

DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

AHMADU BELLO UNIVERSITY – ZARIA

DESIGN AND ENVIRONMENTAL BEHAVIOUR MODELING OF A BLUETOOTH CONTROLLED PLANTER ROBOT

BY

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DESIGN AND ENVIRONMENTAL - BEHAVIOUR MODELLING

OF A BLUETOOTH CONTROLLED PLANTER ROBOT

BY

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DECEMBER, 2014

DECLARATION

I, Kabir Ahmad hereby declare that this dissertation titled **"Design and Environmental - Behaviour Modeling of a Bluetooth Controlled Planter Robot (PLANTBOT)"** presented to the School of Post Graduate Studies of Ahmadu Bello University, Zaria is the result of my own research and it has not been presented in any form, anywhere for the award of any certificate.

All literature herein referenced and cited have been duly acknowledged. All shortcomings in this work are entirely my responsibility.

Kabir Ahmad _____ _____

Signature **Date**

CERTIFICATION

This is to certify that the PhD dissertation titled **"Design and Environmental - Behaviour Modeling of a Bluetooth Controlled Planter Robot (PLANTBOT)"** meet the regulations governing the award of the degree of Doctor of Philosophy (PhD) in Electrical Engineering of Ahmadu Bello University, and is approved for its contribution to literary presentation.

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DEDICATION

I dedicate this work to my beloved parents and my entire family and to Muslim Refresher Course Programme Zaria and to my colleagues at Muslim Special Training Centre Zaria.

ACKNOWLEDGEMENTS

All Praise is due to Allah, we are grateful to Him and unto Him we implore for help. We repent to Him and we seek refuge in Allah from the evils of our souls and our bad deeds. He who Allah guided no one can mislead him and he who go astray no one can guide him. I bear witness that there is no deity worthy of worship but Allah (He is alone without partner) and I bear witness that Muhammad is His servant and messenger (SAW).

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LIST OF ABBREVIATION

ABU	Ahmadu Bello University
ANSI	The American National Standards Institute
APPS	Applications
ARX	Regressive with eXogenous input
BIOS	Basic Input/Output System
BZZ	Bizara Zaria
CAD	Computer Aided Design
CAE	Computer-aided engineering
CPU	Central Processing Unit
DBZ	Dambo Zaria
DC	Direct Current
DGZ	Dogarawa Zaria
DKZ	Dakace Zaria
DRW	Drawing
DTMF	Dual Tone Multi – Frequency
EEPROM	Electronically Erasable Read Only Memory
Est	Early steering output
FMZ	Filin Mallawa Zaria
FRCL	Front and Rear Converging Linkages
FRP	Fiber Reinforced Plastic
GS	Gain Selects
GSM	Global System of Mobile – Communication
GUI	Graphical User Interface
IAR	Institute of Agricultural Research
IBM	International Business Machine
IC	Integrated Circuit
ISM Band	Industrial, Scientific and Medical Band
ITU-T	International Telecommunication Union for Telecommunication
KGZ	Kofan Gayan Zaria
KKZ	Kofan Kona Zaria
LED	Light Emitting Diode
MATLAB	MATrix LABoratory
MF	Multi Frequency
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MS	Mobile Station
NOP	No Operation
OSC	Oscillator
PC	Personal Computer
PCB	Printed Circuit Board
PDA	Personal Digital Assistant

PIC	Peripheral Interface Controller
PL	parallel linkages
PLANTBOT	Planter Robot
PWM	Pulse Width Modulation
RAM	Random Access Memory
RISC	Reduced instruction set computing
ROM	Read Only Memory
SDP	Service discovery protocol
SS 7	Signaling System 7
St/GT	Steering input/guard time output
StD	Steering output
Tf	Transfer Function
THZ	Tohu Zaria
TTZ	Tukur – Tukur Zaria
TV	Television
UDZ	Unguwan Dankali Zaria
USB	Universal Serial Bus
VCR	Video Cassette Recorder
VHP	Virtual Hitch Point
WPAN	Wireless Personal Area Networks
XT	Crystal

LIST OF SYMBOLS

SYMBOL	MEANING
Φ_{max}	Angle of twist
C_S	Static load
$S_e^{/}$	Rotating endurance limit
σ_{axial}	Axial stress
τ_{max}	Maximum sheer stress
A	Acceleration of the Plantbot
A	Area
Ah	Ampere –Hour
B	Breadth
C	Capacitor
C_E	Extended static load
C_{ends}	Coefficient of joint type
C_R	Rolling resistance coefficient
d	Diameter
E	Modulus of Elasticity
E	Noise component
F	Frequency
F_D	Drag force
F_G	Grade requirement force
F_I	Inertia force
F_R	Rolling resistance force
F_{TR}	Tractive force
g	Acceleration of freefall due to gravity
G(s)	Ratio of output to input
H	Height
I	Current
J	Polar moment of inertia
K	Stiffness; Duty ratio
K	Joint constant
k_b	Size factor
L	Length, Bearing life rating
M	Mass of the Plantbot
N	Number: of wheels; of connected points; of gear teeth
η	Efficiency
$n_{separation}$	Factor of safety against separation
P	Power
P_R	Power requirement due to F_R

P_T	Total power
R	Radius of wheels; Reliability; Resistor
r_0	Radial distance
S	Frequency domain variable
S_f	Fatigue strength
S_{ut}	Tensile strength
S_y	Yield strength
T	Torque; Transistor
T	Time
T(s)	Transfer function
t_0	Initial time
tr	Transfer function
u(t)	System input
V	Voltage
W	Weight
W	Width
X_c	Capacitive reactance
y(t)	System output
H	Effective slant height
Θ	Theta-angle of inclination
Π	Constant – pie (3.142)
ρ	Density
Ω	Rotational speed of the Plantbot

ABSTRACT

This research is aimed at the design and implementation of a Bluetooth controlled planter robot. It involved a mechanical design, a Bluetooth control design, an implementation of prototype and environmental behaviour modelling as well as validation of the robot's model. The design was optimized for planting maize as a case study in Zaria. In the mechanical design section, several aspects, starting from selection of dimensions, materials to production of complete engineering drawings were presented and the Plantbot was constructed using the engineering drawings of the robot. In the design of the Bluetooth control segment, detailed procedure from selection of Bluetooth module to design of microcontroller relay driver were presented. The designed Bluetooth control system was then interfaced with the mechanical part and the Plantbot was tested. The average speed of the Plantbot obtained from the experiments was 30.70cm/s which is 85.26% of the designed value (36cm/s). The depth of seed planting was 3cm which agreed with the recommended 2 – 3cm by Institute of Agricultural Research of Ahmadu Bello University-Zaria (2012). The percentage of successful planting was 89.8% and percentage of successful planting of two seeds per hole was 86.6%. The effective range of the Bluetooth control was 57.61m (189.013 feet) i.e. 94% of design range. The MATLAB was used as system identification toolbox to develop the environmental behaviour model of the Plantbot. The linear model of the ARX structure (i.e. arx411) obtained showed the best fit of 83.47%. A transfer function relating the speed of the Plantbot with the soil moisture content was then developed.

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

The agricultural industry is behind other complementary industries in using automated systems because the type of jobs involved in agriculture are not straightforward, and many repetitive tasks are not exactly the same every time.

This work is therefore, aimed at developing a Bluetooth controlled planter robot, hence forth called Plantbot which is expected to ease the planting process and increases the efficiency of the farmers. This Bluetooth controlled agricultural machinery also takes into consideration the environmental conditions of the case study location "Zaria" in order to develop a model representing its behaviour with respect to the changes in environmental conditions. This is expected to improve the process of future designs for the same or similar environment. The Plantbot is also optimized for planting maize, which is the predominant crop in Zaria and virtually most of northern Nigeria.

The Bluetooth controlled planter robot (Plantbot) being a mechatronic device has mechanical structure as the physical segment with the electronic segment as the control part of the system. Fig. 1.1 gives the general block diagram of the processes involved in the development of the Plantbot.

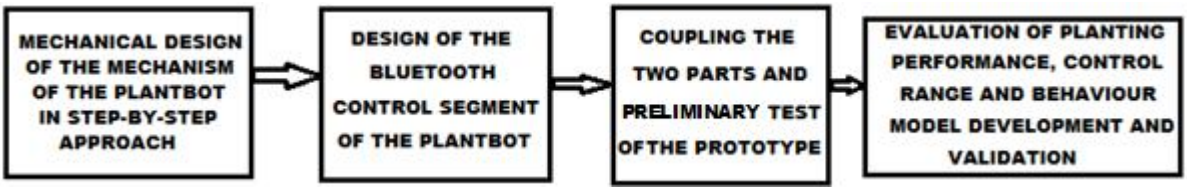


Fig. 1.1 General Block Diagram of the Complete Work.

The mechanical design part of the work was carried out by defining the required forms of movement of the machine during its planting operation, selection of the various

dimensions that were needed for accurate planting by the machine. Based on these facts, the various design calculations and decisions were carried out and complete engineering drawing of the Plantbot was produced based on the results from the overall design carried out. Using the engineering drawings the practical construction was done.

The block diagram of the design of the Bluetooth control section of the Plantbot is as follows (see Fig. 3.14):

The first thing done in facilitating the Bluetooth control of the Plantbot was selection of GSM handset that has Bluetooth facility and can produce Dual - Tone Multi – Frequency (DTMF) signal (the other phone signaling method is rotary (analog version by rotating buttons) which is almost completely replaced by DTMF). The Bluetooth module in the block diagram is a device that can be connected to the handset remotely using Bluetooth medium. The module receives the DTMF signal from the handset when DTMF buttons of handset were pressed. The DTMF booster circuit receives DTMF signal from the Bluetooth module and amplifies it, then delivers it to the DTMF decoding circuit. The DTMF decoding circuit receives the DTMF signals and decodes them and produces outputs in form of four (4) bit binary information. The PIC microcontroller circuit receives the four (4) bit binary data decoded from the DTMF signal and uses it to enable six different pins on the microcontroller that were used to drive relay driver circuits. The relay driver circuits were transistor switching circuits that were used to operate six relays that control the operation of motors (M_1, M_2 and M_3) on the Plantbot. The motor M_1 is the main drive motor for forward and reverse movement of the Plantbot. Motor M_2 is the steering motor of the Plantbot. Motor M_3 is motor used for lowering the planting mechanism during planting and raising it when the Plantbot is not planting.

The detailed explanations of the experimental setups, data collection and analyses carried out using MATLAB System Identification Toolbox and Statistical relations for modeling the Environmental Behaviour of the Plantbot are presented in a step – by – step approach under behaviour modeling section. The procedure for Performance Evaluation and Behaviour Modeling of the Plantbot is depicted by block diagram of Fig. 1.2.

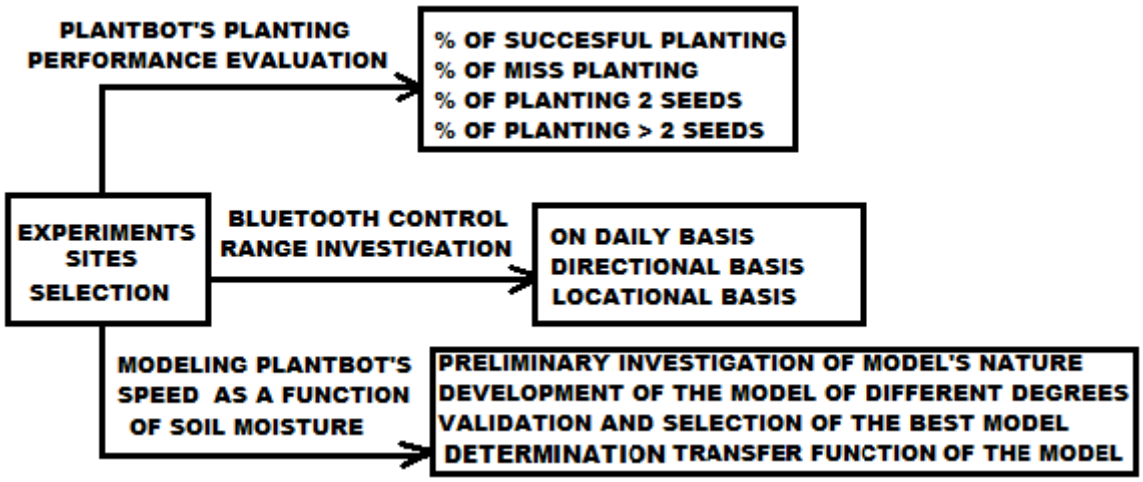


Fig. 1.2. Block Diagram of Performance Evaluation and Behaviour Modelling

The steps of the procedure of Fig. 1.2 can be summarized as follows:

i. Selection of test sites for modeling of variation of Plantbot's speed with change of moisture content of soil.

ii. Selection of measuring devices (for moisture and speed).

iii. Evaluation of planting performance of the Plantbot by finding percentage of successful planting and percentage of planting two seeds per hole.

iv. Analysis of results obtained in (i) to (iii) using MATLAB system identification toolbox and statistical relations.

v. Determination of system transfer function

1.2 AIM AND OBJECTIVES OF THE WORK

The aim of this work is the design and environmental behaviour modelling of a Bluetooth controlled planter robot. The designed robot is to be used for planting maize as a case study since it is the predominant crop in the study area (Zaria). Experiments were conducted in order to model the behaviour of the robot as it interacts with the environment where it operates and the model was validated. Thus, the objectives of the research are as follows:

(A) The comprehensive design of the Plantbot, including the following:

1. Description of the modes of movement and dimensions of the robot and coordination of the related links.
2. Analysis of the load magnitude to be handled by the Plantbot and determination of the torque required to effectively overcome the maximum payload.
3. Determination of the motor size and type (that can suite the type of motion required and the amount of load to overcome) and suitable gear system (that can help to translate the actual motion of the motor(s) into the desired rate and orientation).
4. Designing the Bluetooth control section used for controlling the Plantbot remotely with transmission range of 61m (200 feet).

(B) Development and Implementation of the Plantbot including:

1. Production of detailed engineering drawings of the system based on (1 – 3 above).
2. Interfacing the mechanical section with the Bluetooth control section.

(C) Environmental Modelling including:

1. Carrying out experiments (e.g. effect of the soil moisture on driving force and hence on the velocity) with the coupled Plantbot to model its behaviour as it interacts with the environment using MATLAB System Identification Toolbox and Statistical tools.
2. Investigation of the Bluetooth control range in noise prone and noise free locations.

1.3 MOTIVATION FOR THE RESEARCH

The predominant occupation of people in the northern part Nigeria especially Zaria is farming and most of them still employ the traditional means of farming which is labour intensive and not necessarily effective. The main motivation for this work therefore, is to produce a low cost Bluetooth controlled planter robot (Plantbot) that could be used for planting (using maize as a case study) in order to enhance the quality and the affordability of planting process, hence improving the productivity of the farmers from the small-scale category to the large scale ones.

The transfer function model of the system is also developed. The transfer function can subsequently be used for the design of a controller that could maintain the speed of the Plantbot despite the changes in the soil moisture content.

1.4 PROBLEM DEFINITION

The literature reviewed showed that the most of the works carried out are on transplanting vegetables. There are also works in the areas of direct planting of seeds like onions and potatoes. The grain planters developed were mostly operated manually. Therefore, the problem that this research work on design and environmental behaviour modelling of

Bluetooth controlled planter robot is aimed at solving is that of improving the aspect of grain planting by developing a remote controlled planting machine. It also aimed at developing behaviour model of the machine to help in enriching theory in planting robot design. The design is also optimized for maize planting because maize is the most commonly grown crop around Zaria, (**Ofor *et al*, 2009**).

1.9 METHODOLOGY

In carrying out the research work the following methodologies were adopted:

i- **DESIGN AND CONSTRUCTION OF THE PLANTBOT MECHANISM**. This stage was accomplished as follows:

Selection of dimensions of the Plantbot; Mode of movements of the Plantbot; selection of the main drive motor; selection of the steering motor; selection of the planting mechanism control motor; battery pack selection; gearbox design; gearbox design for fastener; torque conversion of the gearbox; rear shaft design; shaft design for allowable torque; shaft design for fatigue failure; hollow / solid shaft selection; shaft design for critical speed; weld fastening of shaft to brake disc; rear shaft bearing design; rear shaft bearing load design; bearing failure evaluation; bearing life design; design of the frame of the Plantbot; front wheels bearing design; load design for front wheel bearings; front wheel bearing failure evaluation; front wheel bearing life design; design of the holder of the planting mechanism

ii- DESIGN OF THE BLUETOOTH CONTROL SEGMENT OF THE PLANTBOT. This stage was accomplished as follows:

Bluetooth module selection and connection; design and analysis of DTMF booster circuit; design and analysis of DTMF decoding circuit; design of DTMF decoder steering circuit; design of DTMF decoder input circuit; design of microcontroller oscillator circuit; configuring the ports of PIC16F84A; programming of PIC16F84A; design of relay driver ciruit; design of power supply circuit; complete circuit diagram; producing Printed Circuit Board (PCB) version of the control circuit; constructing the circuit; interfacing and testing the Plantbot prototype

iii- **TESTING THE PROTOTYPE PLANTBOT.** The prototype was tested by evaluating the planting performance, vis – a - vis the percentage of successful planting, percentage of unsuccessful planting and percentage of multiple planting, determination of the speed of the Plantbot; determining the Bluetooth control range (distance) of the Plantbot.

iv- **ENVIRONMENTAL MODELING OF THE PLANTBOT BEHAVIOUR.** This was carried out by collecting data of soil moisture and speed of the Plantbot; pre – processing the moisture – speed data; preliminary analysis of the data; dividing the data into modeling and validating parts; processing the modeling data and validation data; model development using system identification toolbox

v- **VALIDATION OF THE DEVELOPED MODEL.** This part was accomplished using MATLAB system identification toolbox which compared the simulated data with the real validation data; and extraction of the transfer function of the validated model.

1.10 SCOPE OF THE WORK

The research is limited to (1) detailed mechanical design of the planting machine, (2) detailed electrical design of the Bluetooth control circuit for the machine and interfacing the mechanical and the control parts, (3) the transfer function relating the speed of the Plantbot to the soil moisture content was but the development of the controller is not defined within the scope of the work.

1.11 SIGNIFICANT CONTRIBUTIONS

The significant contributions of this research are as follows:

1) Development of a prototype low-cost Bluetooth controlled planter robot (Plantbot) for improving the planting of maize being the predominant crop in the study area which is expected to increase the efficiency and output of the farmers.
2) The Plantbot on field test had a 10.2% unsuccessful planting which outperformed other systems reported in literature: Subo *et al* (1996) (27.2%); Ronaldo (2001) (30 – 34%); Olaoye and Bolufawi (2001) (33%); Kim *et al* (2001) (23.5%); Chaudhuri (2002) (29.4 – 30.2%); Ebubekir (2005) (35%); Shaaban *et al* (2009) (28.1%) and Turbatmath *et al* (2011) (29 – 30.9%).
3) The Plantbot Bluetooth control has an effective range of 57.69 m (189.3 feet) in all directions which is sufficient for most farms and it has also being shown to be immune to radio interference or environmental noise.
4) Determination of the transfer function relating the speed of the Plantbot to the soil moisture content which is critical to the development of a controller to ensure consistent performance irrespective of the operational environment conditions.

1.12 DISSERTATION OUTLINE

The dissertation is arranged in five chapters. Chapter One is the introductory chapter which contains the aim and objectives of the work, motivation, problem definition, methodology and scope of the work. Chapter Two contains the literature review. Chapter Three is on Materials and Methods. It contains the detailed mechanical design and the Bluetooth control unit of the Plantbot. Chapter Four is on Results and Discussions. It contains details of the field tests to evaluate the performance of the prototype in terms of planting accuracy, depth of seed planting and behaviour modeling and validation of the model developed. It also contains the results and discussions and analysis of data obtained. Conclusion and recommendations are contained in Chapter Five. References and Appendices presented at the end of the report.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

The review of fundamental concepts relevant to the research are presented in this chapter in addition to a review of previous similar works.

2.2 REVIEW OF FUNDAMENTAL CONCEPTS

A review of concepts fundamental to this research is presented in this section.

2.2.1 Robots

The word "robot" originated from Slavic; Russia. The word pa6oTa (rabota) refers to labor or work. The current popular meaning has been proposed by the Czechoslovakian dramatist Karel Capek (1890-1938) in the beginning of twentieth century. In his play titled *"*Rosum's Universal Robots", Capek invented autonomous substitutes for human labourers, that may have a human outlook and with ability of "human" feelings. Historically, the concept "robot" emerged much later than the real systems that are capable to answer to that name. *Robot* is also defined as mechanical device which can be programmed to perform some task of manipulation or locomotion under automatic or semi-automatic control (**Sandler, 1991**).

Encyclopedia Britannica gives the following definition: **"**A robot device is an instrumented mechanism used in science or industry to take the place of a human being. It may or may not physically resemble a human or perform its tasks in a human way, and the line separating robot devices from merely automated machinery is not always easy to define. In general, the

more sophisticated and individualized the machine, the more likely it is to be classed as a robot device." (Encyclopedia Britannica, 2007).

2.2.1.1 *Mobile Robots*

Mobile robots are devices with wide scope of applications which are mostly not of an industrial type. They could be classified based on their methods of propulsion, i.e., wheels or crawler tracks.

A mobile robot may be operated in one of the following methods:

1. Remotely controlled by wire means, or wirelessly by radio;
2. Automatically (autonomously) controlled using sensors and programming; or
3. Guided by tracks, or inductive or optic means.

Mobile robots are mostly applied in the following situations:

In harmful or hostile environments, such as under water, rescue operations in areas of disaster, in a radioactive location, or in space; or handling explosive, poisons, biologically dangerous, or other suspect objects. It is also used in agriculture particularly for fruits picking. (**Sandler, 1991**)

2.2.2 Mechatronic Design Approach

Mechatronics systems are systems that involve the integration of **MECHAnics** and **elecTRONICS**. A definition is given as follows: “Mechatronics is the synergetic integration of mechanical engineering with electronics and intelligent computer control in the design and manufacture of industrial products and processes”, (Billingsley, 2006).

This definition suggests that mechatronics is an interdisciplinary field, in which the following disciplines act together as shown in Fig. 2.1.

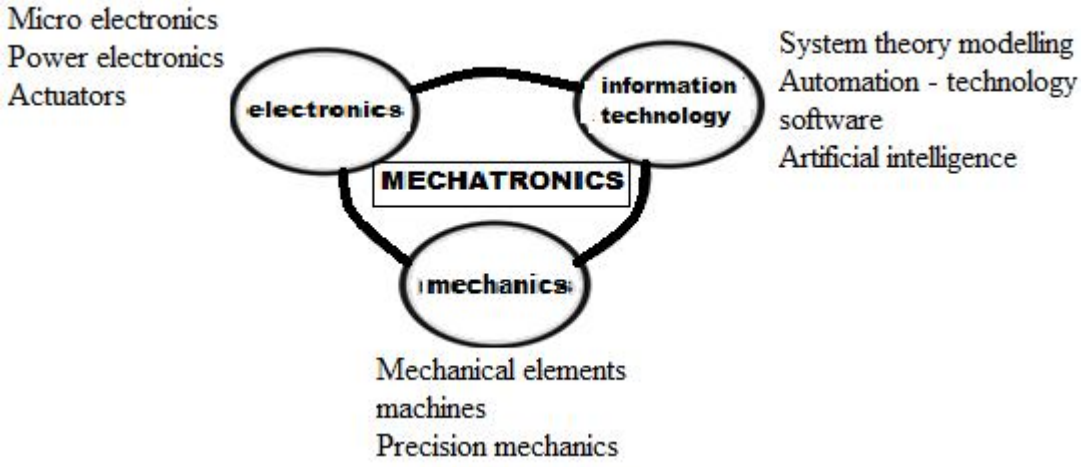


Fig. 2.1. Fundamental Components of Mechatronics Engineering

1. **Mechanical systems** (mechanical elements, machines, precision mechanics);
2. **Electronic systems** (microelectronics, power electronics, sensor and actuator technology); and
3. **Information technology** (systems theory, automation, software engineering, artificial intelligence).

Mechatronic systems can be subdivided into:

i- Mechatronic systems

ii- Mechatronic machines

iii- Mechatronic vehicles

iv- Precision mechatronics

v- Micro mechatronics

This shows that the integration with electronics comprises many classes of technical systems. In several cases, the mechanical part of the process is coupled with an electrical, thermal, thermodynamic, chemical, or information processing part. Therefore, **mechatronic systems** in a wider sense comprise mechanical and also non-mechanical processes. However, the mechanical part normally dominates the system.

2.2.2.1 *Division of Functions between Mechanics and Electronics*

For developing mechatronic systems, the interplay for the realization of functions in the mechanical and electronic part is very important. Compared to pure mechanical realizations, the application of amplifiers and actuators with electrical auxiliary energy led to great simplifications in devices. Another important simplifications in the mechanics is achieved from introducing microcomputers as well as decentralized electrical drives, as can be seen from sewing machines, electronic typewriters, and automatic gears transmission system.

Fig. 2.2 shows the general schematic diagram of a (classical) mechanical-electronic system. **(Onwubolu, 2004)**

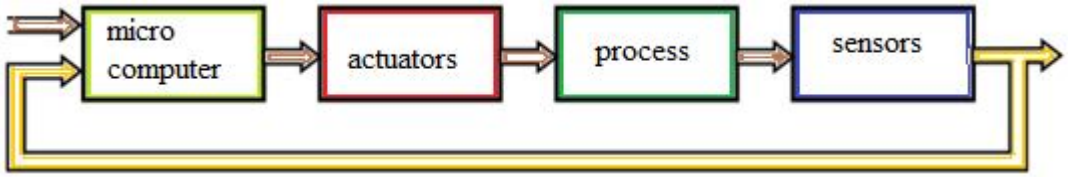


Fig. 2.2. General Scheme of a (Classical) Mechanical-Electronic System.

2.2.2.2 *Concurrent Design Procedure for Mechatronic Systems*

The design of mechatronic systems requires a systematic development and use of modern design tools.

a) DESIGN STEPS

The five important development steps for mechatronic systems start from a purely mechanical system and resulting in a fully integrated mechatronic system. Depending on the kind of mechanical system, the intensity of the single development steps is different. For precision mechanical devices, fairly integrated mechatronic systems do exist. The influence of the electronics on mechanical elements may be considerable, as shown by adaptive dampers, anti-lock system brakes, and automatic gears. However, complete machines and vehicles show first a mechatronic design of their elements, and then slowly a redesign of parts of the overall structure as can be observed in the development of machine tools, robots, and vehicle bodies.

b) REQUIRED CAD/CAE TOOLS

The computer aided development of mechatronic systems comprises:

1. Constructive specification in the Engineering Development Stage using CAD and CAE tools,
2. Model building for obtaining static and dynamic process models,
3. Transformation into computer codes for system simulation, and
4. Programming and implementation of the final mechatronic software, (**Billingsley, 2006).**

2.2.3 Gears and Gearing

A gear is a wheel with evenly sized and spaced teeth machined or formed around its perimeter. Gears are used in rotating machinery not only to transmit motion from one point to another, but also for the mechanical advantage they offer. Two or more gears transmitting

motion from one shaft to another is called **a gear train,** and gearing is a system of wheels or cylinders with meshing teeth. Gearing is chiefly used to transmit rotating motion but can also be adapted to translate reciprocating motion into rotating motion and vice versa.

Gears are versatile mechanical components capable of performing many different kinds of power transmission or motion control. Examples of these are

1. Changing rotational speed
2. Changing rotational direction
3. Changing the angular orientation of rotational motion
4. Multiplication or division of torque or magnitude of rotation
5. Converting rotational to linear motion, and its reverse
6. Offsetting or changing the location of rotating motion

The teeth of a gear can be considered as levers when they mesh with the teeth of an adjoining gear. However, gears can be rotated continuously instead of rocking back and forth through short distances as is typical of levers. A gear is defined by the number of its teeth and its diameter. The gear that is connected to the source of power is called the driver, and the one that receives power from the driver is the driven gear. It always rotates in a direction opposing that of the driving gear; if both gears have the same number of teeth, they will rotate at the same speed. However, if the number of teeth differs, the gear with the smaller number of teeth will rotate faster. The size and shape of all gear teeth that are to mesh properly for working contact must be equal **(Alan, 2008)**.

Fig. 2.3 shows two gears, one with 15 teeth connected at the end of shaft A, and the other with 30 teeth connected at the end of shaft B. The 15 teeth of smaller driving gear A will mesh with 15 teeth of the larger gear B, but while gear A makes one revolution gear B will

make only ½ revolutions. The number of teeth on a gear determines its diameter. When two gears with different diameters and numbers of teeth are meshed together, the number of teeth on each gear determines gear ratio, velocity ratio, distance ratio, and mechanical advantage. In Fig. 2.3, gear A with 15 teeth is the driving gear and gear B with 30 teeth is the driven gear. The gear ratio GR is determined as **(Alan, 2008)**:

$$\mathbf{GR} = \frac{\textbf{number of teeth on driven gear B}}{\textbf{number of teeth on driven gear A}}$$

(2.1)

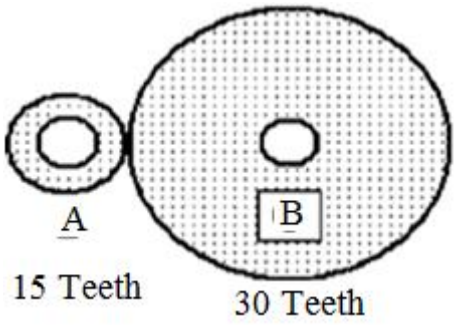


Fig. 2.3. Simple Gear System

The number of teeth in both gears determines the rotary distance traveled by each gear and their angular speed or velocity ratio. The angular speeds of gears are inversely proportional to the numbers of their teeth **(Alan, 2008).**

2.2.3.1 *Simple Gear Trains*

A gear train made up of multiple gears can have several drivers and several driven gears. If the train contains an odd number of gears, the output gear will rotate in the same direction as the input gear, but if the train contains an even number of gears, the output gear will rotate opposite that of the input gear. The number of teeth on the intermediate gears

does not affect the overall velocity ratio, which is governed purely by the number of teeth on the first and last gear.

` In simple gear trains, high or low gear ratios can only be obtained by combining large and small gears. In the simplest basic gearing involving two gears, the driven shaft and gear revolves in a direction opposite that of the driving shaft and gear. If it is desired that the two gears and shafts rotate in the same direction, a third idler gear must be inserted between the driving gear and the driven gear. The idler revolves in a direction opposite that of the driving gear.

A simple gear train containing an idler is shown in Fig. 2.4. Driven idler gear B with 20 teeth will revolve 4 times as fast counterclockwise as driving gear A with 80 teeth turning clockwise. However, gear C, also with 80 teeth, will only revolve one turn clockwise for every four revolutions of idler gear B, making the velocities of both gears A and C equal except that gear C turns in the same direction as gear A. In general, the velocity ratio of the first and last gears in a train of simple gears is not changed by the number of gears inserted between them **(Sclater, 2007).**

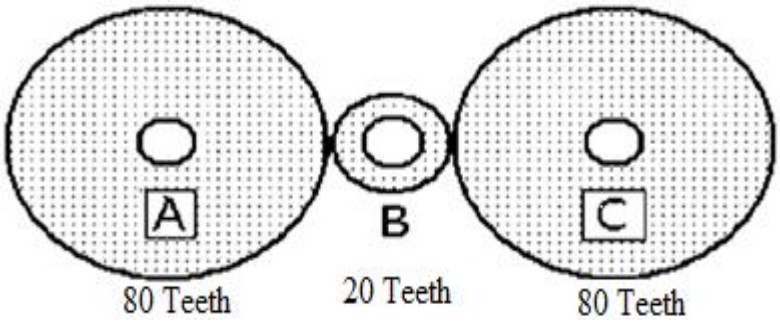


Fig. 2.4. Simple Gear Train

2.2.3.2 *Compound Gear Trains*

More complex compound gear trains can achieve high and low gear ratios in a restricted space by coupling large and small gears on the same axle. In this way gear ratios of adjacent gears can be multiplied through the gear train. Figure 2.5 shows a set of compound gears with the two gears B and D mounted on the middle shaft. Both rotate at the same speed because they are fastened together. If gear A (80 teeth) rotates at 100 rpm clockwise, gear B (20 teeth) turns at 400 rpm counterclockwise because of its velocity ratio of 1 to 4. Because gear D (60 teeth) also turns at 400 rpm and its velocity ratio is 1 to 3 with respect to gear C (20 teeth), gear C will turn at 1200 rpm clockwise. The velocity ratio of a compound gear train can be calculated by multiplying the velocity ratios for all pairs of meshing gears. For example, if the driving gear has 45 teeth and the driven gear has 15 teeth, the velocity ratio is**):** $\frac{15}{45} = \frac{1}{3}$ **(Nisbett, 2006**

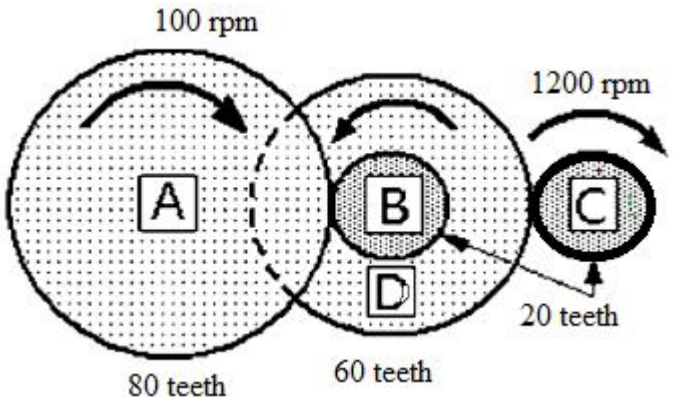


Fig. 2.5. Compound Gears

2.2.3.3 *Practical Gear Configurations*

Fig. 2.6 shows the isometric view of a **special planetary gear configuration.** The external driver spur gear (lower right) drives the outer ring spur gear (center) which, in turn, drives three **internal planet spur gears;** they transfer torque to the driven gear (lower left).

Simultaneously, the **central planet spur gear** produces a summing motion in the pinion gear (upper right) which engages a rack with a roller follower contacting a radial disk cam (middle right). **(Eugene *et al*, 2007).**

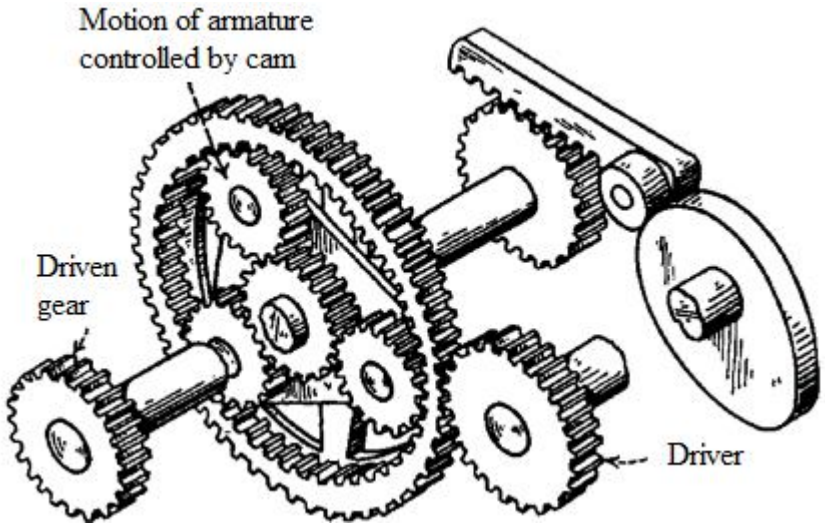


Fig. 2.6. Special Planetary Gear Configuration

Isometric drawing of Fig. 2.7 shows a **unidirectional drive.** The output shaft B rotates in the same direction at all times, regardless of the rotation of the input shaft A. The angular velocity of output shaft B is directly proportional to the angular velocity of input shaft A. The **spur gear** C on shaft A has a face width that is twice as wide as the faces on **spur gears** F and D, which are mounted on output shaft B. **Spur gear** C meshes with idler E and with **spur gear** D. Idler E meshes with the **spur gears** C and F. Output shaft B carries two free-wheel disks, G and H, which are oriented unidirectionally.

When input shaft A rotates clockwise (bold arrow), **spur gear** D rotates counterclockwise and it idles around free-wheel disk H. Simultaneously, idler E, which is also rotating counterclockwise, causes **spur gear** F to turn clockwise and moves the rollers on free-wheel disk G. Thus, shaft B is made to rotate clockwise. On the other hand, if the input shaft A

turns counterclockwise, **spur gear** F will idle while **spur gear** D engages free-wheel disk H, which drives shaft B so that it continues to rotate clockwise. **(Alan, 2008)**.

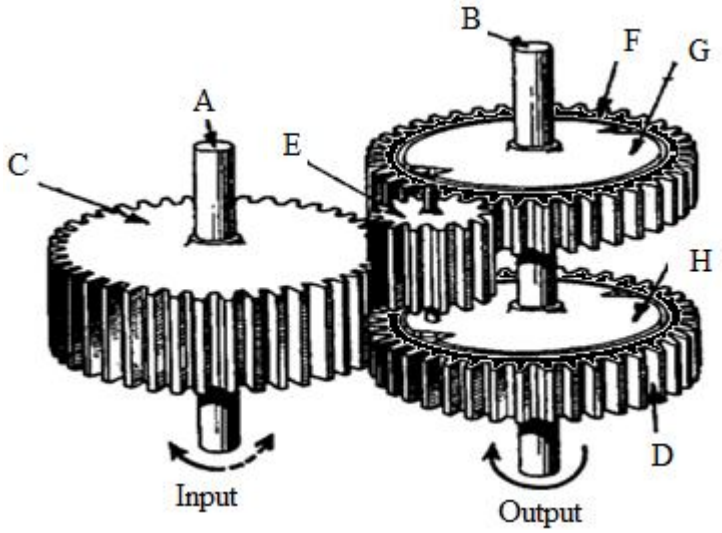


Fig. 2.7. Isometric View of Unidirectional Gear

2.2.3.5 Gear Dynamics Terminology

The following gear terminologies are defined **(Nisbett, 2006):**

a) **Backlash:** The amount by which the width of a tooth space exceeds the thickness of the engaging tooth measured on the pitch circle. It is the shortest distance between the non-contacting surfaces of adjacent teeth.

b) **Gear efficiency:** The ratio of output power to input power taking into consideration power losses in the gears and bearings and from windage and the churning of the gear lubricant.

c) **Gear power:** A gear's load and speed capacity. It is determined by gear dimensions and type. Helical and helical-type gears have capacities to approximately 30,000 hp, spiral bevel gears to about 5000 hp, and worm gears to about 750 hp.

d) **Gear ratio:** The number of teeth in the larger gear of a pair divided by the number of teeth in the pinion gear (the smaller gear of a pair). It is also the ratio of the speed of the pinion to the speed of the gear. In reduction gears, the ratio of input speed to output speed.

e) **Gear speed:** A value determined by a specific pitch line velocity. It can be increased by improving the accuracy of the gear teeth and the balance of all rotating parts.

f) **Undercutting:** The recessing in the bases of gear tooth flanks to improve clearance.

2.2.3.5 *Conventional Gearbox*

The conventional gearbox might contain spur or helical gears. The cluster ACE can be moved to the left and right along splines so that three velocity ratios can be obtained, i.e. A driving B, C driving D and E driving F (as in the epicyclic gearbox shown in Fig. 2.8).

This type of gear train and gearbox gets its name from the curve traced out by a point on a circle as it rolls inside a circle of larger diameter. It is called an *epicycloid*. The gear C is known as the sun wheel and the gears B, which can rotate about the sun wheel, are called planet gears. The two planet gears are connected to the arm which can rotate around the sun wheel with them **(Alan, 2008).**

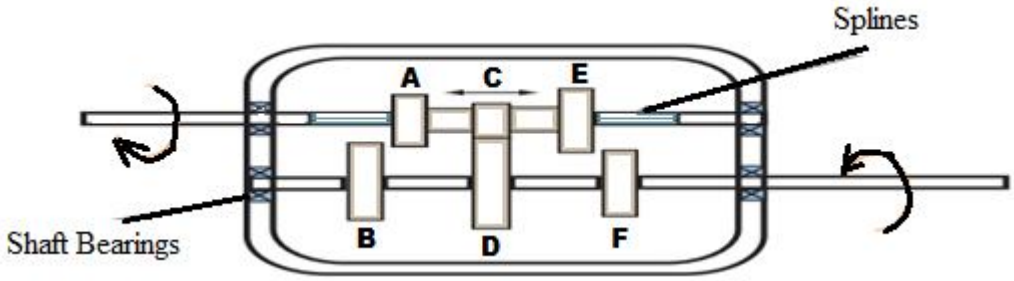


Fig. 2.8. Epicyclic Gearbox

The basic steps in the design of gear box is illustrated in the Fig. 2.9.

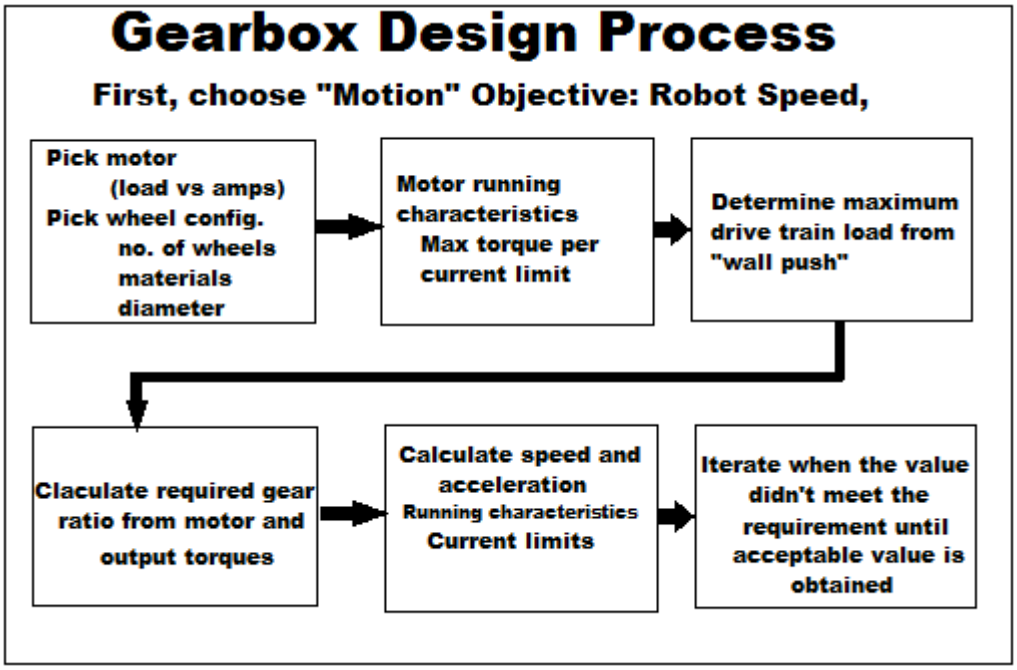


Fig. 2.9. The Basic Steps in the Design of Gear Box

2.2.4 Coefficient of Safety in Engineering Design

Determination of the corresponding coefficient of safety is a complicated and responsible task. A high coefficient of safety usually results in a safer design, however with a higher weight and thus a higher price and vice versa. It is the basic engineering compromise of "price vs. safety". Profession organizations often specify minimum coefficients of safety for various systems; however, it is the responsibility of the designer to determine such coefficient of safety that ensures corresponding safety at an acceptable price. At the same time, the coefficient of safety can vary within a wide range. A coefficient close to 1.0 (one-off use, short service life) may be sufficient for a military missile; a coefficient at 1.2 for military aircraft (it is equipped with a parachute, it passes through an inspection process); in civil aviation it is about 1.5 (inspection process, regular maintenance). A dam with a

coefficient of safety higher than 2.0 can be found at the other end of the range (service life of many decades, faults have catastrophic consequences). Table 2.1 shows the recommended coefficients of safety for tensile materials on the yield strength.

Table 2.1. Recommended Coefficient of Safety for Tensile Materials on the Yield Strength.

Coefficient of safety	Knowledge of loading	Knowledge of permitted stress	Knowledge of properties of material	Knowledge of environment
1.2-1.5	Exact	Exact	very good	fully under control
1.5-2.0	Good	Good	very good	Invariable
2.0-2.5	Good	Good	Average	Common
2.5-3.0	Average	Average	randomly tested	Common
3.0-4.0	Average	Average	not tested	Common
3.0-4.0	Indefinite	Indefinite		Indefinite

2.2.5 Selection of a Rolling Bearing

The motion in most of the mechanical systems involves a lot of friction that interferes with the efficiency of the machine as well as the life span of the moving parts as a result of wearing effects. Rolling bearing is commonly used component in the moving parts of machines to reduce the effects of friction greatly. The following comparison of basic properties of types of rolling bearings may help in selecting the suitable type. When selecting the type, it is necessary to take into account, above all, the following facts:

a) **Amount and type of the load**

b) **Design of seating and way of lubrication of the bearing**

c) **Operational parameters of the bearing (speed, thermal conditions, etc.)**

d) **Requirements for accuracy**

e) **Requirements for installation and dismantling**

Rolling bearings are usually composed of two rings, rolling bodies and a cage. The bearings are divided into several basic types (see Fig. 2.10) according to their inner design, the shape of rolling bodies and directions of the forces that can be retained.

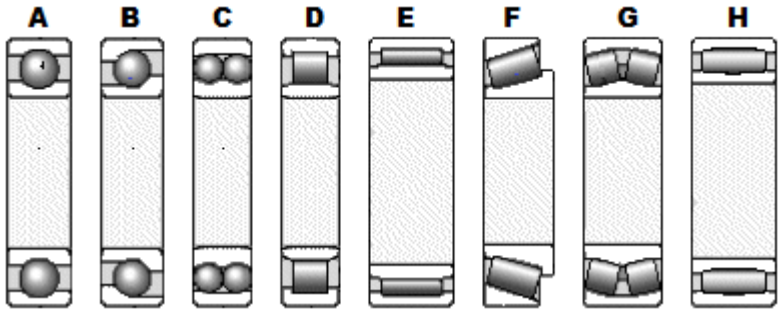


Fig. 2.10. Types of Rolling Bearing

Basic types of rolling bearings are internationally standardized. Within the scope of each type the bearings are produced in various designs whose properties may differ from the basic design. The following subsections gives brief characteristics of individual types of rolling bearings, **(KMS Incorporated, 2011).**

2.2.5.1 *Deep Groove Ball Bearings*

It has the following properties (KMS inc., 2011):

a) it is the cheapest; most commonly used; b) produced in many designs and sizes; c) simple designs and cannot be disassembled; d) can handle operational conditions; e) maintenance is simple; f) show relatively good load rating; g) suitable for high and very high speeds; h) require good alignment of the journal and bearing body; i) delivered with shields or seals.

2.2.5.2 *Angular Contact Ball Bearings*

It has the following properties (KMS inc., 2011):

a) Orbital paths are offset mutually in the direction of the bearing axis; b) Designed to retain combined load with relatively large axial forces; c) Single-row bearings enable the retention of axial forces only in one direction; d) can be paired or double-row; e) lower load rating than tapered roller bearings; f) can retain tilting moments in the axial plane; g) double-row bearings are also delivered with shields or seals

2.2.5.3 *Self-Aligning Ball Bearings*

It has the following properties (KMS inc., 2011):

a) it is provided with two rows of ball bearings; b) design allows mutual tilting of rings; c) suitable, above all, for seating; d) load rating of these bearings is lower than with single-row ball bearings of the same size; e) not suitable for retaining larger axial forces; f) produced usually with cylindrical or tapered holes; g) delivered also with seals.

2.2.5.4 *Cylindrical Roller Bearings*

It has the following properties (KMS inc., 2011):

a) dismountable bearings; b) designed for transmissions of large radial loadings; c) High rigidity; d) suitable for fluctuating and surge loads; e) bearings without cages (full complement) show higher loading capacities; f) bearings with guiding collars on the outer and inner rings allow the retention of higher axial forces; g) cylindrical roller bearings require perfect alignment of the journal and bearing body; h) the permissible maximum tilting angle is $3\text{-}4^{0}$; i) double-row cylindrical roller bearings are usually produced with both cylindrical and tapered holes

2.2.5.5 *Needle Roller Bearings*

It has the following properties (KMS inc., 2011):

a) cylindrical roller bearings with long slim rollers; b) show small installation height, high accuracy and rigidity; c) have a high load rating hence very suitable for seating where radial dimensions are limited; d) used for low speeds or swinging movements; e) also suitable for fluctuating and surge loads; f) cannot retain any axial forces, however, allow axial misalignment of the rings; g) delivered also with seals.

2.2.5.6 *Taper Roller Bearings*

It has the following properties (KMS inc., 2011):

a) designed usually as dismountable; b) provided with tapered orbital paths on the outer and inner rings with tapered rollers arranged in the paths; c) high load rating; d) suitable especially for retaining simultaneously acting large radial and axial forces; e) allow the retention of axial forces in one direction only, therefore installed in pairs in opposite positions and as close to each other as possible; f) higher load rating than angular contact ball bearings, however, these types are designed for lower speeds; g) seating surfaces for tapered roller bearings must be aligned; the permissible tilting angle is $2\text{-}4^0$.

2.2.5.7 *Spherical Roller Bearings*

It has the following properties (KMS inc., 2011):

a) two rows of spherical rollers with a common spherical path on the outer ring; b) design allows mutual tilting of rings; c) high load rating, retention of radial and simultaneously also axial forces in both directions; d) suitable for large loads with misaligned seating and

deflections of shafts; e) produced usually with cylindrical and tapered holes; f) non-dismountable; g) delivered also with seals

2.2.5.8 *Toroidal Roller Bearings*

It has the following properties (KMS inc., 2011):

a) single-row bearings with long, slightly spherical rolling elements; b) orbital paths of the outer and inner rings are concave and symmetrical along the axis running through the bearing centre; c) design combines the tilting ability of a spherical roller bearing; d) ability of axial balancing, typical for rolling elements; e) they also show relatively small installation height; f) high radial load rating even if the bearing must compensate a misalignment or axial shifts; g) reduce vibrations in seating; h) axial vibrations of the shaft are not transferred to the body; i) load rating of full complement bearings is significantly higher than bearings with cages; j) produced with both cylindrical and tapered holes; k) delivered also with seals.

2.2.6 General Overview of Bluetooth Technology

Bluetooth is a standardized technology that is used to create temporary (adhoc) short-range wireless communication systems. These Bluetooth wireless personal area networks (WPAN) are used to connect personal accessories such as headsets, keyboards, and portable devices to communications equipment and networks.

