpoint-in; if (error<0)

{  error=0-error;  } //delay_ms(3000);
```

```
if ( error > 255) { duty=255; }

else

{    ierror+=error; if (ierror>255)

{duty=255;} else {if (ierror<0)

{duty=0;}}}

edot=error-errorold;

drive= (kp*error)+( ki*ierror)-(kd*edot);

if (drive > 255 )

{    duty=255;   } else

{      duty=drive;     }

errorold=error;

return drive;       }
```