The Bluetooth system operates in 2.4 GHz to 2.483 GHz unlicensed (uncontrolled) frequency bands with very low radio transmission power of 1 milliwatt to 100 milliwatt. Devices within the frequency bands are required to operate in such a way that they can co-

exist in the same area with each other with minimal interference with each other **(Harte, 2004).**

2.2.6.1 *Bluetooth Basics*

Bluetooth is a wireless personal area network (WPAN) communication system standard that allows for wireless data connections to be dynamically added and removed between nearby devices. Each Bluetooth wireless network can contain up to 8 active devices and is called a **Piconet.** Piconets can be linked to each other (overlap) to form larger area **Scatternets, (Harte, 2004).**

The system control for Bluetooth requires one device to operate as the coordinating device (a master) and all the other devices are slaves. This is very similar to the structure of a universal serial bus (USB) system that is commonly used in personal computers and devices such as digital cameras. However, unlike USB connections, most Bluetooth devices can operate as either a master (coordinator) or slave (follower) and Bluetooth devices can reverse their roles if necessary **(Harte, 2004).**

The characteristics of Bluetooth include an unlicensed frequency band that ranges from 2.4 GHz to 2.483 GHz (ISM Band). This frequency band was chosen because it is unlicensed and available for use in most countries throughout the world **(Harte, 2004)**. The use of a smaller frequency band does not change the data transmission rate (which is 64 kbps channels in both directions), however, these devices will be more sensitive to interference (such as other wireless devices in the same ISM Band and coverage range). Every Bluetooth device has a unique 48-bit address BD_ADDR (pronounced “B-D-Adder”).

In addition to identifying each Bluetooth device, this address is used to determine the frequency hopping pattern that is used by the Bluetooth device **(Harte, 2004)**.

Bluetooth devices may have different power classification levels. The 3 power versions for Bluetooth include; 1 mW (class 3), 2.5 mW (class 2) and 100 mW (class 1). Devices that have an extremely low power level of 1 milliwatt have a very short range of approximately 1m. Bluetooth devices have a power level of up to 100 mW can provide a transmission range of approximately 100m. The high power version (class 1) is required to use adjustable (dynamic) power control that automatically is reduced when enough signal strength is available between Bluetooth devices.

Fig. 2.11 shows that the structure of a Bluetooth contains the address code of the piconet (local system), device identifier (specific device within the piconet), logical channel identifiers (to identify ports), and a payload of data **(Harte, 2004)**.

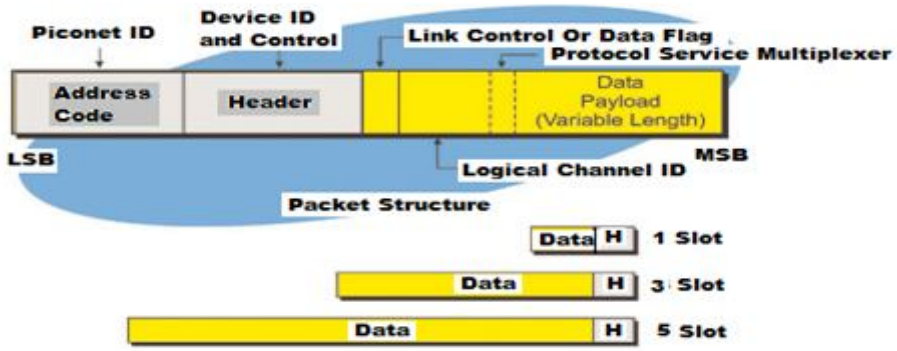


Fig. 2.11. Bluetooth Protocol Structure **(Harte, 2004)**.

2.2.6.2 *Service Discovery*

Service discovery is the process of finding other devices that can communicate with your device and determining what capabilities they have that you may want to use. Service

discovery protocol (SDP) is the communication messaging protocol used by a communication system (such as the Bluetooth system) to allow devices to discover the availability and capabilities of other nearby devices. The SDP process is similar to a registry in Windows as it dynamically creates a list of available resources **(Harte, 2004)**.

The discovery process begins with an inquiry message that a device sends searching for nearby devices. These devices are constantly looking for an inquiry message to respond to. When a device receives an inquiry message, it responds with this address that can be used to establish a connection with the device **(Harte, 2004)**. Fig. 2.12 shows the typical service discovery operation of a PDA device that desires to print to a nearby printer **(Harte, 2004)**.

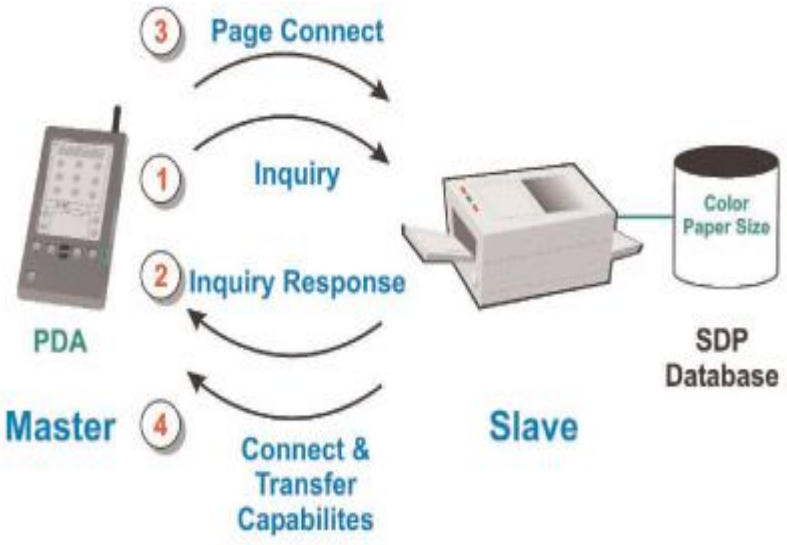


Fig. 2.12. Bluetooth Service Discovery Process **(Harte, 2004)**

2.2.6.3 *List of Applications of Bluetooth*

There are many areas where Bluetooth communication is applied in various devices which include the following **(Harte, 2004)**:

i. Wireless control of communication between a mobile phone and a hands-free headset. This was one of the earliest applications to become popular.
ii. Wireless networking between PCs in a confined space and where little bandwidth is required.
iii. Wireless communication with PC input and output devices, the most common being the mouse, keyboard and printer.
iv. For controls where infrared was traditionally used.
v. For low bandwidth applications where higher USB bandwidth is not required and cable-free connection desired.
vi. Wireless bridge between two Industrial Ethernet networks.
vii. Dial-up internet access on personal computers or PDAs using a data-capable mobile phone as a wireless modem like Novatel mifi.
viii. Short range transmission of health sensor data from medical devices to mobile phone, set-top box or dedicate telehealth devices.
ix. Allowing a Digital Enhanced Cordless Telecommunications (DECT) phone to ring and answer calls on behalf of a nearby cell phone

2.2.6.4 *Avoiding Interference in the 2.4GHz Band*

As a result of increase in the number of devices that use 2.4GHz to 2.483GHz portion of RF spectrum increase, interference is highly probable. The regulations on unlicensed portion of the spectrum state that devices must expect interference.

With existing wireless standards: Wi – Fi, Bluetooth, WiMAX and ZigBee there is more that can be done beyond what architects of the standard provide. This include use of amplifiers and adaptive filters to counteract the effect of interference.

There are two methods of RF modulation in the 2.4GHz ISM band which are: Frequency Hopping Spread Spectrum (FHSS) and Direct Sequence Spread Spectrum (DSSS). Bluetooth uses FHSS; Wireless USB, 802.11b/g/a (commonly known as Wi–Fi) and 802.15.4 (commonly known as ZigBee) use DSSS. All these use ISM band which is available worldwide Although, DSSS is better at resisting noise up to a certain point. However, if the combined interference throughout the band rises above a certain level, throughput dramatically drops-nearly to zero. However, it only takes a few nearby FHSS systems to cripple a DSSS system. On the other hand, because a DSSS system is always transmitting on every frequency in the band, a nearby FHSS system may be unable to find any clear channel to hop to. So, the use of FHSS for Bluetooth is considered better, **(Ryan and Mark, 2005)**.

2.2.6.5 *Handling Interference in Bluetooth*

In Bluetooth interference from other Bluetooth piconet is minimal, because each piconet uses its own pseudo-random frequency hopping algorithm. If two co-located piconets are active the probability of collision is one over 79 $\left(\frac{1}{79}\right)$ and it increases linearly with the number of active co-located piconets **(Ryan and Mark, 2005)**.

Bluetooth originally relied on frequency hopping algorithm to handle interference, but it was realized that single Wi – Fi network can cause heavy interference on 25% of Bluetooth channels. Packets lost due to overlap have to be retransmitted on quite channels, thereby reducing the throughput of Bluetooth devices **(Ryan and Mark, 2005)**.

Bluetooth specification version 1.2 addresses this issue by defining an Adaptive Frequency Hopping (AFH) algorithm which allows Bluetooth devices to mark channel as good, bad or unknown. The bad channels are replaced by good ones via look-up table. The Bluetooth

master may periodically listen to bad channels to find if the interference has disappeared. AFH algorithm allows Bluetooth to avoid channel occupied by DSSS systems like Wi – Fi and wireless USB. Cordless phones may still cause interference with Bluetooth since both systems are hopping over the entire 2.4GHz ISM band, but since the Bluetooth signal is only 1MHz wide, the frequency of collision between them is very much less than the frequency of collision between Wi – Fi and FHSS cordless phones **(Ryan and Mark, 2005)**.

2.2.6.6 *Fading*

Fading is applied to signal loss that changes fairly slowly relative to the signal bandwidth and the term *scintillation* is used to describe rapid variations in signal strength. Fading is roughly grouped into two categories: large-scale and small-scale fading. Large-scale fading is sometimes called slow fading or shadowing, although the term *slow fading* has a more precise definition in the context of small-scale fading. The *small-scale fading* may be characterized as fast or slow and time-dispersive or frequency-dispersive (**John, 2005).**

2.2.6.7 *Rayleigh Fading*

Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver. The central limit theorem holds that, if there is sufficiently much scatter, the channel impulse response will be well-modelled as a Gaussian process irrespective of the distribution of the individual components. The envelope of the channel response will therefore be Rayleigh distributed. With respect to random variable R, the probability density function (**John, 2005) is given as**:

(2.2)

Where:

(2.3)

2.2.6.8 *Correlation*

The normalized autocorrelation function of a Rayleigh faded channel with motion at a constant velocity is a zeroth-order Bessel function of the first kind given as (**John, 2005)**:

(2.4)

At delay 'T' when the maximum Doppler shift is f_d and J_0 is interleaving depth. The autocorrelation function of the Rayleigh fading channel is periodic in delay and its envelope decays slowly after the initial zero-crossing.

2.2.6.9 *Level Crossing Rate*

The level crossing rate is a measure of the rapidity of the fading. It quantifies how often the fading crosses some threshold, usually in the positive-going direction. For Rayleigh fading, the level crossing rate is given as (**John, 2005)**:

(2.5)

Where f_d the maximum Doppler is shift and ρ is the threshold level normalized to the root mean square (RMS) signal level.

2.2.6.10 *Average Fade Duration*

The average fade duration quantifies how long the signal spends below the thresholdρ. For Rayleigh fading, the average fade duration is given as (**John, 2005)**:

(2.6)

The level crossing rate and average fade duration taken together give a useful means of characterizing the severity of the fading over time.

For a particular normalized threshold value ρ, the product of the average fade duration and the level crossing rate is a constant and is given by (**John, 2005)**:

(2.7)

2.2.7 Fundamentals of PIC Microcontroller

The name **PIC, (Peripheral Interface Controller),** refers to a group of microcontrollers, produced by Arizona Microchip. As its name suggests, a microcontroller is an electronic device used to control other electronic devices.

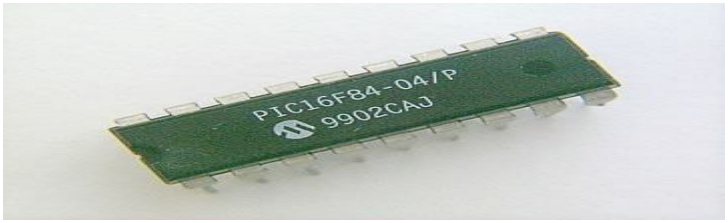


Plate 2.1 PIC16F84 PIC Micro Microcontroller

- A microcontroller as shown in Plate 2.1 **(Microchip Technology Inc., 2012)** is a single chip computer consisting of:

i. Central processing unit

ii. Memory

iii. Input ports

iv. Output ports

At the heart of the microcontroller there is a Central Processing Unit **(**CPU**)**.

2.2.7.1 *Types of Electronics Memory*

There are several types of electronic memory, each with a slightly different job to do. They are divided into two main groups:

i. **Read Only Memory (ROM)**

ii. **Random Access Memory (RAM)**

RAM, and EEPROM. These names give hints as to the purpose of the memory type and its area of application. For the 18 pin 16F84 the graphic on Fig. 2.13 illustrates the organization of the memory:

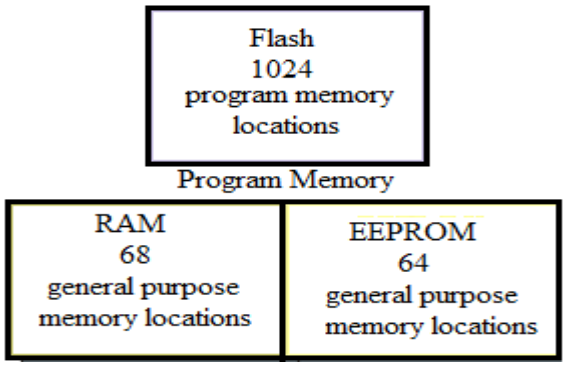


Fig. 2.13. Memory Organization of PIC

The program memory (EPROM) is used to store the program! In some PIC microchips, such as the 16F84, this memory uses FLASH technology, **(Microchip Technology Inc., 2012).**

2.2.7.2 *Pin Diagram of PIC16f84A*

PIC16F84A has 18-pins as shown by pin diagram in Fig. 2.14.

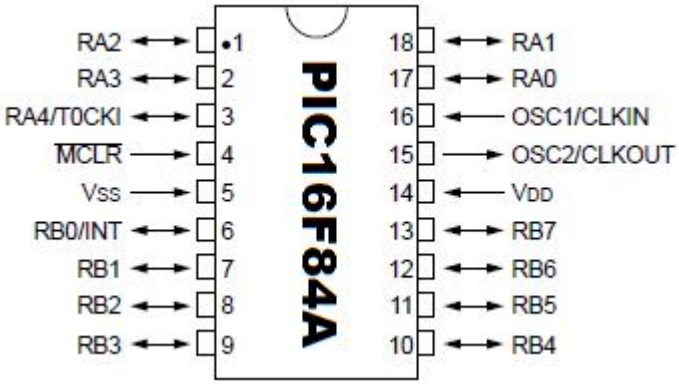


Fig. 2.14. Pin Diagram of PIC16F84A

Two of the pins are used for power supply (V_{DD} at pin 14 as positive terminal and V_{SS} at pin 5 as ground), two pins are used as oscillator terminals (OSC1 and OSC2 at pins 16 and 15 respectively). It has port A with five pins RA0, RA1, RA2, RA3 and RA4 and port B with eight pins from RB0 to RB7. The pins of the two pins can be configured as input or output during the programming. The remaining pin is used for memory clearing ($\overline{\boldsymbol{MCLR}}$) **(Microchip Technology Inc., 2012).**

2.2.7.3 *Special Features of Microcontroller PIC16f84A*

PIC16F84A has some very special features that makes it very attractive in different applications. These features are as follows **(Microchip Technology Inc., 2012)**:

1. Power-on Reset (POR)
2. Power-up Timer (PWRT)
3. Oscillator Start-up Timer (OST)
4. Watchdog Timer (WDT) with its own on-chip RC oscillator for reliable operation
5. Code-protection
6. Power saving SLEEP mode
7. Selectable oscillator options
8. Serial In-System Programming - via two pins (ROM devices support only Data EEPROM programming)

2.2.7.4 *Program Memory Organization*

The PIC16FXX has a 13-bit program counter capable of addressing an 8K x 14 program memory space. For the PIC16F84 and PIC16CR84, the first 1K x 14 (0000h-03FFh) are

physically implemented (Fig. 2.15). Accessing a location above the physically implemented address will cause a wraparound. For example, for the PIC16F84 locations 20h, 420h, 820h, C20h, 1020h, 1420h, 1820h, and 1C20h will be the same instruction.

The reset vector is at 0000h and the interrupt vector is at 0004h **(Microchip Technology Inc., 2012).**

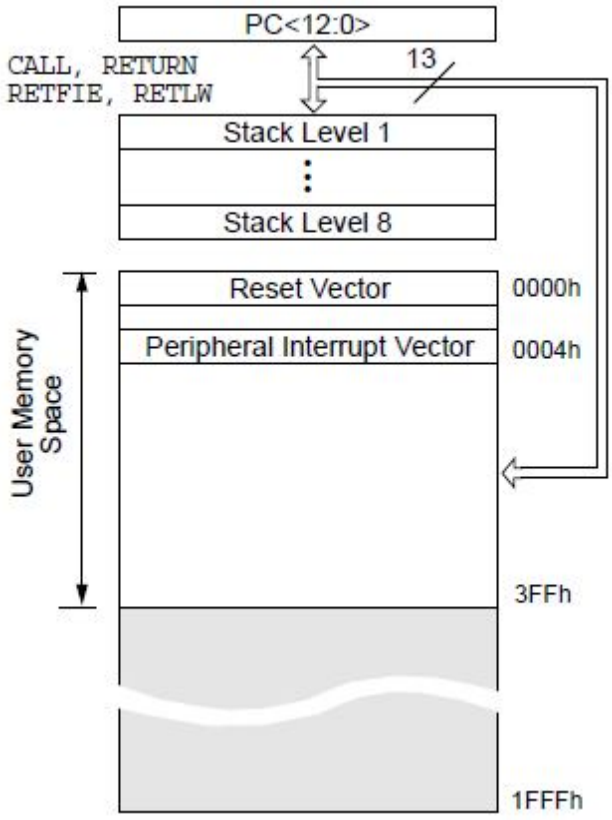


Fig. 2.15. Program Memory Organization of PIC16F84

2.2.7.5 *Special Features of the CPU*

What sets a microcontroller apart from other processors are special circuits to deal with the needs of real time applications. The PIC16F84A has a host of such features intended to maximize system reliability, minimize cost through elimination of external components, provide power saving operating modes and offer code protection. These features are:

1. OSC Selection
2. Reset
3. Power-on Reset (POR)
4. Power-up Timer (PWRT)
5. Oscillator Start-up Timer (OST)
6. Interrupts
7. Watchdog Timer (WDT)
8. SLEEP
9. Code protection
10. ID locations
11. In-circuit serial programming

The PIC16F8X has a Watchdog Timer which can be shut off only through configuration bits. It runs off its own RC oscillator for added reliability. There are two timers that offer necessary delays on power-up. One is the Oscillator Start-up Timer (OST), intended to keep the chip in reset until the crystal oscillator is stable. The other is the Power-up Timer (PWRT), which provides a fixed delay of 72 ms (nominal) on power-up only. This design keeps the device in reset while the power supply stabilizes. With these two timers on-chip, most applications need no external reset circuitry. SLEEP mode offers a very low current power-down mode. The user can wake-up from SLEEP through external reset, Watchdog Timer time-out or through an interrupt. Several oscillator options are provided to allow the part to fit the application. The RC oscillator option saves system cost while the crystal (XT) option saves power. A set of configuration bits are used to select the various options **(Microchip Technology Inc., 2012).**

2.2.8 Dual Tone Multi – Frequency (DTMF)

Dual-tone multi-frequency signaling (**DTMF**) is used for telecommunication signaling over analog telephone lines in the voice-frequency band between telephone handsets and other communications devices and the switching center. The version of DTMF that is used in push-button telephones for tone dialing is known as **Touch-Tone**. It was developed by Western Electric and first used by the Bell System in commerce, using that name as a registered trademark. DTMF is standardized by ITU-T Recommendation Q.23 **(Dodd, 2002)**.

Introduced by AT&T in 1963, the Touch-Tone system using the telephone keypad gradually replaced the use of rotary dial and has become the industry standard for landline service.

Multi-frequency signaling is a group of signaling methods that use a mixture of two pure tone (pure sine wave) sounds. This semi-automated signaling and switching proved successful in both speed and cost effectiveness. Based on this prior success with using MF by specialists to establish long-distance telephone calls, Dual-tone multi-frequency (DTMF) signaling was developed for the consumer to signal their own telephone-call's destination telephone number instead of talking to a telephone operator **(Dodd, 2002)**.

The signaling is sent in-band over the same channel as the bearer channel used for voice traffic. Multi-frequency signaling is a precursor of modern DTMF signaling (Touchtone), now used for subscriber signaling. DTMF uses eight frequencies **(Dodd, 2002)**.

Operation: Digits are represented by two simultaneous tones selected from a sets of five frequencies. The frequency combinations are played, one at a time for each digit, to the remote multi-frequency receiver in a distant telephone exchange. Using MF signaling, the originating telephone switching office sends a starting signal such as a seizure (off-hook) by toggling the AB bits. After the initial seizure, the terminating office acknowledges a ready state by responding with a wink (short duration seizure) and then goes back on-hook (wink start). The originating office sends the destination digits to the terminating switch **(Dodd, 2002)**.

MF and other in-band signaling systems differ from Signaling System 7 (SS7) in that the routing digits are out-pulsed in MF format in the same voice band channel used for voice. In some countries, the dialing user cannot detect these digits being out-pulsed because the audio connection is not established all the way to the user's handset or device until after the connection is established with the terminating switch. Following a full connection, the same audio channel is connected to the user in order to communicate the voice **(Dodd, 2002)**.



DTMF keypad frequencies (with sound clips)

	1209 Hz	1336 Hz	1477 Hz	1633 Hz
697 Hz	1	2	3	A
770 Hz	4	5	6	B
852 Hz	7	8	9	C
941 Hz	*	0	#	D

Fig. 2.16. DTMF Keypad

The DTMF keypad shown in Fig. 2.16, is laid out in a 4×4 matrix in which each row represents a *low* frequency and each column represents a *high* frequency. Pressing a single

key sends a sinusoidal tone for each of the two frequencies. For example, the key 1 produces a superimposition of tones of 697 and 1209 Hertz (Hz). Initial pushbutton designs employed levers, so that each button activated two contacts. The tones are decoded by the switching center to determine the keys pressed by the user **(Dodd, 2002).**

The DTMF signal produced when a button is pressed on the DTMF keypad can be decoded into a four – bit binary number. The keys and their binary equivalents are given in Table 2.2.

Table 2.2 DTMF Keys and their Binary Output Equivalents

KEY	Q4	Q3	Q2	Q1
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
0	1	0	1	0
*	1	0	1	1
#	1	1	0	0

2.2.9 Assembly Language

An **assembly language** is a low-level programming language for a computer, or other programmable device, in which there is a very strong (generally one-to-one) correspondence between the language and the architecture's machine code instructions.

Assembly language is converted into executable machine code by a utility program referred to as an ***assembler***; the conversion process is referred to as ***assembly*, or *assembling*** the code.

Assembly language uses a mnemonic to represent each low-level machine instruction or operation. Typical operations require one or more **operands** in order to form a complete instruction, and most assemblers can therefore take **labels, symbols and expressions** as operands to represent addresses and other constants, freeing the **programmer** from tedious manual calculations.

Macro assemblers include a macroinstruction facility so that assembly language text can be represented by a name, and that name can be used to insert the expanded text into other code. Many assemblers offer additional mechanisms to facilitate program development, to control the assembly process, and to aid debugging.

2.2.9.1 *Number of Passes*

There are two types of assemblers based on how many passes through the source are needed to produce the executable program **(Intel Corporation, 1999).**

a) One-pass assemblers go through the source code once. Any symbol used before it is defined will require "errata" at the end of the object code (or, at least, no earlier than the point where the symbol is defined) telling the linker or the loader to "go back" and overwrite a placeholder which had been left where the undefined symbol was used.

b) Multi-pass assemblers create a table with all symbols and their values in the first passes, then use the table in later passes to generate code.

2.2.9.2 *High-Level Assemblers*

More sophisticated high-level assemblers provide language abstractions such as:

a) Advanced control structures
b) High-level procedure/function declarations and invocations
c) High-level abstract data types, including structures/records, unions, classes, and sets
d) Sophisticated macro processing (although available on ordinary assemblers since the late 1950s for IBM 700 series and since the 1960s for IBM/360, amongst other machines)
e) Object-oriented programming features such as classes, objects, abstraction, polymorphism, and inheritance

2.2.9.3 *Basic Elements*

There is a large degree of diversity in the way the authors of assemblers categorize statements and in the nomenclature that they use. In particular, some describe anything other than a machine mnemonic or extended mnemonic as a pseudo-operation (pseudo-op). A typical assembly language consists of 3 types of instruction statements that are used to define program operations:

a) Opcode mnemonics
b) Data definitions

c) Assembly directives

2.2.9.4 *Data Directives*

There are instructions used to define data elements to hold data and variables. They define the type of data, the length and the alignment of data. These instructions can also define whether the data is available to outside programs (programs assembled separately) or only to the program in which the data section is defined. Some assemblers classify these as pseudo-ops **(Intel Corporation, 1999).**

2.2.9.5 *Assembly Directives*

Assembly directives, also called pseudo-opcodes, pseudo-operations or pseudo-ops, are instructions that are executed by an assembler at assembly time, not by a CPU at run time. The names of pseudo-ops often start with a dot to distinguish them from machine instructions. Pseudo-ops can make the assembly of the program dependent on parameters input by a programmer, so that one program can be assembled different ways, perhaps for different applications. Or, a pseudo-op can be used to manipulate presentation of a program to make it easier to read and maintain. Another common use of pseudo-ops is to reserve storage areas for run-time data and optionally initialize their contents to known values **(Intel Corporation, 1999).**

2.2.9.6 *Typical Applications*

The following are typical areas of applications

a) Assembly language is typically used in a system's boot code, (BIOS on IBM-compatible PC systems and CP/M), the low-level code that initializes and tests the

system hardware prior to booting the operating system, and is often stored in ROM **(Intel Corporation, 1999).**

b) Some compilers translate high-level languages into assembly first before fully compiling, allowing the assembly code to be viewed for debugging and optimization purposes (**Intel Corporation, 1999).**

c) High-level languages, such as C, allow the programmer to embed assembly language directly in the source code. Programs using such facilities, such as the Linux kernel, can then construct abstractions using different assembly language on each hardware platform. The system's portable code can then use these processor-specific components through a uniform interface (**Intel Corporation, 1999).**

d) Assembly language is valuable in engineering. Many programs are distributed only in machine code form which is straightforward to translate into assembly language, but more difficult to translate into a higher-level language. Tools such as the Interactive Disassembler make extensive use of disassembly for such a purpose. (Intel Corporation, 2010) (**Intel Corporation, 1999).**

2.2.10 MATLAB

MATLAB ® is one of a number of commercially available mathematical computation tools. MATLAB ® (short for **Mat**rix **Lab**oratory) excels at computations involving matrices. At a fundamental level of these program can be thought as sophisticated computer-based calculators. In many Engineering classes, the use of programs such as MATLAB ® to perform computations is replacing more traditional computer programming. Programs such as MATLAB ® have become a standard tool for engineers and scientists.

Because MATLAB ® is so easy to use, one can perform many programming tasks. It excels at numerical calculations especially matrix calculations and graphics. For large applications, such as operating systems or design software, C++, JAVA, or FORTRAN would be the programs of choice. In fact, MATLAB ®, which *is* a large application program, was originally written in FORTRAN and later rewritten in C, a precursor of C++. Usually, high level programs do not offer easy access to graphing an application at which MATLAB ® excels (**Intel Corporation, 1999).**

The primary area of overlap between MATLAB ® and high-level programs is "number crunching"—repetitive calculations or the processing of large quantities of data. Thus, if a problem can be formulated with a matrix solution, MATLAB ® executes substantially faster than a similar program in a high-level language. MATLAB ® is available in both a professional and a student version. MATLAB ® has many Toolboxes as application tools for different areas of Engineering and scientific researches. Some of these toolboxes are System Identification Toolbox, Control Toolbox and Communication Toolbox. (MATLAB ® 2013b).

2.2.10.1 *System Identification Toolbox*

System Identification Tool provides an interactive environment for data analysis, model estimation and response visualization. Using this GUI, a variety of models (non-parametric, and linear/nonlinear parametric) can be estimated and their responses visualized and compared to each other. The GUI facilitates estimation of both continuous-time and discrete-time models, using both time and frequency-domain data.

"ident" opens a blank session of System Identification Tool, if the GUI is not already open, otherwise, it brings the GUI's main window into focus.

All input/output model objects in Control System Toolbox and System Identification Toolbox derive from the @Input Output Model base class.

Fig. 2.17 shows the GUI of the System Identification Toolbox.

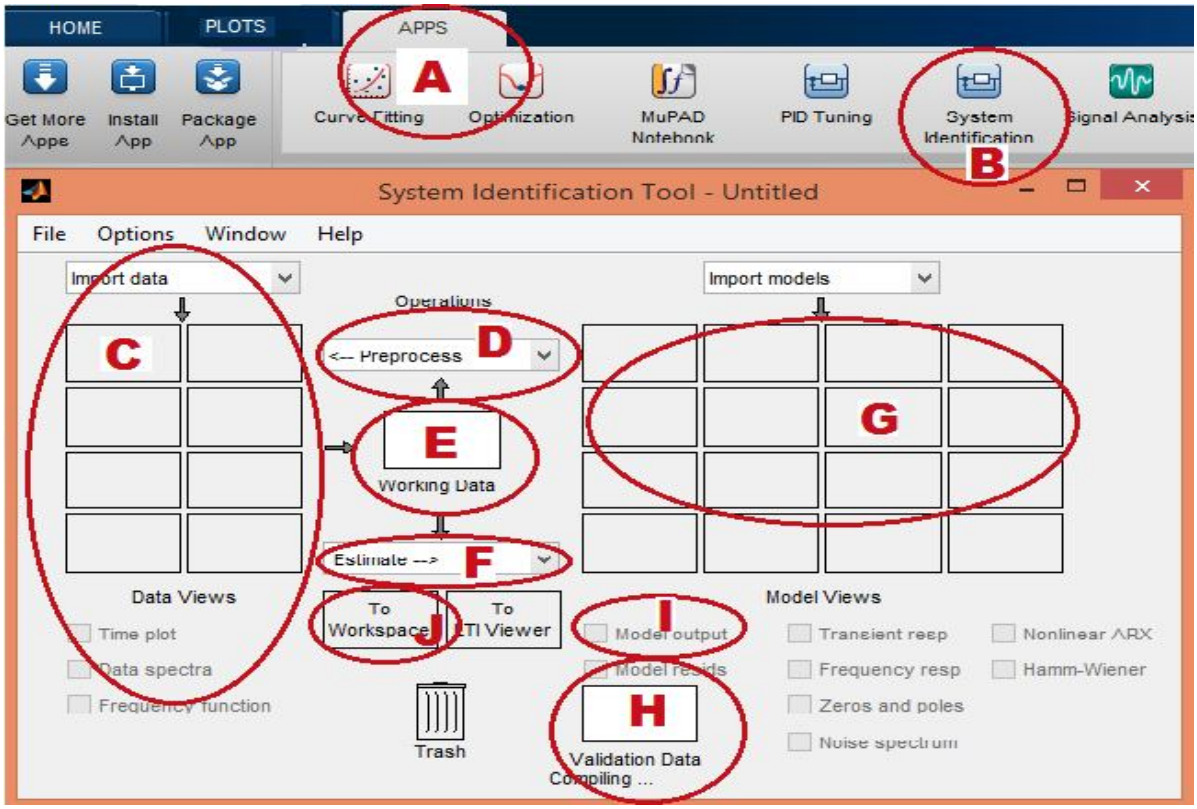


Fig. 2.17. System Identification Toolbox GUI in MATLAB

When MATLAB is launched the toolbox is opened by clicking the APPS bar **(labeled A in Fig. 2.17).** The bar **(labeled B)** is clicked to open the GUI of the system identification toolbox. The **field labeled C** is used for importing data from MATLAB workspace. Time domain and frequency domain data can be imported. For time domain data, the starting time and sampling interval must be specified.

The imported data can be preprocessed in the **field labeled D**. Under preprocessing, the data channel can be selected, experiment can be selected and different experiments can be merged and also the range to be processed can be selected.

The final data to be used for modeling is moved to **field labeled E** as the working data of the session. **Field labeled F** is the processing region. Using this, different models mentioned above can be developed using the working data.

The different models estimated appear in the **field labeled G.** Among the data imported to **field – C** the one to be used for validating the models is dragged to **field labeled H.**

To validate the models for selecting the best, the **field labeled I** is checked. This field called model output gives the plots of all the models with different colours together with the plot of the validation data in black. It also shows the percentage of best fit of each of the models. Based on the displayed percentages of best fit, the model can either be accepted as valid or rejected as invalid depending on the set conditions.

The validated model can be moved to the MATLAB workspace by dragging it from the **field labeled – G to field labeled – J.** This model can be called by typing its name in the command prompt of the MATLAB command window. This would display the transfer function or state space equation of the model which can be used for designing controller for manipulating the behaviour of the system.

2.2.10.2 *Transfer Functions*

The need to investigate any control system in depth makes it mandatory to produce transfer function or state a model of the system. This can be done by determining response information from an existing system or by integrating the information from individual components to evaluate the general system obtained by putting those components together.

For a good model to be formed there is need to provide an answer to the question 'What is to be the system response to the specific stimulus?', that is the ability of the model to produce required output whenever an input is send to it, and this output must agree with that of the real system if the same input were applied ***(*Sandler, 1991)**.

If the system is being modeled in a mathematical way, it is a must to develop a function which manipulates an input in such a way as to finally arrive at the accurate output. If a given input is applied to the function, it will transfer it to a corresponding output value – and as such, this function is referred to a ***transfer function.*** In most cases the relationship between system input, ***u(t),*** and system output, ***y(t),*** can be written in the form of differential equation. So in general terms, the input to output transfer function represented as ***(*Sandler, 1991)**:

$$(D^n + a_{n-1}D^{n-1} + a_{n-2}D^{n-2} + __ + a_1D^1 + a_0)y(t) = (b_mD^m + b_{m-1}D^{m-1} + b_{m-2}D^{m-2} + __ + b_1D^1 + b_0)u(t)$$

(2.8)

In which

$$Dy(t) = \frac{d}{dt}y(t),$$

(2.9)

$$D^2y(t) = \frac{d^2}{dt^2}y(t) \quad etc$$

(2.10)

The coefficients a_o, ..., a_{n-1} and b_o, ..., b, are real values that are defined by the system characteristics, whereas the differential orders n and m are related directly with the structure of the system under consideration.

Once all the integers ***n*** and ***m*** are known, as well as all of the coefficients:

$\mathbf{a_i}$**:** ***i*** **= 0,** ..., ***n*** **- 1;** and $\boldsymbol{b_i}$***: i***= 0, ..., ***m;*** when a set of initial values at ***t*** = t_o, are given the output response for any time ***t*** > ***to,*** can be evaluated by obtaining the solution to the differential equation **(2.9**), in relation to a set of input and input differential values for the same ***t*** > ***to.*** But, this is not a very simple issue, particularly for large values of ***n*** and ***m.*** Note also that, for specific cases it may well be to resort to a differential equation format of **(2.9)** to find an exact solution. A much easier method of analyzing a system transfer function is that of taking the Laplace transform of **(2.9)** and to assume all initial signal values to be zero when time t = t_o. This makes it simple to replace the D operator in **(2.9)** by the Laplace operator s, and this changes the transfer function to ***(*****Sandler, 1991)**:

$$(S^n + a_{n-1}S^{n-1} + a_{n-2}S^{n-2} + __ + a_1S^1 + a_0)y(t) = (b_mS^m + b_{m-1}S^{m-1} + b_{m-2}S^{m-2} + __ + b_1S^1 + b_0)u(t)$$

(2.11)

In this case, it should be noted that both the input and output signals are also transformed values. Equation **(2.11)** can be written as

Y(s) = ***G(s)U(s)***

(2.12)

Where it can be noted that *G(s),* which is independent of the input and output signals, (because it is a constant parameter) establishes the function which transfers the input ***U(s)*** to the output ***Y(s).*** In general, the transfer function could be regarded, as the ratio of the Laplace operator polynomials with initial conditions zero, such that ***(*****Sandler, 1991)**:

$$G(s) = \frac{b_mS^m+b_{m-1}S^{m-1}+b_{m-2}S^{m-2}+__+b_1S^1+b_0}{S^n+a_{n-1}S^{n-1}+a_{n-2}S^{n-2}+__+a_1S^1+a_0}$$

(2.13)

Also it will be considered that ***G(s)*** is linear and that the coefficients a_i and b_i are time-invariant.

A system is said to be linear if it obeys superposition principle by satisfying the following two properties ***(*Sandler, 1991)**:

1. Additivity. If an input $U_1(t)$ to a particular system produces an output $y_1(t)$ and if an input $U_2(t)$ to the same system produces an output $y_2(t)$, then in order for the system to be linear it is necessary that an input $U_1(t) + U_2(t)$ will produce an output $y_1(t) + y_2(t)$.

2. Homogeneity: If an input $u_1(t)$ to a particular system produces an output $y_1(/)$, then in order for the system to be linear it is necessary that an input $b_1U_1(t)$, where b_1 is a constant multiplier will produce an output $b_1y_1(t)$.

2.3 REVIEW OF PREVIOUS SIMILAR WORKS

A lot of important research works have been done in the area of robotic machineries in agriculture and planting in particular. The robots (autonomous or semi – autonomous) developed have been used at different stages and applications in the agricultural process to substitute or complement human labour. Such works are reviewed here.

Subo and Brian (1996) carried out a work on development of plug seedlings transplanter. In this work, on the basis of knowing the development of transplanting technology and transplanter, a simple, practical transplanter for plug seedling, including manipulator, conveyor system for plug tray and flowerpots, overall structure and control system based on

Programmable Logic Controller was designed. Finally, Prototype was manufactured and performance tests were conducted. Results showed that the transplanter had reliable transplanting performance. However, percentage miss was as high as 27.2% and this was due to some design problems which the researchers recommended ways of improvement.

Rolando *et al* (2001) developed a manually operated disc-type corn seeder and evaluated its performance as to seeding efficiency, capacity and number of seeds dropped. The 2-row seeding machine which was primarily designed for planting corn was also tested using soybeans and peanuts to determine its usability and applicability. Actual field testing was carried out in three different soil types. Results revealed that the device had a seeding efficiency of 66 -70%. Field evaluation also showed that the three types of soil had no significant effect on the number of seeds dropped. On the other hand, average field capacity was noted to be 0.76 ha/day. As compared to the traditional practice, a savings in labor of 52 – 56% can be realized by using the seeder. The device is easy to operate, simple in design/mechanism, light in weight, requires less labour, low cost of planting and can also be used for seeding other seeds. The drawback of this work was the high percentage error in seedling of 30% to 34%.

Olaoye and Bolufawi (2001) designed and constructed a planting machine for planting grains on both flat lands and ridges. The power transmission from the ground wheel was used to operate and control the seed holding device. A grooved disc roller type seed-metering device was used. The discharge outlet was provided with a precision seed supply metallic terminal. The test results indicated averagely good performance for cowpea and soybean. The effects of main factors, two different types of seed, levels of variation of moisture content of the soil and the loading capacities of the hopper were investigated to

establish the average percentage of seed breakage of the seed by the planter. The results indicated that the planter had a major setback due to high percentage of seed breakage (33%).

Kim *et al* (2001) developed an automatic transplanter for planting Chinese cabbage. The automatic transplanter is mainly composed of a pick-up system, a planting system, and a feeding system for cabbage seedlings. The accuracy of the pick-up system was evaluated in the laboratory and the rate of successful picking was 69.5% for 20-day-old cabbage seedlings. The performance of the prototype was tested with cabbage seedlings and showed that the pick-up system correctly separated the cabbage seedling from the tray one by one and planted it in the soil with a maximum failure of 23.5%. The major issue with this transplanter was the low percentage of successful picking (69.5%) and the high percentage of maximum failure (23.5%).

Chaudhuri *et al* (2002) designed and developed a vegetable transplanter. The transplanter is a row unit which is modular in design. Each unit is mounted on a tool frame. The feeding of seedlings is carried out manually by person sitting on machine. One person is required for each row. A runner type opener opens the furrow and two covering wheels are used to close furrow and compact soil around the plant. Depth adjustment is made with help of two pneumatic depth wheels. The transplanter was used for transplanting tomato and chilly crop. Field capacity of adopted unit ranged from 0.08 to 0.10 ha/h depending upon row and plant spacing adopted. The labour requirement was about 20–25 man-h/ha as against 300–320 man-h/ha in manual transplanting. The major problem of this transplanter was the high percentage of miss of about 29.4% - 30.2%.

Staggenborg *et al* (2004) designed and developed a corn planter and evaluated the effect of speed on the performance of the planter. A planter equipped with a vacuum metering system and seed firming devices was used. Corn was seeded in a randomized complete block experiment at three speeds. Plant stand was counted at regular intervals after the first plant emerged to determine emergence rate. Plant spacing within each treatment was measured after complete emergence. Mean plant spacing, standard deviation in spacing, and four spacing indices (miss, multiple, quality of feed, and precision) were calculated to evaluate the plant spacing data. The miss and multiple indices indicate the number of skips and doubles. The results showed that as the speed increased the rate of miss and multiple (doubles) increased and this reduced the efficiency of the planter.

Dhalin *et al* (2005) developed power tiller operated seeder. Field evaluations were conducted on a power tiller operated cup feed seeder to assess the uniformity of seed spacing in the row. Even though the seeder could maintain the row to row spacing, the uniformity of plant spacing in the row was poor as indicated by a wide frequency distribution of plant spacing. So, a check valve system was incorporated with the cup feed seeder, so that the plant spacing could be maintained properly. The concept of the check valve system was to accumulate the seeds coming through the delivery tube at the tube end and to drop them collectively at pre-determined intervals or spacing. Field trials were undertaken sowing black gram and maize, to compare the seeder's performance with and without the inclusion of the hill dropping system. The observed spacing distribution of the crop planted using the check valve equipped seeder was almost that of a normal distribution, with the peak frequency aligning exactly at the desired hill spacing in the row. The

mechanical lag of the check valve was a serious constraint on the planting speed of the seeder.

Santos and Brian (2005) conducted a research on the kinematic performance of front and rear converging linkages (FRCL) in comparison with the performance of parallel linkages (PL), both as might be applied to individual precision planter units. The mathematical model developed predicted the tine weight transfer required for soil penetration with an accuracy of 90% for the FRCL based on comparisons with experimental results obtained under laboratory conditions. It was observed that the weight transfer from the main frame to the planter unit depended mainly on the magnitude of the draft force and on the height of the virtual hitch point (VHP). This weight transfer represented only 50% of the total weight required for the planter unit to reach the desired planting depth as compared with the weight transfer provided by the (PL) system. Although the (PL) system required an additional tensile spring to achieve the required weight transfer, this system was shown to be more stable with regard to planting depth performance in comparison with the (FRCL) system. The basic problem of this planter (PL) system is that it required an additional tensile spring to achieve the required weight transfer and planting depth.

Ebubekir (2005) carried out a study to determine the effects of tuber size and forward speed on full automatic potato planter's performance. The results were related by linear regression. Uniformity of seed tuber spacing was determined by a computer program and quantified by determining the ratio of misses, doubles and coefficient of variation of spacing. The trials were conducted on four different tuber sizes (35 to 45mm; 45 to 55 mm, 55 to 65mm; 65 to 75 mm (whole or cut) and at three different forward speeds of machine (3.60 km/h, 5.40 km/h and 8.64 k m/h). It was found that seed tuber distribution pattern in the row was

disturbed as tuber size and machine forward speed increased. Small tuber gave better in row tuber distribution pattern than big tubers. However, lower coefficient of variation of spacing and miss ratio were found with the usage of cut tubers than with whole tubers. The percentage of miss plantings of the planter was very high (about 35%).

Behera *et al* (2007) developed a self-propelled transplanter and conducted an experiment that showed that it had problems of poor traction and sinkage and required ideal soil condition for proper working. It was observed that too soft soil increased the sinkage of the float of the transplanter and led to a higher percentage of buried and floating hills and subsequently increases the hill mortality. A study was conducted to determine the sinkage of the transplanter through a sinkage device under simulated conditions and later on verified on the field by the transplanter itself. Good agreement between the simulated sinkage and actual sinkage was observed. Further study on the performance of the transplanter showed that ideal transplanting time should be 48 hours after puddling for a silty clay loam soil. Sinkage of the float had good correlation with buried and floating hill as well as with the hill mortality. But despite this improvement, lack of ideal soil condition made it impossible to achieve good traction.

Sirisha *et al* (2008) developed and evaluated the performance of direct paddy seeders. Three types of paddy seeders namely two row, three row and four row paddy seeders to reduce the drudgery of women and three types of material namely plastic, galvanized iron (GI) and fiber reinforced plastic (FRP) for reducing the weight of the unit were developed and evaluated for ergonomically evaluation. Ten female subjects were selected for the investigation based on the age. The parameters used for the ergonomically evaluation of the direct paddy seeders include energy cost of operation, acceptable work load, work pulse,

overall discomfort rating and force required for the operation of direct paddy seeder. A swinging type handle was developed for pulling the seeder to avoid the awkward posture of farm women. The field capacity for the four row, three row and two row paddy seeders with plastic, galvanized iron and fiber reinforced plastic materials varied from 0.025 to 0.0625 ha hr^{-1}. Based on the ergonomical evaluation and field capacity, the four row paddy seeders of three materials were chosen for performance evaluation and the four-row paddy seeder with plastic material was adjudged as the best seeder for rural women folk.

Shaaban *et al* (2009) developed and tested a vacuum precision seeder prototype suitable for onion seeds. The developed prototype was fabricated from local materials (Stainless Steel). It was also designed to plant two rows with 70 mm apart instead of one row as the most onion vacuum seeders in the market. Tests were conducted at an indoor soil bin facility under different operational parameters. Measurements were taken for the actual seed spacing, seed miss index, seed multiple index, quality of feed index, precision in spacing and the vacuum pressure in the hole. Results indicated that the optimum values of the actual seed spacing (5.93 mm), seed miss index (28.1%), seed multiple index (38.12%), quality of feed index (83.7%) and precision in spacing (23.4%) were obtained with the seed plate of 1.0 mm hole diameter. The main disadvantages of this planter are the high miss index (28.1%) and the high multiple seeding index (38.12%).

Ismail *et al* (2009) designed and developed a sugar beet planter with vertical seed discharge device. The planter system consists of a seed hopper, seed metering device, agitator unit, transmission system and seed delivery tubes. The individual seed hopper which was made from iron sheet is connected on the planter frame. On the bottom of the hopper, the control lever is connected to regulate the seeding rate. The tank capacity is regulated to plant 100-

120 kg seeds per hectare. The seeds are picked by brush hair from the hopper and dropped into the seed tube. The revolution number of brush device can be regulated by using the power transmission of the planter land wheel. The major setback of the planter as observed by the designers was the high linear speed and low peripheral speed which resulted in more spaces between seeds in row and this lowered the yield of the sugar beet.

Turbatmath *et al* (2011) designed, developed and evaluated the field performance of tractor operated onion transplanter. Engineering physical properties like height, weight, diameter, moisture content and compressive strength of the onion seedlings were the parameters used to design different mechanisms of the transplanter which are responsible for detaching and transplanting the onion seedlings. Two metering mechanism (Fingure type and Plug type) were used for evaluating the three different travel speed of 0.75 km/h, 1.00 km/h and 1.25 km/h for different age group of onion seedlings. It was observed that plug type metering mechanism at speed of 0.75km/h with seventh week age seedling were more suitable for transplanting. The miss percentage of transplanting as high as 29.00 - 30.9% was observed. Also the capacity of the machine was as low as 0.1088 – 0.1174 ha/hr with highest field efficiency of 60.49 -61.60 per cent.

Kumar and Raheman (2012) designed an automatic feeding mechanism for a vegetable transplanter. The automatic feeding mechanism consisting of a timing shaft, an actuating device and a clutch for feeding paper pot seedlings from a horizontal slat type chain conveyor to a horizontal pusher type chain conveyor of a vegetable transplanter was developed. The slat type chain conveyor carried the pot seedlings in upright orientation in the form of a rectangular array with each linear array of pot seedlings on a slat. The pusher type chain conveyor received a linear array of pot seedlings and delivered them to the

seedling drop tube. Feeding of each linear array of pot seedlings to the pusher type conveyor at appropriate times was done using an automatic feeding mechanism. The laboratory evaluation indicated that the feeding rate of 33 to 50 pot seedlings per minute can be achieved with single set of conveyors. The feeding mechanism did not work effectively under actual field conditions with 58% to 59% of all the pot seedlings properly separated and fed for planting when the forward speed of the vegetable transplanter was 0.9 km/h.

From the literature discussed here it is evident that a lot of work has been done in an effort to provide means of mechanizing the planting process. It is, however, clear that the majority of the works are for transplanting vegetables. There are also works in the area of direct planting seeds like onion and potato. The grain planters are mostly operated manually. Therefore this work on design and environmental behaviour modelling of Bluetooth controlled planter robot is aimed at improving the aspect of grain planting by providing a semi - automated planting machine. The design is also optimized for maize planting because maize is the most commonly grown crop around Zaria, (**Ofor *et al*, 2009**).

CHAPTER THREE

MATERIALS AND METHODS

3.1 INTRODUCTION

The detailed design of the mechanical part and the electronic part for control of the Plantbot are presented in this chapter.

3.2 MECHANICAL DESIGN OF THE PLANTBOT

The general mechanical design considerations of the Plantbot are presented in this chapter in step-by-step approach under the subheadings that follow.

3.2.1 The Plantbot

The Plantbot is basically a remote controlled machine which could be used for planting maize. The Plantbot is made up of two main segments: the mechanical segment which serves as the mechanism of the planting machine and the electronic segment which is the control part of the machine using Bluetooth medium.

The Plantbot is a car-like machine with four wheels. The two rear wheels are the drive wheels and the front wheels are steering wheels. A DC motor was used for driving the machine via the rear wheels. This motor was used for forward and backward movements of the Plantbot. The front wheels which are used for steering are also operated using a second DC motor for clockwise and anti-clockwise movements during the turning of the Plantbot.

The planting operation of the machine was done using a planting mechanism to ensure equal spacing from one plant to another. The mechanism is also controlled using a third DC motor. The motor was just used for lowering the mechanism to start planting and rising it when it is not planting.

The three motors are operated using an electronic circuit that is remotely controlled using a GSM handset as mobile station (MS) through Bluetooth channel as the medium of communication between the MS and the electronic circuit. The general operation principle of the Plantbot is given in Fig. 3.1.

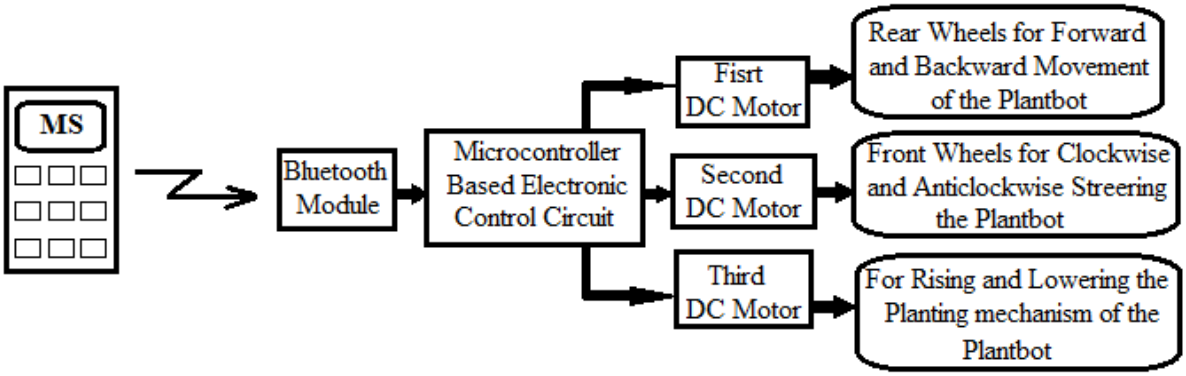


Fig. 3.1. The General Operation Principle of the Plantbot

3.2.2 Dimensions of the Plantbot

In order to streamline the design with respect to the dimensioning, the Plantbot was designed to improve the planting of maize. This is important because of the need to make it possible for the Plantbot to move accurately between the ridges in the farm during the planting exercise. The first dimension considered is the width of the Plantbot**.** The standard interval between one ridge and the next used in modern agriculture for planting maize is 75cm (750mm) (IAR A. B. U. Zaria, 2012). Therefore the width of the Plantbot from wheel to wheel (Centre – to – Centre) was made 700mm with each wheel in one furrow while a ridge (tillage) was placed under the Plantbot at the Centre.

The length of the Plantbot is the second dimension selected and determination of an appropriate value was equally important for the stability and the physical shape of the Plantbot. The value selected for the length was 100cm (1000mm) from end to end of the

Plantbot. This value was used for the length of the Plantbot because the robot is car-like and the length is always a bit longer than the width for stability reasons (Eugene *et al*, 2007). The distance from plant to plant on the same ridge is 25cm (250mm) (IAR A. B. U. Zaria, 2012). Fig. 3.2 shows the sketch of the plan view of the Plantbot with the basic dimensions indicated. As it can be seen in Fig. 3.2 the diameter of the front wheels (14cm) is smaller than that of the rear wheels (28cm). This is because, the smaller diameter would make the steering very simple and the selected diameter of the front wheel is enough for the Plantbot to pass over the ridge without touching it.

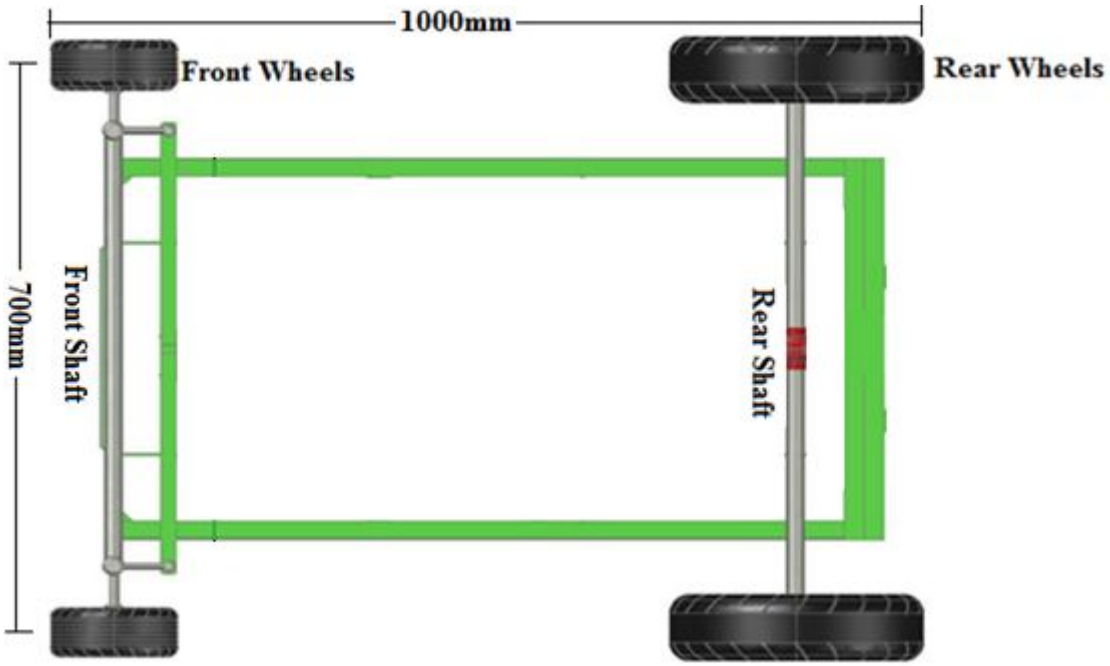


Fig. 3.2. Plan View of the Plantbot with the Basic Dimensions

3.2.3 Mode of Movements of the Plantbot

The basic movements involved in the Plantbot during its operation include the movement of the rear wheel which works as the main driver of the Plantbot and it moves forward and backward only, using first DC motor (See Fig. 3.1) as the source of driving force. The rear

wheels were connected to the rear shaft which was coupled with the main gearbox of the Plantbot. The gearbox was coupled with the DC motor shaft for reducing the high speed (600rpm) of the DC motor to the desired slow speed (50rpm) suitable for the accurate planting exercise (see section 3.2.7). Fig. 3.3 illustrates orthographically the assembly of the rear wheel, rear shaft and gearbox.

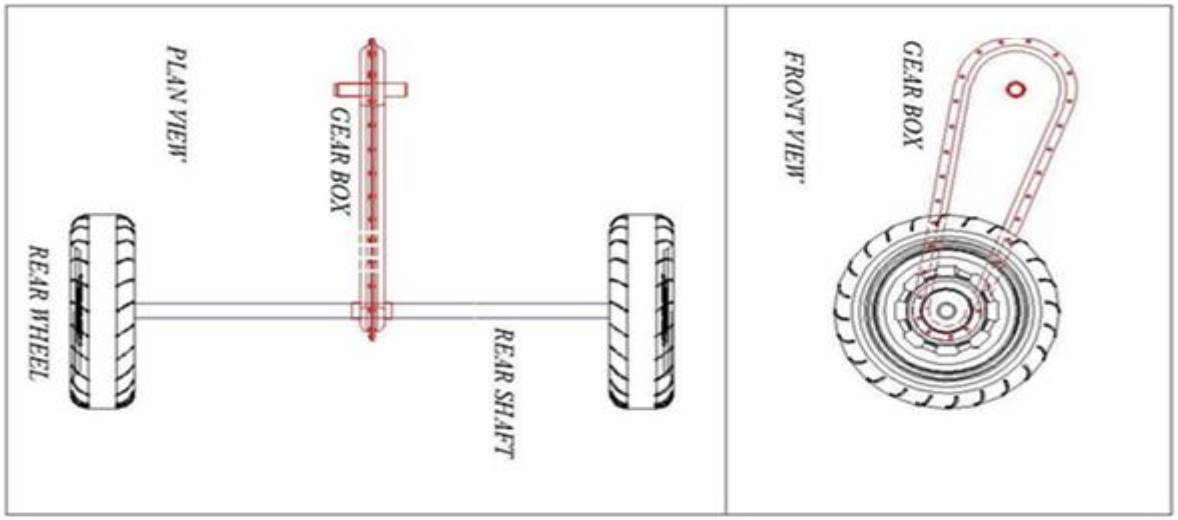


Fig. 3.3. Orthographic Views of Rear Wheels, Rear Shaft and Gearbox Assembly

The second movement of the Plantbot is that of the front wheel which is the driven wheel and the steering terminal of the Plantbot**.** The two front wheels of Plantbot were coupled with the steering mechanism that includes steering shaft with two steering jaws; one connected to each of the two front wheels.

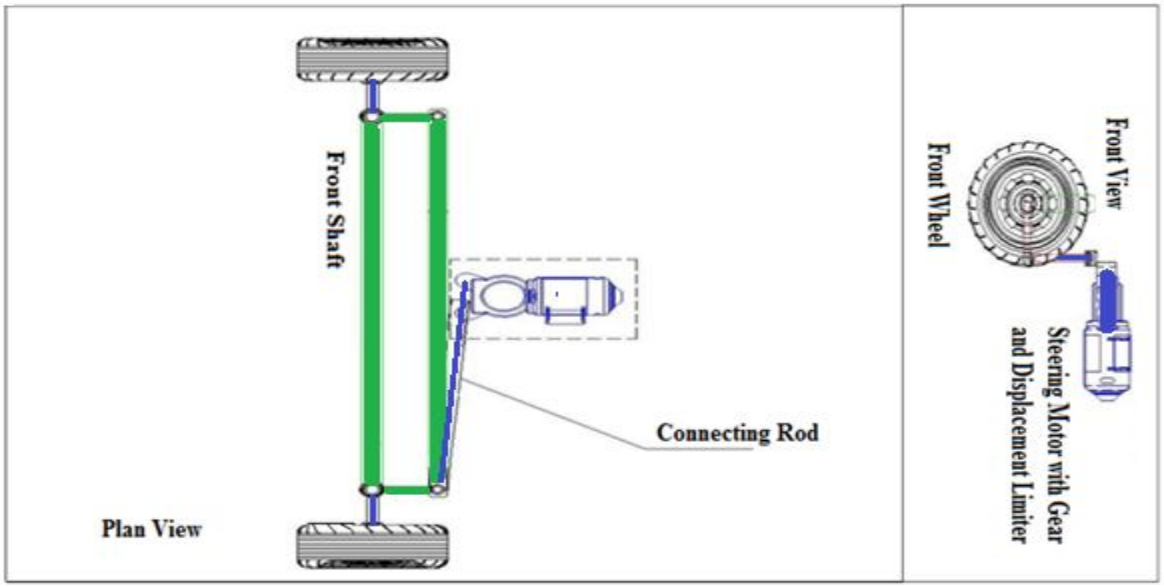


Fig. 3.4. Orthographic Views Showing the Wheels Setup for Plantbot's steering

The front shaft was provided with a connecting rod for coupling to the DC motor that has gear setup together with angular displacement limiter used for turning the front wheels in clockwise and anticlockwise directions during turning of the Plantbot. Fig. 3.4 depicts the orthographic plan view of the front wheel setup for steering.

3.2.4 Coordination of the Related Links

As seen from the Figs. 3.2 – 3.4, the Plantbot is made up of many links responsible for coordinating various motions in the operations of the Plantbot during the planting. Some of the links are on the rear shaft for driving the Plantbot while others are on the front shaft as driven segment and the Plantbot steering point. The main links are shown in Fig. 3.5. The connection of the main drive DC motor which was coupled with the main gearbox of the Plantbot can be seen in Fig. 3.5. The gearbox was then coupled with the rear wheels through the rear shaft which was mounted on bearings. Fig. 3.5 also shows the coupling of the geared steering motor to the front shaft which was connected to the steering jaws and then to the front wheels.

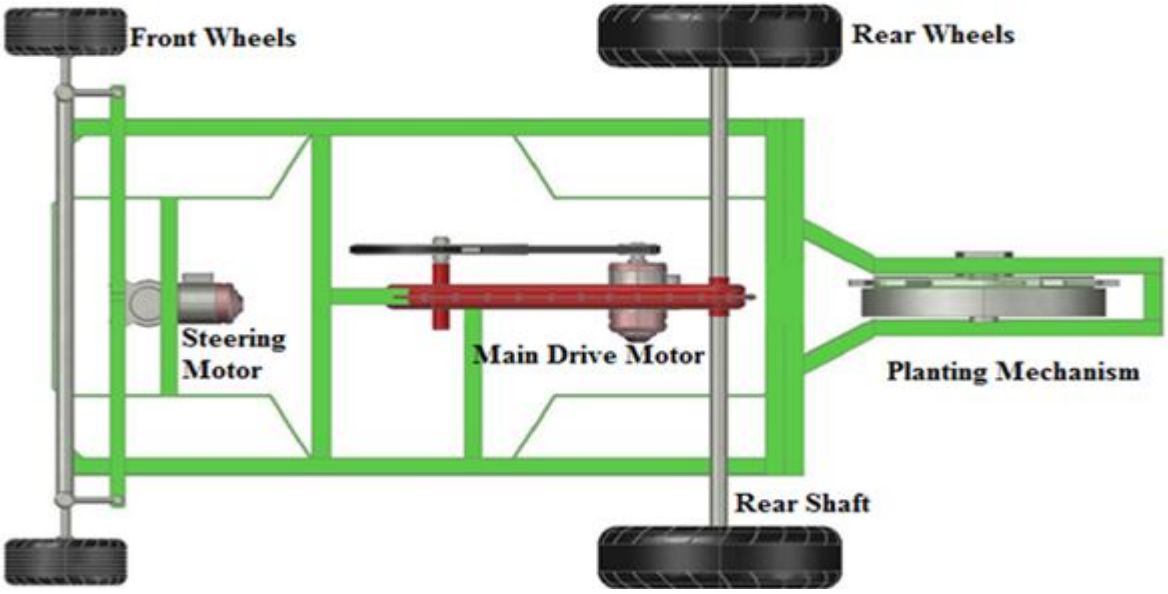


Fig. 3.5. Plan View of the Complete Mechanical Parts of the Plantbot

The complete engineering drawings (DRW 1 to DRW 8) are given in the Appendix A.

3.2.5 Selection of the Main Drive Motor

The drive motor selected for this project was DC type. DC motor is preferred in a situation where precise speed regulation is not required, where frequent start/stop cycles occur, and also where reversing of the mechanism is needed. The DC motor is commonly rated at a single speed and torque. In most cases, the motor can operate at this point continuously.

The drive motor is selected after the total mass (M) of the Plantbot was known, the maximum incline angle $(\theta)$the robot would climb was assumed and the overall radius of the drive wheel (R) was known (Alan, 2008).

The torque of the motor was calculated as (Alan, 2008):

$$\boldsymbol{T} = \left(\frac{\mathbf{100}}{\eta}\right)\frac{(\boldsymbol{a}+\boldsymbol{gSin\theta})\ \boldsymbol{x}\ \boldsymbol{M}\ \boldsymbol{x}\ \boldsymbol{R}}{\boldsymbol{N}} \qquad \textbf{(3.1)}$$

Where "□" is motor efficiency; "a" is acceleration; "g" is acceleration of free fall due to gravity; "□" inclination of the machine; "M" is the mass of the Plantbot; "R" is the radius of the rear wheel and "N" is the total number of wheels of the Plantbot.

The Plantbot is expected to work for planting on a level ground but in some farms there are places where the land is inclined to an angle depending on the nature of the place. This angle of inclination was needed for proper selection of the drive motor. The average inclination angle that is commonly used is 15^0 (Alan, 2008). The Plantbot was also designed to move with uniform speed, therefore, the acceleration (a) is zero (0). The total mass of the Plantbot prototype is measured approximately as 50kg (the motor selection was delayed until the designed prototype was constructed and its mass was measured using spring balance) and the overall radius of the rear wheel which was the drive wheel was selected as 14cm (0.14m). The efficiency (η) of the motor was taken as 85% (Alan, 2008). The number of wheels (N) the Plantbot move on is four (4).

The torque of the motor was calculated from equation (3.1) as:

$$\boldsymbol{T} = \left(\frac{\mathbf{100}}{\eta}\right)\frac{(\boldsymbol{a} + \boldsymbol{gSin\theta})\ \boldsymbol{x}\ \boldsymbol{M}\ \boldsymbol{x}\ \boldsymbol{R}}{\boldsymbol{N}}$$

$$= \left(\frac{\mathbf{100}}{\mathbf{85}}\right)\frac{(\mathbf{9.81})(\boldsymbol{Sin}\mathbf{15^0})\ \boldsymbol{x}\ \mathbf{50}\ \boldsymbol{x}\ \mathbf{0.14}}{\mathbf{4}}$$

$$= \mathbf{5.23}\boldsymbol{N.m}$$

The rotational speed (ω) of the motor was selected as 600 rpm (this is because any speed higher than the final speed of the robot can be used, so that the designed gearbox will reduce it to the desired value, so 600rpm was selected since it is among available ones that can serve the purpose) which was converted to (rad/sec) as (Sclater, 2007):

$$\omega\left(\frac{rad}{sec}\right) = \omega(rpm)\, x \frac{2\pi}{60}$$

(3.2)

$$= 600\, x\, \frac{2\pi}{60}$$

$$= 62.83(rad/sec)$$

The output power of the DC motor (P) in Watt is defined as the product of its torque (T) in N.m and the angular speed (ω) in rad/sec (Nisbett, 2006).

$$P = T\omega$$

(3.3)

The required power to drive the Plantbot was obtained as:

$$P = T\omega$$

$$= 5.23\, x\, 62.83$$

$$\cong 328.61W$$

This power was the one required due to inertia force ($\mathbf{F_I}$) component of the tractive force ($\mathbf{F_{TR}}$) of the machine given as (Eugene *et al*, 2007):

$$F_{TR} = F_R + F_D + F_I + F_G$$

(3.4)

For machine moving with constant speed (like this Plantbot), the aerodynamic drag force component ($\mathbf{F_D}$) and grade requirement force component ($\mathbf{F_G}$) are both zero. So the tractive force ($\mathbf{F_{TR}}$) becomes:

$$F_{TR} = F_R + F_I$$

(3.5)

The force of rolling resistance ($\mathbf{F_R}$) was given as (Eugene *et al*, 2007):

$$F_R = C_R W$$

(3.6)

The rolling resistance coefficient ($\mathbf{C_R}$) of the tires was as low as 0.006 with modern radial tires (Eugene *et al*, 2007). The weight (W) of the Plantbot given as (Eugene *et al*, 2007):

$$W = Mg$$

(3.7)

$$W = 50 \; x \; 9.81$$

$$W = 490.5N$$

The force of rolling resistance was calculated from equation (3.6) as:

$$F_R = 0.006 \; x \; 490.5$$

$$F_R = 2.943N$$

The power requirement ($\mathbf{P_R}$) due to this force ($\mathbf{F_R}$) was given as (Eugene *et al*, 2007):

$$P_R = F_R \; x \; Velocity$$

(3.8)

The velocity of the Plantbot was obtained as 36cm/s (0.36m/s) as shown in section 3.2.7.

$$P_R = 2.943 \; x \; 0.36$$

$$P_R = 2.15W$$

So total power ($\mathbf{P_T}$) is:

$$P_T = 328.61 + 2.15$$

$$P_T = 330.76W$$

From this result, a higher power motor of 1horse-power (746W) with speed of 600 rpm, efficiency of 90% and supply voltage (V) of 24V was chosen.

3.2.5.1 *Selection of the Steering Motor*

The steering motor selected for this project was DC type for turning in clockwise and anticlockwise directions. The steering motor was selected after the percentage of the total mass (M) of the Plantbot that was acting on the steering (front) wheel was estimated, the maximum incline angle (θ) the robot would climb was selected and the overall radius of the front wheel (R) was known.

The torque of the motor was calculated using equation (3.1).

The total mass of the Plantbot was measured as 50kg and most of it is on the rear wheel (this was because the planting mechanism, the heavier rear wheels, the gearbox and the main drive motor are all on the rear wheels side) so the assumed value of the mass on the front wheel was taken as 25% of the total mass (12.5kg, which was the worst case value) and the overall radius of the front wheel which was the driven wheel is selected as 7cm (0.07m). The efficiency (η) of the motor was taken as 85%.

The torque of the motor is calculated as:

$$T = \left(\frac{100}{\eta}\right)\frac{(a + gSin\theta)\ x\ M\ x\ R}{N}$$

$$= \left(\frac{100}{85}\right)\frac{(9.81)(Sin15^0)\ x\ 12.5\ x\ 0.07}{4}$$

$= \mathbf{0.65}\boldsymbol{N.m}$

The rotational speed (ω) of the motor is 200 rpm which was converted to angular displacement by an internal gear system in (rad/sec) using equation (3.2) as:

$$\boldsymbol{\omega}\left(\frac{\boldsymbol{rad}}{\boldsymbol{sec}}\right) = \boldsymbol{\omega}(\boldsymbol{rpm})\ \boldsymbol{x}\frac{\boldsymbol{2\pi}}{\boldsymbol{60}}$$

$$= \mathbf{200}\ \boldsymbol{x}\ \frac{\boldsymbol{2\pi}}{\boldsymbol{60}}$$

$$= \mathbf{20.94}(\boldsymbol{rad/sec})$$

The required power for steering the Plantbot was obtained as:

$$\boldsymbol{P} = \boldsymbol{T\omega}$$

$$= \mathbf{0.65}\ \boldsymbol{x}\ \mathbf{20.94}$$

$$= \mathbf{13.68}\boldsymbol{W}$$

Adding power due to rolling resistance (2.15W), the total power becomes 15.83W.

From this result, a 25W motor with speed of 200 rpm, efficiency of 90% and supply voltage (V) of 24V was chosen.

3.2.5.2 *Selection of the Planting Mechanism Control Motor*

The planting mechanism control motor selected for this project is DC type for raising and lowering of the mechanism. The motor was selected after the total mass (M) of the constructed planting mechanism was measured using a spring balance, the maximum incline angle (Θ) the mechanism would be raised was selected and radial distance of cable from pulley to support point on mechanism (R) was known.

The torque of the motor is calculated using equation (3.1).

The total mass of mechanism was 15kg and raising angle is limited to 20^0 to horizontal, radial distance from pulley to support point on the Plantbot was measured approximately as 25cm. The efficiency (η) of the motor was taken as 85%. The N in this case is number of connected points (N_c = 3). This include, motor point, pulley point and mechanism support point.

The torque of the motor was calculated as:

$$\boldsymbol{T} = \left(\frac{\mathbf{100}}{\eta}\right)\frac{(\boldsymbol{a} + \boldsymbol{gSin\theta})\ \boldsymbol{x}\ \boldsymbol{M}\ \boldsymbol{x}\ \boldsymbol{R}}{\boldsymbol{N_c}}$$

$$= \left(\frac{\mathbf{100}}{\mathbf{85}}\right)\frac{(\mathbf{9.81})(\boldsymbol{Sin}\mathbf{20^0})\ \boldsymbol{x}\ \mathbf{15}\ \boldsymbol{x}\ \mathbf{0.25}}{\mathbf{3}}$$

$$= \mathbf{4.93}\boldsymbol{N.m}$$

The rotational speed (ω) of the motor is 120 rpm which was reduced by an internal gear in (rad/sec) using equation (3.2) as:

$$\boldsymbol{\omega}\left(\frac{\boldsymbol{rad}}{\boldsymbol{sec}}\right) = \boldsymbol{\omega}(\boldsymbol{rpm})\ \boldsymbol{x}\frac{\mathbf{2\pi}}{\mathbf{60}}$$

$$= \mathbf{120}\ \boldsymbol{x}\ \frac{\mathbf{2\pi}}{\mathbf{60}}$$

$$= \mathbf{12.57}(\boldsymbol{rad/sec})$$ The required power for operating the mechanism was obtained as:

$$\boldsymbol{P} = \boldsymbol{T\omega}$$

$$= \mathbf{4.93}\ \boldsymbol{x}\ \mathbf{12.57}$$

$$= \mathbf{61.98}\boldsymbol{W}$$

From this result, a 75W motor with speed of 120 rpm, efficiency of 90% and supply voltage (V) of 24V was chosen.

When determining the battery size the power of this motor is not included. This was because it was not expected that it would work simultaneously with the main drive motor or steering motor.

3.2.6 Battery Pack Selection

The capacity of the battery pack to be used for powering the drive and steering motors was calculated after the selection of the motors was done. The motors selected from sections 3.2.5 and 3.2.5.1 were 746W and 25W, 24V DC type, but the consumed powers were 330.76W and 15.83W respectively.

The current (I) requirement of the motors was calculated as (Boylestad and Nashelsky, 2004):

$$\boldsymbol{I = \frac{P}{V}} \qquad (3.9)$$

$$\boldsymbol{I = \frac{330.76 + 15.83}{24}}$$

$$\boldsymbol{I = 14.44A}$$

The capacity (Ah) of the battery (in Ampere-Hour) was calculated as (Boylestad and Nashelsky, 2004):

$$\boldsymbol{Ah = I(A)\ x\ t(hour)}$$

(3.10)

For the Plantbot to work for an average period (t) of four hours the capacity of the battery was calculated as:

$$\boldsymbol{Ah = 14.44A\ x\ 4(H)}$$

$$\boldsymbol{= 57.76AH}$$

A 75AH, 24V battery which can be discharged to a depth of 80% was chosen.

3.2.7 Gearbox Design

The gearbox in this work uses a gear train with three gears. A gear train made up of multiple gears can have several drivers and several driven gears where the machine was controlled with different motions and speeds or single driver and single driven gear where machine was controlled with single motion and single speed as the one in this design (Shigley *et al*, 2004). If the train contains an odd number of gears, the output gear will rotate in the same direction as the input gear as shown in Fig. 3.6. The gears in the gear train are typically spur gears, meaning straight teeth.

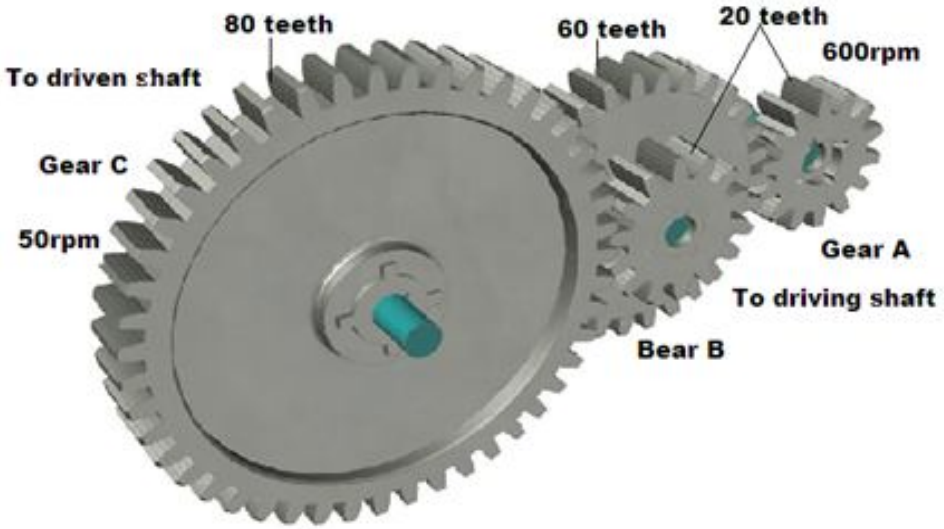


Fig. 3.6 Gears Arrangement in the Gearbox

The driving gear (A) with 20 teeth (N_A) was connected directly to the drive motor with angular velocity (ω_A) of 600 rpm. This drives an intermediate gear (B) with 60 teeth (N_{B1}) and 20 teeth (N_{B2}) respectively in the opposite direction. N_{B2} drives the output (driven) gear (C) in the same direction with the driving gear (A). The driven gear has 80 teeth (N_C).

The angular velocity of the intermediate gear (B) was calculated as (Shigley *et al*, 2004):

$$\frac{\omega_A}{N_{B1}} = \frac{\omega_{B1}}{N_A}$$

(3.11)

and

$$\omega_{B1} = \frac{N_A}{N_{B1}}\omega_A$$

$$= \frac{20}{60}\ x\ 600\ rpm$$

$$= 200\ rpm = \omega_{B2}$$

This was the angular velocity of the gear B for both the 60 teeth (ω_{B1}) and the 20 teeth (ω_{B2}) since they have the same axis of rotation.

To calculate the final angular speed (ω_C) of the driven gear (C) the following relation was used (Eugene *et al*, 2007):

$$\omega_C = \frac{N_{B2}}{N_C}\omega_{B2}$$

(3.12)

$$= \frac{20}{80}\ x\ 200\ rpm$$

$$= 50\ rpm$$

The angular velocity of the driven gear was calculated as 50 rpm (this is very much smaller than the calculated critical speed of the shaft, 926 rpm (see section 3.2.8.4), thus it is very

safe since going above the critical speed causes failure due to fracture of the shaft). Thus the gear train reduces the angular velocity of the Plantbot from 600 rpm to 50 rpm to give the required velocity that is suitable to the planting speed which was calculated as (Eugene *et al*, 2007).:

$$\boldsymbol{Speed} = \frac{\pi R \omega_C}{60}(\boldsymbol{cm/sec})$$

(3.13)

Where the parameter "R" is the radius of the rear wheel, which is the driven wheel by the motor. The overall radius of the rear wheel is 14cm.

$$\boldsymbol{Speed} = \frac{\pi R \omega_C}{60}(\boldsymbol{cm/sec})$$

$$= \frac{\pi \, x \, 14 \, x \, 50}{60}$$

$$\cong 36 \boldsymbol{cm/sec}$$

The recommended interval from one plant to another on a row is 25cm (IAR A. B. U. Zaria) as used on the planter in this work. The calculated speed shows that the Plantbot can approximately plant one (1) seed in every second. This is much faster than the manual planting speed and the speed is not too high which would cause error in the planting.

3.2.7.1 *Gearbox Design for Fastener*

When a connection is desired that can be disassembled without destructive methods and that is strong enough to resist external tensile loads, moment loads, and shear loads, or a combination of these, then the simple bolted joint using hardened-steel is a good solution (Brown, 2005).

The casing of the gearbox of the Plantbot was made of cast iron material and was fastened using assembly of bolts and nuts round the casing. This is shown in Fig. 3.7.

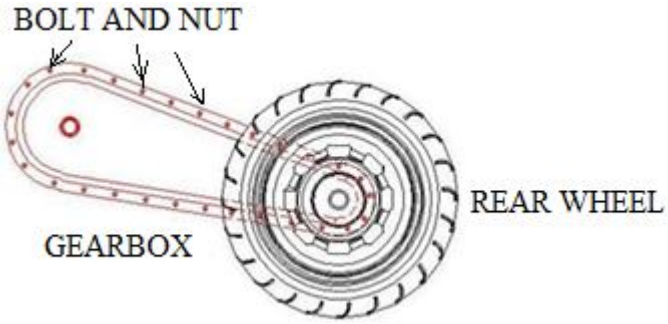


Fig. 3.7. Section Showing the Gearbox Casing with Bolts and Nuts Fastener

A high strength steel bolt and nut assembly was used where the diameter of the bolt (d_{bolt}) is 6mm, the total length of the bolt (L_{total}) is 30mm, the threaded length ($L_{threaded}$) is 15mm, and the grip length (Lgrip) is 22mm and the cross sectional area (A_T) of the threaded part of the bolt is 84.3mm^2. The modulus of elasticity (E) of the high strength steel is 207GPa (McGraw Hill Machine Design Data book, 2004).

The unthreaded length (L_{UT}) of the bolt was first obtained as (Brown, 2005):

$$\boldsymbol{L_{UT} = L_{Total} - L_{threaded}} \qquad \boldsymbol{(3.14)}$$

$$= \boldsymbol{30mm - 15mm}$$

$$= \boldsymbol{15mm\ (0.015m)}$$

The unthreaded cross – sectional area ($\boldsymbol{A_{UT}}$) was calculated as (Brown, 2005):

$$\boldsymbol{A_{UT}} = \frac{\boldsymbol{\pi d_{bolt}^2}}{\boldsymbol{4}}$$

$$= \frac{\boldsymbol{\pi\ x\ 0.006^2}}{\boldsymbol{4}}$$

$$= \boldsymbol{1.13\ x\ 10^{-4} m^2}$$

The stiffness ($\boldsymbol{K_T}$) of the threaded part was calculated as (Brown, 2005):

$$K_T = \frac{A_T E}{L_{threaded} - L_{total} + L_{grip}} \quad (3.15)$$

$$= \frac{(8.43\ x\ 10^{-5})(207\ x\ 10^{9})}{0.015 - 0.03 + 0.022}$$

$$= 1.16\ x\ 10^{9}\ {}^{N}/_{m}$$

The stiffness (K_{UT}) of the unthreaded part was obtained as (Shigley *et al*, 2004):

$$K_{UT} = \frac{A_{UT} E}{L_{UT}}$$

(3.16)

$$= \frac{(1.13\ x\ 10^{-4})(207\ x\ 10^{9})}{0.015}$$

$$= 7.80\ x\ 10^{8} N/m$$

The stiffness (K_{bolt}) of the bolt was then evaluated as (Shigley *et al*, 2004):

$$K_{bolt} = \frac{K_T K_{UT}}{K_T + K_{UT}}$$

(3.17)

$$= \frac{(1.16\ x\ 10^{9})(7.80\ x\ 10^{8})}{1.16\ x\ 10^{9} + 7.80\ x\ 10^{8}}$$

$$= 4.66\ x\ 10^{8} N/m\ \ (466 MN/m)$$

The joint constant (K) was found using the relationship (Shigley *et al*, 2004):

$$K = \frac{K_{bolt}}{K_{bolt} + K_T}$$

(3.18)

$$K = \frac{4.66\ x\ 10^{8}}{4.66\ x\ 10^{8} + 1.16\ x\ 10^{9}}$$

$$K = 0.29$$

The factor of safety against separation ($n_{separation}$) for the joint was calculated as (Shigley *et al*, 2004):

$$\boldsymbol{n_{separation}} = \frac{\boldsymbol{K_T}}{\boldsymbol{K_{bolt}(1-K)}}$$

(3.19)

$$\boldsymbol{n_{separation}} = \frac{\boldsymbol{1.16\ x\ 10^9}}{\boldsymbol{4.66\ x\ 10^8(1-0.29)}}$$

$$\boldsymbol{n_{separation}} = \boldsymbol{3.5}$$

The minimum critical value of the factor of safety that shows safety of the joint is unity (1), the higher it goes above the critical value the safer the joint (Shigley *et al*, 2004).

3.2.7.2 *Torque Conversion of the Gearbox*

Another function served by the gear train is conversion (multiplication or division) of torque on the machine. The basic torque (T) relation is given as the ratio of power (P) and the angular velocity (ω) as (Eugene *et al*, 2007):

$$\boldsymbol{P(W)} = \boldsymbol{T\ (N.m)x\ \omega(rad/sec)}$$

(3.20)

The power (P) remains constant on both the driver and the driven gears, so the speed of the driver and the driven shafts defines the torque on each of them as (Eugene *et al*, 2007):

$$\boldsymbol{T_A\omega_A} = \boldsymbol{T_C\omega_C}$$

(3.21)

The speed of the driven gear ($\boldsymbol{\omega_C}$) as calculated was 50 rpm which was converted to rad/sec as follows (Eugene *et al*, 2007):

$$\boldsymbol{\omega_C}\left(\frac{\boldsymbol{rad}}{\boldsymbol{sec}}\right) = \boldsymbol{\omega_C(rpm)x}\ \frac{\boldsymbol{2\pi}}{\boldsymbol{60}}$$

(3.22)

$$= 50rpm\, x \frac{2\pi}{60}$$

$$= 5.24(rad/sec)$$

The power consumption of the drive motor is (330.76W), the torque on the driven shaft was calculated as:

$$T_C \omega_C = 330.76$$

$$\Rightarrow T_C = \frac{330.76}{\omega_C}$$

$$= \frac{330.76}{5.24}$$

$$= 63.12N.m$$

The torque ($\mathbf{T_B = 63.12Nm}$) acting on the driven shaft is very much less than the maximum allowed value which was calculated as **2173.6N.m** (see section 3.2.8.1) therefore, the shaft is safe from any mechanical failure (Alan, 2008).

3.2.8 Rear Shaft Design

In the process of design of the rear shaft of the Plantbot, analysekis includes determination of the allowable torque on the shaft, the critical speed of the shaft, decision on using either solid or hollow shaft as well as analyzing the fatigue failure of the shaft are necessary. These aspects of the design of shaft were treated in the sub-sections 3.2.8.1; 3.2.8.2; 3.2.8.3 and 3.2.8.4.

3.2.8.1 Shaft Design for Allowable Torque

To design the shaft the material of the shaft was selected as (high strength steel) ANSI 1030. Deflection in shaft is not affected by strength, but rather by stiffness as represented by the modulus of elasticity, which is essentially constant for all steels. For that reason, rigidity

cannot be controlled by material dimensions, but only by geometric dimensions. Necessary strength to resist loading stresses affects the choice of materials and their treatments. Many shafts were made from low carbon, cold-drawn or hot-rolled steel, such as ANSI 1020-1050 steels (Nisbett, 2006).

The maximum permissible shear stress (τ_{max}) was 410MPa and the maximum allowable twist angle (Φ_{max}) for the material is 1.5^0 (0.026rad). The selected diameter (D = 2R) of the used material is 30mm and its length (L) is 700mm. The modulus of rigidity (G) is 80.8GPa (McGraw Hill Machine Design Data book, 2004)

The polar moment of inertia (J) of the shaft was calculated as (Nisbett, 2006):

$$\boldsymbol{J = \frac{1}{2}\pi R^4}$$

(3.23)

$$= \boldsymbol{\frac{1}{2}\, x\, \pi\, x\, 0.015^4}$$

$$= \boldsymbol{7.95\, x\, 10^{-8} m^4}$$

The maximum torque (T_{max}) with respect to the given maximum shear stress was obtained as (Nisbett, 2006):

$$\boldsymbol{T_{max} = \frac{\tau_{max} J}{R}}$$

(3.24)

$$= \boldsymbol{\frac{(4.1\, x\, 10^8)(7.95\, x\, 10^{-8})}{0.015}}$$

$$= \boldsymbol{2173.6 N.m}$$

The maximum torque was also calculated with respect to the maximum angle of twist as (Nisbett, 2006):

$$T_{max} = \frac{\Phi_{max}\, GJ}{L}$$

(3.25)

$$= \frac{0.026\ x\ 80.8\ x\ 10^{9}\ x\ 7.95\ x\ 10^{-8}}{0.7}$$

$$= 2385.9N.m$$

The maximum torque with respect to the maximum shear stress (**2173.6N.m**) is smaller than that with respect to maximum angle of twist (**2385.9N.m**) and therefore, the smaller value was taken as the safe value of the maximum torque to be applied to the shaft (Nisbett, 2006).

3.2.8.2 ***Shaft Design for Fatigue Failure***

Another factor considered in knowing the safety of the shaft design is the fatigue strength. Fatigue failure is reduced moderately by increase in strength, and then only to a certain level before adverse effects in endurance limit and notch sensitivity begins to counteract the benefits of higher strength. A good practice is to start with inexpensive, low or medium carbon steel for the first time through the design calculations. If strength considerations turn out to dominate over deflection, then a higher strength material should be tried, allowing the shaft sizes to be reduced until excess deflection becomes an issue. To identify whether the shaft design is safe, the fatigue strength must be calculated together with the rotating endurance limit and compared with given yield strength of the material of the shaft (Brown, 2005).

The steel shaft has tensile strength (S_{ut}) of 630MPa and yield strength (S_y) of 490MPa (McGraw Hill Machine Design Data book, 2004).

The rotating endurance limit was first evaluated as (Brown, 2005):

$$S_e^{/} = 0.504 S_{ut}$$

(3.26)

$$= 0.504(630MPa)$$

$$= 317.5MPa$$

Then the coefficient **"a"** was calculated as (Brown, 2005):

$$a = \frac{(0.9S_{ut})^2}{S_e^{/}}$$

(3.27)

$$= \frac{\left(0.9(630MPa)\right)^2}{317.5MPa}$$

$$= 1,013MPa$$

The exponent **"b**" was calculated as (Brown, 2005):

$$b = -\frac{1}{3}\log\frac{0.9S_{ut}}{S_e^{(/)}}$$

(3.28)

$$= -\frac{1}{3}\log\frac{0.9(630MPa)}{317.5}$$

$$= -0.084$$

The fatigue strength (S_f) at one million (10^6) cycle (N, standard) was then obtained as (Brown, 2005):

$$S_f = aN^b$$

(3.29)

$$= (1,013MPa)(10)^{(6)(-0.084)}$$

$$= 384.9MPa$$

The fatigue strength calculated was within the safe limit (the shaft is free from fatigue failure) since it was greater than the rotating endurance limit but less than the given yield strength of the material of the shaft (Alan, 2008).

$$S_e^{/} < S_f < S_y$$

$$\Rightarrow 317.5MPa < 384.9MPa < 490MPa$$

3.2.8.3 ***Hollow / Solid Shaft Selection***

However, before the final decision was taken on whether to use hollow or solid shaft, the size factor was determined to guide the selection. The selected diameter (d) of the shaft is 30mm.

The size factor (k_b) for the solid shaft was obtained as (Shigley *et al*, 2004):

$$k_b = \left(\frac{d}{7.62}\right)^{-0.1133}$$

(3.30)

$$= \left(\frac{30}{7.62}\right)^{-0.1133}$$

$$= 0.856mm$$

The effective (d_e) diameter for the hollow shaft was then calculated as (Shigley *et al*, 2004):

$$d_e = 0.370d$$

(3.31)

$$= 0.370\ x\ 30mm$$

$$= 11.1mm$$

The size factor (k_b) for the hollow section was determined as (Shigley *et al*, 2004):

$$k_b = \left(\frac{d}{7.62}\right)^{-0.1133}$$

(3.32)

$$= \left(\frac{11.1}{7.62}\right)^{-0.1133}$$

$$= 0.958$$

The percentage difference in the values of the size factors was determined as follows:

$$percentage\ difference = \frac{(0.958)-(0.856)}{0.958}\ x\ 100\%$$

(3.33)

$$= 10.68\%$$

Note that there was almost 10% difference between the two size factors and therefore, the solid shaft with the smaller value of size factor was preferred to maximize the space utilization (Shigley *et al*, 2004).

3.2.8.4 *Shaft Design for Critical Speed*

However, the shaft, because of its own mass, has a critical speed above which the shaft can fail due to fracture. Estimating this critical speed (ω_1) is a task for the designer to ensure

safety. With a simple geometry (like a shaft of uniform diameter, simply supported), the task is easy. It can be expressed as (Eugene *et al*, 2007):

$$\omega_1 = \left(\frac{\pi}{L}\right)^2 \sqrt{\frac{\pi d^2 E}{4g\rho}}$$

(3.34)

The length of the shaft (L) is 700mm, the diameter (d) is 30mm, the modulus of elasticity (E) is 207GPa and the density (ρ) is 7050kg/m^3 (McGraw Hill Machine Design Data book, 2004).

The critical speed was therefore, evaluated as:

$$\omega_1 = \left(\frac{\pi}{L}\right)^2 \sqrt{\frac{\pi d^2 E}{4g\rho}}$$

$$= \left(\frac{\pi}{0.7}\right)^2 \sqrt{\frac{(\pi)(0.03)^2(207\ x\ 10^9)}{(4)(9.81)(7050)}}$$

$$\cong 926 rpm$$

The shaft can therefore, rotate at speed below 926 rpm without the possibility of failure.

3.2.9 Weld Fastening of Shaft to Brake Disc

The fastening of the rear shaft to the brake disc that carries the rear wheel is by welding. The weld is fillet in nature where the joint is in tee - shape. The diameter of the shaft connected to the brake disc ($\mathbf{d_O}$) is 30mm. The length of the shaft ($\mathbf{L_O}$) is 700mm; the slanted length (height, H) of the applied weld is 20mm at inclination angle of 45^0. The length of the weld

round the shaft (L) is 100mm and the minimum shear stress ($\boldsymbol{\tau_{shear}}$) was 4.8MPa (McGraw Hill Machine Design Data book, 2004).

The assembly of the shaft and the brake disc with their diameters is shown in Fig. 3.8.

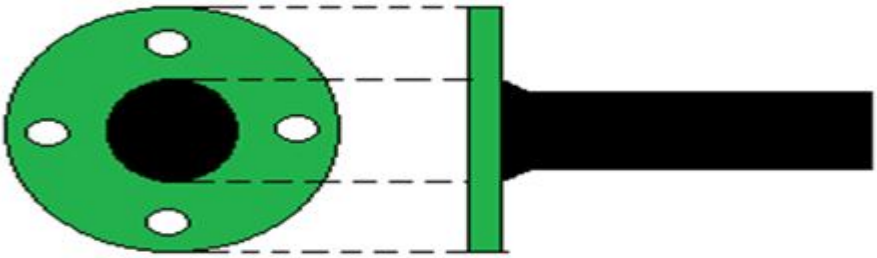


Fig. 3.8. Orthographic View of the Rear Shaft with Brake Disk

The effective slant height (H) was obtained as (Alan, 2008):

$$\boldsymbol{H = 20mm\ x\ Cos45^0}$$

(3.35)

$$\boldsymbol{= 14.1mm}$$

The minimum load due to the minimum given shear stress was obtained as (Shigley *et al*, 2004):

$$\boldsymbol{P = 2HL\tau_{shear}}$$

(3.36)

$$\boldsymbol{= 2\ x\ 0.0141\ x\ 0.1\ x\ 4.8MPa}$$

$$\boldsymbol{= 13,500N}$$

The radial distance ($\mathbf{r_0}$) was calculated as (Shigley *et al*, 2004):

$$r_0 = \sqrt{\left(\frac{L}{2}\right)^2 + d_0^2}$$

$$= \sqrt{\left(\frac{0.1}{2}\right)^2 + (0.03)^2}$$

$$= 0.064m$$

The polar moment of inertia ($\mathbf{J_{group}}$) was then obtained as (Shigley *et al*, 2004):

$$J_{group} = 2\left(\frac{LH^3}{12} + \frac{HL^3}{12} + LHd_0^2\right)$$

(3.37)

$$J_{group} = 2\left(\frac{(0.1)(0.141)^3}{12} + \frac{(0.141)(0.1)^3}{12} + (0.1)(0.141)(0.03)^2\right)$$

$$J_{group} = 3.43\ x\ 10^{-6}m^4$$

Then the shear stress due to torsion ($\boldsymbol{\tau_{torsion}}$) was determined as (Nisbett, 2006):

$$\tau_{torsion} = \frac{PL_0r_0}{J_{group}}$$

(3.39)

$$= \frac{(13500N)(0.7m)(0.064)}{3.43\ x\ 10^{-6}}$$

$$= 75.57MPa$$

From the values of the given minimum shear stress and the calculated shear stress due to torsion, the maximum shear stress ($\boldsymbol{\tau_{max}}$) was determined as (Nisbett, 2006):

$$\tau_{max} = \sqrt{\tau_{shear}^2 + \tau_{torsion}^2}$$

(3.40)

$$= \sqrt{4.8^2 + 75.57^2}$$

$$= 78.69MPa$$

This calculated value of the maximum shear stress was compared with the given value from the data sheet for the steel of ANSI class 1030 which is 410MPa (McGraw Hill Machine Design Data book, 2004). This comparison shows that the design is safe from failure due to weld breaking since the calculated maximum value is far less than the given maximum value (Alan, 2008).

3.2.10 Rear Shaft Bearing Design

The rear shaft of the Plantbot uses two bearings to serve as the support for the weight of the robot for smooth motion of the mechanism. In the design of the bearing the amount of load it can safely carry, the probability of its failure and the estimation of its life span were treated.

3.2.10.1 *Rear Shaft Bearing Load Design*

On the rear shaft, two ball bearings were used one on each side of the gearbox to serve as the support for the frame of the Plantbot. Only two bearings were used in this design. For extremely long shafts carrying several load-bearing components, it may be necessary to provide more than two bearing supports. In this case, particular care must be given to the alignment of the bearings. Shafts should be kept short to minimize bending moments and deflections **(Alan, 2008).**

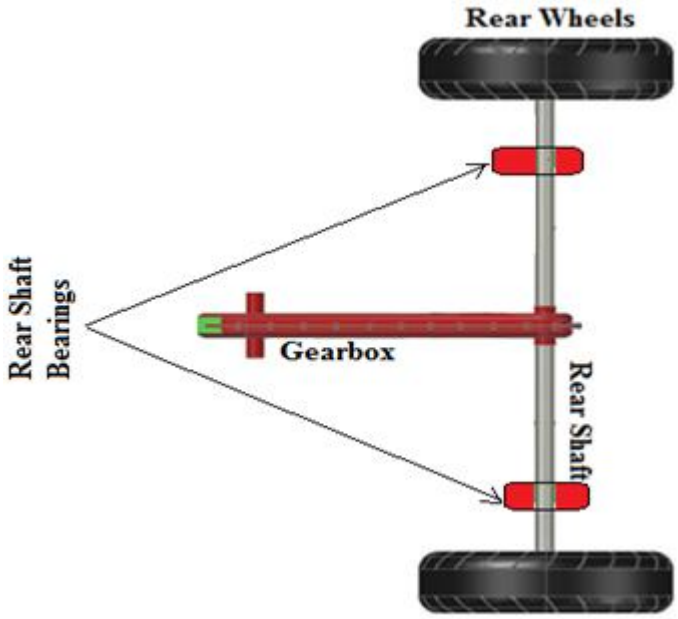


Fig. 3.9. Section Showing Bearings on the Rear Shaft

The distance from the bearing to the brake disc on each side is 100mm. The selected bearing (part number SS5206-6) has an outside diameter of 60mm and bore of 30mm. The bearing has 15 balls ($\mathbf{n_b}$) in ball retainer each with nominal diameter ($\mathbf{d_b}$) of 5mm as given in the manufacturer's datasheet, (**KMS Incorporated**). Fig. 3.9 shows the bearings on the rear shaft.

The basic static load rating ($\mathbf{C_S}$) of the ball bearing is estimated using the relation (Eugene *et al*, 2007):

$$\boldsymbol{C_S = M n_b d_b} \quad \textbf{(3.41)}$$

The constant M is as given in Table 3.1 based on the type of bearing being used. The bearing is of radial ball type, hence the M from Table 3.1(Shigley *et al*, 2004) is $\boldsymbol{5.11\ x\ 10^3 kN.}$

The basic static load rating was then evaluated as:

$$C_S = 5.11\ x\ 10^3 kN\ x\ 15\ x\ 5mm$$

$$= 3.83\ x\ 10^5 N$$

Dividing by acceleration due to gravity (g = 9.81m/s^2) the mass in (kg) was obtained as:

$$= 3.90\ x\ 10^4 kg$$

This calculated value ($3.90\ x\ 10^4 kg$) stands for the static load that each of the bearings can carry safely. This is very much greater than the total mass of the Plantbot which was measured as 50kg (the mass of the wheels should be deducted since they are on the ground).

Table 3.1 Values for Constant M for Different Types of Bearing

Type of bearing	Constant M	
	M (lb)	M (kN)
Radial ball	1.78 x 10^3	5.11 x 10^3
Ball thrust	7.10 x 10^3	20.4 x 10^3
Radial roller	3.13 x 10^3	8.99 x 10^3
Roller thrust	14.2 x 10^3	40.7 x 10^3

3.2.10.2 *Bearing Failure Evaluation*

The probability of failure of the bearing was obtained from the plot of Fig. 3.10 after evaluating the fraction of bearing rating life (L/L_{10}) from equation (3.42). The nominal reliability (R) of the selected bearing was given as 90% as given in the manufacturer's datasheet (**KMS Incorporated**; Eugene *et al*, 2007):

$$R = exp\left[-\left(\frac{\frac{L}{L_{10}} - 0.02}{4.439}\right)^{0.483}\right] \qquad \textbf{(3.42)}$$

$$\Rightarrow 0.9 = exp\left[-\left(\frac{\frac{L}{L_{10}} - 0.02}{4.439}\right)^{0.483}\right]$$

$$\Rightarrow \frac{L}{L_{10}} = 0.062$$

The probability of failure of the calculated fraction of bearing rating life was obtained from Fig. 3.10 as 0.06.

This value of the probability of failure (0.06) of the bearing shows that the bearing is very reliable since it has only a 6% chance of failure.

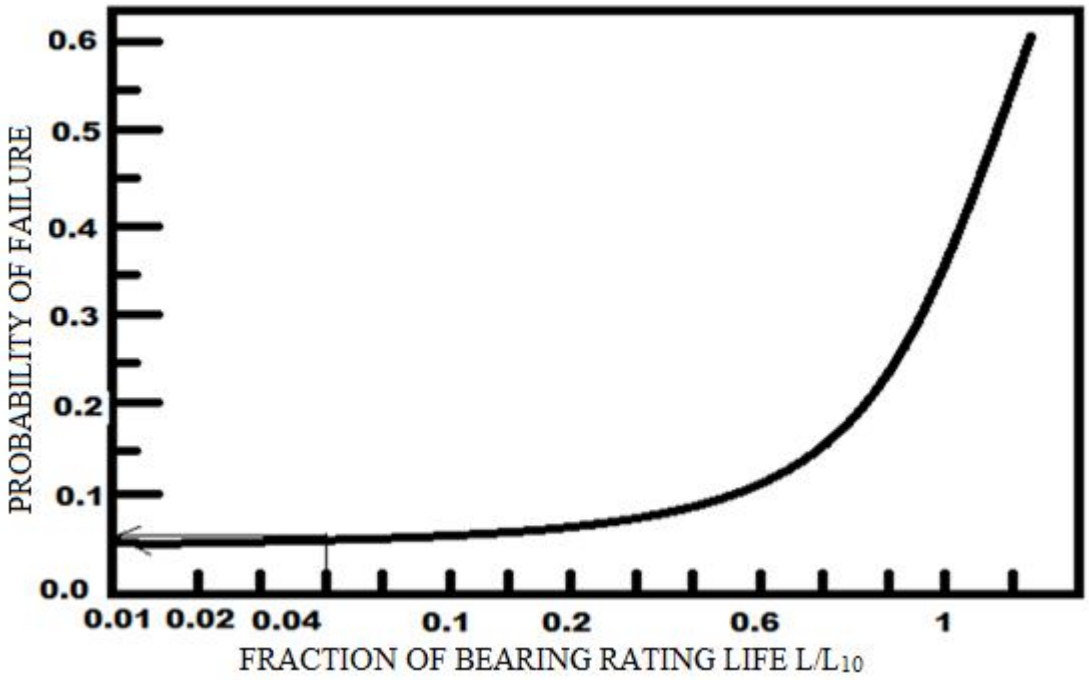


Fig. 3.10. Probability of Failure Graph (Shigley *et al*, 2004)

3.2.10.3 ***Bearing Life Design***

The expected life of the bearings (L_{10}) was evaluated using equation 3.43. The extended basic static load ($\mathbf{C_E}$) on the bearing is the same as the basic static load rating determined as ($\boldsymbol{3.83\ x\ 10^5 N}$). The desired speed in rpm (N) of the machine was selected as 50rpm (as calculated before). The equivalent radial load (P) on the bearing is given as **5 x 10^4N** as given in the manufacturer's datasheet (**KMS Incorporated**).

The life of the bearing in hours was calculated as (Eugene *et al*, 2007):

$$\boldsymbol{L_{10} = \frac{16667}{N}\left[\left(\frac{C_E}{P}\right)^3\right](hours)} \qquad \textbf{(3.43)}$$

$$\boldsymbol{L_{10} = \frac{16667}{50rpm}\left[\left(\frac{3.83\ x\ 10^5 N}{5\ x\ 10^4 N}\right)^3\right](hours)}$$

$$\boldsymbol{= 149821.4\ hours}$$

This calculated expected life is equivalent to 17.1 years. With the given 90% reliability it would last for more than 15 years working under the normal design conditions.

3.2.11 Design of the Frame of the Plantbot

The structure for the frame of the Plantbot (as shown in Fig. 3.11) was made using rectangular metal pipes. The breadth (b) of the pipe is 25mm and the height (h) is 30mm. The length (L) of the pipe from the rear wheel to the front wheel is 1000mm. The pipe is made of steel with 207GPa as the modulus of elasticity (E). The assumed load (P) should be equal to the calculated static load rating as ($\boldsymbol{3.90\ x\ 10^4 kg}$). Since the support is fixed end to end by welding, the coefficient of the joint type (C_{ends}) is 4.

The radius of gyration (k) was first evaluated as (Alan, 2008):

$$k = \frac{b}{2\sqrt{3}}$$

(3.44)

$$= \frac{0.025}{2\sqrt{3}}$$

$$= 0.0072m$$

The slenderness ratio (L/k) was then calculated as (Alan, 2008):

$$slanderness\ ratio = \frac{L}{k} = \frac{1m}{0.0072}$$

(3.45)

$$= 278$$

The critical stress (σ_{cr}) was obtained as (Alan, 2008):

$$\sigma_{cr} = \frac{C_{ends}\pi^2 E}{\left(\frac{L}{k}\right)^2}$$

(3.46)

$$= \frac{(4)\pi^2(207\ x\ 10^9 Pa)}{(278)^2}$$

$$= 105740288.3Pa\ (105.74MPa)$$

The axial stress (σ_{axial}) was also calculated as (Alan, 2008):

$$\sigma_{axial} = \frac{P}{A}$$

(3.47)

$$\Rightarrow \frac{P}{bh} = \frac{3.83\ x\ 10^4 N.}{0.025\ x\ 0.03}$$

$$= 51.1MPa$$

Comparing the critical stress ($105.74MPa$) with the axial stress ($51.1MPa$) it could be seen that the axial stress is less than the critical stress and therefore, the design is safe against buckling of the member.

For the perpendicular pipe running from one wheel to the other across the Plantbot, the length is 600 mm as shown in Fig. 3.11. The slenderness ratio was calculated using equation (3.45) as:

$$\frac{L}{k} = \frac{0.6m}{0.0072}$$

$$= 83.3$$

The critical stress (σ_{cr}) was obtained using equation (3.46) as:

$$\sigma_{cr} = \frac{C_{ends}\pi^2 E}{\left(\frac{L}{k}\right)^2}$$

$$= \frac{(4)\pi^2(207\ x\ 10^9 Pa)}{(83.3)^2}$$

$$= 1177.7MPa$$

In this case the axial stress (σ_{axial}) was also calculated using equation (3.47) as:

$$\sigma_{axial} = \frac{P}{A}$$

$$\Rightarrow \frac{P}{bh} = \frac{3.83\ x\ 10^4 N.}{0.025\ x\ 0.03}$$

$$= 51.1MPa$$

Here also comparing the critical stress ($\mathbf{1177.7MPa}$) with the axial stress ($\mathbf{51.1MPa}$) it could be seen that the axial stress is much less than the critical stress and therefore, the design is safe against buckling of the member.

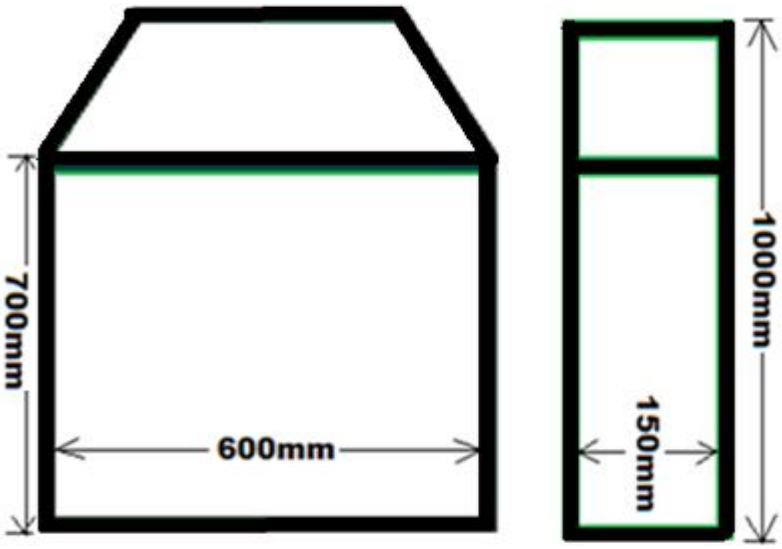


Fig. 3.11. Orthographic Views of the Frame Support

3.2.12 Front Wheels Bearing Design

The front wheels of the Plantbot also use two bearings to serve as support. In this design, the amount of load they can safely carry, the probability of their failure and the estimation of their life span were determined.

3.2.12.1 *Load Design for Front Wheel Bearings*

On the front wheels two ball bearings were used, one on each wheel to serve as the support of the load on the front wheels of the Plantbot. The selected bearing (part number SS609-6) has an outside diameter of 25mm and bore of 10mm. The bearing has 10 balls ($\mathbf{n_b}$) in ball retainer each with nominal diameter ($\mathbf{d_b}$) of 3mm as given in the manufacturer's datasheet, (**KMS Incorporated**).

The basic static load rating ($\mathbf{C_S}$) of the ball bearing was evaluated using the equation (3.41).

The constant M is as given in Table 3.1 depending on the type of bearing used. The bearing is also of radial ball type, hence M fromTable 3.1 is $\mathbf{5.11\ x\ 10^3 kN.}$

The basic static load rating was then evaluated as:

$$\boldsymbol{C_S} = \mathbf{5.11\ x\ 10^3 kN\ x\ 10\ x\ 3mm}$$

$$= \mathbf{1.53\ x\ 10^5 N}$$

Dividing by accelaration of free fall due to gravity (g =9.81m/s^2) the mass (in kg) was obtained as:

$$= \mathbf{1.56\ x\ 10^4 kg}$$

This calculated value ($\mathbf{1.56\ x\ 10^4 kg}$) stands for the static load that each of the front wheel bearings can carry safely. This is very much greater than the total mass of the Plantbot which was measured as 50kg.

3.2.12.2 *Front Wheel Bearing Failure Evaluation*

The probability of failure of the bearing was obtained from the graph in Fig. 3.12 after initially evaluating the fractional bearing rating life (L/L_{10}) from equation (3.42). The nominal reliability of the selected bearing was given as 95% as obtained from the manufacturer's datasheet (**KMS Incorporated**). The fractional bearing life span was obtained as:

$$\boldsymbol{R} = \boldsymbol{exp}\left[-\left(\frac{\frac{L}{L_{10}} - 0.02}{4.439}\right)^{0.483}\right]$$

$$\Rightarrow 0.95 = exp\left[-\left(\frac{\frac{L}{L_{10}} - 0.02}{4.439}\right)^{0.483}\right]$$

$$\Rightarrow \frac{L}{L_{10}} = 0.029$$

The probability of failure of the calculated fraction of bearing life span was obtained from the graph of Fig. 3.12 as 0.05.

This value of the probability of failure (0.05) of the bearing shows that the bearing is very reliable since it has only a 5% chance of failure.

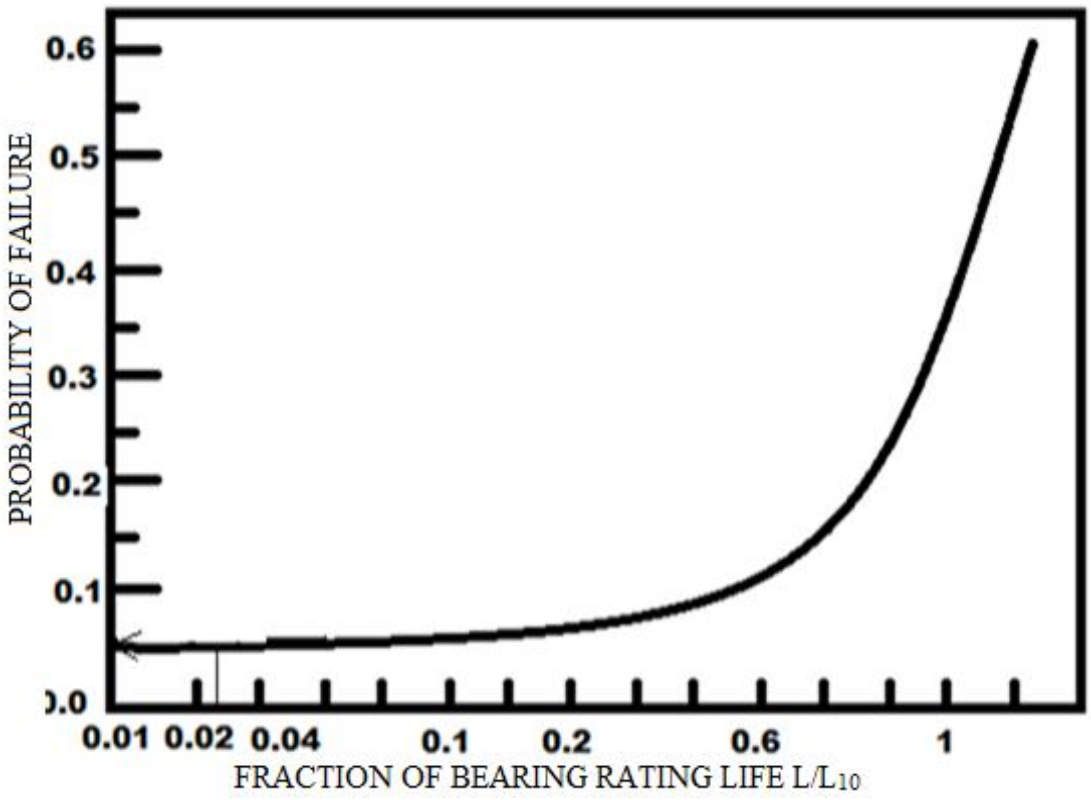


Fig. 3.12. Probability of Failure Graph (Shigley *et al*, 2004)

3.2.12.3 *Front Wheel Bearing Life Design*

The maximum expected life of the bearings was evaluated using equation (3.43). The extended basic static load ($\mathbf{C_E}$) on the bearing is the same as the basic static load rating calculated as ($\mathbf{1.53\ x\ 10^5 N}$) before. The desired speed in rpm (N) of the machine was selected as 50rpm (as calculated before) which is the common speed for both the rear and the front wheels. The equivalent radial load on the bearing is given as **5 x 10^4N** as obtained from the manufacturer's datasheet (**KMS Incorporated**).

The life of the bearing in hours was calculated using equation (3.43) as:

$$\boldsymbol{L_{10}} = \frac{\mathbf{16667}}{\boldsymbol{N}}\left[\left(\frac{\boldsymbol{C_E}}{\boldsymbol{P}}\right)^{\mathbf{3}}\right]\ (\boldsymbol{hours})$$

$$\boldsymbol{L_{10}} = \frac{\mathbf{16667}}{\mathbf{50}\boldsymbol{rpm}}\left[\left(\frac{\mathbf{1.53\ x\ 10^5 N}}{\mathbf{5\ x\ 10^4 N}}\right)^{\mathbf{3}}\right](\boldsymbol{hours})$$

$$= \mathbf{47755.3}\ \boldsymbol{hours}$$

This calculated expected life is equivalent to 5.45 years. With the given 95% reliability it would last for more than 5 years working under the normal design conditions.

3.2.13 Design of the Holder of the Planting Mechanism

The holder of the planting mechanism of the Plantbot was made using a rectangular metal pipe. A spindle was used for connecting the planting mechanism to the holder where it serves as the support on which the planting mechanism rotates. The holder of the planting mechanism was connected to the main frame using a metal hinge with one degree of freedom as shown on Fig. 3.13. The metal pipe has breadth (b) of 20mm and width (w) of

30mm. The minimum shear stress of the material is 4.8MPa as given before. The minimum force that would cause the failure by shearing was calculated as (Nisbett, 2006):

$$\boldsymbol{P = \tau A = \tau bw}$$

(3.48)

$$\boldsymbol{= 4.8\ x\ 10^{6} x 0.02\ x\ 0.03}$$

$$\boldsymbol{= 2880N}$$

The minimum shearing load for the connector of the planting mechanism is 2880N. From the calculated maximum torque created by the main drive motor it was $5.23N.m$. The basic torque equation is given as:

$$\boldsymbol{T = Fr}$$

(3.49)

The maximum dynamic force from the torque of the motor was obtained from equation (3.49) as:

$$\boldsymbol{F = \frac{T}{r}}$$

$$\boldsymbol{= \frac{5.23}{0.14}}$$

$$\boldsymbol{= 37.36SN}$$

(where radius of the rear wheel (r) is 14cm as seen before).

This maximum dynamic force from the torque of the motor (37.36N) is far less than the minimum calculated value (2880N) of force that can cause shearing of the planting mechanism holder.

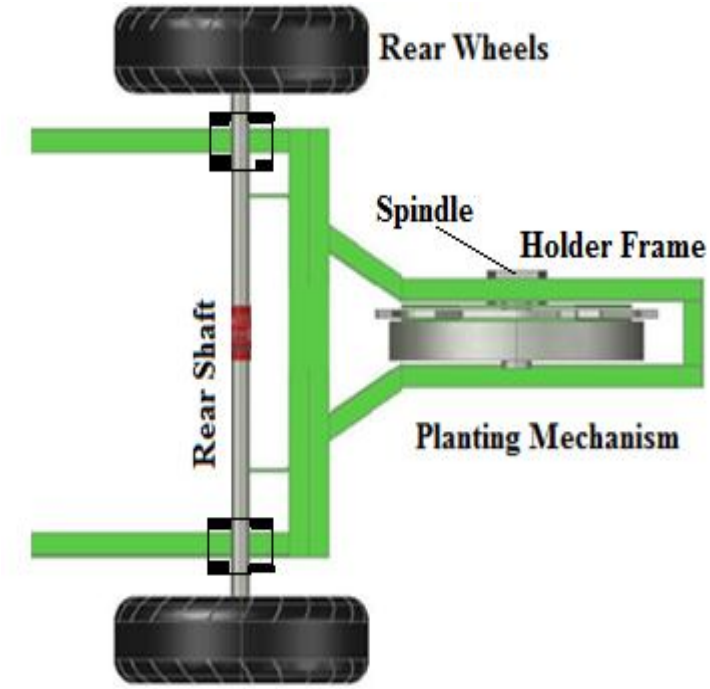


Fig. 3.13. Section Showing the Holder of the Planting Mechanism

3.2.14 Summary of Design Values

The basic calculations that were carried out in this chapter were based on repetitive iterations where the calculations process was done first and then compared with the conditions of safety and the result was accepted when the obtained value is within the safe limit or rejected when it was not within the safe limit. Then another value(s) was chosen and the process was repeated until the value arrived at was within the safe limits given by the standards of the design of the particular element of the machine. Therefore, the calculated

values that are presented in this work are the final values which were arrived at the end of the iteration process. Table 3.2 gives the summary of the major design results obtained

Table 3.2 Summary of the Design Results

S/NO	Design Parameter	Calculated Value	Used Value
1	Main Drive Motor Torque	5.23N.m	5.23N.m
2	Main Drive motor Power	330.76W	746W(1horse power),24V
3	Steering Motor Torque	0.65N.m	0.65N.m
4	Steering Motor Power	15.83W	25W, 24V
5	Battery Pack Capacity	57.76AH	75AH
6	Final Angular Speed	50rpm	50rpm
7	Linear Speed	73cm/sec	73cm/sec
8	Factor of Safety Against Separation of Gearbox Fastener	3.5	Minimum safe Value = 1
9	Allowable Torque on Shaft	2173.6N.m	Max. possible =63.12N.m
10	Fatigue Strength of Shaft	384.9MPa	Safe Range: 317.5MPa to 490MPa
11	Critical Speed of Shaft	926rpm	50rpm
12	Rear Shaft Bearing Load Capacity	3.90×10^4kg	50kg
13	Rear Shaft Bearing Chance of Failure	6%	-
14	Rear Shaft Bearing's Life	17.1 Years	-
15	Front Shaft Bearing Load Capacity	1.56×10^4kg	50kg
16	Front Shaft Bearing Chance of Failure	5%	-
17	Front Shaft Bearing's Life	5.45 Years	-
18	Minimum Force to cause Shearing of Planting Mechanism Holder	2880N	Max. possible Dynamic Force = 37.36N

3.3 BLUETOOTH CONTROL SYSTEM DESIGN CONSIDERATIONS

The Bluetooth controlled planter robot (Plantbot) being a mechatronic device has mechanical structure as physical segment with electronic (Bluetooth) segment as control part of the system. In this section, the detailed explanations of design of Bluetooth control section of the Plantbot is presented in a step – by – step approach. The Bluetooth control segment of the Plantbot is depicted by block diagram given in Fig. 3.14.

The fundamental design requirements of the Bluetooth control segment are:

a) Suitable Bluetooth module must be selected

b) Module with highest range and good working time is best

c) Good selection of GSM handset with Bluetooth facility

d) The handset with class 1 Bluetooth is the best in terms of communication range

e) Only handset that can produce DTMF signal could be used

f) DTMF booster circuit is needed to compensate for attenuation of the signal

g) DTMF decoder circuit is needed to change signal into 4-bit binary equivalent

h) PIC microcontroller is required for accepting the decoded DTMF signal and using it to control circuit relay drivers

i) The relay driver were transistor switching circuits used to operate six relays

j) Two relays control each of the three motors

k) The motor M_1 is the main drive motor for movement of the Plantbot.

l) Motor M_2 is the steering motor of the Plantbot.

m) Motor M_3 was motor used for controlling the planting mechanism

n) The circuit was powered using DC deep cycle battery

o) DC – DC converter was used to obtain higher DC voltages

p) Voltage regulators were also used to obtain different voltages for different parts of the main circuit

Fig. 3.14 shows the General Block Diagram of the Design of Bluetooth Control System

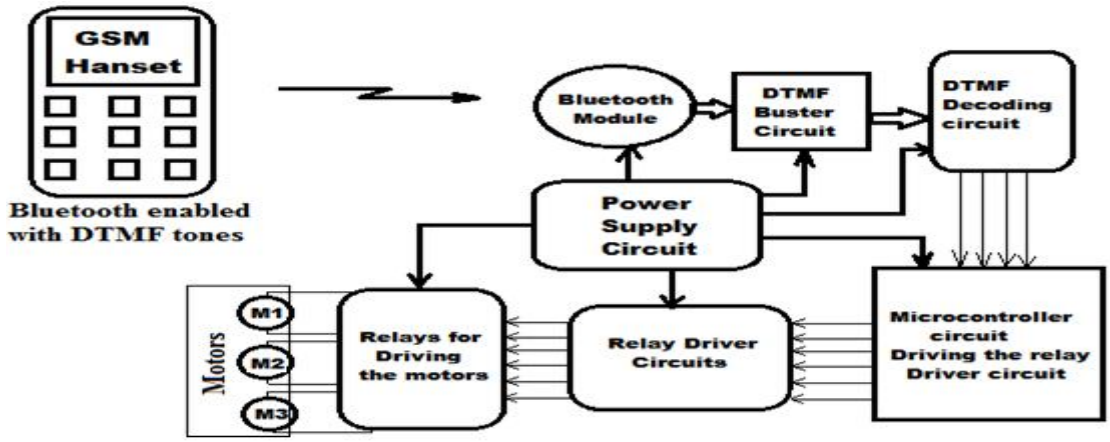


Fig. 3.14. General Block Diagram of the Design of Bluetooth Control System

3.3.1 Bluetooth Module Selection and Connection

The wireless control of the Plantbot was achieved through Bluetooth medium as shown in Fig. 3.14. The Bluetooth enabled GSM handset was used as transmitter and Bluetooth headset module (E9) was used as receiver. There are different types of Bluetooth headset modules each with specific range and power specifications. Table 3.3 shows the list of commonly available headset modules with their specifications (**Trait – Tech. Inc., 2012**).

Table 3.3 Bluetooth Headset Modules with their Specifications

	BLUETOOTH MODULE TYPE			
Specifications	**N8**	**N9**	**E8**	**E9**
Frequency range	2.4-2.48 GHz	2.4-2.48 GHz	2.4-2.48 GHz	2.4-2.48 GHz
Transmission distance	9.75m (32 feet)	15.24 m(50 feet)	45.72m (150 feet)	60.96m (200 feet)
Operating voltage	3.6V	3.6V	5.0V	5.0V
Operating current	≤30 mA	≤30 mA	≤25 mA	≤25 mA
Standby current	≤3 mA	≤3 mA	≤3 mA	≤3 mA
Talking time	≥5 Hours	≥5 Hours	≥6 Hours	≥6 Hours
Standby time	80 Hours	80Hours	100 Hours	100 Hours

From the available Bluetooth headset modules given in Table 3.3, E9 has the highest range of 60.96m (200 feet). Therefore, E9 was selected for this work.

The GSM handset and Bluetooth module were first connected through Service Discovery Process (SDP). The discovery process begins with an inquiry message that the handset sends

and received by Bluetooth module when it was powered on. When the module receives an inquiry message, it responds with its address that can be used to establish a connection with the handset. The two devices then establish connection through pairing process. Pairing requires the handset user to enter a Bluetooth security code or PIN of the E9 module (0000) (**Trait – Tech. Inc., 2012**). The Bluetooth pairing process allows the two devices to authenticate and create a secure link between them. Once the connection was established, the DTMF signals generated from the handset by pressing the buttons on the GSM handset can be received by the E9 provided the range between them does not exceed the maximum range of the E9 (given in Table 3.3). The Bluetooth module (E9) can enter sleep mode when no signal is being received from the handset.

3.3.2 Design and Analysis of DTMF Booster Circuit

When the communication between the handset and the Bluetooth earpiece was established, the actual signal that was being transmitted from the handset to the Bluetooth module is Dual – Tone Multi – Frequency (DTMF). The DTMF is generated when a button on the handset was pressed. The DTMF signal comprises two frequencies in audio frequency range. DTMF signaling converts decimal digits 0 – 9 and symbols '*' and '#' into sounds that share essential characteristics with voice to easily traverse circuits designed for voice **(Dodd, 2002).**

Specifically, the way DTMF signaling works is that each digit is transformed into a pair of tones (hence the name, *dual tone, multi-frequency*). The tones were determined from keypad frequency combinations as shown in Fig. 3.15 **(Dodd, 2002).**

	1209 Hz	1336 Hz	1477 Hz
697 Hz	1	2	3
770 Hz	4	5	6
852 Hz	7	8	9
941 Hz	*	0	#

Fig. 3.15. DTMF Keypad with Frequency Combinations

The DTMF tones transmitted from the handset to the Bluetooth headset module suffer attenuation while travelling through the transmission channel. The attenuation increases with an increase in distance between the transmitter and the receiver. Therefore, there is a need to amplify the weak signal received by the Bluetooth headset module. As can be seen from Fig. 3.15, the DTMF signals have frequency from 697Hz to 1477Hz which is within audio spectrum (of 20 Hz to 20 kHz). Therefore, audio frequency amplifier was used to amplify the received DTMF signal from speaker output of Bluetooth headset. The amplifier's block diagram was given in Fig. 3.16 (Servant, *et al*, 1981).

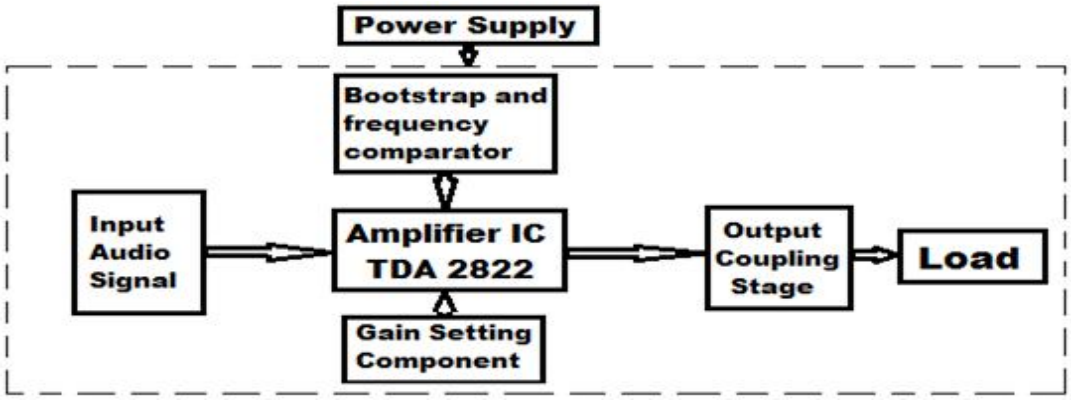


Fig. 3.16. Block Diagram of DTMF Booster Circuit (Audio Amplifier)

The amplifier circuit consist of audio input terminal, gain setting component, bootstrap and frequency setting terminal, main active amplifier IC and output coupling stage.

The amplifier was designed using an integrated circuit TDA2822 (shown in Fig. 3.17 as the active component.

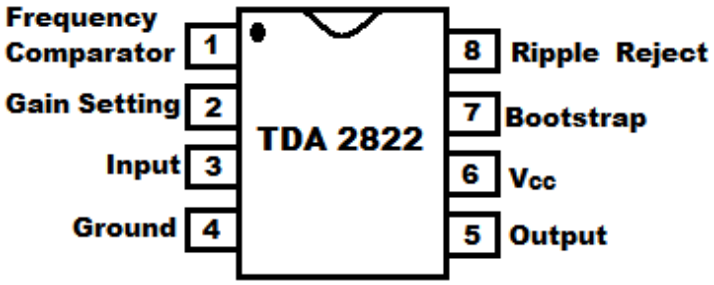


Fig. 3.17. TDA 2822 Audio Amplifier Pin - Out

The TDA2822 can produce a maximum power output of 2W in the range of audio frequency spectrum (UTC, 2011). The voltage supply to the IC is in the range of 3V to 12V from a direct current source. The input signal was taken into the IC through pin-3 while pin-5 produces the output. Pins 6 and 4 serve as the V_{CC} and the ground respectively. Pin-8 is a ripple reject which was used to control any distortion in the input signal. Pins 7 and 1, (bootstrap and frequency comparator) were used to nullify any frequency interference that can distort the signal. Finally the gain of the amplifier was controlled using the gain-adjust pin-2. This design used three-quarter of the maximum voltage (9V) to avoid any distortion. The capacitors C_1 and C_2 were used to remove any ripple that may be present in the supply to further make it smooth. These capacitors may take values from 47µF to 150µF for safe value of capacitive reactance. Any value used in the recommended range would give acceptable reactance at selected operating frequency of the amplifier (Servant, *et al*, 1981). This design used 100µF which is intermediate. Pin-7, bootstrap used for controlling interference, was connected to the V_{CC} through resistor R_3 and feedback was taken from output to the pin-7 through feedback capacitor C_5. The recommended value of this capacitor is between 100µF and 150µF (**Motorola, 2009**). In this design, 100µF capacitor (any value

in the range is okay) was used to limit feedback signal to its minimum value. The value of resistor R_3 was calculated using relation (Servant, *et al*, 1981):

$$\boldsymbol{R_3} = \frac{\boldsymbol{V_{CC} - V_B}}{\boldsymbol{I_B}}$$

(3.50)

Where V_{CC} = supply voltage, I_B = bootstrap current and V_B = bootstrap voltage.

The supply voltage V_{CC} = 9V, bootstrap voltage; $V_B = {}^3/_4 V_{CC}$ to V_{CC}, here V_B = 7V was taken which is in the range and I_B = 36mA (recommended value) (Link, 1996).

$$\boldsymbol{R_3} = \frac{\boldsymbol{9 - 7}}{\boldsymbol{36mA}}$$

$$= \boldsymbol{55.56\Omega}$$

Therefore, 56Ω ± 5% was used as R_3.

The frequency comparator was connected to output via a feedback capacitor which was used to compare frequency of output signal with standard operating frequency for stability to be maintained. The value of the feedback capacitor was calculated using the relation (Link, 1996):

$$\boldsymbol{C_3} = \frac{\boldsymbol{1}}{\boldsymbol{6.28 f X_C}} \qquad \textbf{(3.51)}$$

Where f = frequency of the system X_C = reactance of the capacitor. The operating frequency was chosen to be 2 kHz being higher than highest frequency of DTMF signal. The reactance of feedback capacitor should be in the range of 10MΩ to 30MΩ, the bigger the value, and the more stable the frequency of the system (Servant, *et al*, 1981). In this case it was taken as 27MΩ.

$$C_3 = \frac{1}{6.28\ x\ 2\ x\ 10^3\ x\ 27\ x\ 10^6}$$

$$= 2.2088\ x\ 10^{-10} F$$

$$C_3 \cong 220\ x\ 10^{-12} F$$

Therefore, 220pF was used as capacitor C_3.

The resistor R_1 connected between input terminal and ground was used as a bypass resistor to any dc component that may be present in the input signal. The value of the resistor was calculated as (Michael, 2000):

$$R_1 = \frac{V_{in}}{I_{in}}$$

(3.52)

Where V_{in} = maximum allowed input voltage, I_{in} = maximum allowed input current.

From the data sheet of TDA2822, V_{in} = 2V and I_{in} = 220µA (**Motorola, 2009**).

$$R_1 = \frac{2}{220\ x\ 10^{-6}}$$

$$= 9090.901\Omega$$

In this design a 10kΩ ± 10% was used as R_1.

The gain of the amplifier was adjustable which can be varied up to the point it would give maximum output power of 2W. But by designer's specification, it is not good to operate the IC at its maximum power output (to avoid overloading). The gain adjustment resistor takes values in the range of 100Ω to 150Ω. At 100Ω the gain is maximum and it decreases with increase of R_2. A 120Ω is used as R_2 to give an intermediate gain **(Motorola, 2009).**

The output of the IC from pin-5 is partly bypassed to the ground to improve the distortion prevention in the circuit. This was achieved using a series network of capacitor C_4 and resistor R_4. A standard resistor of 1Ω was recommended in the data sheet while the capacitor value was evaluated using equation (3.51) (**Motorola, 2009**).

Where operating frequency (f =2 kHz) and reactance of the capacitor C_4 was recommended as one-tenth of one percent of that of C_3 (27kΩ) (Michael, 2000).

$$C_4 = \frac{1}{6.28\ x\ 2\ x\ 10^3\ x\ 27\ x\ 10^3}$$

$$C_4 = 2.2088 \times 10^{-7} F$$

Therefore, 220nF capacitor was used as C_4.

The capacitor C_6 was used to couple output of booster circuit to input of DTMF decoding circuit. This capacitor should be chosen in such a way that it should deliver the full output to the load from the IC (by matching impedances). The datasheet shows that it can take values from 220µF to several hundreds of microfarads and operate efficiently **(Motorola, 2009).** A 470µF is selected for this purpose. The complete circuit diagram of DTMF booster circuit (audio amplifier) is given in Fig. 3.18.

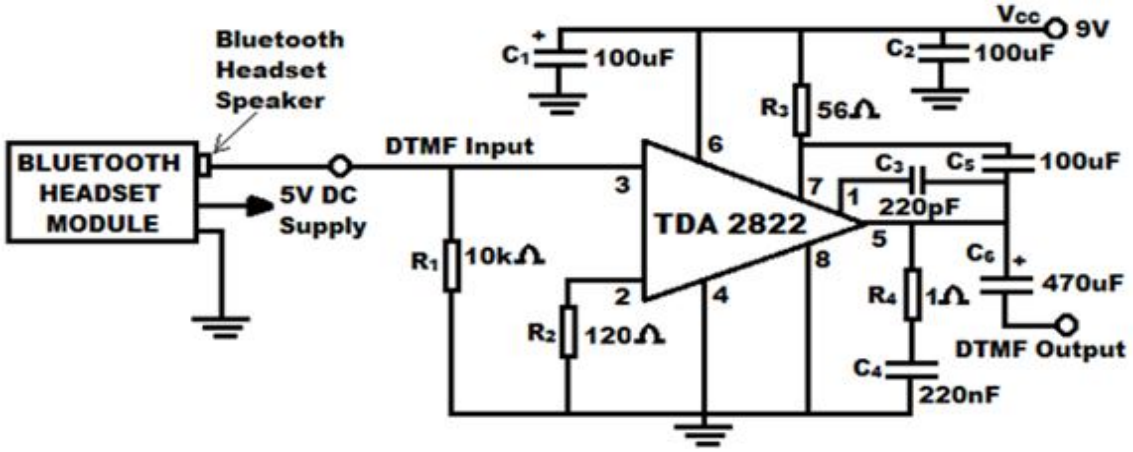


Fig. 3.18 DTMF Headset Module with DTMF Booster Circuit

3.3.3 Design and Analysis of DTMF Decoding Circuit

The output of the DTMF booster circuit was delivered to DTMF decoding circuit whose pin configuration is shown in Fig. 3.19. The DTMF decoding circuit has an integrated circuit MT8870D as main active component in the circuit. The MT8870D circuit shown in Fig. 3.20 is a complete DTMF decoder integrating both the band split filter and digital decoder functions. The filter section uses switched capacitor techniques for high- and low-group filters and dial-tone rejection. Digital counting techniques were employed in the decoder to detect and decode all DTMF tone-pairs into a 4-bit binary code. External component count was minimized by on-chip provision of a differential input amplifier, clock-oscillator and latched 3-state bus interface (Microsemi, 2013).

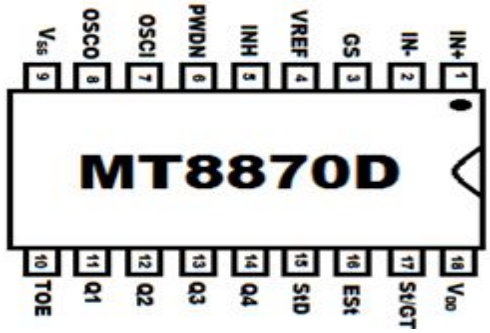


Fig. 3.19. Pin Configuration of DTMF Decoder IC

The complete circuit diagram of the DTMF decoder is given in Fig. 3.20. (Hangzhou, 2011).

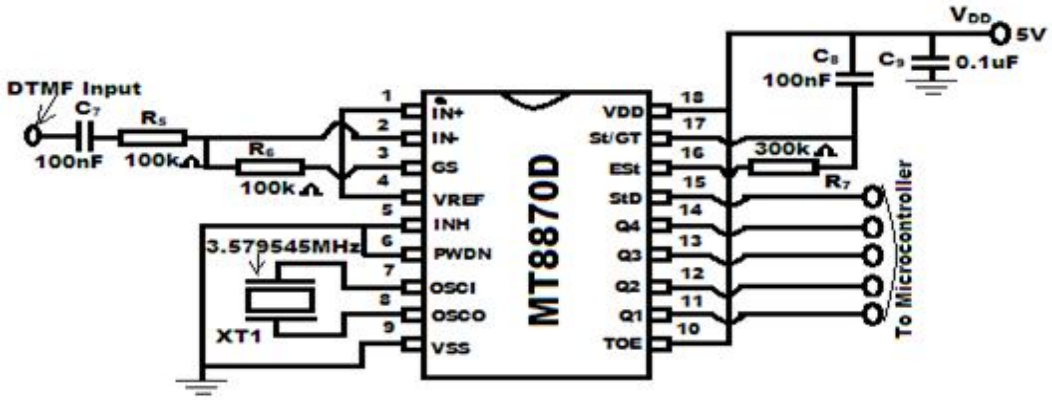


Fig. 3.20. Complete Circuit Diagram of DTMF Decoder

Pins 1 and 2, non – inverting and inverting connections to front end differential amplifier. Pin3 gain selects (GS) gives access to output of front-end differential amplifier for connection of feedback resistor. Pin 4, reference voltage output, nominally $V_{DD}/2$. Pins 5 and 6 inhibit input and power down input. Both were tied to ground (V_{SS}). Pins 7 and 8, clock input and clock output. A 3.579545MHz crystal (XT1) (as recommended by the manufacturer of DTMF decoder IC) was connected between these pins to complete internal oscillator. Pin 9 (V_{SS}), negative power supply, normally connected to 0V. Pin 10 (TOE), state-data output enable. Logic high at this pin enables the outputs Q1-Q4. Pins 11 – 14 (Q_1 – Q_4), state - data outputs. When enabled by TOE, provide the code corresponding to the last valid tone-pair received. Pin 15, Delayed steering output (StD) presents logic high when a received tone-pair has been registered. Pin16, Early steering output (ESt), presents logic high immediately when the digital algorithm detects a recognizable tone-pair. Pin 17 is Steering input/guard time output (St/GT). A voltage detected at St; causes the device to register the detected tone-pair and update the output latch. The GT output acts to reset the external steering time-constant. Pin 18 (V_{DD}), positive power supply (Microsemi, 2013).

3.3.3.1 *Design of DTMF Decoder Steering Circuit*

Before registration of a decoded tone-pair, the receiver checks for a valid signal duration (referred to as "character- recognition-condition"). This check was performed by an external RC time-constant driven by ESt. A logic high on ESt causes V_C (as in Fig. 3.21) to rise as the capacitor discharges. Provided signal-condition was maintained (ESt remains high) for the validation period (t_{GTP}), Vc reaches the threshold ($V_{TSt} = V_{DD}/2$) of the steering logic to register the tone-pair, latching its corresponding 4-bit code into the output latch.

At this point, the GT output was activated and drives V_C to V_{DD}. GT continues to drive high as long as ESt remains high. Finally after a short delay to allow the output latch to settle, the "delayed-steering" output flag, StD, goes high, signaling that a received tone-pair has been registered. The components of the RC timing circuit (R_7 and C_8) were determined using the following equations (Microsemi, 2013):

$$\boldsymbol{t_{REC} = t_{DP} + t_{GTP}}$$

(3.53)

$$\boldsymbol{t_{GTP} = (R_7 C_8) \ln\left(\frac{V_{DD}}{V_{DD} - V_{TSt}}\right)}$$

(3.54)

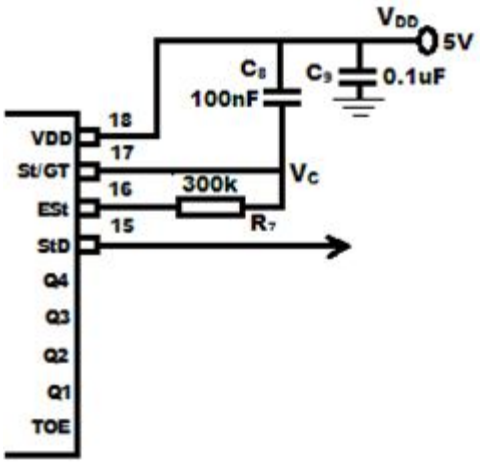


Fig. 3.21 DTMF Decoder Steering Circuit

The recommended times were given in manufacturer datasheet as shown in Table 3.4 (Microsemi, 2013).

Table 3.4 Recommended times for Steering Circuit Design

Time Description	Symbol	Min. Value	Typ. Value	Max. Value	Unit
Tone Present Detection Time	t_{DP}	5	14	16	ms
Tone Absent Detection Time	t_{DA}	0.5	4	8.5	ms
Tone Duration Accept	t_{REC}	20	34	40	ms
Tone Duration Reject	t_{REJ}	20	….	…	ms
Interdigit Pause Accept	t_{ID}	…	…	40	ms
Interdigit Pause Reject	t_{DO}	20	…	…	ms

To find the guard-times for tone-present (t_{GTP}), the typical values of Tone Present Detection Time (t_{DP}) of 14ms and Tone Duration Accept (t_{REC}) of 34ms were used in equation (3.53).

$$\boldsymbol{34ms = 14ms + t_{GTP}}$$

$$\boldsymbol{t_{GTP} = 20ms}$$

A value for C_8 of 0.1μF (100nF) was recommended for most applications (UTC, 2011). The supply voltage to the circuit (V_{DD}) was 5V and $V_{TSt} = V_{DD}/2$ (2.5V). The value of resistor R_7 was evaluated from equation (3.54) as follows:

$$\boldsymbol{20\,x\,10^{-3} = (R_7 x\,0.1\,x\,10^{-6}) \ln\left(\frac{5}{5-2.5}\right)}$$

$$\boldsymbol{\Rightarrow R_7 = 288539\Omega}$$

A 300kΩ ± 5% resistor was used as R_7.

3.3.3.2 *Design of DTMF Decoder Input Circuit*

The input to the DTMF decoder circuit must be purely AC and the input current should not exceed the safe limit. To ensure that only AC component enter the circuit capacitor C_7 in Fig. 3.22 was used to block any DC component from entering the decoder circuit. Recommended value for C_7 was 100nF fast discharge type. Resistor R_5 was used to limit the input current to safe value.

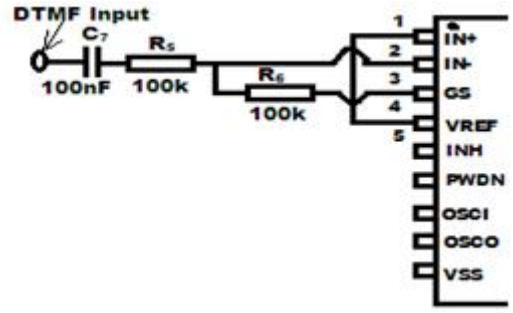


Fig. 3.22. Decoder Input Circuit

The value of the limiting resistor R_5 was evaluated using the relation (UTC, 2011):

$$\boldsymbol{R_5} = \frac{\boldsymbol{V_{DD} - V_{IH}}}{\boldsymbol{I_{SO}}}$$

(3.55)

Where Pull up (Source) Current (I_{SO}) has maximum value of 15µA, the supply voltage (V_{DD}) was 5V and High Level Input Voltage (H_{IH}) has minimum value of 3.5V (Microsemi, 2013). The value of R_5 is obtained using equation (3.55) as:

$$\boldsymbol{R_5} = \frac{\boldsymbol{5 - 3.5}}{\boldsymbol{15\ x\ 10^{-6}}}$$

$$\boldsymbol{R_5} = \boldsymbol{100k\Omega}$$

R_6 is a feedback resistor to the in – built op-amp output (GS) for adjustment of gain. In a single - ended configuration, like the one used in this design the op-amp was connected for unity gain given as (Microsemi, 2013):

$$\boldsymbol{Voltage\ gain} = \frac{\boldsymbol{R_6}}{\boldsymbol{R_5}} \qquad \textbf{(3.56)}$$

Since the voltage gain is unity (1) the R_6 is equal to R_5.

$$\Rightarrow \boldsymbol{R_6} = \boldsymbol{100k\Omega}$$

3.3.4 Design and Programming of PIC Microcontroller Circuit

The 4 – bit binary output of DTMF decoding circuit (Q1 – Q4) and delayed steering output (StD) were fed to PIC microcontroller (PIC16F84A). This PIC was used simply because it has the minimum requirement of this project. It has two ports (A and B). Port A has five input/output pins. Port B has eight input/output pins. Port A was used as input for four bit binary data from DTMF and delayed steering output (Q1 to Q4 and StD). Only six outputs were needed to drive the three motors, so port B was used as output where six out of the eight pins were used to operate the three motors of the Plantbot. So, this PIC was used because it has enough pins and features needed for this system and it is more cost effective

compared to 28 – pins and 40 – pins PICs like PIC16F877, PIC18F4520. The delayed steering output helps the microcontroller recognize and register the 4 – bit binary data from the DTMF decoding circuit. The PIC16F84A is an 18 – pin, dual in line package IC as shown in Fig. 3.23.

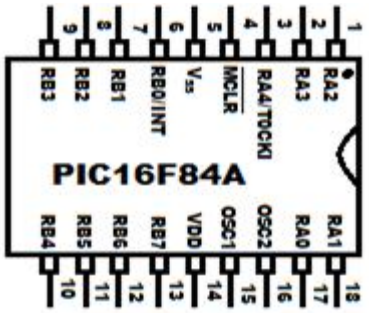


Fig. 3.23. Pin Configuration of PIC16F84A

PIC16F84A is an enhanced Flash/EEPROM 8-Bit Microcontroller with a RISC architecture. It is simple to program since only 35 single word instructions were used for programming. All instructions are single cycle except for program branches which are two-cycle. PIC16F84A has two ports (A and B) which can be configured as either input or output. Port A is 5 – bit wide (RA1 to RA4 on pins 17, 18, 1, 2 and 3 respectively) while port B was 8 – bit wide (RB1 to RB7 on pins 6 to 13 respectively). External crystal oscillator was connected between pin 15 and 16 and voltage supply V_{DD} was supplied to pin 14 while pin 5 is ground (V_{SS}). Pin 4 is master clear (reset) input/programming voltage input. This pin is an active low reset to the device. Therefore, it is normally connected to V_{DD} in normal operation.

3.3.4.1 *Design of Microcontroller Oscillator Circuit*

An external oscillator (XT2) was connected between pins 15 (OSC1) and 16 (OSC2) to complete in – built oscillator circuit of PIC16F84A as shown in Fig. 3.24.

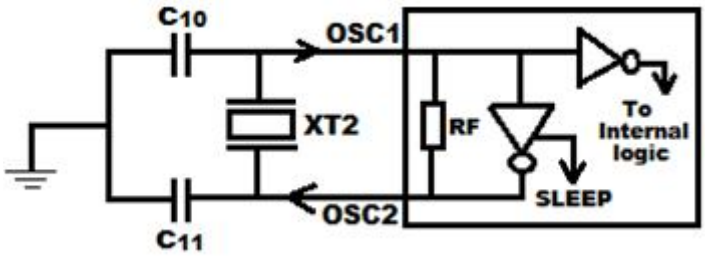


Fig. 3.24. Crystal Oscillator Configuration Circuit

All instructions were executed within one single instruction cycle, except for program branches which are two-cycle. In this case, the execution takes two instruction cycles with the second cycle executed as a NOP (No operation). One instruction cycle consists of four oscillator periods. Thus, the oscillator frequency of the crystal is related with instruction cycle time as (Microchip Technology Inc. 2012):

$$\boldsymbol{Instruction\ Cycle\ Time} = \frac{\mathbf{4}}{\boldsymbol{Oscillator\ Frequency}} \quad \textbf{(3.57)}$$

The recommended instruction cycle by the manufacturer is from 0.4μs to DC (infinity) (Microchip Technology Inc. 2012). If a 4MHz crystal oscillator (XT2) was used, the instruction cycle time was obtained using equation (3.57) as:

$$\boldsymbol{Instruction\ Cycle\ Time} = \frac{\mathbf{4}}{\mathbf{4}\ \boldsymbol{x}\ \mathbf{10^6}}$$

$$\boldsymbol{Instruction\ Cycle\ Time} = \mathbf{1}\mu\boldsymbol{s}$$

The instruction cycle time of 1μs calculated was within the accepted range.

Capacitors C_{10} and C_{11} connected between crystal oscillator and ground were used to improve the stability of oscillation. The recommended values for these capacitors were given by the manufacturer as shown in Table 3.5 (Microchip Technology Inc. 2012).

Table 3.5 Recommended Values of Capacitors C_{10} and C_{11}

Ranges Tested			
Oscillator Type	Frequency	C_{10} (OSC1)	C_{11} (OSC2)
Crystal Oscillator	455kHz	47 – 100pF	47 – 100pF
	2.0MHz	15 – 33pF	15 – 33pF

	4.0MHz	15 – 33pF	15 – 33pF
High Speed Resonator	8.0MHz	15 – 33pF	15 – 33pF
	10.0MHz	15 – 33pF	15 – 33Pf

Recommended values of C_{10} and C_{11} should be identical. Higher capacitance increases the stability of the oscillator but also increases the start-up time. Therefore, for the 4MHz crystal oscillator used in this work, 33pF capacitors were selected as C_{10} and C_{11}.

3.3.4.2 ***Configuring the Ports of PIC16F84A***

The microcontroller PIC16F84A as already mentioned has two ports. Port A has five pins: RA0 on pin 17, RA1 on pin 18, RA2 on pin 1, RA3 on pin 2 and RA4 on pin 3. Port B on the other hand has eight pins: RB0 on pin 6, RB1 on pin 7, RB2 on pin 8, RB3 on pin 9, RB4 on pin 10, RB5 on pin 11, RB6 on pin 12 and RB7 on pin 13. As shown in Fig. 3.29, five pins of DTMF decoder IC were connected to PIC microcontroller (4 – bit binary outputs: Q1 to Q4 and delayed steering output: StD). Therefore, the five pins of port A of PIC16F84A were configured as input pins to receive outputs of DTMF decoder IC (Q1 to Q4 and StD). On the Plantbot there were three DC motors: main drive motor, steering motor and motor for raising and lowering the planting mechanism. Each of the motors needs to be driven in forward and reverse direction for it operation. Therefore, each motor requires two relays to control it, so a total of six control relays were needed. For this reason the eight pins of port B were configured as output pins and six of them were used to control six relay driver circuits that control the six relays. Table 3.6 shows the pin connections between DTMF decoder circuit and PIC16F84A and also the connections of PIC16F84A to relay driver circuits. The arrows show the direction of data flow.

Table 3.6 PIC Pins Connection to DTMF Decoder Pins and Relay Drivers

DTMF Outputs	Port A pins	Port B pins	Relay Driver Circuits
StD ⟶	RA0	RB0 ⟶	Relay Driver 1
Q4 ⟶	RA1	RB1 ⟶	Relay Driver 2

Q3 ⟶	RA2	RB2 ⟶	Relay Driver 3
Q2 ⟶	RA3	RB3 ⟶	Relay Driver 4
Q1 ⟶	RA4	RB4 ⟶	Relay Driver 5
		RB5 ⟶	Relay Driver 6

3.3.4.3 *Programming of PIC16F84A*

The DTMF decodes decimal digits '0 – 9' and symbols '*' and '#' pressed on the handset were converted into 4 – bit binary data as given in Table 3.7.

Table 3.7 DTMF Keys and their Binary Output Equivalents

KEY	Q4	Q3	Q2	Q1
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
0	1	0	1	0
*	1	0	1	1
#	1	1	0	0

Since there are only six relays to be controlled; only keys 1 to 6 were used. The microcontroller was programmed to check binary inputs it receives from the DTMF decoder and activate corresponding output pin that drives required relay driver circuit. The flowchart for the program is shown in Fig. 3.25. The complete program developed using assembly language is given in Appendix B, while the compiled hex code is given in Appendix C.

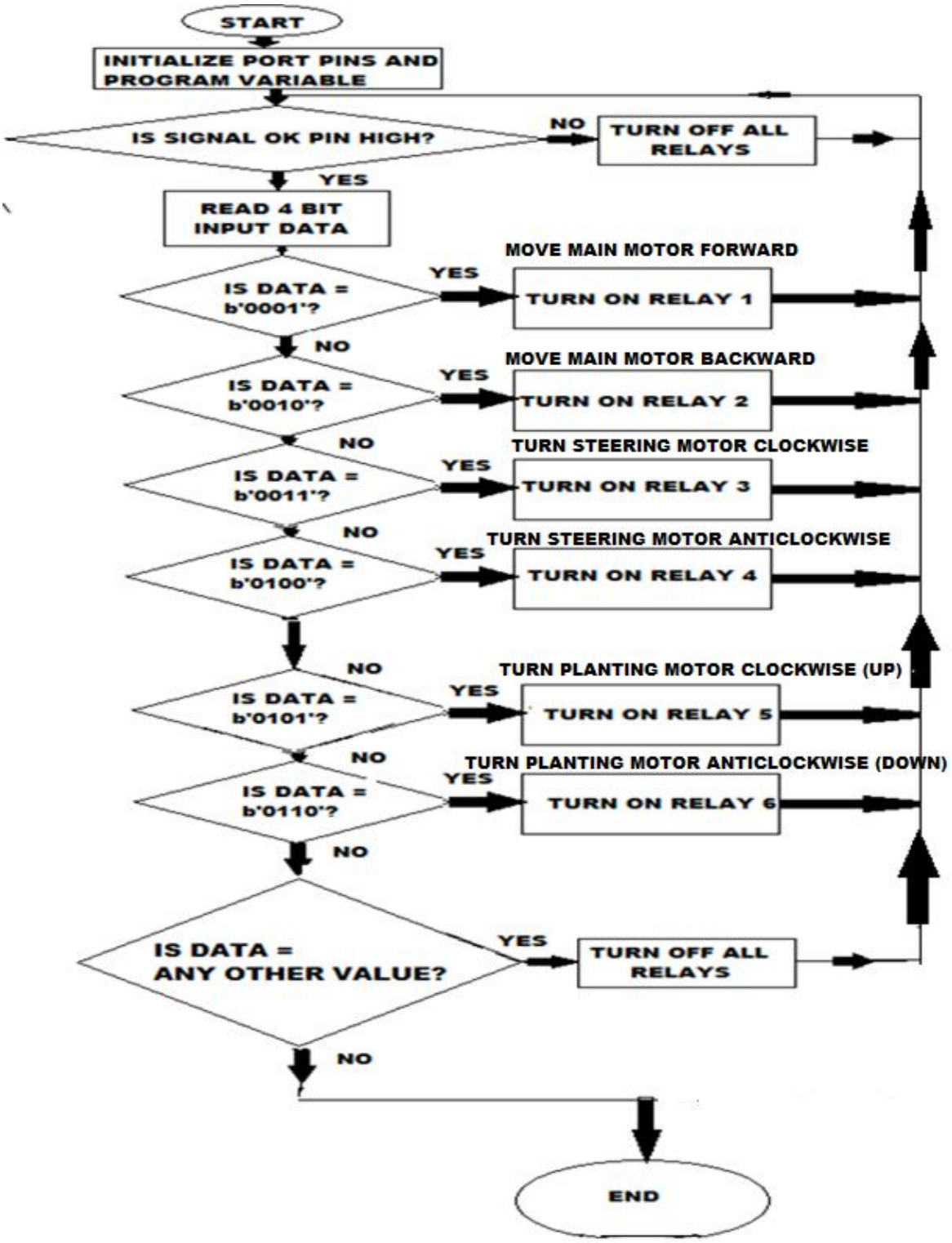


Fig. 3.25. Complete Flow Chart of Programming the PIC16F84A

3.3.5 Design of Relay Driver Ciruit

The three motors that control basic motions of the Plantbot (i.e motor M1, for forward and reverse motion, motor M2 for clockwise and anticlockwise steering and motor M3 for up and down motion of the planting mechanism) are controlled by Bluetooth based electronic circuit through relays which are operated by relay driver circuits. Each motor is operated in clockwise and anti – clockwise directions using two relays. The relay driver circuit as shown in Fig. 3.26 consist of a base resistors (R_8 and R_9) for limiting the base current to a safe value, transistors (T_1 and T_2) for switching action, free wheeling diodes (D_1 and D_2) for protecting the transistors from damage by back emf due to self induction of relay coils and relays (RL1 and RL2) for powering the motor. The capacitors (C12 and C13) used across the relays are anti – flickering capacitors. Their function was to stabilze the triggering of the relays by preventing flickering.

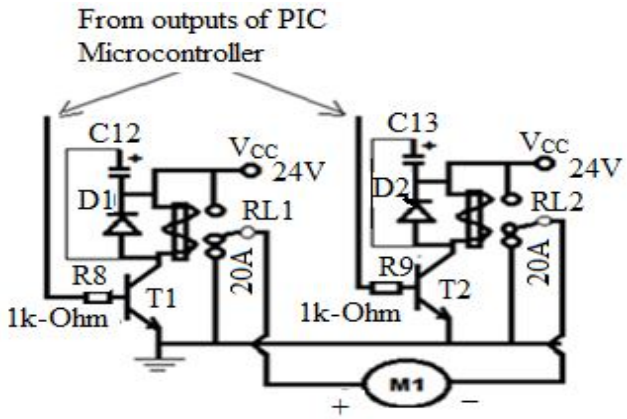


Fig. 3.26. Relay Driver Circuit for Motor Driving

The selected transistors (T_1 and T_2) as in Fig. 3.26 are general purpose NPN transistors with part number C945 and following specifications: V_{CC} = 5V, V_{BE} = 0.7V, I_C = 500mA, β = 120 and P_D = 450mW.

To select the base resistors (R_8 to R_9), base current was first obtained as (Link, 1996):

$$\boldsymbol{I_B} = \frac{\boldsymbol{I_{C\,mA}}}{\boldsymbol{\beta}} \quad (3.58)$$

$$\boldsymbol{I_B} = \frac{\mathbf{500}}{\mathbf{120}}$$

$$\boldsymbol{I_B} = \mathbf{4.17}\boldsymbol{mA}$$

The base resistor for each relay driver circuit was then obtained as (Link, 1996):

$$\boldsymbol{R_8} = \frac{\boldsymbol{V_{CC}-V_{BE}}}{\boldsymbol{I_B}} \quad (3.59)$$

$$\boldsymbol{R_8} = \frac{\mathbf{5}\boldsymbol{V} - \mathbf{0.7}\boldsymbol{V}}{\mathbf{4.17}\boldsymbol{mA}}$$

$$\boldsymbol{R_8} = \mathbf{1.032}\boldsymbol{k}\Omega$$

So a 1 kΩ ± 5% tolerance was used as base resistors (R_8 and R_9).

Since the motors are 24V, the relays R_{L1} and R_{L2} are 24V, 20A, 400Ω type. The anti – flickering capacitors C_{12} to C_{17} as sugessted in the data sheet can take any value between 10µF and 100µF (**Motorola**, 2009). In this work 47µF was used.

The free wheeling diode (D_1 and D_2) used in this work has part number 1N4001 which was a general purpose diode.

3.3.6 Design of Power Supply Circuit

The power supply used in this work uses a DC battery as source. The battery used was 12V, 75AH. As stated earlier, the motors (M1, M2 and M3) are 24V. Therefore, a DC/DC converter circuit was used to change the 12V from battery to 24V for powering the motors.

The DTMF booster circuit needs 9V while DTMF decoder circuit and PIC microcontroller circuit require 5V for their operation. So 5V regulator (7805) and 9V regulator (7809) were used to provide 5V and 9V respectively. The general power supply circuit is shown in Fig. 3.27. While the snapshot of the 12V/24V DC/DC converter is as shown in Plate 3.1.

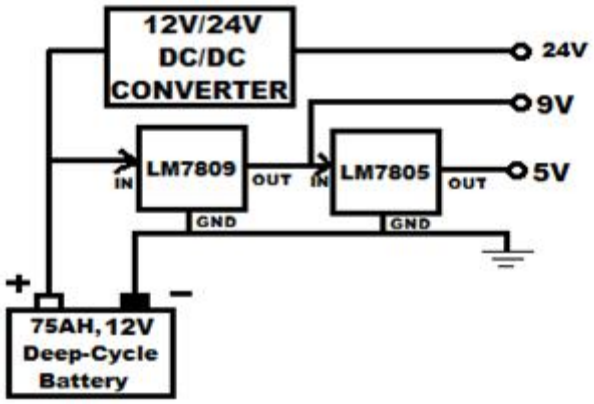


Fig. 3.27. General Power Supply Circuit



Plate 3.1. 12V to 24V DC – DC Converter Circuit

The circuit consists of two P-channel MOSFET (MTW20N50) switches triggered using the pulse width modulation (PWM) switching pulse with variable frequency and duty ratio (k). The switch was operated in two modes with (two each) incorporated passive components C and L at each side. The capacitors increase the input voltage during the switch ON time.

Inductors further lift the voltage across C. During the charging period the voltage across C will be V_1+V_c and this voltage was maintained even when switch was off. The inductors maintains the current direction even during switch OFF. Thus the DC-DC converter maintains current and high voltage (24V) at the output. Output and input voltages are related as (Axiomatic, 2012):

$$V_O = \frac{K}{1-K} V_{in} \tag{3.60}$$

The duty ratio (k) used to double the input voltage was $^2/_3$. (Axiomatic, 2012). The block diagram of the 12V to 24V DC-DC converter is given by Fig. 3.28 (Axiomatic, 2012).

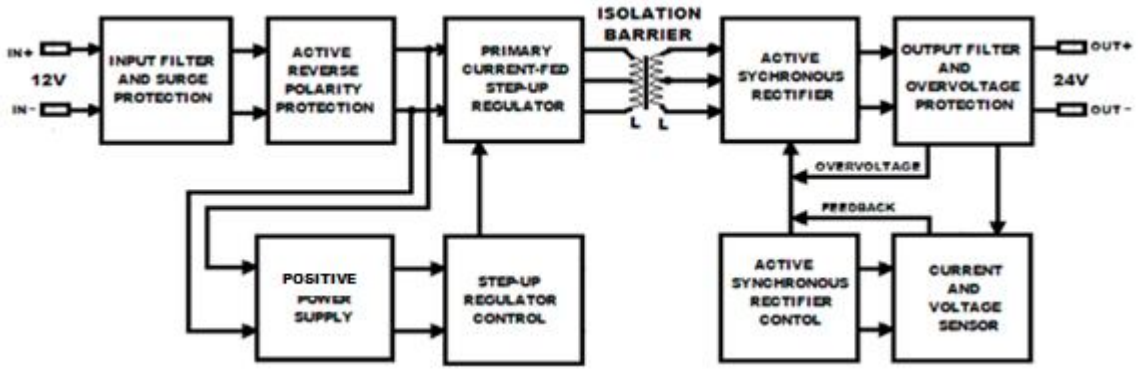


Fig. 3.28. Block Diagram of 12V to 24V DC – DC Converter

The first stage of the block diagram was input filter and surge protection which filters ripples in DC input. Reverse polarity protection ensures that the incoming DC maintains its polarity. Step – up regulator rises the voltage level and delivers it to inductor (L) as transformer. Active synchronous rectifier produces the stepped up DC voltage. The output stage has a filter and helps in making sure that the output is purely DC and the level is always at the desired value of 24V. At the input side a bias power supply was used to drive a

step – up regulator control block which monitors step – up regulator's operation. At ouput side has synchronous filter control block (Axiomatic, 2012).

The general circuit diagram of the control circuit is given in Fig. 3.29.

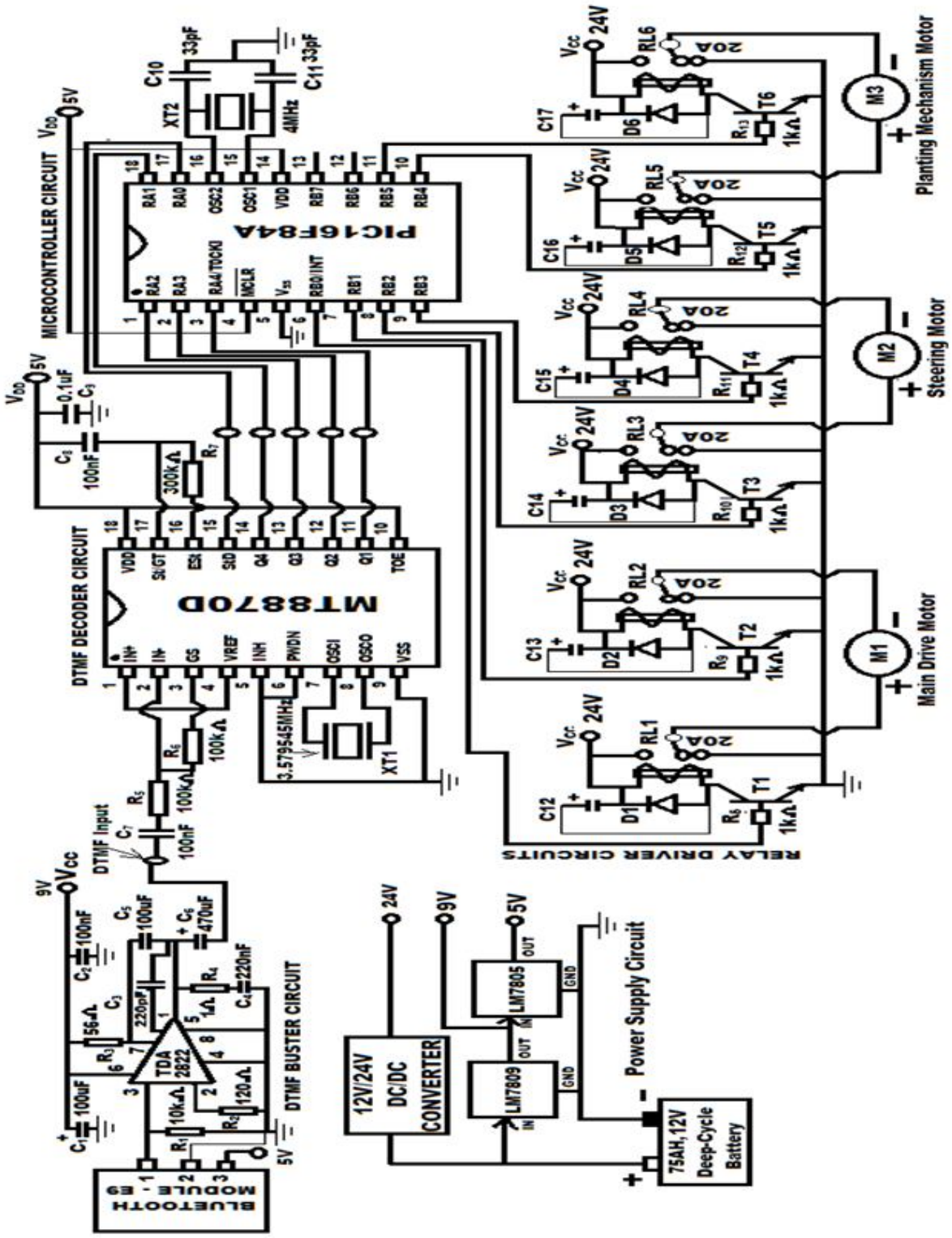


Fig. 3.29. General Bluetooth Control Circuit of the Plantbot

3.3.7 Complete Circuit Diagram

The complete circuit diagram of the Bluetooth control system for the Plantbot is as shown in Fig. 3.29. Using Circuit Wizard ® version 1.5, this circuit diagram was converted to the Printed Circuit Board (PCB) format as shown in Fig. 3.30.

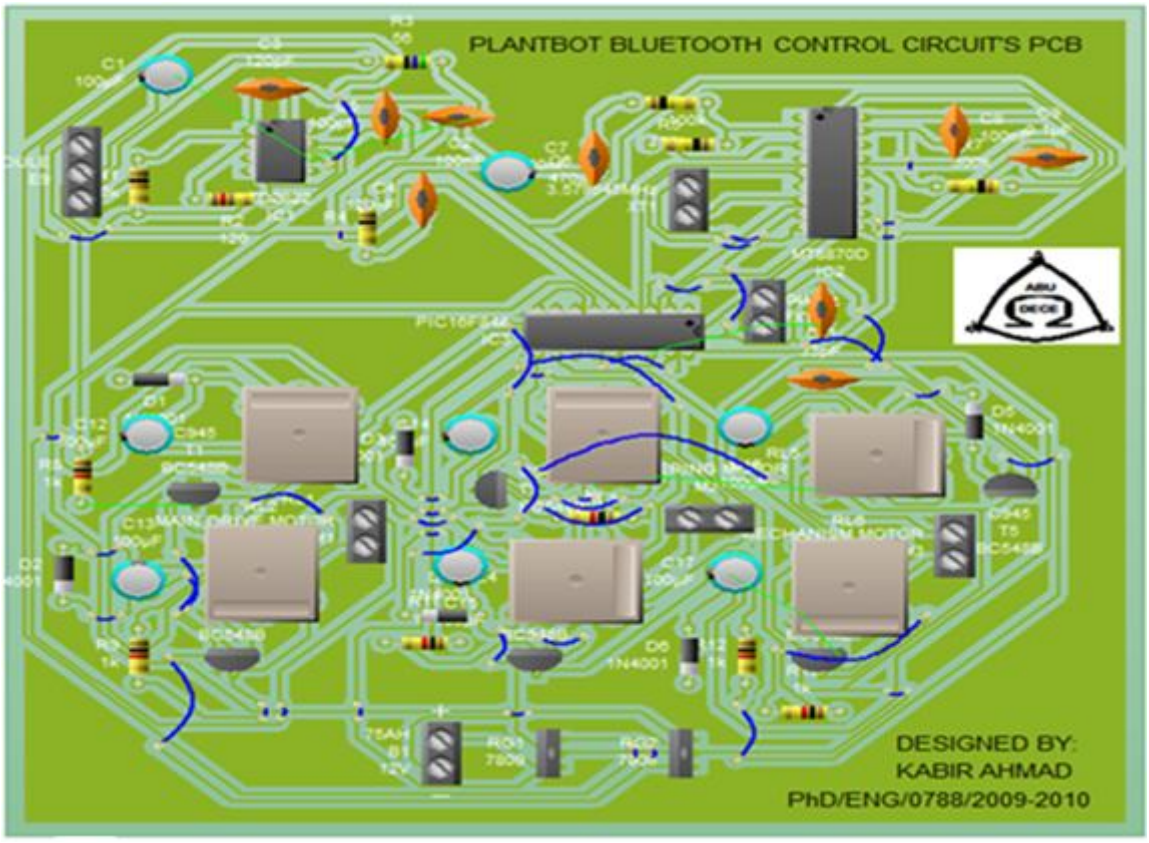


Fig. 3.30. PCB of the Bluetooth Control Circuit of the Plantbot

3.3.8 Interfacing and Testing the Plantbot Prototype

The mechanical segment of the Plantbot constructed based on step by step design carried out using the engineering drawings developed as presented in chapter three is given in Plate 3.2.



Plate 3.2. The Skeletal Structure of the Constructed Plantbot

The Bluetooth - based control circuit as designed in this work was also constructed as shown in Plate 3.3.

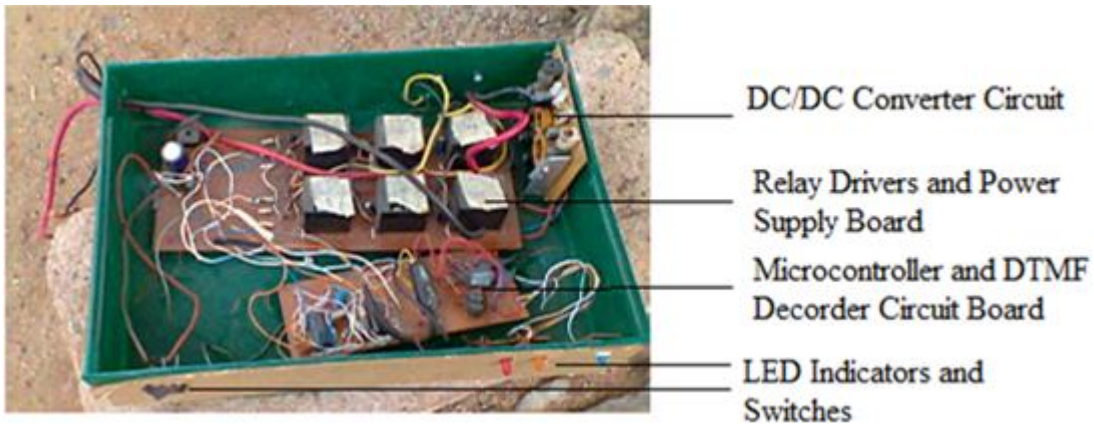


Plate 3.3. Constructed Bluetooth Control Circuit for the Plantbot

Plate 3.4 shows the complete system with Bluetooth Control Circuit and Battery interfaced with the main body of the Plantbot.

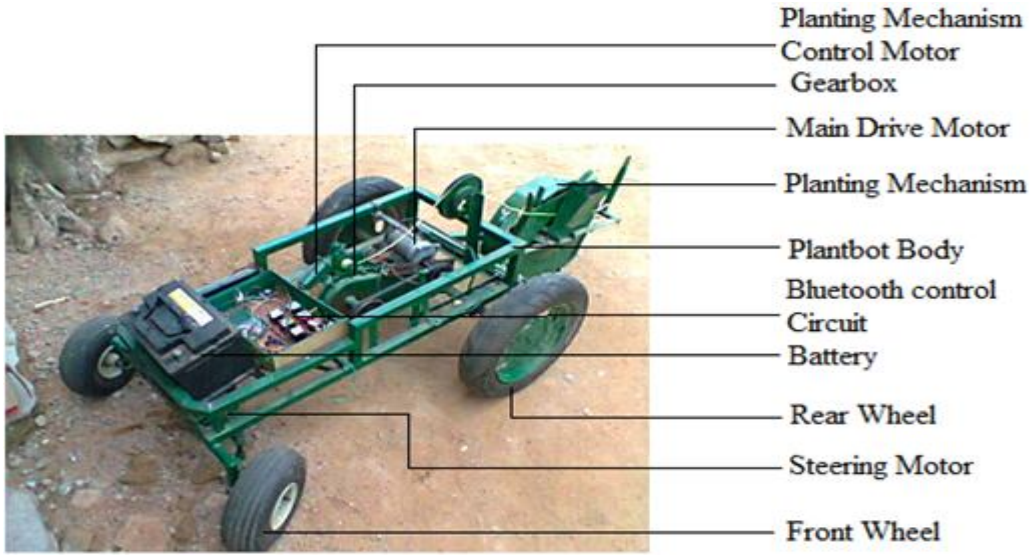


Plate 3.4. Complete Plantbot with Bluetooth Control Circuit and Battery

Plate 3.5 shows the coupled Plantbot with its cover.


Plate 3.5. Coupled Plantbot with Cover

3.3.9 Flowchart of the Model Development

The process of model development and validation described here, can be executed using the flowchart given in Fig. 4.17.

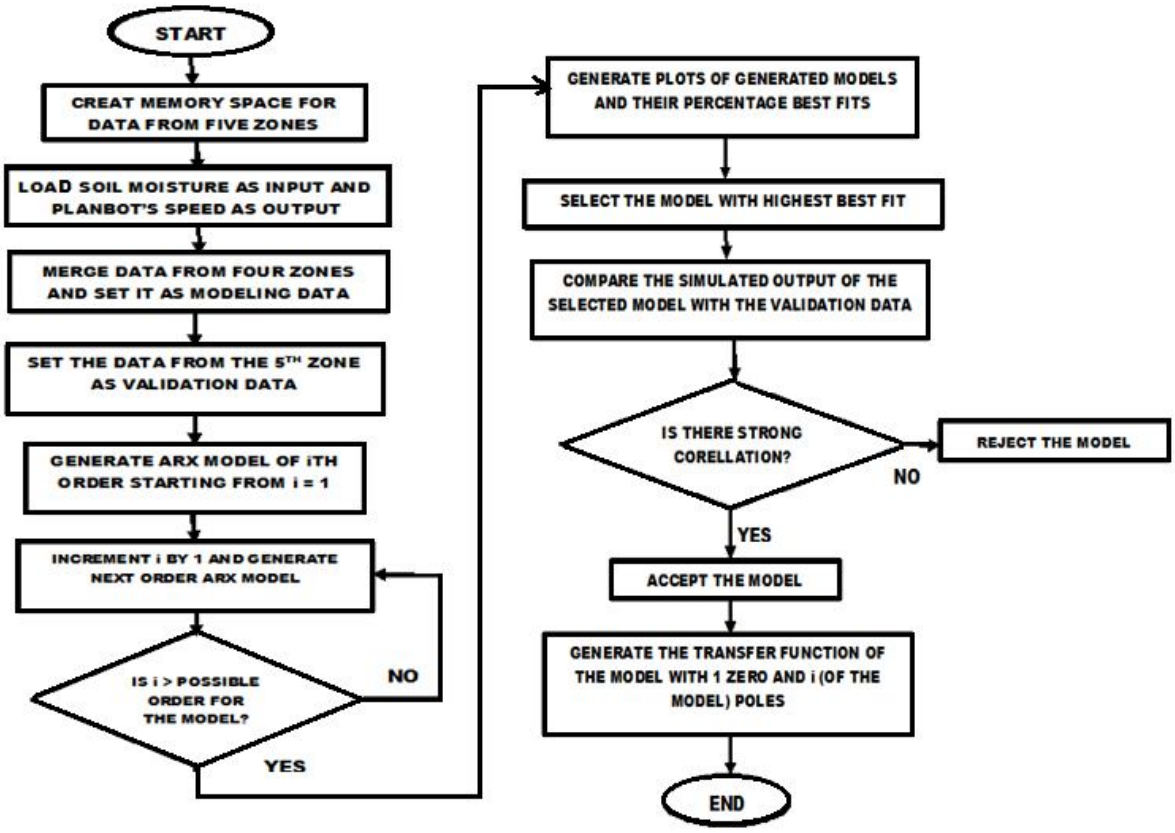


Fig. 4.17. The process of model development and validation

The complete MATLAB script for the developed model is given in Appendix F.

3.3.10 Summary of Design Results

The basic designs that were carried out in this chapter were based on the repetitive iterations where the calculations process was done first and then compared with the conditions of safety and the result was accepted when the obtained value was within the safe limit or rejected when it is not within the safe limit. Then another value(s) was chosen and the process is repeated until the value arrived at was within the safe limits given by the standards of the design of the particular circuit segment. Therefore, the summary of design

results that are presented in Table 3.8 are the final values which were arrived at the end of the iteration process.

Table 3.8 shows the list of components of the complete circuit diagram of Fig. 3.29.

Table 3.8 Summary of the Design Results

S/NO	Design Parameter	Calculated Value	Used Value
1	Bluetooth Headset Module		E9
2	Amplifier IC		TDA2822
3	C_1		100 µF
4	C_2		100 µF
5	C_3	$2.2088\ x\ 10^{-14}F$	220pF
6	C_4	2.2088 x 10^{-11}F	220nF
7	C_5		100 µF
8	C_6		470µF
9	C_7		100nF
10	C_8		0.1µF
11	C_9		0.1µF
12	C_{10} and C_{11}		33pF
13	C_{12} to C_{17}		47µF
14	R_1	9090.901 Ω	10k Ω
15	R_2		120 Ω
16	R_3	55.56Ω	56Ω
17	R_4		1 Ω
18	R_5	$100k\Omega$	$100k\Omega$
19	R_6	$100k\Omega$	$100k\Omega$
20	R_7	288539Ω	300 kΩ
21	R_8 to R_{13}	$1.032k\Omega$	1 kΩ ±5%
22	DTMF Decoder IC		MT8870D
23	crystal (XT1)		3.579545MHz
24	crystal (XT2)		4MHz
25	PIC Microcontroller		PIC16F84
26	Transistors T1 to T6		C945
27	diode (D_1 to D_6)		1N4001
28	relays R_{L1} to R_{L6}		24V, 20A, 400Ω
29	DC battery		12V, 75AH
30	Voltage regulators		LM7805 and LM7809
31	DC/DC Converter		12V to 24V
32	Motors M1, M2 and M3		1HP (746W), 25W and 75W respectively

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

This chapter presents the experiments conducted and results obtained to evaluate the performance of the Plantbot while working in practical planting environment. The experiments were conducted from January 11, 2014 to March 29, 2014 in the dry season to have ability of controlling the soil moisture.

The investigations were focused on **field tests** to evaluate the planting performance of the Plantbot, effect of **radio signals and noise interference** on the Bluetooth range **of communication** and effect of moisture **content of the soil on the speed** of the Plantbot.

4.2 PLANTING PERFORMANCE OF THE PLANTBOT

The general planting performance of the Plantbot was investigated under this section. This investigation involved the percentage of successful planting compared to the percentage of unsuccessful in planting. It also looked at the issue of planting the accurate number of seed (two) per hole as recommended by Institute of Agricultural Research, Ahmadu Bello University (IAR A. B. U. Zaria, 2012).

To carry out this investigation accurately the Plantbot was run on dry land that the planting mechanism could not penetrate so that the seeds released by the planting mechanism would remain on the surface of earth for proper evaluation. The seed container was loaded with the maize (seed), GSM handset via Bluetooth channel was used to lower the planting mechanism to the ground and the Plantbot forward motion was started to start the normal planting. Plate 4.1 shows the Plantbot in planting operation for the investigation.



Plate 4.1 Investigating the Planting Performance of the Plantbot

The Plantbot was run for a distance of around 30.48 m (100 feet). Since the distance from one plant to another as the planting mechanism was designed as 25cm, an average of 120 maize seeds (i.e. more than a minimum of 100 places as suggested by **Ismail *et al*, (2009**) should be planted over this distance. The experiment was repeated 10 times and the results were tabulated as shown in Table 4.1.

Table 4.1 Results for Plantbot's Planting Performance Investigation

Experiment Number	Total Planting Positions	Successfully Planted Positions	Unsuccessful Planting Positions	Positions Planted with Two Seeds	Positions Planted with more than Two Seeds
Experiment 01	107	96	11	83	13
Experiment 02	103	90	13	77	13
Experiment 03	113	104	9	87	17
Experiment 04	108	96	12	85	11
Experiment 05	104	91	13	79	12
Experiment 06	112	104	8	93	11
Experiment 07	98	92	6	79	13
Experiment 08	112	99	13	89	10
Experiment 09	108	93	15	80	13
Experiment 10	109	99	10	83	16
TOTAL	**1074**	**964**	**110**	**835**	**129**
PERCENTAGE		**89.8%**	**10.2%**	**86.6%**	**13.4%**

From the values in the Table 4.1, the following percentages were evaluated.

$$\boldsymbol{Percentage\ of\ Successful\ Planting} = \frac{\mathbf{964}}{\mathbf{1074}} * \mathbf{100\%} \qquad \textbf{(4.1)}$$

$$= 89.8\%$$

$$\textbf{Percentage of Unsuccessful Planting} = \frac{110}{1074} * 100\% \quad \textbf{(4.2)}$$

$$= 10.2\%$$

$$\textbf{Percentage of Planting two seeds} = \frac{835}{964} * 100\% \quad \textbf{(4.3)}$$

$$= 86.6\%$$

$$\textbf{Percentage of Planting more than two seeds} = \frac{129}{964} * 100\% \quad \textbf{(4.4)}$$

$$= 13.4\%$$

These evaluated percentage of unsuccessful planting (**10.2%**) and percentage of planting more than two seeds (**13.4%**) showed significant improvement from the reviewed previous works as summarized in Table 4.2.

Table 4.2. Results Comparison with Previous Works

WORK	PERCENTAGE UNSUCCESSFUL PLANTING (%)	PERCENTAGE OF >2 SEEDS (%)
Plantbot	10.2	13.4
Subo *et al* (1996)	27.2	-
Ronaldo (2001)	30 – 34	-
Olaoye & Bolufawi (2001)	33	-
Kim *et al* (2001)	23.5	-
Chaudhuri *et al* (2002)	29.4 - 30.2	-
Ebubekir (2005)	35	-
Shaaban *et al* (2009)	28.1	38.12
Turbatmath *et al* (2011)	29.0 - 30.9	-

Based on this fact, the designed Plantbot has better planting performance as compared to the previously developed planting machines.

4.3 EFFECTS OF RADIO SIGNAL AND NOISE ON THE BLUETOOTH RANGE OF COMMUNICATION

The Plantbot is controlled through Bluetooth medium using a mobile station (handset) that has Bluetooth facility. Since the Bluetooth signal is in the radio frequency spectrum (2.4GHz), there is tendency of it being affected by other radio signals through interference and other sources of noise in the environment where it operates. This experiment was therefore conducted to see if there was significant difference in the range of Bluetooth control of the Plantbot when it operates in environments that were interference and noise prone (like ISM band devices, etc.) and the environments that were free from radio interference and noise.

Four locations were selected across Zaria to conduct the experiments. These places were:

1. Dakace Zaria (DKZ)
2. Tohu Zaria (THZ)
3. Kofan Kona Zaria (KKZ)
4. Unguwan Dankali Zaria (UDZ)

DKZ was selected as an environment that is noise prone because it has some operating industries around it (like Sunseed Oil, Zaria Industries Limited and Rigid Pack). THZ was selected as an environment that is radio interference prone because it is located very close to the Nigerian College of Aviation Technology (NCAT).

KKZ and UDZ were selected as areas that were free from radio interference and noise because there were no industries that can generate noise and also there was no source

of radio signals (ISM band frequencies) that can interfere with that of the Bluetooth. But still there are existing farmlands in these locations which make them suitable for the research.

To conduct this experiments, a 60.96 m (200 – feet) tape was used for measuring the range (distance) from which the Plantbot can be controlled using the mobile station (MS) with Bluetooth facility. The MS used was **SAMSUNG DUOS**, with Bluetooth output power of 100mW (20dB), which is Class 1 type with rated range of 100m (at 2.4GHz). Plate 4.2 shows one of the scenes of the experiments.



Plate 4.2 Experiments for Measuring Bluetooth Control Distance of the Plantbot

The experiment was done by establishing connection between the MS and the Bluetooth module on the Plantbot via the service discovery process of the Bluetooth network link. When the connection was made the MS remains stationary while the Plantbot moves away from the operator until a point was reached where the communication breaks down, that was, when the Plantbot suddenly stopped moving. The distance from the Plantbot just before the breakdown of the communication and the MS was measured and this was the maximum range of communication between the handset and the control module on the

Plantbot. Four measurements were taken from the **East, West, North and South** directions of the Plantbot to investigate directional effect and the average was then taken as the effective distance. The measurements taken are as shown in Table 4.3.

Table 4.3: Measurements (in meter) for Bluetooth Control Range of the Plantbot

DAY	PLACES	DKZ	THZ	KKZ	UDZ	DIRECTION AVERAGE	OVERALL AVERAGE
DAY – 1	EAST	57.300	57.608	57.151	56.084	57.036	57.426
	WEST	57.150	55.169	57.913	56.389	56.655	
	NORTH	58.220	58.522	57.608	58.065	58.103	
	SOUTH	57.610	58.218	58.218	58.065	58.027	
DAY -2	EAST	57.460	56.389	57.912	56.693	57.113	57.614
	WEST	56.990	57.608	56.846	56.389	56.960	
	NORTH	58.370	57.913	58.522	58.369	58.294	
	SOUTH	58.520	57.608	57.913	58.369	58.103	
DAY – 3	EAST	57.460	56.693	57.608	56.998	57.189	57.662
	WEST	57.610	57.456	57.303	56.998	57.341	
	NORTH	58.070	57.913	58.369	58.065	58.103	
	SOUTH	58.520	57.608	58.218	58.218	58.141	
DAY – 4	EAST	57.610	57.303	57.456	57.913	57.569	57.519
	WEST	56.850	56.084	57.608	56.693	56.808	
	NORTH	58.520	57.913	57.760	58.218	58.103	
	SOUTH	58.070	58.522	58.369	57.760	58.179	
DAY – 5	EAST	56.690	57.608	57.456	56.084	56.960	57.662
	WEST	56.990	56.084	57.608	56.693	56.846	
	NORTH	58.370	57.913	58.218	58.065	58.141	
	SOUTH	57.760	58.522	57.913	58.369	58.141	
DAY -6	EAST	57.610	57.456	57.303	56.998	57.341	57.642
	WEST	57.300	57.608	57.151	56.084	57.036	
	NORTH	58.070	58.522	58.369	57.760	58.179	
	SOUTH	58.520	57.608	57.913	58.369	58.103	
DAY – 7	EAST	57.150	56.693	57.608	57.608	57.265	57.662
	WEST	56.990	57.913	57.303	56.693	57.227	
	NORTH	58.220	58.522	58.369	58.065	58.294	
	SOUTH	58.370	57.303	57.608	58.218	57.875	
LOCATION AVE		57.730	57.121	57.771	57.450	57.617	57.602

The overall daily average values are represented on a bar chart as given by Fig. 4.1.

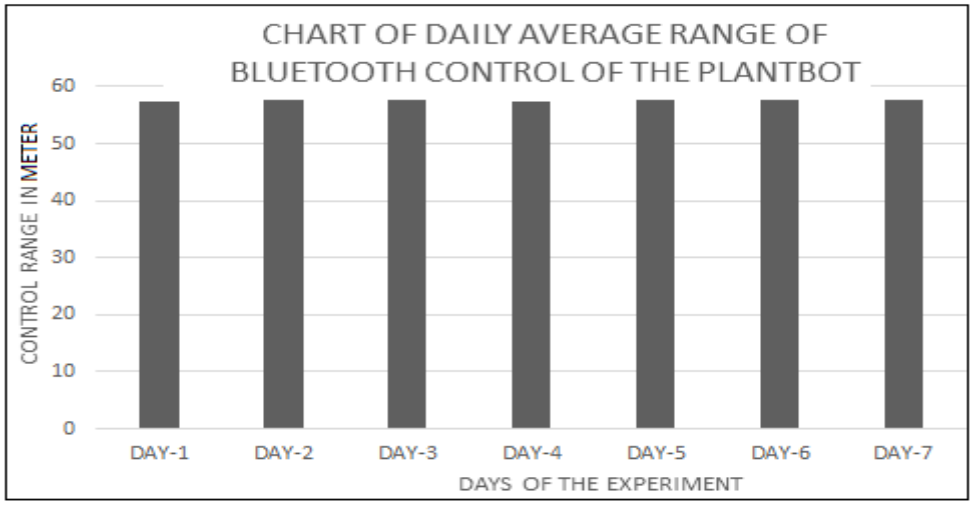


Fig. 4.1 Bar Chart of Daily Average Bluetooth Control Distance of the Plantbot

From Table 4.3 the percentage difference between the highest value (57.662m) and the lowest value (57.426) was calculated as:

$$\boldsymbol{Percentage\ Diffrence} = \frac{57.662-57.426}{57.662} * 100\% \qquad (4.5)$$

$$= 0.41\%$$

This small value of percentage difference (0.41%) shows that the control distance (range) over the period of the seven days has very insignificant variation (as can be seen also from Fig. 4.1) and based on this, it could be concluded that the distance of Bluetooth control remains the same on daily basis. Therefore, the overall average control distance (range) from Table 4.3 was 57.602m which was about 94% of the rated range for Bluetooth module E9 (61m) used in this work.

From Table 4.3, average ranges (distances) of Bluetooth control of the Plantbot with respect to the four locations over the period of seven days were evaluated and plotted on bar chart shown on Fig. 4.2.

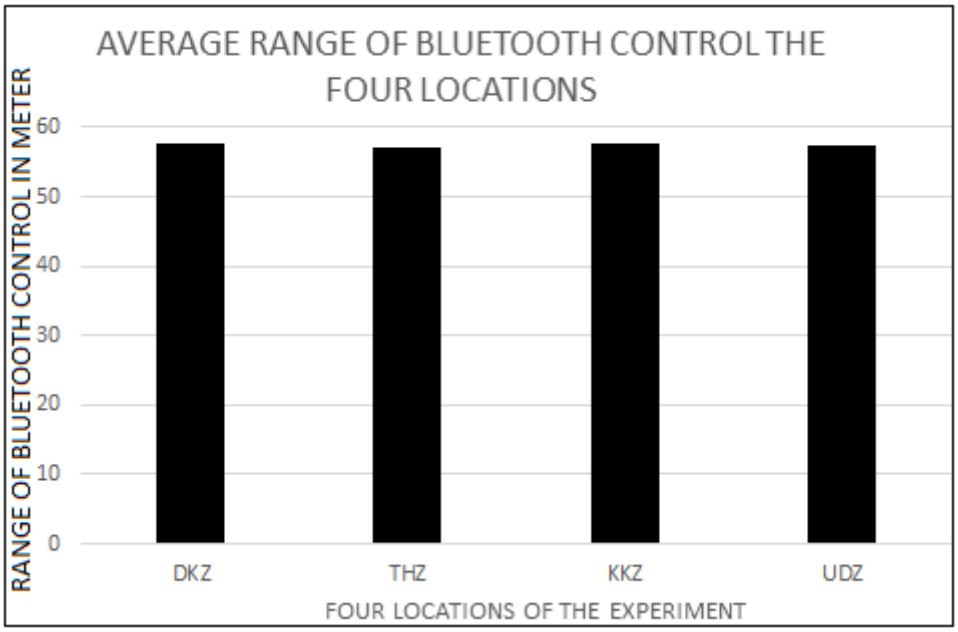


Fig. 4.2. Average Distances of Bluetooth Control with Respect to Locations

This result showed that the highest control range (57.771m) was obtained in KKZ which was one of the locations not prone to noise and interference. But this value was followed by that obtained in DKZ (57.730m) which was noise prone due to existence of industries in the area. But looking at the two results it could be seen that the percentage difference between the two values was very small as calculated as follows:

$$\boldsymbol{Percentage\ Diffrence} = \frac{57.771-57.730}{57.771} * 100\% \qquad (4.6)$$

$$= 0.075\%$$

This very low percentage difference of 0.075% (as also depicted by Fig. 4.2) and the fact that the lowest values of 57.212m and 57.450m were obtained from noise prone location (THZ) and noise free prone location (UDZ) show that there was no any significant effect on the range of Bluetooth control in the areas that were expected to produce interference and noise. The reason for this was the fact that the Bluetooth frequency (2.4GHz) is different

from those of communication systems like GSM (900MHz – 1800MHz and 2.1GHz for 2G and 3G respectively), so there was no any expectation of any significant interference from most of the farmlands in the study area.

4.4 EFFECTS OF SOIL MOISTURE CONTENT ON THE SPEED OF THE PLANTBOT

This experiment was conducted to establish the relationship between the soil moisture of the environment where the Plantbot works and the speed of the Plantbot. The experiments were conducted on ten (10) different farmlands in ten (10) different locations across Zaria. Data obtained from eight of the locations (80%) from of the four zones of the study area was used for modeling the behaviour while the remaining two (20%) from the fifth zone of the study was used for validating the developed model. The places used for carrying out the experiments were:

A. Dambo Zaria (DBZ)
B. Dakace Zaria (DKZ)
C. Bizara Zaria (BZZ)
D. Filin Mallawa Zaria (FMZ)
E. Kofan Kona Zaria (KKZ)
F. Kofan Gayan Zaria (KGZ)
G. Tukur – Tukur Zaria (TTZ)
H. Unguwan Dankali Zaria (UDZ)
I. Dogarawa Zaria (DGZ)
J. Tohu Zaria (THZ)

These ten (10) places were selected such that two were from five zones of Zaria so as to have basis for making general conclusion on results with respect to whole case study area. Dambo and Dakace are from eastern zone, Bizara and Filin Mallawa are from central zone and Kofan Kona and Kofan Gayan are from the southern zone. The Tukur – Tukur and Unguwan Dankali are from western zone, while Dogarawa and Tohu are from the northern zone of Zaria. Measurements were taken for a period of seven days in each farmland.

The soil on which the experiments were conducted was wetted using water –tank with perforated plastic pipe of diameter of two-inch and span of 4.5-inches (1371.6mm) about twice the width of the Plantbot (700mm). The length of the area wetted during the experiment was 30.48m (100 feet). The watering tank with its tap open, was driven from one end to the other and then reading of the moisture content of the soil was taken after about five minute to allow the water to penetrate into the soil (**Ismail *et al*, 2009**). The readings of the soil moisture were taken using digital moisture meter **'ELCO7420'** at three points along the length of the wetted land and the average was evaluated. Then the Plantbot was ran on the wetted land and its speed was taken using digital tachometer **'EXTECH 461995'.** Plate 4.3 shows one of the scenes of the experiments.



Plate 4.3. One of the scenes of experiments to determine the effect of soil moisture on speed

Plate 4.4 shows one of the pictures of readings of soil moisture content taken during the experiment using the meter. Wetting of the soil was repeated ten times and the Plantbot was run on the land each time and the readings of the soil moisture and the corresponding speeds were recoded and tabulated in the Tables D1 to D10 given on Appendix D.



Plate 4.4 One of the Readings of the Soil Moisture Content Using Moisture Meter **ELCO7420**

The moisture meter used was volumetric type which gives readings as ratio of moisture volume to the soil volume (m^3/m^3) and the results were given in percentage. The experiment was concerned with the surface soil moisture of the farmlands because it was the one that has direct contact with moving tires of the Plantbot.

4.4.1 Pre – Processing the Moisture – Speed Data

The data given in Tables D1 to D10 in Appendix 'D' show the actual captured readings on daily basis and the average values of the measured percentage moisture of

the soil and the corresponding average values of the measured speed of the Plantbot over the period of seven days for each of the ten locations of the experiment.

To simplify the process of analyzing the data for modeling the behaviour of the Plantbot, the overall average values of the percentage moisture content of the soil and the corresponding Plantbot's speed of each of the ten locations were evaluated and tabulated in Table E1 to Table E10 in Appendix E.

4.4.2 Preliminary analysis of the Data

In order to determine the best method of modeling the behaviour of the Plantbot a preliminary investigation was carried out to fully understand the nature of the data as suggested by **Bozdogan (2004)** and **Gertheiss *et al* (2013)**. This investigation was to explore the linearity or nonlinearity of the data. To do this, five out of the ten locations of experiments were selected (one from each of the five zones of the study area). The selected locations were: DBZ, FMZ, THZ, KKZ and UDZ.

The overall weekly average Plantbot's speed of the selected location was plotted against the overall weekly average percentage moisture on a scatter diagram using 2013 Microsoft excel. The scatter diagrams were plotted using average values of percentage moisture and average values of speed from the data in Tables E1, E4, E5, E8 and E10 in Appendix E. The scatter diagrams of the five locations are given in Fig. 4.3 to Fig. 4.7.

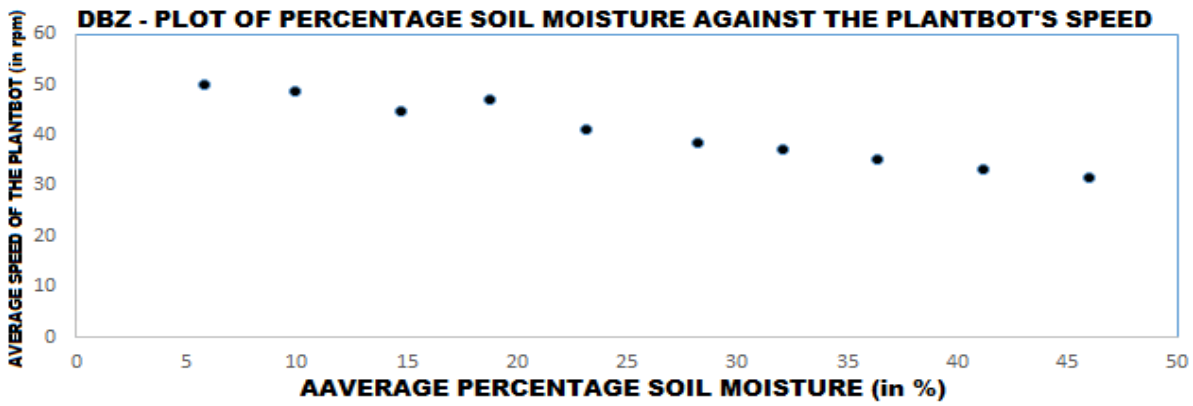


Fig. 4.3 Scatter Diagram of Soil Plantbot's Speed against Moisture in DBZ

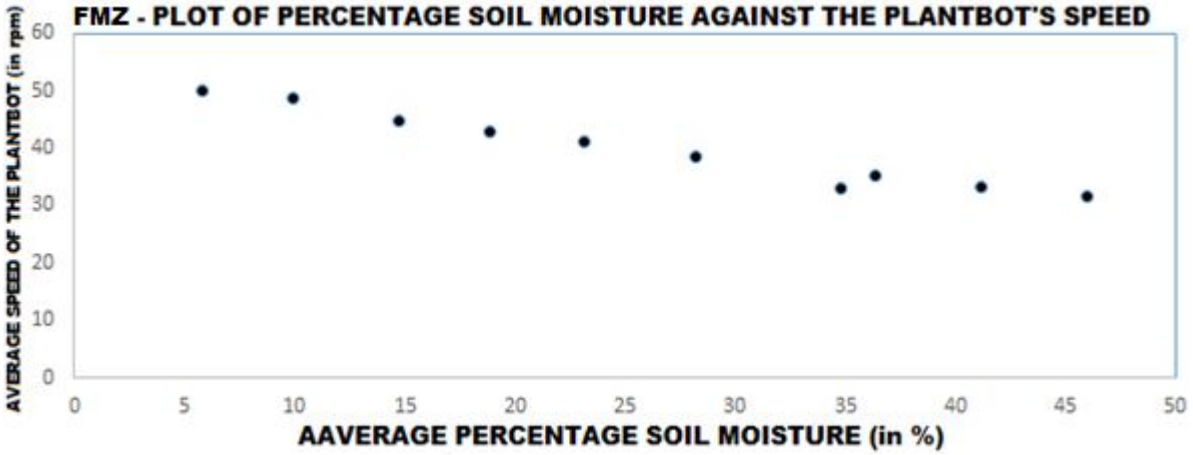


Fig. 4.4 Scatter Diagram of Soil Plantbot's Speed against Moisture in FMZ

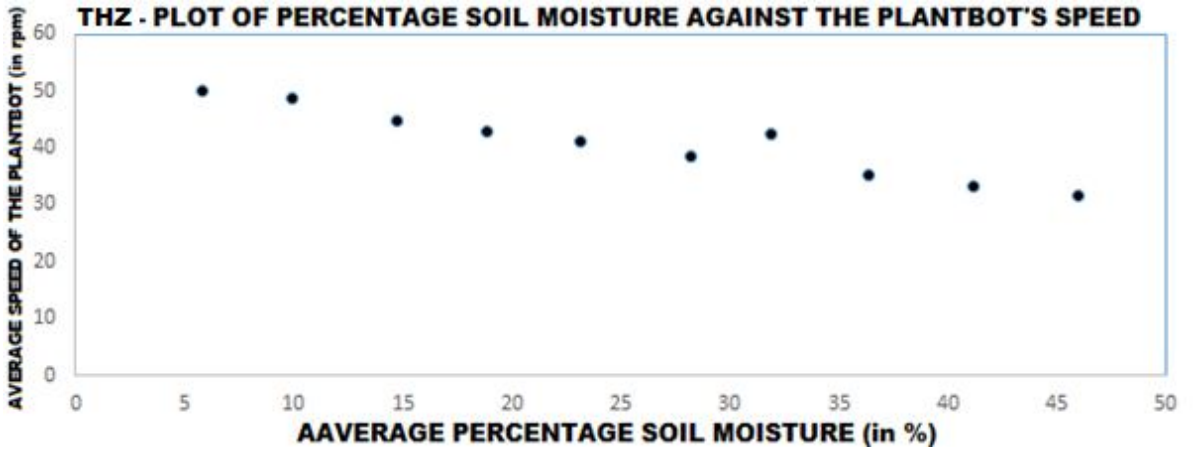


Fig. 4.5 Scatter Diagram of Soil Plantbot's Speed against Moisture in THZ

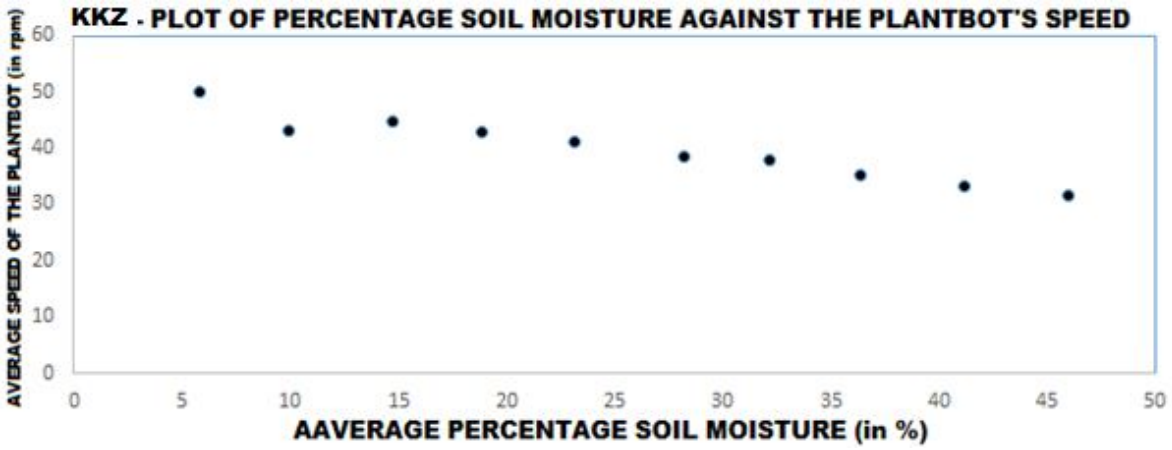


Fig. 4.6 Scatter Diagram of Soil Plantbot's Speed against Moisture in KKZ

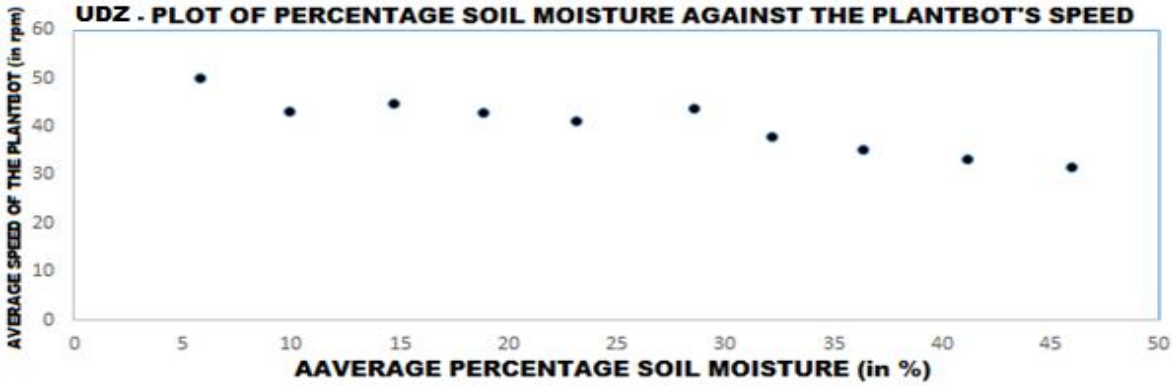


Fig. 4.7 Scatter Diagram of Soil Plantbot's Speed against Moisture in UDZ

These scatter diagrams in Fig. 4.3 to Fig. 4.7 indicate that the data was somehow linear in nature since line of best fit can be drawn on each of the scatter diagrams to have most of the points on or very close to the line. This information therefore, suggests that the best model for the data was linear – model. The model of the data was developed using **system identification toolbox of MATLAB** as explained under section 4.5.

4.5 DEVELOPMENT OF PLANTBOT'S ENVIRONMENTAL BEHAVIOUR MODEL

The preliminary investigation of the best model for the Plantbot behaviour as carried out under Section 4.4.2 shows that linear model would be the best option. Based on this fact, the behaviour was modeled using system identification toolbox of MATLAB.

The model developed falls under black box modeling since the input and the corresponding output of the system under consideration were already known variables from the measurements taken **(Yuhong, 2007).**

According to **Ronald (1977)** and **Yuhong (2007),** the best way of modeling was by considering different degrees of the selected model for comparison to select the best fit. Also, the developed model can be validated by one of the following methods:

i) comparison of the model predictions with physical theory,

ii) collection of new data to check model predictions,

iii) comparison of results with theoretical models and simulated data,

iv) Reservation of a portion of the available data to obtain an independent measure of the model prediction accuracy.

Hence the collected data was from ten (10) different locations with two locations from each of the five (5) zones of the study area. Data from four zones which was 80% of the total data was used for developing the model while the independent data from the fifth zone was used for validating the developed model.

4.5.1 Processing the Modeling Data and Validation Data

From Tables B1 to B10 in Appendix B, the average soil moisture and the Plantbot's speed were combined in pairs from five zones to obtain the average values for each of the zones. The average values from four of the five zones were used as the model development data while the remaining data from the fifth zone was used for model validation. The average values for these five zones were given in Table 4. 4 to Table 4.8.

Table 4.4 Average Soil Moisture and Speed of Eastern Zone

AVERAGE SOIL MOISTURE FOR EASTERN ZONE (in %)					AVERAGE SPEED FOR EASTERN ZONE (in rpm)		
S/NO	DBZ	DKZ	AVERAGE		DBZ	DKZ	AVERAGE
1	05.77	05.99	05.88		49.95	49.97	49.96
2	09.94	09.99	9.965		48.88	47.92	48.40
3	14.77	14.89	14.83		46.92	46.83	46.88
4	18.78	18.89	18.84		45.04	43.10	44.07
5	23.16	23.33	23.25		41.16	41.20	41.18
6	28.18	28.39	28.28		38.46	38.44	38.45
7	32.04	32.21	32.13		37.11	37.10	37.11
8	36.33	36.32	36.33		35.21	35.14	35.18
9	41.20	41.26	41.23		33.20	33.14	33.17
10	45.97	46.06	46.02		31.71	31.37	31.54

Table 4.5 Average Soil Moisture and Speed of Central Zone

AVERAGE SOIL MOISTURE FOR EASTERN ZONE (in %)					AVERAGE SPEED FOR EASTERN ZONE (in rpm)		
S/NO	BZZ	FMZ	AVERAGE		BZZ	FMZ	AVERAGE
1	05.90	05.85	05.88		49.83	49.55	49.69
2	10.02	10.00	10.01		48.00	48.05	48.03
3	14.89	14.98	14.94		46.81	46.63	46.72
4	18.96	19.16	19.06		43.02	43.08	43.05
5	23.23	23.22	23.23		41.14	41.31	41.23
6	28.21	28.35	28.28		38.41	38.45	38.43
7	32.09	32.35	32.22		36.92	36.78	36.85
8	36.62	36.48	36.55		35.20	35.24	35.22
9	41.28	41.53	41.42		33.14	32.99	33.07
10	46.13	45.98	46.05		31.32	31.17	31.25

Table 4.6 Average Soil Moisture and Speed of Southern Zone

AVERAGE SOIL MOISTURE FOR EASTERN ZONE (in %)		AVERAGE SPEED FOR EASTERN ZONE (in rpm)

S/NO	KKZ	KGZ	AVERAGE		KKZ	KGZ	AVERAGE
1	05.90	05.83	05.87		43.61	49.95	46.78
2	09.99	09.98	14.99		42.50	47.90	45.20
3	14.76	14.81	14.79		42.24	46.99	44.62
4	18.84	18.88	18.86		39.51	43.06	41.29
5	23.18	23.21	23.20		38.56	41.16	39.86
6	28.21	28.28	28.25		36.88	38.48	37.68
7	32.03	32.06	32.05		36.38	37.18	36.78
8	36.32	36.34	36.33		35.39	35.21	35.30
9	41.22	41.24	46.23		34.30	33.24	33.77
10	45.92	45.96	45.94		33.59	31.68	32.64

Table 4.7 Average Soil Moisture and Speed of Western Zone

AVERAGE SOIL MOISTURE FOR EASTERN ZONE (in %)					AVERAGE SPEED FOR EASTERN ZONE (in rpm)		
S/NO	TTZ	UDZ	AVERAGE		TTZ	UDZ	AVERAGE
1	05.88	05.87	05.88		49.99	49.96	49.98
2	10.00	09.99	09.99		47.94	47.91	47.93
3	14.82	14.82	14.82		46.96	46.97	46.97
4	18.89	18.91	18.90		43.08	43.01	43.05
5	23.22	23.17	23.20		41.22	41.18	41.20
6	28.24	28.32	28.28		38.46	38.53	38.50
7	32.10	32.08	32.09		37.18	37.23	37.21
8	36.36	36.34	36.35		35.19	35.13	35.16
9	41.25	41.24	41.25		33.25	33.21	33.23
10	45.97	45.95	45.96		31.60	31.61	31.61

Table 4.8 Average Soil Moisture and Speed of Northern Zone

AVERAGE SOIL MOISTURE FOR EASTERN ZONE (in %)					AVERAGE SPEED FOR EASTERN ZONE (in rpm)		
S/NO	DGZ	THZ	AVERAGE		DGZ	THZ	AVERAGE
1	5.91	5.911	05.91		50.06	50.07	50.07
2	9.99	10.01	10.00		47.93	47.97	47.95
3	14.79	14.81	14.80		46.94	47.13	47.04
4	18.88	18.89	18.89		43.03	43.03	43.03
5	23.23	23.20	23.22		41.17	41.2	41.19
6	28.31	28.28	28.23		38.52	38.53	38.53
7	32.19	32.17	32.18		37.24	37.20	37.22
8	36.35	36.35	36.35		35.16	35.29	35.23
9	41.21	41.26	41.24		33.12	33.12	33.12
10	46.01	46.01	46.01		31.61	31.66	31.64

4.5.2 Loading the Data to MATLAB Workspace

To start the modeling processing using the system identification toolbox of MATLAB, the data must be made available on the MATLAB workspace by importing or direct loading. The average values of the soil moisture and the corresponding average Plantbot's speed were loaded to the workspace of the MATLAB. These ten (10) sets of average values were named with zone – name followed by **moisture or speed** (e.g. ***EZMOISTURE, EZSPEED, where EZ means Eastern Zone*****)** for all the five zones. The loaded data is depicted on Fig. 4.8.

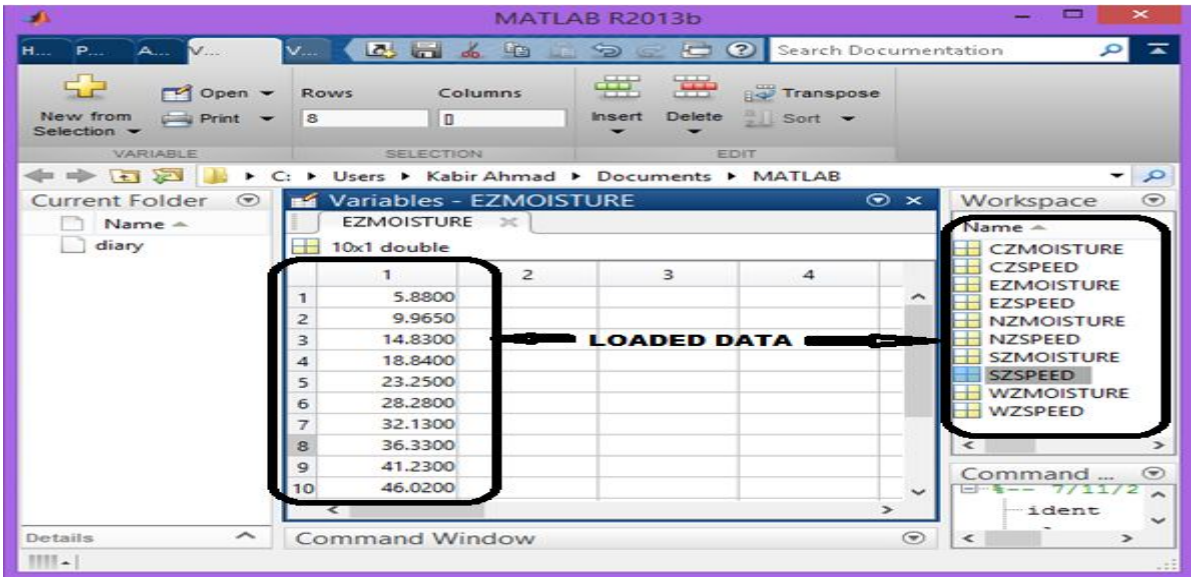


Fig. 4.8. Five Zones data loaded to MATLAB workspace

4.5.3 Model Development Using System Identification Toolbox

To start the model development process, the system identification toolbox was started and the data was imported to the toolbox as discrete time series data.

The moisture data is used as the input variable while the speed data was used as the output variable. The imported data for the five zones were named EZDATA, CZDATA, SZDATA, WZDATA and NZDATA as shown in Fig. 4.9.

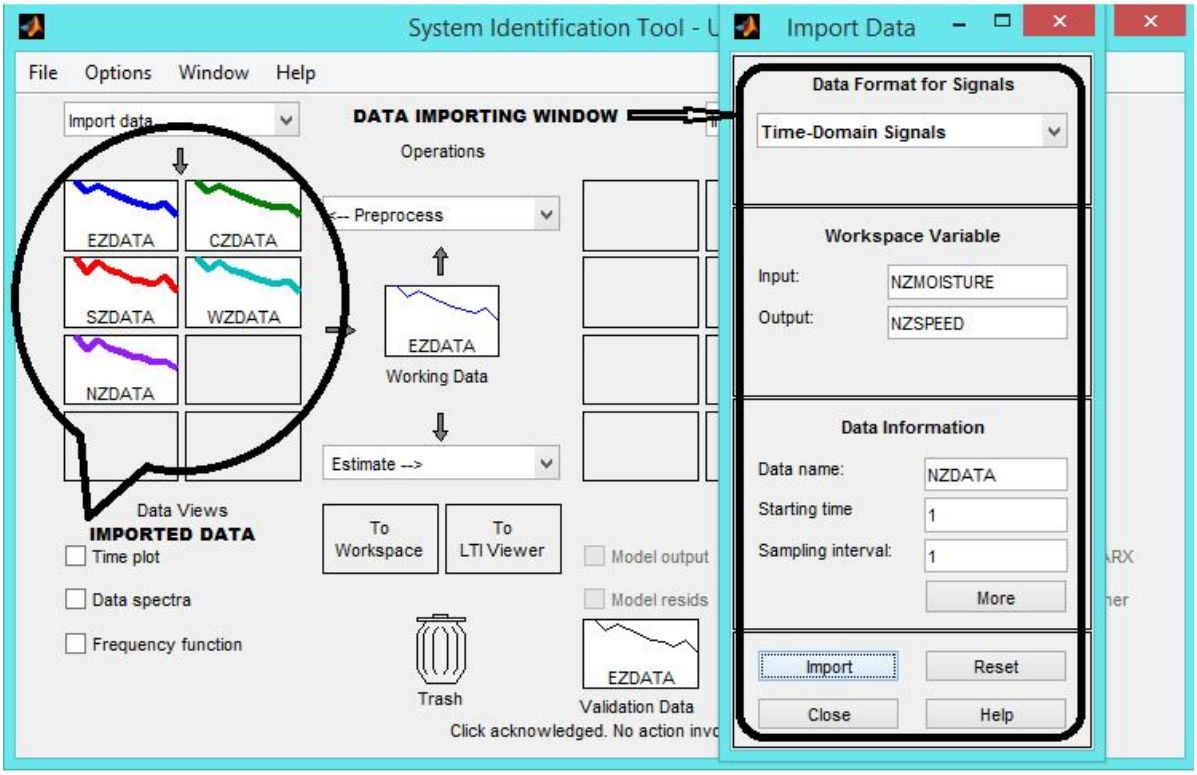


Fig. 4.9. Five – Zone Data Imported to System Identification Tool – Box

The imported data of the five zones was preprocessed in the toolbox by merging the data from four of the five zones to obtain the modeling data. The zones that were merged to be modeling data were EZDATA, CZDATA, SZDATA and WZDATA. The remaining data "NZDATA" was used as the validation data. The merged data was named MD – DATA (i.e. modeling data). The merging process is shown in Fig. 4.10.

The modeling data (MD-DATA) was moved to the working data location and the northern zone (NZDATA) was moved to validation data location of the system identification window as shown In Fig. 4.10.

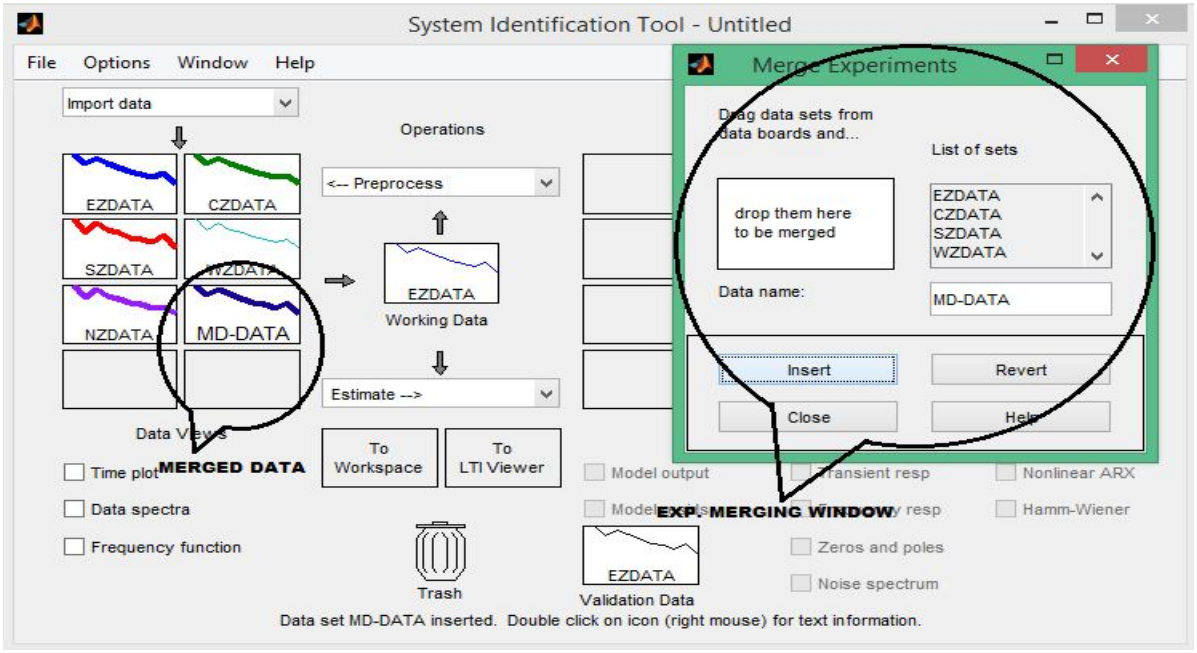


Fig. 4.10. Data (Experiments) Merging Process to Obtain Modeling data.

From the preliminary data analysis presented under section 4.4.2, it was seen that the data should be best modelled using linear parametric methods. Therefore, the model estimation was done by selecting parametric linear models from the drop down list under model estimation tap. The structure selected was Auto – Regressive with eXogenous input (for it has linear relation given by equation 4.7) (ARX: na nb nk) where "na nb nk" were the orders of the generic linear equation of the model given as:

$$\boldsymbol{Ay} = \boldsymbol{Bu} + \boldsymbol{e}$$

(4.7)

Where: **A** and **B** were constants coefficients of output **'y'** and input **'u'** respectively and **'e'** is error component of the model.

The ARX model was generated based on the orders of the constant orders "na nb nk"; each of them can have order from 1 to 10. The order was selected from the values given under parametric linear models window. Fig. 4.11 shows the models developed using different

orders selected. As it can be seen the 'nb' and 'nk' which were the orders of constants B and the fixed variable term respectively can take maximum powers of one (since the model was linear) but 'na' the order of 'A' for the output variable 'y' can take higher powers. This means that the model would have maximum of one zero and more than one pole.

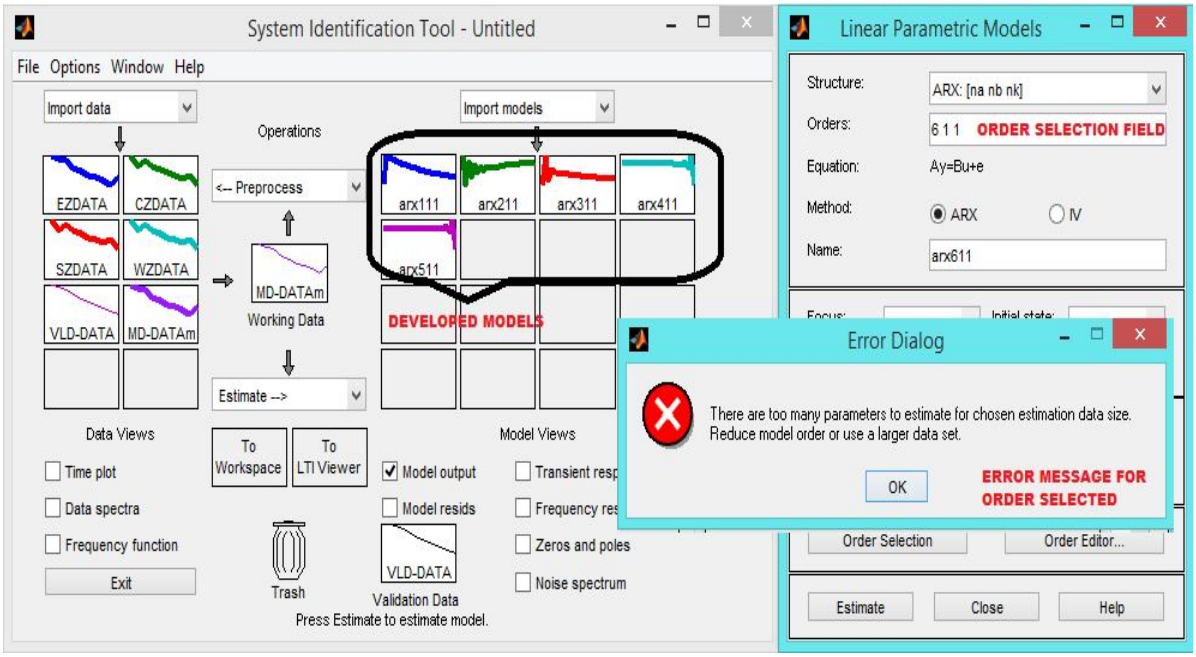


Fig. 4.11. Estimating models with different orders

As shown on Fig. 4.11 the possible models developed were **"arx111", "arx211", "arx311", "arx411" and "arx511".** This means orders of 'na' from 1 to 5. But when order of 6 for 'na' (for model **arx611**) was tried an error message was returned as shown on Fig. 4.11. This message says that it cannot take up to order of 6 for the data under consideration.

4.5.4 Validating the Developed Model

The developed model was validated using the separate validation data from the fifth zone (see section4.4) which was not among the four zones used for modeling. To do this, the validation data was already moved to the validation field of the system identification toolbox

window as shown on Fig. 4.12. To proceed for validation, the model output field (see Fig. 4.12) was checked which subsequently gives the plots of the models and the percentage fit of each model with respect to agreement between the simulated output and the validating data output. The validation result is shown in Fig. 4.12.

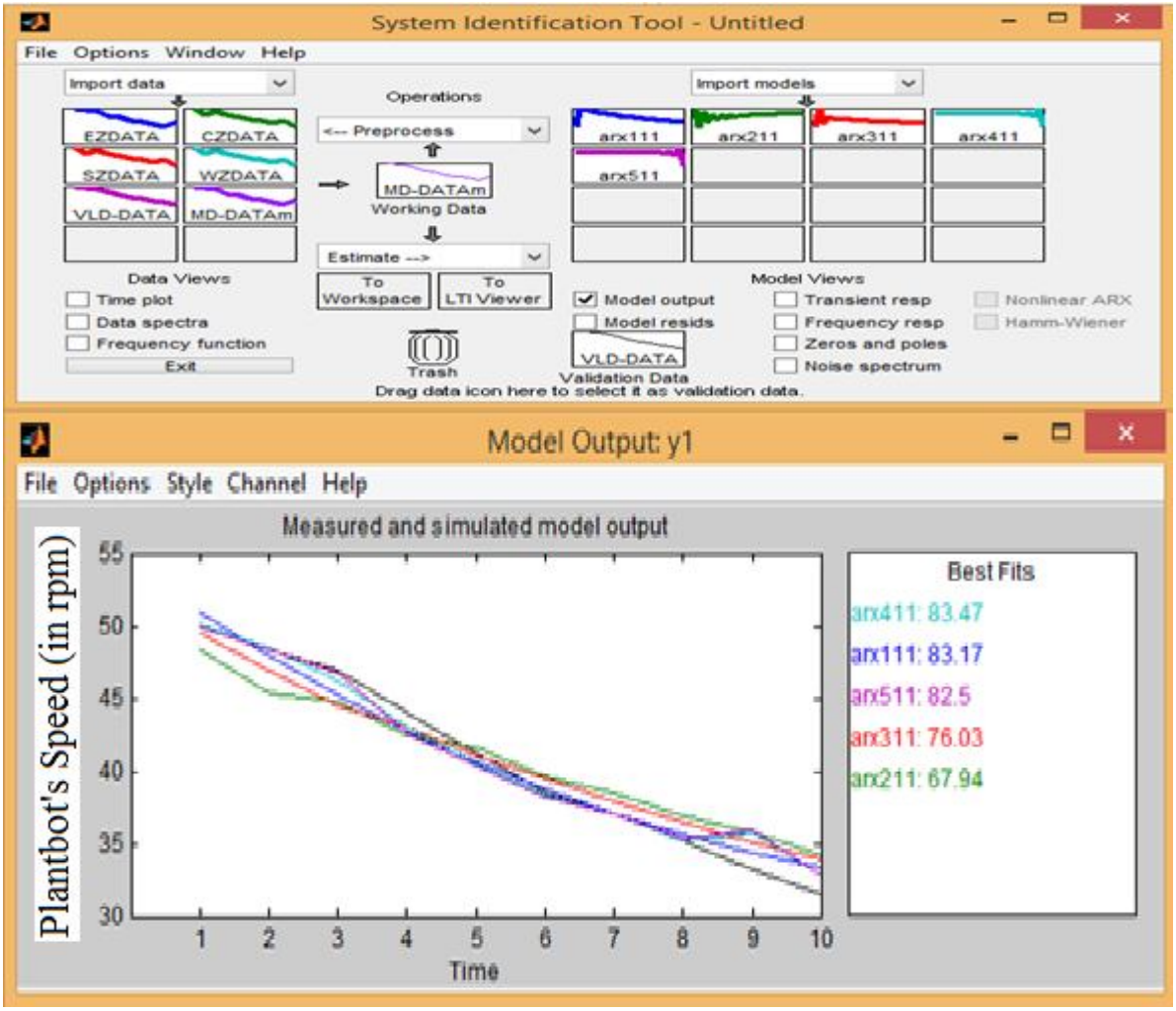


Fig. 4.12. Validation of the Developed Model

The validation was done by comparing the real measured output from the validation data against the simulated output from each of the five linear models. The output window gives the graphs of the five models compared with the graph of the measured validation

data. The modeling output was given by black line while the five models were given by five different colours as on the lower window of Fig. 4.12.

However, looking at the right hand side of the lower window of Fig. 4.12, the percentages of best fit of each of the five models were given. From the values it could be seen that model **'arx411'** has the highest value of best fit of 83.47%, followed by model **'arx111'** with best fit of 83.17%. Hence the best model selected was **'arx411'.**

This selected model has a very strong correlation coefficient of 0.835 (83.47%) and it was therefore concluded that this model was good enough and valid to be used as the representative of the system under consideration.

4.5.5 Determination of the Transfer Function of the Developed Model

The model developed under section 4.5.3 showed that a parametric linear model with structure ARX (na nb nk) was the best for the data at hand. Also five models of this type with different orders were developed and the validation results showed that the best of the five was **"arx411"** because it has highest best fit of 83.47%**.** From this model, 'na = 4' which was the order of the constant A in equation 4.7 and 'nb = 1' which was order of the constant B of the same equation. This orders suggest that the transfer function of the model should have maximum of one (1) zero and maximum of four (4) poles. Therefore, the transfer function developed as in Fig. 4.13 has one zero and four poles.

Fig. 4.13 shows the transfer function estimation window with four poles and one zero. The function was discrete, so discrete field was checked.

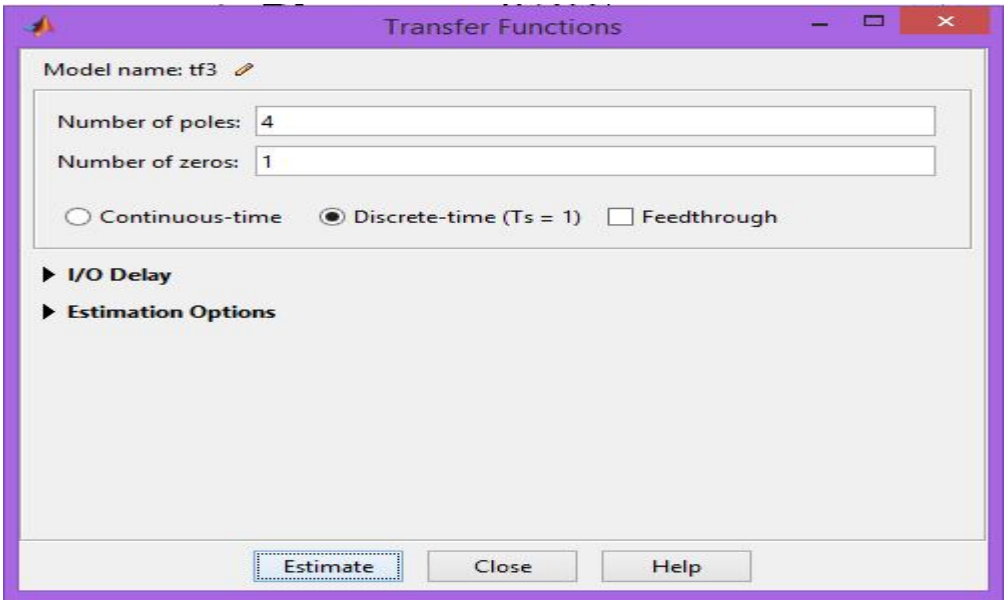


Fig. 4.13. Transfer Function Estimation Window

The estimation progress was shown in Fig. 4.14. The estimation was completed in total of twenty (20) iterations as can be seen in Fig. 4.14.

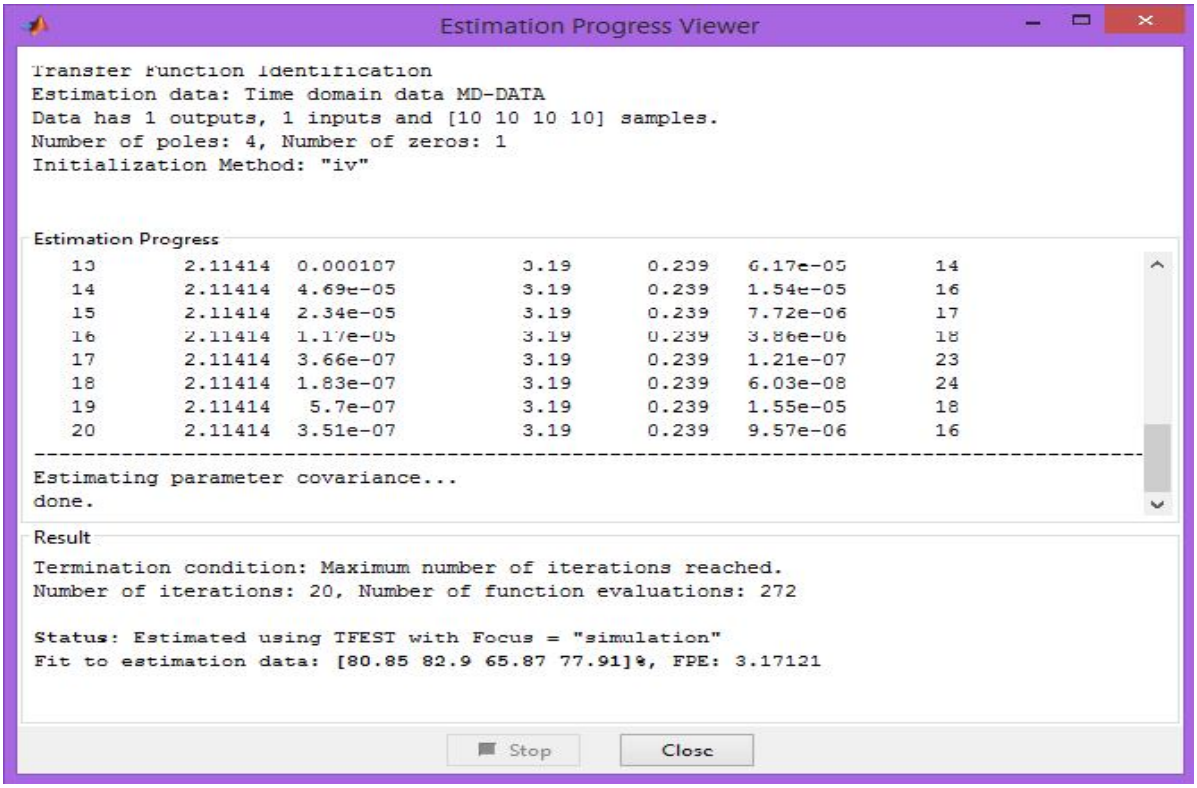


Fig. 4.14. Transfer Function Estimation Viewer

The transfer function developed was moved to the main workspace of the MATLAB for extraction. Fig. 4.15 shows the developed transfer function (tf1) being moved to the workspace.

The developed transfer function was called on the MATLAB command window by typing its name **'tf1'**. Fig. 4.16 shows the complete transfer function with summary of its basic properties.

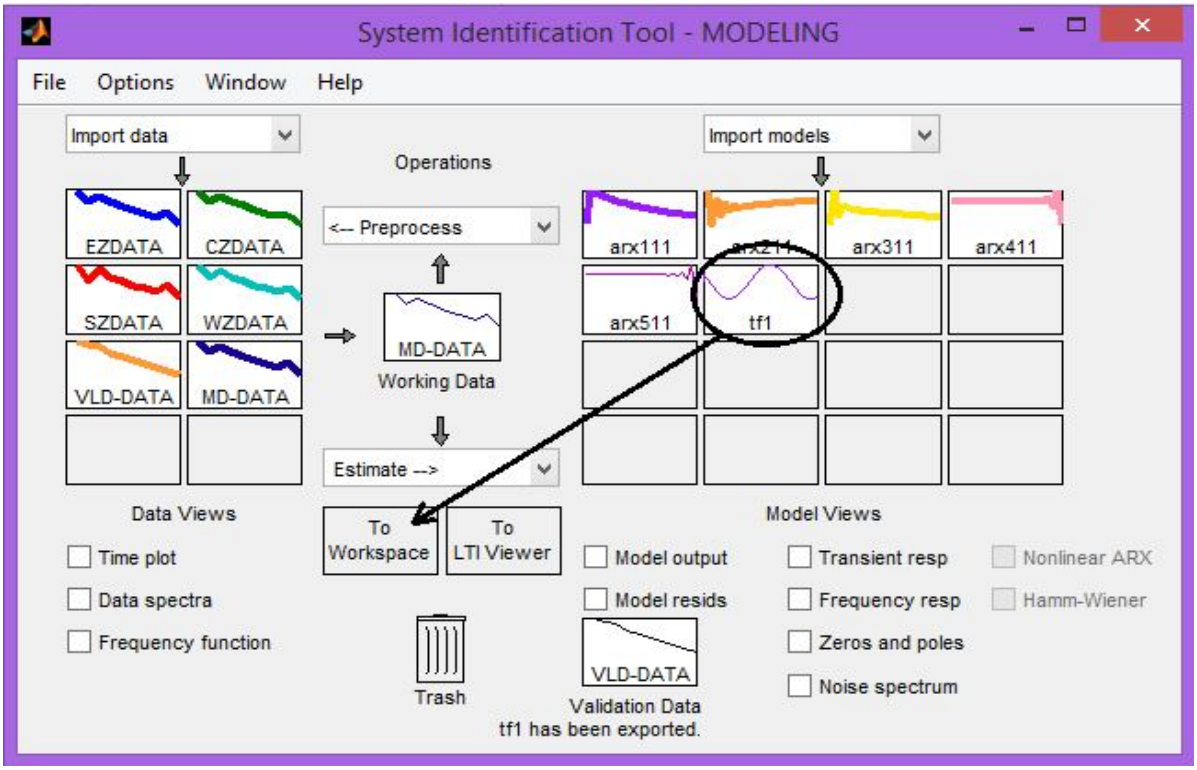


Fig. 4.15. Moving the Developed Transfer Function (tf1) to the Workspace.

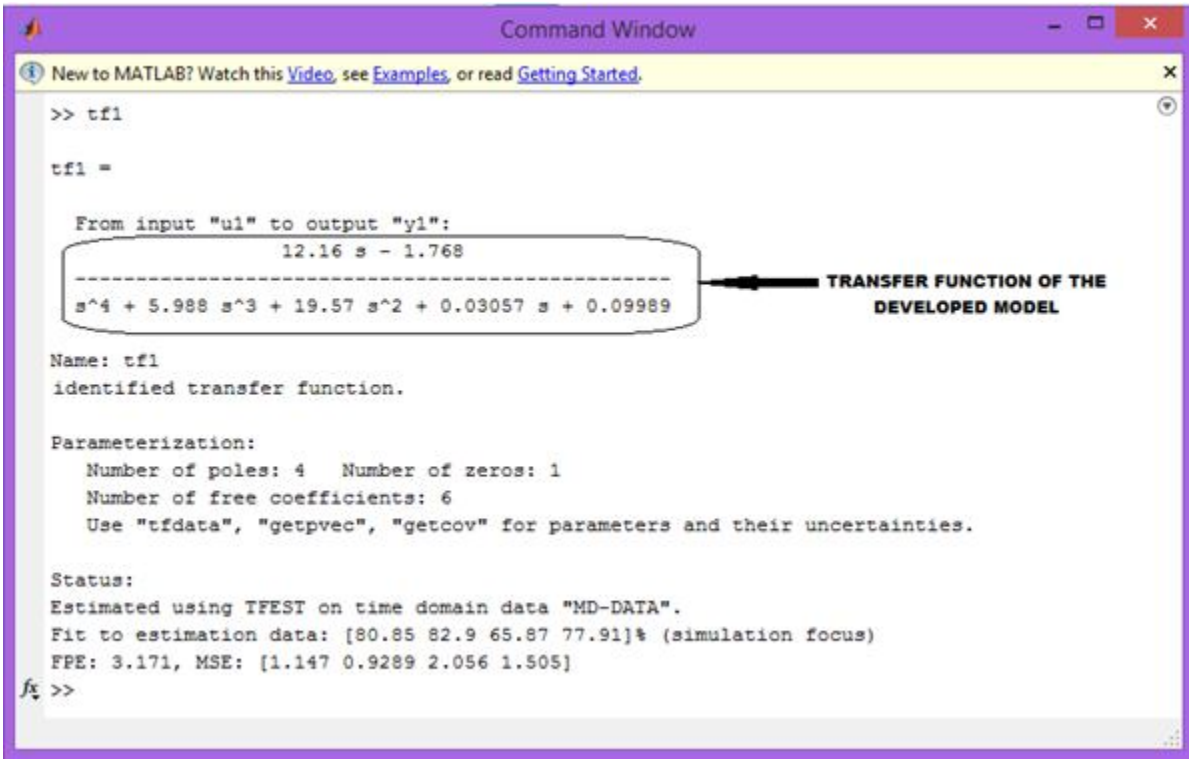


Fig. 4.16. Model's Transfer Function with its Basic Features

This transfer function gives the ratio of the output variable (Speed of the Plantbot) to the input variable (Soil Moisture of the Environment). Using this result in future works, a controller can be designed to keep the speed of the Plantbot constant as the soil moisture of the environment varies.

The transfer function relating the speed of the Plantbot and the soil moisture of the case study area was given as:

$$\boldsymbol{T_s = \frac{12.16s - 1.768}{s^4 + 5.988s^3 + 19.57s^2 + 0.03057s + 0.09989}}$$

(4.8)

This transfer function can subsequently be used to design a controller for the Plantbot to ensure that the speed was maintained for any change in the soil moisture.

4.6 MECHANICAL DESIGN RESULTS DISCUSSION

The main drive motor of the Plantbot has power requirement of 330.76W from the calculations and efficiency of 85%. Based on this, a 1 horse-power (746W) with 90% efficiency was selected as the main motor. This makes the Plantbot more reliable since the selected motor has capacity of more than twice the maximum calculated required power by the Plantbot and it has higher efficiency of 90%. Also the steering motor need 15.83W from calculations, but 25W motor was used and planting mechanism control motor needs 61.98W but 75W motor was used for better reliability.

The minimum critical value of the factor of safety that shows safety of the joint is unity (1), but in this work 3.5 factor of safely was achieved which makes the Plantbot of better safety.

The maximum torque (T_{max}) with respect to the given maximum shear stress was obtained as 2173.6Nm, while the maximum torque was also calculated with respect to the maximum angle of twist as 2385.9N.m. The smaller value (2173.6N.m) was used to make it safe from both shear stress and angle of twist.

The torque acting on the driven shaft was calculated as **63.12Nm,** was very much less than the maximum allowed value of **2173.6N.m** (Alan, 2008) which means the Plantbot is free from failure due to excess torque on the shaft.

The critical speed of the shaft above which can cause failure was calculated as 926rpm, but the designed value of the speed was only 50rpm. This result confirms that the shaft is safe from failure due to over speed. The shear stress due to torsion was determined as 78.69MPa but the maximum allowed is 410MPa (McGraw Hill Machine Design Data

book, 2004). This results confirms that the Plantbot is not likely to have weld failure due to excess torsion stress.

Design calculations showed that rear wheels bearing and front wheels bearings can carry loads of 3.5 x 10^5kg and 1.56 x 10^4kg respectively without failure for their life spans of 17.1 years and 5.45 years respectively, but the overall mass of the Plantbot is about 50kg. This signifies that the loading condition of the bearings were not violated and the Plantbot would be more reliable in this respect. Also the rear and front wheels bearings have 6% and 5% respectively of chance of failure which means the failure was much unlikely.

The maximum dynamic force from the torque of the motor was calculated as 37.36N and this was far less than the minimum calculated value (2880N) of force that can cause shearing of the planting mechanism holder. So the planting mechanism is safe from shearing based on this results.

4.7 BLUETOOTH CONTROL DESIGN RESULTS DISCUSSION

The Bluetooth headset module used was E9 with the highest range of control of 60.96m (200 feet) which makes the control distance of the Plantbot averagely high (57.96m) compared to the small sizes in farms in the study area. DTMF booster circuit designed in the work, help in counteracting the effect of attenuation on the range of the Bluetooth control on the Plantbot.

The microcontroller circuit designed makes the DTMF control possible by interpreting the four bit command signal received for controlling particular motor on the Plantbot.

The overall range of Bluetooth control of Plantbot during preliminary tests achieved was 57.54 m (188.78 feet) which was 94.39% of the rated range of 60.96 m (200 feet). The overall average speed of the Plantbot obtained from the experimental results was 30.70cm/s which was 85.26% of the design value (36cm/s). These values showed that performance of the Plantbot were within a reasonable range.

4.8 ENVIRONMENTAL BEHAVIOUR MODELING RESULTS DISCUSSION

The percentage of successful planting was obtained as 89.8% (hence unsuccessful planting was 10.2%) and percentage of planting exactly two seeds per hole was 86.6% (hence planting more than two seeds was 13.4%). These evaluated percentage of unsuccessful planting (**10.2%**) and percentage of planting more than two seeds (multiple index) (**13.4%**) showed significant improvement from the previous literatures reviewed.

The range of Bluetooth control of the Plantbot on daily basis was obtained as 57.450m which was about 94% of the rated range for Bluetooth module E9 (61m) used in this work. And the range over a period of seven days remains almost the same since the difference between the highest and the lowest was only 0.41%. The range of Bluetooth control in environments prone to noise and interference and those free from noise and interference were almost the same since the percentage difference between the two environments was only 0.071% which shows insignificant difference.

Preliminary investigation of the data relating moisture content of the soil and the speed of the Plantbot shows linear relationship between the two parameters (as shown by Fig. 4.3 to Fig. 4.7).

The linear models developed using system identification toolbox was of ARX structure and it has orders from 1 to 4 (arx111, arx211, arx311 and arx411) but the validation results shows that model “arx411” has the highest best fit of 83.47% which makes it acceptable for it has very strong correlation coefficient of 0.835 when compared with the validation data. The transfer function of the model (arx411) was developed with one zero and four poles. This transfer function can be used to design a controller for keeping the speed constant with changes of the moisture content of the soil.

4.9 SUMMARY OF DESIGN RESULTS

The high percentage of successful planting was obtained as 89.8% and percentage of planting exactly two seeds per hole was 86.6% showed better performance compared to previous works.

The range of Bluetooth control of the Plantbot on daily basis was obtained as 57.61m (189.013 feet) and the range of Bluetooth control based on locations showed insignificant difference.

The linear models developed using system identification toolbox was of ARX structure showed that model “arx411” has the highest best fit of 83.47% which makes it acceptable for it has very strong correlation coefficient of 0.835 when compared with the validation data. The transfer function of the model could be used to design a controller for keeping the speed constant with changes of the moisture content of the soil.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

5.1 INTRODUCTION

This chapter gives the general conclusions on the work done and the results obtained at the end of the work. It also gives the basic limitations of the work as well as fundamental recommendations for further work to be done in this area.

5.2 CONCLUSIONS

The aim of this work as stated earlier was to design a Bluetooth controlled planter robot to be used for planting maize as a case study since it is the predominant crop in the study area (Zaria); and to model the behaviour of the robot as it interacts with the environment where it operates and to validate the model. The aim was intended to be achieved through the following objectives:

1. Detailed mechanical design of the Plantbot in step by step procedure, development of complete engineering drawing of the Plantbot from the design and construction of the machine based on the engineering drawing. This objective was achieved through the mechanical design carried out as shown under Materials and Methods presented in chapter three. The results obtained were based on repetitive iterations process and satisfying established design rules and safety conditions.
2. Detailed design of the Bluetooth control section used for controlling the Plantbot remotely with transmission range of 61 m (200 feet); interfacing the control section with the mechanical section; and testing the prototype Plantbot. This objective was achieved as shown under chapter three (Materials and Methods) through the design

of the Bluetooth controlled circuit in step by step approach and using fundamental design procedures and constructing the designed circuit and testing to confirm its workability. The constructed control circuit was then interfaced with the mechanical part and the prototype was tested in field. The results obtained from the testing (control distance of 57.61m (189.013 feet) about 94% of the rated value and no significant variation with locations) were very satisfactory because of their close agreement with the design goals.

3. Environmental Behaviour Modelling of the Plantbot through: carrying out experiments with the coupled Plantbot to investigate its planting performance, Bluetooth control range and development of its environmental behaviour model using MATLAB System Identification Toolbox and Statistical tools. This objective was averagely achieved as presented in chapter four. The planting performance achieved greater than 90% and the Bluetooth range achieved was also above 90% and the percentages of unsuccessful planting (10.2%) and multiple seed index planting (13.4%) were very low compared with the previous relevant works. The model developed was also very acceptable based on the high best fit obtained (83.47%). The best model helped in obtaining transfer function which could be used for controller design.

In view of the foregoing, it is reasonable that the overall aim and objectives of this research work have been broadly met.

5.3 LIMITATIONS OF THE WORK

This work, development of a planter robot for planting maize has many significances as outlined earlier and at the same time has some limitations to its performance. The basic limitations of this work are outlined as follows:

1. The operation of the Plantbot is semi –autonomous since the machine is controlled remotely through Bluetooth medium.
2. It does not have capability of obstacle avoidance while in operation and it does not have sensors to enable it follow the desired line autonomously.
3. It does not have adaptive capability to enable it automatically adapt to different environments and crops.
4. Its operational speed is affected by the variation of soil moisture content of the environment.

5.4 RECOMMEDATIONS FOR FURTHER WORK

Any research conducted in any field must have some fundamental limitations which create room for further work to be done in that same area with the aim of improving on the current work.

The following are some of the recommended works that can be carried out in this field to improve on the current work:

1. Development of a fully autonomous Plantbot with obstacle and line – following sensors.

2. Development of Plantbot with adaptive capabilities (i.e. abilities to adapt to environment, crop type, etc.
3. Development of a feedback optimal controller for the Plantbot to ensure that the speed is maintained constant in the presence of varying soil moisture content depending on the operational environment.

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APPENDIX A

GENERAL ENGINEERING DRAWINGS OF THE PLANTBOGT FROM DRW1 TO DRW8

APPENDIX B

The assembly language program for the PIC16F84A microcontroller;

```
BLUETOOTH - DTMF PLANTBOT CONTROL PROGRAM   ;date: 16-10-2012
;crystal - 16mhz
;IC - PIC16F84A
__config 0x0002
LIST   P=PIC16F84A
include "p16f84a.inc"
Zs macro
btfss STATUS,Z
endm
Zc macro
btfsc STATUS,Z
ENDM
Cs macro
btfss STATUS,C
endm
Cc macro
btfsc STATUS,C
endm
#define bank0 bcf STATUS,RP0
#define bank1 bsf STATUS,RP0
;#define digit1con subPORTA,0
;#define digit2con subPORTA,1
;#define digit3con subPORTA,2
;#define digit4con subPORTA,3
;#define turnout subPORTA,4
;#define adjplusbutton PORTB,4
;#define adjminusbutton PORTB,5
;#define modebutton PORTB,6
#define pin1on bsf subPORTB,0
#define pin2on bsf subPORTB,1
#define pin3on bsf subPORTB,2
#define pin4on bsf subPORTB,3
#define pin5on bsf subPORTB,4
#define pin6on bsf subPORTB,5
#define pin7on bsf subPORTB,6
#define pin8on bsf subPORTB,7
#define allpinsoff clrf subPORTB
```

```
#define offflag genreg,0
cblock 0x0C
genreg
datareg
subPORTB
delaycount1
delaycount2
STATUS_temp
w_temp
endc
                org 0h
                goto  start             ;goto start
                org  4h             ;org 4h
                movwf  w_temp               ;movwf w_temp
                swapf  STATUS,w             ;swapf STATUS,w
                movwf  STATUS_temp              ;movwf STATUS_temp
                bank0               ;bank0
                movlw  .7               ;movlw .7
                movwf  TMR0             ;movwf TMR0
                bcf  INTCON,02H             ;bcf INTCON,02H
                btfss offflag               ;if offflag = 1 then
                goto lbl0
                incfsz  delaycount1,f               ;incfsz delaycount1,f
                goto  i1                ;goto i1
                incf  delaycount2,f             ;incf delaycount2,f
i1
                movlw .3                ;if delaycount2 = 3 and delaycount1 = 232 then
                subwf delaycount2,w
                btfss STATUS,Z
                goto lbl1
                movlw .232              ;and delaycount1 = 232 then
                subwf delaycount1,w
                btfss STATUS,Z
                goto lbl1
                clrf delaycount1                ;delaycount1 = 0
                clrf delaycount2                ;delaycount2 = 0
                bcf offflag             ;offflag = 0
                allpinsoff              ;allpinsoff
lbl1
```

```
lbl0
            movf subPORTB,w             ;PORTB = subPORTB
            movwf PORTB
            swapf  STATUS_temp,w            ;swapf STATUS_temp,w
            movwf  STATUS             ;movwf STATUS
            swapf  w_temp,f             ;swapf w_temp,f
            swapf  w_temp,w             ;swapf w_temp,w
            retfie            ;retfie
start        bank1            ;bank1
            movlw  b'00011111'            ;movlw b'00011111'
            movwf  TRISA            ;movwf TRISA
            movlw  b'00000000'            ;movlw b'00000000'
            movwf  TRISB            ;movwf TRISB
            movlw  b'11010010'            ;movlw b'11010010'
            movwf  OPTION_REG             ;movwf OPTION_REG
            bank0            ;bank0
            clrf  subPORTB            ;clrf subPORTB
            clrf  PORTB             ;clrf PORTB
            bsf  INTCON,GIE             ;bsf INTCON,GIE
            bsf  INTCON,T0IE             ;bsf INTCON,T0IE
            bcf  INTCON,02H             ;bcf INTCON,02H
            clrf  genreg            ;clrf genreg
            clrf  datareg             ;clrf datareg
            clrf  delaycount1             ;clrf delaycount1
            clrf  delaycount2             ;clrf delaycount2
main
            movf  PORTA,w             ;movf PORTA,w
            movwf  datareg            ;movwf datareg
            btfss datareg,4             ;if datareg,4 = 1 then
            goto lbl2
            bcf  datareg,4            ;bcf datareg,4
            movlw b'00000000'             ;if datareg = b'00000000' then
            subwf datareg,w
            btfss STATUS,Z
            goto lbl3
            goto lbl4
lbl3
            movlw b'00000001'             ;elseif datareg = b'00000001' then
            subwf datareg,w
```

```
        btfss STATUS,Z
        goto lbl5
        allpinsoff          ;allpinsoff
        bcf offflag         ;offflag = 0
        pin1on          ;pin1on
        goto lbl4
lbl5
        movlw b'00000010'           ;elseif datareg = b'00000010' then
        subwf datareg,w
        btfss STATUS,Z
        goto lbl6
        allpinsoff          ;allpinsoff
        bcf offflag         ;offflag = 0
        pin2on          ;pin2on
        goto lbl4
lbl6
        movlw b'00000011'           ;elseif datareg = b'00000011' then
        subwf datareg,w
        btfss STATUS,Z
        goto lbl7
        allpinsoff          ;allpinsoff
        bcf offflag         ;offflag = 0
        pin3on          ;pin3on
        goto lbl4
lbl7
        movlw b'00000100'           ;elseif datareg = b'00000100' then
        subwf datareg,w
        btfss STATUS,Z
        goto lbl8
        allpinsoff          ;allpinsoff
        bcf offflag         ;offflag = 0
        pin4on          ;pin4on
        goto lbl4
lbl8
        movlw b'00000101'           ;elseif datareg = b'00000101' then
        subwf datareg,w
        btfss STATUS,Z
        goto lbl9
        allpinsoff          ;allpinsoff
```

```
                bcf offflag             ;offflag = 0
                pin5on          ;pin5on
                goto lbl4
lbl9
                movlw b'00000110'               ;elseif datareg = b'00000110' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl10
                allpinsoff              ;allpinsoff
                bcf offflag             ;offflag = 0
                pin6on          ;pin6on
                goto lbl4
lbl10
                movlw b'00000111'               ;elseif datareg = b'00000111' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl11
                allpinsoff              ;allpinsoff
                bcf offflag             ;offflag = 0
                pin7on          ;pin7on
                goto lbl4
lbl11
                movlw b'00001000'               ;elseif datareg = b'00001000' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl12
                allpinsoff              ;allpinsoff
                bcf offflag             ;offflag = 0
                pin8on          ;pin8on
                goto lbl4
lbl12
                movlw b'00001001'               ;elseif datareg = b'00001001' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl13
                goto lbl4
lbl13
                movlw b'00001010'               ;elseif datareg = b'00001010' then
                subwf datareg,w
```

```
                btfss STATUS,Z
                goto lbl14
                goto lbl4
lbl14
                movlw b'00001011'       ;elseif datareg = b'00001011' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl15
                goto lbl4
lbl15
                movlw b'00001100'       ;elseif datareg = b'00001100' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl16
                goto lbl4
lbl16
                movlw b'00001101'       ;elseif datareg = b'00001101' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl17
                goto lbl4
lbl17
                movlw b'00001110'       ;elseif datareg = b'00001110' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl18
                goto lbl4
lbl18
                movlw b'00001111'       ;elseif datareg = b'00001111' then
                subwf datareg,w
                btfss STATUS,Z
                goto lbl19
lbl4
lbl19
                goto lbl20
lbl2                    ;else
                bsf offflag             ;offflag = 1
lbl20
                goto  main              ;goto main
                end             ;end
```

APPENDIX C

The HEX version of the program for PIC microcontroller.

```
:020000040000FA
:020000002328B3
:080008009200030E9100831227
:10001000073081000B110C1C1C288F0F1028900A30
:1000200003301002031D1C28E8300F02031D1C289A
:100030008F0190010C108E010E088600110E8300B6
:10004000920E120E090083161F30850000308600C4
:10005000D230810083128E0186018B178B160B1113
:100060008C018D018F01900105088D000D1EA128C6
:100070000D1200300D02031D3E28A02801300D0294
:10008000031D46288E010C100E14A02802300D020C
:10009000031D4E288E010C108E14A02803300D0273
:1000A000031D56288E010C100E15A02804300D02D9
:1000B000031D5E288E010C108E15A02805300D0240
:1000C000031D66288E010C100E16A02806300D02A6
:1000D000031D6E288E010C108E16A02807300D020D
:1000E000031D76288E010C100E17A02808300D0273
:1000F000031D7E288E010C108E17A02809300D02DA
:10010000031D8328A0280A300D02031D8828A0287B
:100110000B300D02031D8D28A0280C300D02031D8D
:100120009228A0280D300D02031D9728A0280E301C
:100130000D02031D9C28A0280F300D02031DA028CE
:06014000A2280C14342873
:02400E000200AE
:00000001F
```

APPENDIX D.

TABLE D1: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT DAMBO ZARIA (DBZ)

DAY 1								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.20	05.40	05.38	05.33	50.24	50.12	49.70	50.02
2	09.72	09.94	09.86	09.84	47.72	48.02	47.74	47.83
3	14.24	14.32	14.34	14.30	45.76	47.54	47.34	46.88
4	18.80	18.76	18.90	18.82	43.52	43.06	43.28	43.29
5	23.16	23.34	23.24	23.25	40.58	41.42	41.30	41.10
6	27.72	27.82	27.72	27.75	38.42	39.08	39.06	38.85
7	32.34	32.18	32.28	32.27	37.20	38.08	37.32	37.53
8	36.84	36.72	36.72	36.76	34.84	35.52	35.76	35.37
9	41.28	41.26	41.24	41.26	33.54	33.24	33.24	33.34
10	45.92	45.74	45.88	45.85	32.26	32.32	31.58	32.05

DAY 2								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.44	05.40	05.42	05.42	49.96	50.34	50.10	50.13
2	09.82	09.88	09.68	09.79	48.02	47.84	47.80	47.89
3	14.42	14.40	14.52	14.45	46.04	47.46	46.92	46.81
4	18.68	18.78	18.94	18.80	43.88	42.48	42.94	43.10
5	23.22	23.40	23.30	23.31	40.82	40.86	41.82	41.17
6	27.68	27.84	27.80	27.77	38.84	38.78	38.94	38.85
7	32.40	32.22	32.32	32.31	37.44	37.62	36.86	37.31
8	36.76	36.80	36.82	36.79	34.90	34.68	35.48	35.02
9	41.18	41.34	41.30	41.27	33.90	32.84	32.68	33.14
10	45.90	45.82	45.92	45.88	31.84	31.68	31.84	31.79

DAY 3								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.82	05.58	05.66	05.69	50.42	49.86	49.98	50.09
2	10.02	09.94	09.72	09.89	47.88	48.20	48.34	48.14
3	14.84	14.88	13.96	14.56	45.84	46.92	46.94	46.57
4	17.98	18.78	18.66	18.47	43.64	43.06	43.12	43.27
5	22.88	23.48	22.54	22.97	40.74	40.54	40.96	40.75
6	27.68	28.12	27.46	27.75	38.66	37.94	38.58	38.39
7	31.94	31.86	31.78	31.86	36.96	37.38	36.96	37.10
8	36.72	36.76	35.96	36.48	35.06	34.94	34.88	35.02

9	40.94	40.86	41.42	41.07	33.86	33.16	32.84	33.29
10	45.58	45.94	45.68	45.73	31.68	32.04	31.78	31.83

DAY 4

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.04	05.62	05.86	05.84	49.34	50.14	50.22	49.90
2	09.84	10.14	09.84	09.94	48.34	47.88	47.98	48.07
3	15.06	14.92	14.64	14.87	46.06	47.42	47.20	46.89
4	18.10	19.24	18.90	18.75	42.92	43.24	42.96	43.04
5	23.20	23.22	23.16	23.19	41.02	40.84	41.16	41.01
6	28.44	28.48	28.12	28.35	38.74	37.98	37.88	38.20
7	32.24	32.16	31.96	32.12	36.54	37.48	37.14	37.05
8	35.88	36.48	36.24	36.20	35.12	34.88	35.36	35.12
9	41.26	40.92	41.64	41.27	33.76	33.38	33.22	33.45
10	46.20	45.92	46.32	46.15	31.80	32.12	31.96	31.96

DAY 5

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.04	05.94	06.10	06.03	49.42	49.86	50.48	49.92
2	10.02	09.88	10.12	10.01	47.86	47.94	47.90	47.90
3	14.82	15.10	14.90	14.94	46.94	47.54	47.42	47.30
4	19.04	18.66	18.78	18.83	43.34	43.10	42.84	43.09
5	22.96	23.34	22.84	23.05	41.62	41.12	41.72	41.49
6	27.92	28.66	28.34	28.31	37.98	37.84	37.92	37.91
7	31.82	32.22	31.88	31.97	36.82	36.96	37.28	37.02
8	35.94	36.54	35.90	36.13	35.34	34.74	35.60	35.23
9	41.44	41.32	41.86	41.54	32.98	33.44	33.52	33.31
10	46.40	46.14	45.98	46.17	31.74	31.68	31.98	31.80

DAY 6

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.92	06.02	05.88	05.94	48.86	50.24	50.16	49.75
2	09.88	10.10	09.94	09.97	46.90	47.88	47.68	47.49
3	15.20	15.22	14.98	15.13	47.02	46.34	47.34	46.90
4	18.68	18.76	18.84	18.76	42.96	43.22	41.88	42.69
5	23.24	23.22	22.92	23.13	41.38	41.46	40.84	41.23
6	28.32	28.44	28.50	28.42	38.44	38.26	38.14	38.28
7	31.64	31.72	31.54	31.63	37.34	36.88	36.88	37.03

8	35.78	35.72	35.88	35.79	34.98	35.26	35.72	35.32
9	40.82	40.98	41.48	41.09	32.94	32.86	32.96	32.92
10	45.66	46.54	45.86	46.02	30.98	31.54	31.86	31.46

DAY 7								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.14	06.08	06.10	06.11	49.72	49.38	50.34	49.81
2	10.12	10.04	10.24	10.13	47.94	48.24	47.38	47.85
3	15.42	14.96	15.08	15.15	46.94	46.66	47.62	47.07
4	19.14	19.12	18.92	19.06	43.24	42.86	42.20	42.77
5	22.88	23.34	23.42	23.21	40.48	41.74	41.92	41.38
6	29.16	28.62	28.88	28.89	39.22	38.34	38.62	38.73
7	32.22	31.90	32.28	32.13	36.76	36.58	36.94	36.76
8	36.14	35.98	36.28	36.13	34.86	35.34	35.98	35.39
9	40.90	41.04	40.78	40.91	33.38	32.26	33.12	32.92
10	45.92	45.94	46.12	45.99	30.88	30.82	31.58	31.09

TABLE D2: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT DAKACE ZARIA (DKZ)

DAY 1								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.10	05.82	06.02	05.98	49.82	50.20	49.94	49.99
2	10.24	09.94	10.54	10.24	48.20	48.14	47.66	48.00
3	15.28	14.64	14.56	14.83	46.12	47.68	47.22	47.01
4	19.22	18.88	19.12	19.07	42.98	43.26	43.34	43.19
5	23.54	24.62	23.86	24.01	41.06	41.64	41.58	41.43
6	28.48	27.90	28.22	28.20	38.86	38.86	39.22	38.98
7	33.10	32.44	32.62	32.72	37.44	37.84	37.92	37.73
8	37.02	36.54	36.80	36.79	34.68	34.94	35.96	35.19
9	42.12	41.76	41.52	41.80	33.68	32.86	33.58	33.37
10	45.84	46.02	45.92	45.93	31.78	31.68	31.74	31.73

DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.68	06.10	05.86	05.88	48.98	49.88	50.32	49.73
2	09.82	10.24	09.68	09.91	48.46	48.38	48.10	48.31
3	15.24	14.62	14.84	14.90	46.24	46.86	46.84	46.65
4	19.34	18.84	18.68	18.95	44.22	43.14	42.26	43.21

5	24.14	23.60	22.84	23.53	40.54	41.16	41.56	41.09
6	28.34	28.04	27.32	27.90	39.10	38.54	39.02	38.89
7	32.72	33.06	32.54	32.77	37.32	38.14	37.36	37.61
8	35.98	36.56	36.74	36.43	34.76	35.02	34.98	34.92
9	41.38	40.12	41.44	40.98	32.96	32.54	33.14	32.88
10	46.28	46.36	45.74	46.13	30.96	31.86	31.58	31.47
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.94	05.88	06.14	05.99	48.94	49.96	50.22	49.71
2	09.84	10.12	09.86	09.94	47.92	47.84	48.62	48.13
3	13.98	14.54	14.22	14.25	46.14	45.98	46.84	46.32
4	18.32	17.86	17.84	18.01	42.88	43.34	42.94	43.05
5	23.04	23.18	22.66	22.96	41.32	40.92	41.26	41.17
6	27.76	27.74	27.68	27.73	37.98	37.86	37.94	37.93
7	32.24	31.68	31.82	31.91	37.04	36.84	36.64	36.84
8	35.90	36.82	36.04	36.25	35.28	34.88	35.26	35.14
9	40.86	41.22	41.64	41.24	33.74	32.66	32.92	33.11
10	46.24	45.76	46.18	46.06	30.94	31.84	31.84	31.54
DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.90	06.08	06.10	06.03	50.18	50.32	50.16	50.22
2	09.78	10.22	10.06	10.02	48.42	47.94	47.86	48.07
3	15.12	15.22	14.82	15.05	46.24	48.32	47.74	47.43
4	18.66	19.22	19.24	19.05	42.88	42.94	42.78	42.87
5	24.04	23.56	22.96	23.52	41.24	41.32	41.24	41.27
6	28.36	29.02	28.24	28.54	38.36	38.24	37.92	38.17
7	32.36	31.84	32.12	32.11	36.86	36.97	37.5	37.11
8	36.24	36.46	36.12	36.27	35.37	35.13	34.87	35.12
9	41.18	40.86	41.46	41.17	33.97	32.89	33.47	33.44
10	46.34	46.20	46.18	46.24	31.65	31.87	30.89	31.47

DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	06.05	06.13	06.01	50.20	49.94	50.54	50.23
2	09.83	09.97	10.03	09.94	48.34	47.78	47.94	48.02
3	14.95	14.91	14.96	14.94	46.87	46.84	47.64	47.12

4	19.04	19.13	18.69	18.95	43.41	42.88	42.93	43.03
5	22.75	22.88	22.79	22.81	41.76	40.13	41.75	41.21
6	28.21	28.57	28.52	28.43	38.25	37.93	37.87	38.02
7	31.93	31.72	31.89	31.85	36.56	37.22	37.17	36.98
8	35.88	36.75	36.25	36.29	35.24	35.12	35.23	35.20
9	40.37	41.53	41.92	41.27	32.75	33.38	33.75	33.29
10	46.64	45.55	45.87	46.02	30.95	31.49	31.73	31.39

DAY 6								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	05.97	06.12	05.98	49.24	49.86	50.34	49.81
2	09.37	10.04	10.13	09.85	47.23	46.98	47.95	47.39
3	15.13	14.96	14.84	14.98	46.43	46.46	46.28	46.39
4	19.21	18.64	19.12	18.99	43.39	43.32	42.88	43.30
5	23.15	23.43	23.20	23.26	40.84	40.87	41.43	41.05
6	29.12	28.54	29.06	28.91	38.23	37.86	38.74	38.28
7	32.26	31.85	32.04	32.05	36.76	36.38	37.75	36.96
8	36.24	35.86	36.15	36.08	35.04	35.25	34.93	35.07
9	40.98	41.24	41.74	41.32	32.85	33.04	32.84	32.91
10	45.38	46.34	46.32	46.01	31.27	30.85	31.36	31.16

DAY 7								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.98	06.21	05.91	06.03	50.21	50.15	49.89	50.08
2	09.97	10.23	09.85	10.02	47.86	47.84	46.85	47.52
3	15.38	15.27	15.19	15.28	46.85	47.32	46.54	46.90
4	18.94	19.74	18.97	19.22	43.41	43.22	42.54	43.06
5	23.24	22.97	23.35	23.19	40.87	40.93	41.75	41.18
6	28.68	29.34	28.97	29.00	38.74	39.03	38.69	38.82
7	32.35	31.89	31.85	32.03	35.98	36.45	36.95	36.46
8	35.86	36.14	36.38	36.13	35.24	34.87	35.89	35.33
9	40.87	41.23	41.11	41.07	32.87	32.69	33.34	32.97
10	46.24	45.99	45.93	46.05	29.97	30.79	31.77	30.84

TABLE D3: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT BIZARA ZARIA (BZZ)

DAY 1		
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**	**PLANTBOT SPEED(ω) in (rpm)**

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.74	05.93	06.95	06.21	50.34	49.93	49.75	50.01
2	09.88	09.89	09.95	09.91	47.97	47.76	47.45	47.73
3	14.88	15.37	14.96	15.07	46.78	46.86	46.75	46.80
4	18.89	19.84	19.43	19.39	43.42	43.51	43.47	43.47
5	23.52	23.23	22.78	23.18	40.98	40.78	40.96	40.91
6	28.75	29.22	29.23	29.07	38.88	38.92	38.58	38.79
7	32.43	32.14	31.93	32.17	36.23	36.22	37.35	36.60
8	35.98	35.76	36.41	36.13	34.87	34.76	35.78	35.14
9	40.98	40.87	41.43	41.09	31.98	32.58	33.86	32.81
10	46.33	46.34	46.12	46.26	30.45	29.75	31.83	30.68

DAY 2

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.76	05.98	06.22	05.99	49.76	49.97	50.62	50.12
2	09.79	10.18	10.14	10.04	48.42	48.54	47.65	48.20
3	15.21	14.87	15.22	15.10	46.75	47.32	47.28	47.12
4	19.13	18.94	18.95	19.01	41.88	43.22	42.76	42.62
5	23.16	22.77	22.82	22.92	41.65	41.24	41.52	41.47
6	28.33	29.12	28.36	28.60	37.78	37.85	37.67	37.77
7	31.87	32.21	31.78	31.95	36.54	36.98	37.06	36.86
8	35.98	36.66	37.11	36.58	34.78	35.23	34.96	34.99
9	40.76	41.44	41.76	41.32	32.82	33.21	33.67	33.23
10	47.23	46.77	45.45	46.48	31.22	30.92	31.68	31.27

DAY 3

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.87	06.15	06.07	06.03	49.40	48.97	50.34	49.57
2	09.95	10.00	10.22	10.06	48.23	47.68	48.75	48.22
3	14.31	13.76	13.85	13.97	45.88	46.32	46.73	46.31
4	17.96	17.76	18.40	18.04	42.95	42.75	43.10	42.93
5	23.13	22.85	22.72	22.90	40.91	41.31	41.08	41.10
6	27.67	27.66	28.32	27.88	37.86	38.54	37.86	38.09
7	32.33	31.56	32.34	32.08	37.32	36.97	35.88	36.72
8	35.80	36.93	35.86	36.20	35.34	35.18	35.32	35.28
9	40.75	40.89	41.53	41.06	32.95	32.89	33.87	33.24
10	46.32	45.16	45.86	45.78	31.40	31.75	32.03	31.73

DAY 4

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**	**PLANTBOT SPEED(ω) in (rpm)**

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.93	05.94	06.16	06.01	50.20	50.13	49.76	50.03
2	09.75	10.21	10.16	10.04	48.34	48.41	47.35	48.03
3	15.21	14.78	14.69	14.89	46.33	46.54	47.73	46.87
4	18.30	18.75	20.23	19.09	43.22	43.36	43.13	43.24
5	24.05	24.78	23.97	24.27	41.33	40.92	41.43	41.23
6	28.51	27.64	27.95	28.03	38.77	39.24	39.14	39.05
7	33.22	33.13	32.75	33.03	36.78	37.76	38.03	37.52
8	37.13	36.67	37.02	36.94	34.87	34.75	36.17	35.26
9	41.75	41.85	40.65	41.42	33.80	32.91	33.65	33.45
10	45.66	46.34	45.84	45.95	30.85	31.74	31.82	31.47

DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.87	06.12	05.997	05.94	49.43	49.75	50.23	49.80
2	09.79	10.06	10.24	10.03	47.54	47.79	48.15	47.83
3	15.36	14.87	14.75	14.99	46.82	45.87	47.51	46.73
4	18.88	19.13	19.24	19.08	42.87	43.65	41.79	42.77
5	23.34	22.78	22.88	23.00	40.87	40.93	41.42	41.07
6	28.42	27.78	27.98	28.06	38.56	37.96	38.33	38.28
7	31.76	30.93	30.77	31.15	36.75	36.73	37.21	36.90
8	36.13	36.25	36.02	36.13	34.85	34.96	35.68	35.16
9	40.93	41.34	41.54	41.27	33.05	32.75	33.02	32.94
10	45.78	45.93	46.86	46.19	31.21	30.87	31.73	31.27

DAY 6								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	05.88	06.32	06.02	48.79	49.97	50.14	49.63
2	09.86	10.13	09.95	09.98	48.23	47.69	48.21	48.04
3	15.42	14.95	15.32	15.23	46.32	46.25	47.52	46.70
4	18.83	19.31	18.78	18.97	43.27	43.09	42.72	43.03
5	22.89	23.43	23.51	23.28	40.97	41.43	41.11	41.17
6	27.78	27.67	28.05	27.83	38.87	38.12	37.88	38.29
7	31.25	31.18	31.32	31.25	36.95	37.21	36.87	37.01
8	35.74	36.77	37.23	36.58	34.75	35.21	35.14	35.03
9	41.43	41.37	41.35	41.38	32.74	33.07	33.83	33.21
10	46.32	46.54	45.86	46.24	31.86	30.96	31.75	31.52

DAY 7								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.21	05.17	04.94	05.11	48.87	49.83	50.27	49.66
2	10.11	09.94	10.15	10.07	48.11	47.86	47.93	47.97
3	14.87	14.95	15.10	14.97	45.76	47.84	47.72	47.11
4	19.22	19.34	18.80	19.12	43.12	43.45	42.76	43.11
5	23.14	23.23	22.73	23.03	41.35	40.78	40.98	41.04
6	27.96	27.75	28.22	27.98	37.87	39.17	38.69	38.58
7	33.21	33.12	32.58	32.97	36.83	36.85	36.86	36.85
8	38.16	37.76	37.38	37.77	35.32	35.53	35.79	35.55
9	40.78	42.32	41.55	41.45	33.52	32.73	33.05	33.10
10	45.56	46.51	45.88	45.98	31.24	30.95	31.77	31.32

TABLE D4: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT FILIN MALLAWA ZARIA (FMZ)

DAY 1								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.33	06.01	05.43	05.11	47.96	50.32	49.76	49.35
2	09.88	10.21	09.89	09.99	48.33	48.34	47.87	48.18
3	15.23	15.16	14.88	15.09	46.44	46.95	47.34	46.91
4	20.04	19.42	18.56	19.34	42.76	43.66	43.64	43.35
5	22.87	22.76	23.32	22.98	41.45	41.23	41.42	41.37
6	28.12	27.68	27.96	27.92	38.34	38.76	38.54	38.55
7	32.66	33.23	32.85	32.91	35.89	37.04	36.69	36.54
8	37.66	38.21	37.56	37.81	36.20	35.76	36.23	36.06
9	41.35	41.76	41.74	41.62	34.11	32.64	32.25	33.00
10	46.43	45.75	45.76	45.98	30.47	31.53	31.86	31.29

DAY 2								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.23	06.12	05.76	06.04	48.74	49.53	50.23	49.50
2	09.88	09.67	10.2231	09.92	47.76	47.56	48.68	48.00
3	15.33	14.45	14.27	14.68	46.45	46.31	46.55	46.44
4	18.53	17.58	17.94	18.02	43.14	42.65	42.81	42.87
5	22.76	22.79	22.93	22.83	41.88	41.43	40.85	41.39
6	28.23	28.15	27.83	28.07	37.78	37.83	38.33	37.98
7	31.27	31.73	31.96	31.65	35.78	36.74	36.32	36.28
8	34.87	36.87	35.91	35.88	34.47	34.81	35.18	34.82

9	41.35	40.75	41.65	41.25	33.46	33.15	32.24	32.95
10	45.76	46.11	46.23	46.03	30.67	31.58	31.74	31.33

DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.14	05.72	06.04	05.97	49.66	50.22	50.31	50.06
2	10.35	09.76	09.76	09.96	48.24	48.31	47.87	48.14
3	14.86	15.32	14.97	15.05	45.93	46.58	46.47	46.33
4	19.42	19.97	18.88	19.42	42.74	43.43	43.31	43.16
5	22.84	23.21	23.32	23.12	41.47	41.35	41.58	41.47
6	29.22	28.89	28.86	28.99	39.42	38.75	38.56	38.91
7	33.23	32.67	31.88	32.59	35.85	36.51	35.79	36.05
8	36.43	35.75	36.43	36.20	34.45	35.23	34.75	34.81
9	40.78	40.84	41.23	40.95	31.92	31.84	33.15	32.30
10	45.75	46.21	45.85	45.94	30.73	30.53	30.86	30.71

DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.12	05.74	05.42	05.76	48.55	49.47	50.31	49.44
2	10.23	09.78	10.31	10.11	48.20	47.85	48.05	48.03
3	15.11	14.75	15.13	15.00	45.88	46.54	47.12	46.51
4	19.04	18.83	19.25	19.04	42.75	42.13	42.77	42.55
5	24.22	23.54	24.14	23.97	40.76	40.64	41.54	40.98
6	27.85	28.21	27.66	27.91	38.67	38.36	39.11	38.71
7	33.23	32.52	32.33	32.69	37.42	36.85	38.23	37.50
8	37.21	36.83	36.35	36.80	35.37	35.53	34.80	35.23
9	41.83	40.65	41.34	41.27	34.12	33.51	34.08	33.90
10	46.23	45.64	45.73	45.87	31.65	30.76	32.06	31.49

DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	06.23	05.95	06.03	48.74	50.21	49.83	49.59
2	09.84	10.15	10.10	10.01	48.13	47.75	47.86	47.91
3	15.23	15.22	15.04	15.16	46.74	46.68	46.69	46.70
4	20.01	18.35	18.17	18.84	43.56	42.83	43.45	43.28
5	22.75	23.13	23.21	23.03	41.73	40.88	41.58	41.40
6	27.84	27.71	28.23	27.93	38.57	37.87	38.23	38.22

7	31.76	31.68	32.38	31.94	37.05	37.11	36.86	37.01
8	36.32	36.61	35.82	36.25	36.12	35.55	35.76	35.81
9	42.23	41.74	41.91	41.96	31.87	32.75	33.65	32.76
10	45.75	46.31	45.77	45.94	30.78	31.56	30.85	31.06

DAY 6								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.81	06.21	06.02	05.98	50.11	49.25	48.88	49.41
2	09.93	09.84	10.25	10.01	47.86	48.34	48.37	48.19
3	14.87	14.77	15.25	14.96	46.35	46.85	47.43	46.88
4	19.75	20.12	19.34	19.74	43.39	43.31	42.81	43.17
5	23.44	24.25	23.54	23.74	40.67	41.55	42.07	41.43
6	28.37	28.09	27.68	28.05	39.23	38.75	38.90	38.96
7	33.06	30.95	31.96	31.99	36.73	36.93	38.01	37.22
8	37.10	35.89	36.73	36.57	35.34	34.62	34.67	34.87
9	41.24	42.07	41.66	41.66	32.85	32.77	33.49	33.04
10	46.43	45.87	46.27	46.19	31.29	30.94	31.68	31.30
DAY 7								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.12	05.86	06.05	06.01	48.93	50.10	49.45	49.49
2	10.21	09.76	10.07	10.01	48.03	47.73	47.85	47.87
3	15.10	14.88	14.79	14.92	47.02	46.53	46.41	46.65
4	20.11	19.73	19.35	19.73	42.91	43.20	43.33	43.15
5	22.75	23.14	22.82	22.90	41.42	40.76	41.25	41.14
6	30.03	29.41	29.22	29.55	38.43	37.68	37.25	37.79
7	33.17	32.85	32.04	32.67	37.02	36.75	36.84	36.87
8	36.24	35.75	35.58	35.86	34.48	35.32	35.34	35.05
9	42.02	42.11	41.85	41.99	33.05	33.12	32.69	32.95
10	45.84	46.15	45.74	45.91	30.71	31.37	30.87	30.98

TABLE D5: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT KOFAN KONA ZARIA (KKZ)

DAY 1								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.01	05.42	05.50	05.64	50.11	50.02	49.90	50.01
2	09.81	09.89	09.81	09.84	47.62	48.02	47.69	47.78
3	14.04	14.12	14.24	14.13	46.56	47.14	47.20	46.97

4	18.86	18.79	18.88	18.84	43.32	43.08	43.23	43.21
5	23.06	23.31	23.31	23.23	40.88	41.22	41.34	41.15
6	27.62	27.72	27.68	27.67	38.52	39.02	39.01	38.85
7	32.03	32.08	32.22	32.11	37.30	37.96	37.35	37.54
8	36.80	36.75	36.79	36.78	34.89	35.42	35.66	35.32
9	41.08	41.16	41.27	41.17	33.35	33.23	33.14	33.24
10	45.82	45.79	45.86	45.82	32.06	32.12	31.88	32.02

DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.72	05.48	05.83	05.68	50.22	49.84	49.92	49.99
2	10.10	09.91	09.82	09.94	47.96	48.13	48.29	48.13
3	14.74	14.68	13.93	14.45	45.95	46.82	46.88	46.55
4	17.94	18.71	18.60	18.42	43.34	43.16	43.23	43.24
5	22.82	23.43	22.51	22.92	40.65	40.58	40.86	40.70
6	27.64	28.02	27.55	27.74	38.63	37.90	38.54	38.36
7	31.90	31.84	31.80	31.85	36.90	37.32	36.93	37.05
8	36.67	36.73	35.93	36.44	35.16	34.74	34.80	34.9
9	40.91	40.81	41.32	41.01	33.58	33.43	32.99	33.33
10	45.56	45.87	45.70	45.71	31.72	32.01	31.79	31.84
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.09	05.72	05.78	05.86	49.54	50.04	50.18	49.92
2	09.88	10.04	09.86	09.93	48.24	47.91	47.95	48.03
3	15.08	14.82	14.78	14.89	46.73	47.12	47.07	46.97
4	18.36	19.01	18.94	18.77	42.91	43.14	42.93	42.99
5	23.02	23.10	23.20	23.11	41.03	40.94	41.08	41.02
6	28.38	28.43	28.17	28.33	38.61	37.96	37.92	38.16
7	32.25	32.19	31.95	32.13	36.84	37.28	37.14	37.09
8	35.97	36.43	36.31	36.24	35.02	34.89	35.26	35.06
9	41.38	40.97	41.46	41.27	33.50	33.24	33.18	33.31
10	46.18	45.82	46.27	46.09	31.84	32.07	31.93	31.95

DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.89	06.06	06.13	06.03	48.93	50.14	50.19	49.75
2	09.87	10.08	09.91	09.95	46.95	47.80	47.65	47.47
3	15.13	15.18	14.95	15.09	47.02	46.54	47.19	46.92

4	18.70	18.74	18.80	18.75	42.91	43.12	41.78	42.60
5	23.14	23.29	22.72	23.05	41.28	41.33	40.80	41.14
6	28.22	28.34	28.48	28.35	38.37	38.21	38.13	38.24
7	31.54	31.78	31.67	31.66	37.39	36.83	36.83	37.02
8	35.71	35.75	35.84	35.77	34.93	35.56	35.62	35.37
9	40.90	40.96	41.43	41.10	32.84	32.86	32.88	32.86
10	45.76	46.24	45.91	45.97	30.96	31.56	31.79	31.44

DAY 5

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.01	06.06	06.12	06.06	49.62	49.51	50.24	49.79
2	10.21	10.01	10.18	10.13	47.84	48.17	47.56	47.86
3	15.32	14.91	15.06	15.10	46.84	46.78	47.62	47.08
4	19.14	19.19	18.88	19.07	43.21	42.81	42.20	42.74
5	22.96	23.24	23.31	23.17	40.40	41.70	41.90	41.33
6	29.06	28.72	28.84	28.87	39.26	38.39	38.63	38.76
7	32.02	31.95	32.18	32.05	36.75	36.53	36.89	36.72
8	36.04	35.91	36.18	36.04	34.89	35.27	35.95	35.37
9	40.88	41.03	40.75	40.89	33.33	32.13	33.18	32.88
10	45.89	45.91	46.02	45.94	30.78	30.83	31.68	31.10

DAY 6

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.10	05.89	06.06	06.02	49.87	50.16	49.91	49.98
2	10.21	09.93	10.52	10.22	48.90	48.15	47.56	48.20
3	15.26	14.61	14.53	14.8	46.52	47.28	47.12	46.97
4	19.18	18.91	19.14	19.08	42.91	43.16	43.29	43.12
5	23.72	24.63	23.81	24.05	41.36	41.34	41.39	41.36
6	28.44	27.87	28.21	28.17	38.81	38.81	39.12	38.91
7	33.11	32.40	32.57	32.69	37.64	37.74	37.81	37.73
8	37.01	36.55	36.79	36.78	34.58	34.83	35.85	35.09
9	42.03	41.73	41.64	41.80	33.58	32.77	33.47	33.27
10	45.71	46.12	45.88	45.90	31.66	31.56	31.64	31.62

DAY 7

S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.87	06.03	06.10	06.00	50.14	49.88	50.49	50.17
2	09.81	09.91	10.02	9.91	48.29	47.74	47.902	47.98
3	14.85	14.80	14.86	14.84	46.87	46.80	47.61	47.09
4	19.24	19.15	18.53	18.97	43.36	42.84	42.90	43.03

5	22.65	22.78	22.68	22.70	41.71	40.09	41.72	41.17
6	28.11	28.48	28.42	28.34	38.20	37.89	37.84	37.98
7	31.84	31.63	31.77	31.75	36.51	37.18	37.14	36.94
8	35.78	36.67	36.16	36.20	35.19	35.08	35.20	35.16
9	40.30	41.66	41.85	41.27	32.70	33.34	33.72	33.25
10	46.60	45.51	45.82	45.98	30.90	31.45	31.70	31.35

TABLE D6: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT KOFAN GAYAN ZARIA (KGZ)

DAY 1								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.23	05.35	05.18	05.25	49.84	50.22	49.74	49.93
2	09.62	09.93	09.89	09.81	47.82	48.00	47.88	47.90
3	14.15	14.22	14.37	14.25	45.67	47.74	47.54	46.98
4	18.81	18.67	18.93	18.80	43.32	43.16	43.26	43.25
5	23.25	22.98	23.23	23.15	40.48	41.52	41.34	41.11
6	27.75	27.90	27.69	27.78	38.32	39.11	39.07	38.83
7	32.24	31.98	32.18	32.13	37.19	38.05	37.37	37.54
8	36.95	36.62	36.79	36.79	34.74	35.62	35.86	35.41
9	41.19	41.30	41.26	41.25	33.44	33.34	33.24	33.34
10	45.85	45.89	45.95	45.90	32.26	32.32	31.48	32.02
DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.72	05.59	05.63	05.65	50.11	49.76	49.88	49.92
2	10.03	09.94	09.72	09.90	47.83	48.12	48.24	48.06
3	14.80	14.84	13.98	14.54	45.94	46.82	46.85	46.54
4	17.96	18.75	18.68	18.46	43.44	43.35	43.28	43.36
5	22.98	23.23	22.84	23.02	40.63	40.77	40.83	40.74
6	27.78	28.15	27.66	27.86	38.96	37.64	38.69	38.43
7	31.91	31.84	31.77	31.84	36.98	37.28	36.98	37.08
8	36.76	36.66	35.98	36.47	35.12	34.91	34.84	34.96
9	40.97	40.92	41.32	41.07	33.66	33.76	32.94	33.45
10	45.78	45.86	45.63	45.76	31.78	32.14	31.79	31.90
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.09	05.82	05.87	05.93	49.84	50.11	50.19	50.05
2	09.74	10.24	09.74	09.91	48.15	47.86	47.92	47.98
3	15.07	14.82	14.76	14.88	46.82	47.22	47.30	47.11

4	18.93	19.17	18.91	19.00	42.88	43.24	42.93	43.02
5	23.11	23.23	23.29	23.21	41.05	40.87	41.18	41.03
6	28.35	28.47	28.22	28.35	38.54	37.88	37.81	38.08
7	32.13	31.98	31.96	32.02	36.94	37.38	37.25	37.19
8	35.91	36.32	36.24	36.16	35.13	34.98	35.26	35.12
9	41.26	40.82	41.74	41.27	33.56	33.46	33.32	33.45
10	46.08	45.97	46.19	46.08	31.84	32.10	31.94	31.96

DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.82	06.01	05.87	05.90	48.96	50.04	50.14	49.71
2	09.84	10.04	09.94	09.94	46.97	47.78	47.64	47.46
3	15.13	15.21	14.98	15.11	47.07	46.84	47.13	47.01
4	18.78	18.70	18.89	18.79	42.99	43.11	41.98	42.69
5	23.32	23.54	22.42	23.09	41.18	41.26	40.94	41.13
6	28.28	28.40	28.49	28.39	38.34	38.22	38.13	38.23
7	31.69	31.69	31.64	31.67	37.14	36.90	36.94	36.99
8	35.68	35.75	35.78	35.74	34.88	35.36	35.62	35.29
9	40.72	40.88	41.68	41.09	32.89	32.93	32.90	32.91
10	45.76	46.67	45.81	46.08	30.88	31.69	31.76	31.44
DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.11	06.05	06.10	06.09	49.62	49.68	50.14	49.81
2	10.14	10.03	10.28	10.15	47.84	48.04	47.78	47.89
3	15.22	14.97	15.31	15.17	46.84	46.86	47.42	47.04
4	19.07	19.19	18.96	19.07	43.04	42.84	42.70	42.86
5	22.98	23.24	23.32	23.18	40.98	41.54	41.62	41.38
6	29.06	28.72	28.90	28.89	39.02	38.70	38.67	38.80
7	32.12	31.96	32.23	32.10	36.77	36.78	36.72	36.76
8	36.14	35.93	36.18	36.08	34.96	35.64	35.58	35.39
9	40.94	41.04	40.78	40.92	33.18	32.36	33.32	32.95
10	45.98	45.96	46.02	45.99	30.86	30.92	31.48	31.09

DAY 6								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.09	05.72	06.08	05.96	49.92	50.13	49.93	49.99
2	10.34	09.91	10.38	10.21	48.16	48.11	47.86	48.04

3	15.08	14.69	14.63	14.8	46.92	47.38	47.12	47.14
4	19.02	18.91	19.17	19.03	42.91	43.24	43.36	43.17
5	23.75	24.42	23.82	24.00	41.26	41.61	41.42	41.43
6	28.29	27.98	28.30	28.19	38.96	38.83	39.16	38.98
7	33.23	32.84	32.32	32.80	37.64	37.76	37.82	37.74
8	37.02	36.64	36.78	36.81	34.98	34.95	35.70	35.21
9	42.02	41.78	41.69	41.83	33.48	32.96	33.56	33.33
10	45.94	46.03	45.91	45.96	32.05	31.88	31.94	31.96

DAY 7								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.92	06.03	06.09	06.01	50.30	49.97	50.44	50.24
2	09.89	09.92	10.04	09.95	48.07	47.98	47.91	47.99
3	14.89	14.93	14.91	14.91	46.88	46.92	47.44	47.08
4	19.01	19.10	18.89	19.00	43.28	42.98	42.90	43.05
5	22.73	22.85	22.80	22.79	41.46	40.93	41.55	41.31
6	28.41	28.47	28.55	28.48	38.12	37.94	37.97	38.01
7	31.83	31.82	31.88	31.84	36.86	37.02	37.08	36.99
8	35.98	36.55	36.51	36.35	35.04	35.11	35.20	35.12
9	40.87	41.43	41.46	41.25	32.95	33.34	33.52	33.27
10	46.34	45.68	45.81	45.94	30.96	31.51	31.62	31.36

TABLE D7: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT TUKUR – TUKUR ZARIA (TTZ)

DAY 1								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.23	05.47	05.39	05.36	50.14	50.18	49.90	50.07
2	10.02	09.84	09.90	09.92	47.88	48.08	47.91	47.96
3	14.14	14.37	14.26	14.26	45.86	47.59	47.48	46.98
4	18.84	18.79	18.92	18.85	43.77	43.16	43.38	43.44
5	23.10	23.29	23.35	23.25	40.88	41.32	41.26	41.15
6	27.62	27.71	27.80	27.71	38.72	39.18	39.02	38.97
7	32.36	32.15	32.27	32.26	37.15	38.07	37.33	37.52
8	36.88	36.79	36.67	36.78	34.88	35.42	35.56	35.29
9	41.20	41.27	41.30	41.26	33.64	33.14	33.14	33.31
10	45.96	45.79	45.84	45.86	32.16	32.22	31.68	32.02

DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE

1	05.84	05.68	05.76	05.76	50.32	49.86	49.88	50.02
2	10.07	09.89	09.82	9.93	47.89	48.10	48.24	48.08
3	14.81	14.90	13.99	14.57	45.94	46.42	46.64	46.33
4	17.94	18.80	18.65	18.46	43.44	43.12	43.32	43.29
5	22.98	23.38	22.44	22.93	40.84	41.04	40.96	40.95
6	27.88	28.12	27.26	27.75	38.46	37.98	38.54	38.33
7	31.91	31.84	31.77	31.84	36.86	37.28	36.86	37.00
8	36.82	36.71	35.98	36.50	35.03	34.94	34.98	34.98
9	40.84	40.90	41.32	41.02	33.46	33.56	32.74	33.25
10	45.78	45.94	45.66	45.79	31.98	32.00	31.88	31.95
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.04	06.09	05.66	05.93	49.94	50.14	50.18	50.09
2	09.88	10.10	09.88	09.95	48.24	47.90	47.98	48.04
3	15.12	14.82	14.74	14.89	46.96	47.22	47.12	47.10
4	18.80	19.14	18.90	18.95	42.94	43.14	42.95	43.01
5	23.11	23.22	23.33	23.22	41.02	40.94	41.10	41.02
6	28.44	28.38	28.18	28.33	38.34	37.94	37.90	38.06
7	32.07	32.15	31.93	32.05	36.94	37.28	37.14	37.12
8	35.87	36.38	36.14	36.13	35.12	34.98	35.26	35.12
9	41.20	40.97	41.38	41.18	33.66	33.48	33.32	33.49
10	46.25	45.91	46.32	46.16	31.89	32.07	31.96	31.97
DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.94	06.05	05.90	05.96	48.96	50.04	50.17	49.72
2	09.84	10.14	09.94	09.97	46.93	47.81	47.63	47.46
3	15.12	15.22	14.92	15.09	47.05	46.44	47.44	46.98
4	18.70	18.79	18.84	18.78	42.46	43.32	41.98	42.59
5	23.18	23.22	22.97	23.12	41.28	41.33	40.82	41.14
6	28.12	28.24	28.39	28.25	38.34	38.19	38.04	38.19
7	31.68	31.81	31.74	31.74	37.14	36.90	36.88	36.97
8	35.71	35.82	35.87	35.80	34.97	35.26	35.42	35.22
9	40.86	40.97	41.49	41.11	32.95	32.98	32.96	32.96
10	45.76	46.34	45.86	45.99	30.98	31.24	31.46	31.23
DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.04	06.18	06.13	6.12	49.82	49.88	50.04	49.91
2	10.22	10.08	10.17	10.16	47.93	48.14	47.68	47.92

3	15.32	14.94	15.10	15.12	46.84	46.69	47.42	46.98
4	19.24	19.12	18.98	19.11	43.07	42.94	42.83	42.95
5	22.97	23.24	23.32	23.18	40.88	41.64	41.72	41.41
6	29.19	28.82	28.88	28.96	39.12	38.69	38.52	38.78
7	32.12	31.95	32.25	32.11	37.00	36.78	36.84	36.87
8	36.14	35.89	36.24	36.09	34.96	35.34	35.68	35.33
9	40.93	41.07	40.88	40.96	33.18	32.86	33.32	33.12
10	45.90	45.93	46.02	45.95	30.88	30.82	31.38	31.03

DAY 6								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.13	05.87	06.01	06.00	49.87	50.18	49.94	50.00
2	10.14	09.98	10.34	10.15	48.28	48.15	47.86	48.10
3	15.18	14.74	14.66	14.86	46.92	47.58	47.34	47.28
4	19.12	18.98	19.18	19.09	42.88	43.43	43.38	43.23
5	23.74	24.42	23.91	24.02	41.26	41.54	41.68	41.49
6	28.38	27.96	28.23	28.19	38.76	38.76	39.12	38.88
7	33.10	32.74	32.82	32.89	37.64	37.74	37.82	37.73
8	37.02	36.74	36.87	36.88	34.78	34.84	35.86	35.16
9	42.09	41.86	41.62	41.86	33.58	32.86	33.58	33.34
10	45.87	46.09	45.95	45.97	31.58	31.66	31.77	31.67

DAY 7								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.95	06.05	06.10	06.03	50.20	49.84	50.34	50.13
2	09.88	09.96	10.03	09.96	48.24	47.88	47.92	48.01
3	14.91	14.95	14.97	14.94	46.88	46.84	47.54	47.09
4	19.06	19.14	18.79	19.00	43.21	42.98	42.95	43.05
5	22.79	22.86	22.80	22.82	41.76	40.83	41.65	41.41
6	28.41	28.53	28.56	28.50	38.15	37.98	37.89	38.01
7	31.83	31.74	31.90	31.82	36.86	37.12	37.19	37.06
8	35.98	36.65	36.35	36.33	35.34	35.13	35.28	35.25
9	40.97	41.33	41.82	41.37	32.85	33.36	33.65	33.29
10	46.44	45.75	45.81	46.00	30.97	31.44	31.53	31.31

TABLE D8: DAY 1-7. EXPERIMENTAL RESULTS OF MEASUREMENT TAKEN AT UNGUWAN DANKALI ZARIA (UDZ)

DAY 1		
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**	**PLANTBOT SPEED(ω) in (rpm)**

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.10	05.18	05.28	05.19	50.14	50.06	49.97	50.06
2	10.17	09.89	09.90	09.99	47.92	48.14	47.84	47.97
3	14.24	13.98	14.44	14.22	46.96	47.14	47.24	47.11
4	19.07	18.86	18.90	18.94	43.62	43.16	43.20	43.33
5	23.10	23.24	23.39	23.24	40.99	41.32	41.27	41.19
6	27.62	27.85	28.12	27.86	38.82	39.03	39.09	38.98
7	32.14	32.18	32.28	32.20	37.90	38.00	37.62	37.84
8	36.89	36.69	36.71	36.76	34.88	35.22	35.36	35.15
9	40.99	41.31	41.26	41.19	33.44	33.38	33.24	33.35
10	45.90	45.71	45.83	45.81	31.96	32.12	31.88	31.98

DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.92	06.18	05.76	05.95	50.12	49.96	49.99	50.02
2	10.02	09.98	09.82	09.94	47.98	48.19	48.24	48.14
3	14.90	14.88	13.94	14.57	45.88	46.82	46.74	46.48
4	17.98	18.88	18.76	18.54	42.94	43.16	43.12	43.07
5	22.98	23.28	22.74	23.00	40.64	40.58	40.86	40.69
6	27.98	28.02	27.96	27.99	38.86	37.84	38.85	38.52
7	31.94	31.84	31.70	31.83	36.97	37.18	36.96	37.04
8	36.72	36.74	35.99	36.48	35.06	34.94	34.98	34.99
9	40.90	41.00	41.02	40.97	33.88	33.06	32.84	33.26
10	45.68	45.84	45.78	45.77	31.88	32.14	31.78	31.93
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.04	05.52	06.00	05.85	49.94	50.04	50.12	50.03
2	09.74	10.07	09.74	09.85	48.14	47.98	47.97	48.03
3	15.07	14.92	14.84	14.94	46.96	47.22	47.12	47.10
4	18.90	19.04	18.91	18.95	42.92	43.14	42.96	43.01
5	23.08	23.12	23.16	23.12	41.02	40.94	41.13	41.03
6	28.40	28.44	28.39	28.41	38.19	37.98	37.78	37.98
7	32.14	32.18	31.99	32.10	36.84	37.28	37.14	37.09
8	35.98	36.28	36.14	36.13	35.12	34.98	35.26	35.12
9	41.26	40.99	41.34	41.20	33.46	33.33	33.22	33.34
10	46.12	45.93	46.22	46.09	31.90	32.10	31.96	31.99

DAY 4		
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**	**PLANTBOT SPEED(ω) in (rpm)**

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.82	06.12	05.80	05.91	48.96	50.14	50.19	49.76
2	09.78	10.05	09.84	09.89	46.93	47.38	47.58	47.30
3	15.10	15.21	14.88	15.06	47.02	46.94	47.14	47.03
4	18.60	18.75	18.84	18.73	42.96	43.12	41.78	42.62
5	22.94	23.02	22.92	22.96	41.28	41.16	40.94	41.13
6	28.22	28.34	28.40	28.32	38.34	38.26	38.18	38.26
7	31.68	31.71	31.52	31.64	37.14	36.98	36.88	37.00
8	35.78	35.72	35.88	35.79	34.98	35.16	35.42	35.19
9	40.92	40.96	41.38	41.09	32.84	32.86	32.96	32.89
10	45.96	46.14	45.92	46.01	30.98	31.14	31.46	31.19
				DAY 5				
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.14	06.08	06.21	06.14	49.62	49.48	50.14	49.75
2	10.06	10.14	10.24	10.15	47.97	48.14	47.68	47.93
3	15.14	14.98	15.08	15.07	46.64	46.76	47.32	46.91
4	19.12	19.18	18.98	19.09	43.14	42.86	42.80	42.93
5	22.98	23.14	23.24	23.12	40.98	41.74	41.62	41.45
6	29.10	28.82	28.88	28.93	39.12	38.84	38.72	38.89
7	32.12	31.98	32.23	32.11	36.79	36.88	36.94	36.87
8	36.07	35.98	36.18	36.08	34.96	35.24	35.38	35.19
9	40.94	41.06	40.88	40.96	33.18	32.76	33.02	32.99
10	45.96	45.94	46.02	45.97	30.86	30.82	31.88	31.19
				DAY 6				
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.14	05.92	06.07	06.04	49.85	50.16	49.97	49.99
2	10.24	09.99	10.44	10.22	48.15	48.20	47.69	48.01
3	15.18	14.74	14.86	14.93	46.09	47.88	47.62	47.20
4	19.12	18.98	19.08	19.06	42.88	43.36	43.39	43.21
5	23.64	24.42	23.96	24.01	41.16	41.54	41.68	41.46
6	28.47	27.97	28.20	28.21	38.96	38.96	39.32	39.08
7	33.10	32.84	32.72	32.89	37.34	37.68	37.91	37.64
8	37.03	36.74	36.83	36.87	34.96	34.92	35.46	35.11
9	42.11	41.86	41.72	41.90	33.71	32.96	33.50	33.39
10	45.87	46.12	45.84	45.94	31.69	31.72	31.79	31.73

	DAY 7	
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**	**PLANTBOT SPEED(ω) in (rpm)**

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.01	06.05	06.03	06.03	50.10	49.96	50.24	50.10
2	09.85	09.94	10.06	09.95	48.14	47.86	47.91	47.97
3	14.92	14.91	14.95	14.93	46.81	46.87	47.24	46.97
4	19.09	19.19	18.89	19.06	43.13	42.84	42.80	42.92
5	22.70	22.89	22.73	22.77	41.72	40.83	41.35	41.30
6	28.27	28.67	28.72	28.55	38.15	37.91	37.87	37.98
7	31.97	31.62	31.88	31.82	36.96	37.25	37.17	37.13
8	35.78	36.65	36.35	36.26	35.14	35.06	35.27	35.16
9	40.87	41.43	41.72	41.34	32.85	33.18	33.65	33.23
10	46.54	45.75	45.86	46.05	30.95	31.40	31.48	31.28

TABLE D9: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT DOGARAWA ZARIA (DGZ)

DAY 1								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.28	05.38	05.48	05.38	50.18	50.22	49.95	50.12
2	09.80	09.99	09.80	09.86	47.98	48.02	47.94	47.98
3	13.99	14.26	13.98	14.08	46.99	47.34	47.24	47.19
4	19.08	18.94	18.98	19.00	42.97	43.22	43.16	43.12
5	23.16	23.24	23.32	23.24	40.98	41.12	41.06	41.05
6	27.92	28.00	27.99	27.97	38.96	39.00	39.05	39.00
7	32.14	31.98	32.08	32.07	37.98	38.03	37.97	37.99
8	36.86	36.82	36.79	36.82	34.90	35.12	35.44	35.15
9	41.06	41.18	41.24	41.16	33.21	33.14	33.07	33.14
10	46.10	45.94	45.88	45.97	31.96	32.12	31.68	31.92
DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.88	06.02	06.08	05.99	50.12	49.99	49.98	50.03
2	10.02	09.93	09.89	09.95	47.99	48.05	48.14	48.06
3	14.74	14.68	13.99	14.47	45.97	46.22	46.14	46.11
4	17.99	18.38	18.46	18.28	43.14	43.28	43.42	43.28
5	22.98	23.18	22.96	23.04	40.88	40.84	40.86	40.86
6	27.99	28.01	27.86	27.95	38.66	37.98	38.78	38.47
7	32.02	31.96	31.90	31.96	36.99	37.18	36.98	37.05
8	36.48	36.42	35.99	36.30	35.06	34.99	34.97	35.01
9	41.04	40.86	41.10	41.00	33.16	33.26	32.95	33.12
10	45.98	45.94	45.90	45.94	31.98	32.14	31.89	32.00
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			

	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.02	05.76	05.89	05.89	49.94	50.24	50.12	50.10
2	09.91	10.07	09.88	09.95	48.24	47.98	47.98	48.07
3	15.12	14.93	14.74	14.93	46.92	47.32	47.24	47.16
4	18.90	19.14	18.94	18.99	42.97	43.14	42.99	43.03
5	23.18	23.28	23.32	23.26	41.12	40.94	41.18	41.08
6	28.14	28.28	29.02	28.48	38.14	37.98	37.99	38.04
7	33.04	32.26	31.99	32.43	36.94	37.28	37.12	37.11
8	35.98	36.28	36.34	36.20	35.02	34.98	35.06	35.02
9	40.96	40.99	41.44	41.13	33.46	33.28	33.24	33.33
10	46.10	45.97	46.22	46.10	31.90	32.12	31.98	32.00

DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.98	06.04	05.97	06.00	49.86	50.14	50.16	50.05
2	09.92	10.07	09.96	09.98	46.99	47.48	47.38	47.28
3	15.10	15.18	14.99	15.09	47.02	46.14	47.14	46.77
4	18.80	18.86	18.84	18.83	42.98	43.11	41.98	42.69
5	23.14	23.18	22.97	23.10	41.38	41.26	40.94	41.19
6	28.32	28.24	28.10	28.22	38.34	38.22	38.14	38.23
7	32.04	31.92	31.84	31.93	37.14	36.98	36.96	37.03
8	35.83	35.89	35.90	35.87	34.98	35.16	35.12	35.09
9	40.84	40.98	41.18	41.00	32.90	32.86	32.87	32.88
10	45.96	46.44	45.93	46.11	30.98	31.34	31.46	31.26
DAY 5								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.07	06.18	06.07	06.11	49.82	49.88	50.14	49.95
2	10.10	10.07	10.20	10.12	47.97	48.14	47.98	48.03
3	15.12	14.97	15.04	15.04	46.94	46.96	47.12	47.01
4	19.04	19.12	18.99	19.05	43.24	42.88	42.90	43.01
5	22.98	23.14	23.24	23.12	40.98	41.64	41.82	41.48
6	29.18	28.92	28.98	29.03	39.12	38.94	38.82	38.96
7	32.32	31.99	32.18	32.16	36.72	36.83	36.91	36.82
8	36.04	35.98	36.18	36.07	34.96	35.24	35.78	35.33
9	40.99	41.02	40.88	40.96	33.30	32.18	33.12	32.87
10	45.92	45.94	45.96	45.94	30.98	30.92	31.18	31.03

DAY 6								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.07	05.92	06.02	06.00	49.72	50.13	49.89	49.91
2	10.14	09.91	10.34	10.13	48.02	48.14	47.96	48.04
3	15.08	14.94	14.86	14.96	46.95	47.48	47.32	47.25
4	19.12	18.98	19.06	19.05	42.98	43.16	43.07	43.07
5	23.94	24.12	23.96	24.01	40.96	41.54	41.48	41.33
6	28.18	27.93	28.10	28.07	38.76	39.00	39.02	38.93
7	33.10	32.84	32.90	32.95	37.56	37.74	37.82	37.71
8	37.05	36.84	36.90	36.93	35.08	34.98	35.96	35.34
9	42.17	41.86	41.92	41.98	33.18	32.96	33.48	33.21
10	45.94	46.13	45.98	46.02	31.58	31.48	32.04	31.70

DAY 7								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	06.05	06.13	06.01	50.20	49.94	50.54	50.23
2	09.83	09.97	10.03	09.94	48.34	47.78	47.94	48.02
3	14.95	14.91	14.96	14.94	46.87	46.84	47.64	47.12
4	19.04	19.13	18.69	18.95	43.41	42.88	42.93	43.03
5	22.75	22.88	22.79	22.81	41.76	40.13	41.75	41.21
6	28.21	28.57	28.52	28.43	38.25	37.93	37.87	38.02
7	31.93	31.72	31.89	31.85	36.56	37.22	37.17	36.98
8	35.88	36.75	36.25	36.29	35.24	35.12	35.23	35.20
9	40.37	41.53	41.92	41.27	32.75	33.38	33.75	33.29
10	46.64	45.55	45.87	46.02	30.95	31.49	31.73	31.39

TABLE D10: DAY 1 - 7. EXPERIMENTAL RESULTS OF MEASUREMENTS TAKEN AT TOHU ZARIA (THZ)

DAY 1								
S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.15	05.23	05.35	05.33	50.26	50.24	49.86	50.12
2	09.82	09.93	09.76	09.84	47.78	48.12	47.76	47.89
3	14.20	14.38	14.44	14.30	46.84	47.26	47.40	47.17
4	19.10	18.86	18.99	18.82	43.64	43.12	43.24	43.33
5	22.96	23.45	23.32	23.25	40.68	41.02	40.86	40.85
6	27.87	27.93	28.05	27.75	39.16	39.12	39.06	39.11
7	32.27	31.99	32.40	32.27	37.65	38.08	37.84	37.86
8	37.04	36.82	36.94	36.76	35.84	35.82	35.80	35.82

9	41.30	41.28	41.26	41.26	32.92	33.14	33.07	33.04
10	46.12	45.84	45.86	45.85	31.82	32.43	31.78	32.01

DAY 2								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.72	05.68	06.02	05.81	49.98	49.96	49.94	49.96
2	10.22	10.11	09.92	10.08	48.10	48.20	48.20	48.17
3	13.97	14.98	13.86	14.27	46.64	47.22	46.84	46.90
4	17.89	18.87	18.85	18.54	42.94	43.12	43.28	43.11
5	22.86	23.63	22.58	23.02	41.04	40.98	40.86	40.96
6	27.78	28.14	27.82	27.91	37.96	38.55	38.68	38.40
7	32.24	31.68	31.88	31.93	36.86	37.18	37.26	37.10
8	35.92	36.46	35.96	36.11	34.99	34.97	34.95	34.97
9	40.72	41.26	41.24	41.07	32.86	33.36	32.88	33.03
10	45.85	45.89	46.46	46.07	32.32	31.84	31.77	31.98
DAY 3								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.08	05.82	05.96	05.95	50.12	50.18	50.32	50.21
2	09.78	09.66	09.87	09.77	47.84	47.89	47.97	47.90
3	15.12	14.98	14.74	14.95	46.96	47.47	47.25	47.23
4	18.89	19.12	18.89	18.97	42.86	43.23	42.98	43.02
5	22.88	23.26	23.18	23.11	41.12	40.94	41.26	41.11
6	28.24	28.38	28.42	28.35	38.24	37.99	37.78	38.00
7	32.42	32.08	31.99	32.16	36.95	37.46	37.40	37.27
8	35.98	36.47	36.44	36.30	35.02	34.98	35.26	35.09
9	40.96	40.89	41.44	41.10	32.86	33.48	33.32	33.22
10	45.98	45.94	46.32	46.08	31.89	32.14	31.16	31.73
DAY 4								
S/NO	**SOIL MOISTURE (m^3/m^3) in (%)**				**PLANTBOT SPEED(ω) in (rpm)**			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.99	06.12	05.98	6.03	50.12	49.98	50.26	50.12
2	09.98	10.15	09.96	10.03	47.98	47.68	47.58	47.75
3	15.24	15.28	14.99	15.17	47.12	46.94	47.24	47.10
4	18.86	18.80	18.83	18.83	42.98	43.12	41.98	42.69
5	22.96	23.32	22.94	23.07	41.40	41.48	40.94	41.27
6	28.38	27.94	28.48	28.27	38.48	37.96	38.24	38.23
7	31.87	31.97	32.04	31.96	37.24	36.98	36.98	37.07
8	35.98	36.02	35.89	35.96	34.89	35.36	35.49	35.25
9	41.28	40.88	41.40	41.19	32.98	33.06	32.99	33.01

10	45.86	46.24	45.90	46.00	31.18	31.54	31.86	31.53

DAY 5

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.24	06.18	06.12	06.18	49.82	49.68	50.04	49.85
2	10.18	10.14	10.20	10.17	47.98	48.14	47.78	47.97
3	15.12	14.99	15.10	15.07	46.98	46.96	47.42	47.12
4	18.94	19.16	18.98	19.03	43.20	42.94	42.80	42.98
5	22.98	23.24	22.96	23.06	40.28	41.84	41.99	41.37
6	29.26	28.92	28.98	29.05	39.12	38.84	38.92	38.96
7	32.20	31.94	32.18	32.11	36.76	36.68	36.98	36.81
8	36.24	36.12	36.06	36.14	34.96	35.44	35.88	35.43
9	40.98	41.14	40.88	41.00	33.28	32.86	33.06	33.07
10	46.12	45.98	46.16	46.09	30.90	30.94	31.38	31.07

DAY 6

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	06.10	06.12	05.98	06.07	49.92	50.15	49.96	50.01
2	10.28	09.98	10.38	10.21	48.10	48.24	47.96	48.10
3	15.18	14.94	14.86	14.99	46.98	47.88	47.02	47.29
4	19.20	18.98	19.18	19.12	42.78	43.16	43.24	43.06
5	23.94	24.42	23.96	24.11	41.46	41.74	41.68	41.63
6	28.40	28.10	28.12	28.21	38.96	38.90	39.12	38.99
7	33.04	32.84	32.92	32.93	36.98	36.94	37.98	37.30
8	37.12	36.84	36.70	36.89	35.08	34.98	35.76	35.27
9	42.05	41.96	41.72	41.91	32.98	32.68	33.98	33.21
10	46.14	45.82	45.90	45.95	32.04	31.88	31.79	31.90

DAY 7

S/NO	SOIL MOISTURE (m^3/m^3) in (%)				PLANTBOT SPEED(ω) in (rpm)			
	FIRST READING	SECOND READING	THIRD READING	AVERAGE	FIRST READING	SECOND READING	THIRD READING	AVERAGE
1	05.85	06.05	06.13	06.01	50.20	49.94	50.54	50.23
2	09.83	09.97	10.03	09.94	48.34	47.78	47.94	48.02
3	14.95	14.91	14.96	14.94	46.87	46.84	47.64	47.12
4	19.04	19.13	18.69	18.95	43.41	42.88	42.93	43.03
5	22.75	22.88	22.79	22.81	41.76	40.13	41.75	41.21
6	28.21	28.57	28.52	28.43	38.25	37.93	37.87	38.02
7	31.93	31.72	31.89	31.85	36.56	37.22	37.17	36.98

8	35.88	36.75	36.25	36.29	35.24	35.12	35.23	35.20
9	40.37	41.53	41.92	41.27	32.75	33.38	33.75	33.29
10	46.64	45.55	45.87	46.02	30.95	31.49	31.73	31.39

APPENDIX E.

TABLE E1. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT DAMBO ZARIA (DBZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.33	05.42	05.69	05.84	06.03	05.94	06.11	05.77	50.02	50.13	50.09	49.90	49.92	49.75	49.81	49.95
2	09.84	09.79	09.89	09.94	10.01	09.97	10.13	09.94	47.83	48.89	48.14	48.07	48.90	47.49	48.85	48.88
3	14.30	14.45	14.56	14.87	14.94	15.13	15.15	14.77	46.88	46.81	46.57	46.89	47.30	46.90	47.07	46.92
4	18.82	18.80	18.47	18.75	18.83	18.76	19.06	18.78	45.29	43.1	46.27	44.04	45.09	43.69	44.77	45.04
5	23.25	23.31	22.97	23.19	23.05	23.13	23.21	23.16	41.10	41.17	40.75	41.01	41.49	41.23	41.38	41.16
6	27.75	27.77	27.75	28.35	28.31	28.42	28.89	28.18	38.85	38.85	38.39	38.20	37.91	38.28	38.73	38.46
7	32.27	32.31	31.86	32.12	31.97	31.63	3.13	32.04	37.53	37.31	37.10	37.05	37.02	37.03	36.76	37.11
8	36.76	36.79	36.48	36.2	36.13	35.79	36.13	36.33	35.37	35.02	35.02	35.12	35.23	35.32	35.39	35.21
9	41.26	41.27	41.07	41.27	41.54	41.09	40.91	41.20	33.34	33.14	33.29	33.45	33.31	32.92	32.92	33.20
10	45.85	45.88	45.73	46.15	46.17	46.02	45.99	45.97	32.05	31.79	31.83	31.96	31.80	31.46	31.09	31.71

TABLE E2. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT DAKACE ZARIA (DKZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.98	05.88	05.99	06.03	06.01	05.98	06.03	05.99	49.99	49.73	49.71	50.22	50.23	49.81	50.08	49.97
2	10.24	09.91	09.94	10.02	09.94	09.85	10.02	09.99	48.00	48.31	48.13	48.07	48.02	47.39	47.52	47.92
3	14.83	14.9	14.25	15.05	14.94	14.98	15.28	14.89	47.01	46.65	46.32	47.43	47.12	46.39	46.90	46.83
4	19.07	18.95	18.01	19.05	18.95	18.99	19.22	18.89	43.19	43.21	43.05	42.87	43.03	43.30	43.06	43.10
5	24.01	23.53	22.96	23.52	22.81	23.26	23.19	23.33	41.43	41.09	41.17	41.27	41.21	41.05	41.18	41.20
6	28.20	27.90	27.73	28.54	28.43	28.91	29.00	28.39	38.98	38.89	37.93	38.17	38.02	38.28	38.82	38.44
7	32.72	32.77	31.91	32.11	31.85	32.05	32.03	32.21	37.73	37.61	36.84	37.11	36.98	36.96	36.46	37.10
8	36.79	36.43	36.25	36.27	36.29	36.08	36.13	36.32	35.19	34.92	35.14	35.12	35.20	35.07	35.33	35.14
9	41.80	40.98	41.24	41.17	41.27	41.32	41.07	41.26	33.37	32.88	33.11	33.44	33.29	32.91	32.97	33.14
10	45.93	46.13	46.06	46.24	46.02	46.01	46.05	46.06	31.73	31.47	31.54	31.47	31.39	31.16	30.84	31.37

TABLE E3. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT BIZARA ZARIA (BZZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	06.21	05.99	06.03	06.01	05.94	06.02	05.11	05.90	50.01	50.12	49.57	50.03	49.80	49.63	49.66	49.83
2	09.91	10.04	10.06	10.04	10.03	09.98	10.07	10.02	47.73	48.20	48.22	48.03	47.83	48.04	47.97	48.00
3	15.07	15.10	13.97	14.89	14.99	15.23	14.97	14.89	46.80	47.12	46.31	46.87	46.73	46.70	47.11	46.81
4	19.39	19.01	18.04	19.09	19.08	18.97	19.12	18.96	43.47	42.62	42.93	43.24	42.77	43.03	43.11	43.02
5	23.18	22.92	22.90	24.27	23.00	23.28	23.03	23.23	40.91	41.47	41.10	41.23	41.07	41.17	41.04	41.14
6	29.07	28.60	27.88	28.03	28.06	27.83	27.98	28.21	38.79	37.77	38.09	39.05	38.28	38.29	38.58	38.41
7	32.17	31.95	32.08	33.03	31.15	31.25	32.97	32.09	36.60	36.86	36.72	37.52	36.9	37.01	36.85	36.92
8	36.13	36.58	36.20	36.94	36.13	36.58	37.77	36.62	35.14	34.99	35.28	35.26	35.16	35.03	35.55	35.20
9	41.09	41.32	41.06	41.42	41.27	41.38	41.45	41.28	32.81	33.23	33.24	33.45	32.94	33.21	33.10	33.14
10	46.26	46.48	45.78	45.95	46.19	46.24	45.98	46.13	30.68	31.27	31.73	31.47	31.27	31.52	31.32	31.32

TABLE E4. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT FILIN MALLAWA ZARIA (FMZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.11	06.04	05.97	05.76	06.03	05.98	06.01	05.85	49.35	49.50	50.06	49.44	49.59	49.41	49.49	49.55
2	09.99	09.92	09.96	10.11	10.01	10.01	10.01	10.00	48.18	48.00	48.14	48.03	47.91	48.19	47.87	48.05
3	15.09	14.68	15.05	15.00	15.16	14.96	14.92	14.98	46.91	46.44	46.33	46.51	46.70	46.88	46.65	46.63
4	19.34	18.02	19.42	19.04	18.84	19.74	19.73	19.16	43.35	42.87	43.16	42.55	43.28	43.17	43.15	43.08
5	22.98	22.83	23.12	23.97	23.03	23.74	22.90	23.22	41.37	41.39	41.47	40.98	41.40	41.43	41.14	41.31
6	27.92	28.07	28.99	27.91	27.93	28.05	29.55	28.35	38.55	37.98	38.91	38.71	38.22	38.96	37.79	38.45
7	32.91	31.65	32.59	32.69	31.94	31.99	32.67	32.35	36.54	36.28	36.05	37.50	37.01	37.22	36.87	36.78
8	37.81	35.88	36.20	36.80	36.25	36.57	35.86	36.48	36.06	34.82	34.81	35.23	35.81	34.87	35.05	35.24
9	41.62	41.25	40.95	41.27	41.96	41.66	41.99	41.53	33.00	32.95	32.30	33.90	32.76	33.04	32.95	32.99
10	45.98	46.03	45.94	45.87	45.94	46.19	45.91	45.98	31.29	31.33	30.71	31.49	31.06	31.30	30.98	31.17

TABLE E5. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT FILIN KOFAN KONA ZARIA (KKZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.64	05.68	05.86	06.03	06.06	06.02	06.00	05.90	05.64	49.99	49.92	49.75	49.79	49.98	50.17	43.61
2	09.84	09.94	09.93	09.95	10.13	10.22	09.91	09.99	09.84	48.13	48.03	47.47	47.86	48.20	47.98	42.50
3	14.13	14.45	14.89	15.09	15.10	14.80	14.84	14.76	14.13	46.55	46.97	46.92	47.08	46.97	47.09	42.24
4	18.84	18.42	18.77	18.75	19.07	19.08	18.97	18.84	18.84	43.24	42.99	42.60	42.74	43.12	43.03	39.51
5	23.23	22.92	23.11	23.05	23.17	24.05	22.70	23.18	23.23	40.70	41.02	41.14	41.33	41.36	41.17	38.56
6	27.67	27.74	28.33	28.35	28.87	28.17	28.34	28.21	27.67	38.36	38.16	38.24	38.76	38.91	37.98	36.88
7	32.11	31.85	32.13	31.66	32.05	32.69	31.75	32.03	32.11	37.05	37.09	37.02	36.72	37.73	36.94	36.38
8	36.78	36.44	36.24	35.77	36.04	36.78	36.20	36.32	36.78	34.90	35.06	35.37	35.37	35.09	35.16	35.39
9	41.17	41.01	41.27	41.10	40.89	41.80	41.27	41.22	41.17	33.33	33.31	32.86	32.88	33.27	33.25	34.30
10	45.82	45.71	46.09	45.97	45.94	45.90	45.98	45.92	45.82	31.84	31.95	31.44	31.10	31.62	31.35	33.59

TABLE E6. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT FILIN KOFAN GAYAN ZARIA (KGZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.25	05.65	05.93	05.90	06.09	05.96	06.01	05.83	49.93	49.92	50.05	49.71	49.81	49.99	50.24	49.95
2	09.81	09.90	09.91	09.94	10.15	10.21	09.95	09.98	47.90	48.06	47.98	47.46	47.89	48.04	47.99	47.90
3	14.25	14.54	14.88	15.11	15.17	14.80	14.91	14.81	46.98	46.54	47.11	47.01	47.04	47.14	47.08	46.99
4	18.80	18.46	19.00	18.79	19.07	19.03	19.00	18.88	43.25	43.36	43.02	42.69	42.86	43.17	43.05	43.06
5	23.15	23.02	23.21	23.09	23.18	24.00	22.79	23.21	41.11	40.74	41.03	41.13	41.38	41.43	41.31	41.16
6	27.78	27.86	28.35	28.39	28.89	28.19	28.48	28.28	38.83	38.43	38.08	38.23	38.8	38.98	38.01	38.48
7	32.13	31.84	32.02	31.67	32.10	32.80	31.84	32.06	37.54	37.08	37.19	36.99	36.76	37.74	36.99	37.18
8	36.79	36.47	36.16	35.74	36.08	36.81	36.35	36.34	35.41	34.96	35.12	35.29	35.39	35.21	35.12	35.21
9	41.25	41.07	41.27	41.09	40.92	41.83	41.25	41.24	33.34	33.45	33.45	32.91	32.95	33.33	33.27	33.24
10	45.90	45.76	46.08	46.08	45.99	45.96	45.94	45.96	32.02	31.90	31.96	31.44	31.09	31.96	31.36	31.68

TABLE E7. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT FILIN TUKUR TUKUR ZARIA (KGZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.36	05.76	05.93	05.96	06.12	06.00	06.03	05.88	50.07	50.02	50.09	49.72	49.91	50.00	50.13	49.99
2	09.92	09.93	09.95	09.97	10.16	10.15	09.96	10.00	47.96	48.08	48.04	47.46	47.92	48.1	48.01	47.94
3	14.26	14.57	14.89	15.09	15.12	14.86	14.94	14.82	46.98	46.33	47.10	46.98	46.98	47.28	47.09	46.96
4	18.85	18.46	18.95	18.78	19.11	19.09	19.00	18.89	43.44	43.29	43.01	42.59	42.95	43.23	43.05	43.08
5	23.25	22.93	23.22	23.12	23.18	24.02	22.82	23.22	41.15	40.95	41.02	41.14	41.41	41.49	41.41	41.22
6	27.71	27.75	28.33	28.25	28.96	28.19	28.50	28.24	38.97	38.33	38.06	38.19	38.78	38.88	38.01	38.46
7	32.26	31.84	32.05	31.74	32.11	32.89	31.82	32.10	37.52	37.00	37.12	36.97	36.87	37.73	37.06	37.18
8	36.78	36.50	36.13	35.80	36.09	36.88	36.33	36.36	35.29	34.98	35.12	35.22	35.33	35.16	35.25	35.19
9	41.26	41.02	41.18	41.11	40.96	41.86	41.37	41.25	33.31	33.25	33.49	32.96	33.12	33.34	33.29	33.25
10	45.96	45.79	46.16	45.99	45.95	45.97	46.00	45.97	32.02	31.95	31.97	31.23	31.03	31.67	31.31	31.60

TABLE E8. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT UNGUWAN DANKALI ZARIA (UDZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	05.19	5.95	05.85	05.91	06.14	06.04	06.03	05.87	50.06	50.02	50.03	49.76	49.75	49.99	50.1	49.96
2	09.99	9.94	09.85	09.89	10.15	10.22	09.95	09.99	47.97	48.14	48.03	47.30	47.93	48.01	47.97	47.91
3	14.22	14.57	14.94	15.06	15.07	14.93	14.93	14.82	47.11	46.48	47.10	47.03	46.91	47.2	46.97	46.97
4	18.94	18.54	18.95	18.73	19.09	19.06	19.06	18.91	43.33	43.07	43.01	42.62	42.93	43.21	42.92	43.01
5	23.24	23.00	23.12	22.96	23.12	24.01	22.77	23.17	41.19	40.69	41.03	41.13	41.45	41.46	41.3	41.18
6	27.86	27.99	28.41	28.32	28.93	28.21	28.55	28.32	38.98	38.52	37.98	38.26	38.89	39.08	37.98	38.53
7	32.20	31.83	32.10	31.64	32.11	32.89	31.82	32.08	37.84	37.04	37.09	37.00	36.87	37.64	37.13	37.23
8	36.76	36.48	36.13	35.79	36.08	36.87	36.26	36.34	35.15	34.99	35.12	35.19	35.19	35.11	35.16	35.13
9	41.19	40.97	41.20	41.09	40.96	41.90	41.34	41.24	33.35	33.26	33.34	32.89	32.99	33.39	33.23	33.21
10	45.81	45.77	46.09	46.01	45.97	45.94	46.05	45.95	31.98	31.93	31.99	31.19	31.19	31.73	31.28	31.61

TABLE E9. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT DOGARAWA ZARIA (DGZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	5.38	5.99	5.89	6	6.11	6	6.01	5.91	50.12	50.03	50.1	50.05	49.95	49.91	50.23	50.06
2	9.86	9.95	9.95	9.98	10.12	10.13	9.94	9.99	47.98	48.06	48.07	47.28	48.03	48.04	48.02	47.93
3	14.08	14.47	14.93	15.09	15.04	14.96	14.94	14.79	47.19	46.11	47.16	46.77	47.01	47.25	47.12	46.94
4	19	18.28	18.99	18.83	19.05	19.05	18.95	18.88	43.12	43.28	43.03	42.69	43.01	43.07	43.03	43.03
5	23.24	23.04	23.26	23.1	23.12	24.01	22.81	23.23	41.05	40.86	41.08	41.19	41.48	41.33	41.21	41.17
6	27.97	27.95	28.48	28.22	29.03	28.07	28.43	28.31	39	38.47	38.04	38.23	38.96	38.93	38.02	38.52
7	32.07	31.96	32.43	31.93	32.16	32.95	31.85	32.19	37.99	37.05	37.11	37.03	36.82	37.71	36.98	37.24
8	36.82	36.3	36.2	35.87	36.07	36.93	36.29	36.35	35.15	35.01	35.02	35.09	35.33	35.34	35.2	35.16
9	41.16	41	41.13	41	40.96	41.98	41.27	41.21	33.14	33.12	33.33	32.88	32.87	33.21	33.29	33.12
10	45.97	45.94	46.1	46.11	45.94	46.02	46.02	46.01	31.92	32	32	31.26	31.03	31.7	31.39	31.61

TABLE E10. SEVEN DAYS AVERAGE OF MEASUREMENTS TAKEN AT TOHU ZARIA (THZ)

SEVEN DAYS AVERAGE MEASURED SOIL MOISTURE									SEVEN DAYS AVERAGE MEASURED PLANTBOT'S SPEED							
S/N	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE	DAY1	DAY2	DAY3	DAY4	DAY5	DAY6	DAY7	AVERAGE
1	5.33	5.81	5.95	6.03	6.18	6.07	6.01	5.911	50.12	49.96	50.21	50.12	49.85	50.01	50.23	50.07
2	9.84	10.08	9.77	10.03	10.17	10.21	9.94	10.01	47.89	48.17	47.9	47.75	47.97	48.1	48.02	47.97
3	14.3	14.27	14.95	15.17	15.07	14.99	14.94	14.81	47.17	46.9	47.23	47.1	47.12	47.29	47.12	47.13
4	18.82	18.54	18.97	18.83	19.03	19.12	18.95	18.89	43.33	43.11	43.02	42.69	42.98	43.06	43.03	43.03
5	23.25	23.02	23.11	23.07	23.06	24.11	22.81	23.20	40.85	40.96	41.11	41.27	41.37	41.63	41.21	41.2
6	27.75	27.91	28.35	28.27	29.05	28.21	28.43	28.28	39.11	38.4	38	38.23	38.96	38.99	38.02	38.53
7	32.27	31.93	32.16	31.96	32.11	32.93	31.85	32.17	37.86	37.1	37.27	37.07	36.81	37.3	36.98	37.20
8	36.76	36.11	36.3	35.96	36.14	36.89	36.29	36.35	35.82	34.97	35.09	35.25	35.43	35.27	35.2	35.29
9	41.26	41.07	41.1	41.19	41	41.91	41.27	41.26	33.04	33.03	33.22	33.01	33.07	33.21	33.29	33.12
10	45.85	46.07	46.08	46	46.09	45.95	46.02	46.01	32.01	31.98	31.73	31.53	31.07	31.9	31.39	31.66

APPENDIX F

COMPLETE MATLAB SCRIPT FOR THE DEVELOPED MODEL

```
Created         "Sat Jun 07 13:28:59 2014"
Creator         "Kabir A"
Model {
  Name            "Model_2"
  Version         7.9
  MdlSubVersion       0
  GraphicalInterface {
    NumRootInports      0
    NumRootOutports     0
    ParameterArgumentNames  ""
    ComputedModelVersion    "1.3"
    NumModelReferences      0
    NumTestPointedSignals   0
  }
  SavedCharacterEncoding  "windows-1252"
  slprops.hdlmdlprops {
    $PropName           "HDLParams"
    $ObjectID           1
    Array {
      Type            "Cell"
      Dimension           2
      Cell            "HDLSubsystem"
      Cell            "Model_2"
      PropName            "mdlProps"
    }
  }
  SaveDefaultBlockParams  on
  ScopeRefreshTime    0.035000
  OverrideScopeRefreshTime on
  DisableAllScopes    off
  DataTypeOverride    "UseLocalSettings"
  DataTypeOverrideAppliesTo "AllNumericTypes"
  MinMaxOverflowLogging   "UseLocalSettings"
  MinMaxOverflowArchiveMode "Overwrite"
  FPTRunName          "Run 1"
  MaxMDLFileLineLength    120
  InitFcn         "init"
  StopFcn         "plot_results"
  UpdateHistory       "UpdateHistoryNever"
  ModifiedByFormat    "%<Auto>"
  LastModifiedBy      "user"
  ModifiedDateFormat      "%<Auto>"
  LastModifiedDate    "Tue Feb 25 05:35:49 2014"
  RTWModifiedTimeStamp    320090062
  ModelVersionFormat      "1.%<AutoIncrement:3>"
  ConfigurationManager    "None"
  SampleTimeColors    off
  SampleTimeAnnotations   off
  LibraryLinkDisplay      "disabled"
  WideLines       off
  ShowLineDimensions      off
  ShowPortDataTypes   off
```

```
ShowDesignRanges    off
ShowLoopsOnError    on
IgnoreBidirectionalLines off
ShowStorageClass    off
ShowTestPointIcons      on
ExtModeTrigPort     "1"
ExtModeTrigElement      "any"
ExtModeTrigDuration     1000
ExtModeTrigDurationFloating "auto"
ExtModeTrigHoldOff      0
ExtModeTrigDelay    0
ExtModeTrigDirection    "rising"
ExtModeTrigLevel    0
ExtModeArchiveMode      "off"
ExtModeAutoIncOneShot   off
ExtModeIncDirWhenArm    off
ExtModeAddSuffixToVar   off
ExtModeWriteAllDataToWs off
ExtModeArmWhenConnect   on
ExtModeSkipDownloadWhenConnect off
ExtModeLogAll       on
ExtModeAutoUpdateStatusClock on
BufferReuse         on
ShowModelReferenceBlockVersion off
ShowModelReferenceBlockIO off
Array {
  Type            "Handle"
  Dimension           1
  Simulink.ConfigSet {
    $ObjectID           3
    Version             "1.12.0"
    Array {
  Type            "Handle"
  Dimension       9
  Simulink.SolverCC {
    $ObjectID       4
    Version         "1.12.0"
    StartTime       "0.0"
    StopTime        "350"
    AbsTol          "auto"
    FixedStep       "auto"
    InitialStep         "auto"
    MaxNumMinSteps      "-1"
    MaxOrder        5
    ZcThreshold         "auto"
    ConsecutiveZCsStepRelTol "10*128*eps"
    MaxConsecutiveZCs   "1000"
    ExtrapolationOrder      4
    NumberNewtonIterations  1
    MaxStep         "auto"
    MinStep         "auto"
    MaxConsecutiveMinStep   "1"
    RelTol          "1e-3"
    SolverMode          "Auto"
    EnableConcurrentExecution off
    ConcurrentTasks     off
    Solver          "ode45"
```

```
  SolverName          "ode45"
  SolverJacobianMethodControl "auto"
  ShapePreserveControl    "DisableAll"
  ZeroCrossControl    "UseLocalSettings"
  ZeroCrossAlgorithm      "Nonadaptive"
  ConditionallyExecuteInputs on
  InlineParams        off
  UseIntDivNetSlope   off
  UseFloatMulNetSlope     off
  UseSpecifiedMinMax      off
  InlineInvariantSignals  off
  OptimizeBlockIOStorage  on
  BufferReuse         on
  EnhancedBackFolding     off
  StrengthReduction   off
  ExpressionFolding   on
  BooleansAsBitfields     off
  BitfieldContainerType   "uint_T"
  EnableMemcpy        on
  MemcpyThreshold     64
  PassReuseOutputArgsAs   "Structure reference"
  ExpressionDepthLimit    128
  FoldNonRolledExpr   on
  LocalBlockOutputs   on
  RollThreshold       5
  SystemCodeInlineAuto    off
  StateBitsets        off
  DataBitsets         off
  UseTempVars         off
  ZeroExternalMemoryAtStartup on
  ZeroInternalMemoryAtStartup on
  InitFltsAndDblsToZero   off
  NoFixptDivByZeroProtection off
  EfficientFloat2IntCast  off
  EfficientMapNaN2IntZero on
  OptimizeModelRefInitCode off
  LifeSpan        "inf"
  MaxStackSize        "Inherit from target"
  BufferReusableBoundary  on
  SimCompilerOptimization "Off"
  AccelVerboseBuild   off
  ParallelExecutionInRapidAccelerator on
}
Simulink.DebuggingCC {
  $ObjectID       7
  Version         "1.12.0"
  RTPrefix        "error"
  ConsistencyChecking     "none"
  ArrayBoundsChecking     "none"
  SignalInfNanChecking    "none"
  SignalRangeChecking     "none"
  ReadBeforeWriteMsg      "UseLocalSettings"
  WriteAfterWriteMsg      "UseLocalSettings"
  WriteAfterReadMsg   "UseLocalSettings"
  AlgebraicLoopMsg    "warning"
  ArtificialAlgebraicLoopMsg "warning"
  SaveWithDisabledLinksMsg "warning"
```

```
  SaveWithParameterizedLinksMsg "warning"
  CheckSSInitialOutputMsg on
  UnderspecifiedInitializationDetection "Classic"
  MergeDetectMultiDrivingBlocksExec "none"
  CheckExecutionContextPreStartOutputMsg off
  StrictBusMsg        "ErrorLevel1"
  BusNameAdapt        "WarnAndRepair"
  NonBusSignalsTreatedAsBus "none"
  LoggingUnavailableSignals "error"
  BlockIODiagnostic   "none"
  SFUnusedDataAndEventsDiag "warning"
  SFUnexpectedBacktrackingDiag "warning"
  SFInvalidInputDataAccessInChartInitDiag "warning"
  SFNoUnconditionalDefaultTransitionDiag "warning"
  SFTransitionOutsideNaturalParentDiag "warning"
  SFUnconditionalTransitionShadowingDiag "warning"
}
Simulink.HardwareCC {
  $ObjectID       8
  Version         "1.12.0"
  ProdBitPerChar      8
  ProdBitPerShort     16
  ProdBitPerInt       32
  ProdBitPerLong      32
  ProdBitPerFloat     32
  ProdBitPerDouble    64
  ProdBitPerPointer   32
  ProdLargestAtomicInteger "Char"
  ProdLargestAtomicFloat  "None"
  ProdIntDivRoundTo   "Undefined"
  ProdEndianess       "Unspecified"
  ProdWordSize        32
  ProdShiftRightIntArith  on
  ProdHWDeviceType    "32-bit Generic"
  TargetBitPerChar    8
  TargetBitPerShort   16
  TargetBitPerInt     32
  TargetBitPerLong    32
  TargetBitPerFloat   32
  TargetBitPerDouble      64
  TargetBitPerPointer     32
  TargetLargestAtomicInteger "Char"
  TargetLargestAtomicFloat "None"
  TargetShiftRightIntArith on
  TargetIntDivRoundTo     "Undefined"
  TargetEndianess     "Unspecified"
  TargetWordSize      32
  TargetTypeEmulationWarnSuppressLevel 0
  TargetPreprocMaxBitsSint 32
  TargetPreprocMaxBitsUint 32
  TargetHWDeviceType      "Specified"
  TargetUnknown       off
  ProdEqTarget        on
}
Simulink.ModelReferenceCC {
  $ObjectID       9
  Version         "1.12.0"
```

```
UpdateModelReferenceTargets "IfOutOfDateOrStructuralChange"
CheckModelReferenceTargetMessage "error"
EnableParallelModelReferenceBuilds off
ParallelModelReferenceErrorOnInvalidPool on
ParallelModelReferenceMATLABWorkerInit "None"
TLCAssert       off
ProcessScriptMode   "Default"
ConfigurationMode   "Optimized"
ConfigAtBuild       off
RTWUseLocalCustomCode   off
RTWUseSimCustomCode     off
IncludeHyperlinkInReport off
LaunchReport        off
TargetLang          "C"
IncludeBusHierarchyInRTWFileBlockHierarchyMap off
IncludeERTFirstTime     off
GenerateTraceInfo   off
GenerateTraceReport     off
GenerateTraceReportSl   off
GenerateTraceReportSf   off
GenerateTraceReportEml  off
GenerateCodeInfo    off
GenerateWebview     off
GenerateCodeMetricsReport off
GenerateCodeReplacementReport off
RTWCompilerOptimization "Off"
CheckMdlBeforeBuild     "Off"
CustomRebuildMode   "OnUpdate"
Array {
  Type            "Handle"
  Dimension           2
  Simulink.CodeAppCC {
    $ObjectID           12
    Version             "1.12.0"
    Array {
  Type            "Cell"
  Dimension       22
  Cell            "IgnoreCustomStorageClasses"
  Cell            "IgnoreTestpoints"
  Cell            "InsertBlockDesc"
  Cell            "InsertPolySpaceComments"
  Cell            "SFDataObjDesc"
  Cell            "MATLABFcnDesc"
  Cell            "SimulinkDataObjDesc"
  Cell            "DefineNamingRule"
  Cell            "SignalNamingRule"
  Cell            "ParamNamingRule"
  Cell            "InternalIdentifier"
  Cell            "InlinedPrmAccess"
  Cell            "CustomSymbolStr"
  Cell            "CustomSymbolStrGlobalVar"
  Cell            "CustomSymbolStrType"
  Cell            "CustomSymbolStrField"
  Cell            "CustomSymbolStrFcn"
  Cell            "CustomSymbolStrFcnArg"
  Cell            "CustomSymbolStrBlkIO"
  Cell            "CustomSymbolStrTmpVar"
```

```
Cell            "CustomSymbolStrMacro"
Cell            "ReqsInCode"
PropName        "DisabledProps"
  }
  ForceParamTrailComments off
  }
  TargetFcnLib        "ansi_tfl_table_tmw.mat"
  TargetLibSuffix         ""
  TargetPreCompLibLocation ""
  CodeReplacementLibrary  "ANSI_C"
  UtilityFuncGeneration   "Auto"
  ERTMultiwordTypeDef     "System defined"
  CodeExecutionProfiling  off
  ERTMultiwordLength      256
  MultiwordLength         2048
  GenerateFullHeader      on
  GenerateSampleERTMain   off
  GenerateTestInterfaces  off
  IsPILTarget         off
  ModelReferenceCompliant on
  ParMdlRefBuildCompliant on
  CompOptLevelCompliant   on
  ConcurrentExecutionCompliant on
  IncludeMdlTerminateFcn  on
  GeneratePreprocessorConditionals "Disable all"
  CombineOutputUpdateFcns on
  CombineSignalStateStructs off
  SuppressErrorStatus     off
  ERTFirstTimeCompliant   off
  IncludeFileDelimiter    "Auto"
  ERTCustomFileBanners    off
  SupportAbsoluteTime     on
  LogVarNameModifier      "rt_"
  MatFileLogging          on
  MultiInstanceERTCode    off
  SupportNonFinite        on
  SupportComplex          on
  PurelyIntegerCode       off
  SupportContinuousTime   on
  SupportNonInlinedSFcns  on
  SupportVariableSizeSignals off
  EnableShiftOperators    on
  ParenthesesLevel        "Nominal"
  PortableWordSizes       off
  ModelStepFunctionPrototypeControlCompliant off
  CPPClassGenCompliant    off
  AutosarCompliant        off
  GRTInterface        off
  UseMalloc           off
  ExtMode             off
  ExtModeStaticAlloc      off
  ExtModeTesting          off
  ExtModeStaticAllocSize  1000000
  ExtModeTransport        0
  ExtModeMexFile          "ext_comm"
  ExtModeIntrfLevel       "Level1"
  RTWCAPISignals          off
```

```
        RTWCAPIParams       off
        RTWCAPIStates       off
        RTWCAPIRootIO       off
        GenerateASAP2       off
      }
  FontWeight          "normal"
  FontAngle           "normal"
}
BlockParameterDefaults {
  Block {
    BlockType           Gain
    Gain            "1"
    Multiplication          "Element-wise(K.*u)"
    ParamMin            "[]"
    ParamMax            "[]"
    ParamDataTypeStr        "Inherit: Same as input"
    OutMin              "[]"
    OutMax              "[]"
    OutDataTypeStr          "Inherit: Same as input"
    LockScale           off
    RndMeth             "Floor"
    SaturateOnIntegerOverflow on
    SampleTime          "-1"
  }
  Block {
    BlockType           Inport
    Port            "1"
    OutputFunctionCall      off
    OutMin              "[]"
    OutMax              "[]"
    OutDataTypeStr          "Inherit: auto"
    LockScale           off
    BusOutputAsStruct       off
    PortDimensions          "-1"
    VarSizeSig          "Inherit"
    SampleTime          "-1"
    SignalType          "auto"
    SamplingMode        "auto"
    LatchByDelayingOutsideSignal off
    LatchInputForFeedbackSignals off
    Interpolate         on
  }
  Block {
    BlockType           Integrator
    ExternalReset       "none"
    InitialConditionSource  "internal"
    InitialCondition        "0"
    LimitOutput         off
    UpperSaturationLimit    "inf"
    LowerSaturationLimit    "-inf"
    ShowSaturationPort      off
    ShowStatePort       off
    AbsoluteTolerance       "auto"
    IgnoreLimit         off
    ZeroCross           on
    ContinuousStateAttributes "''"
  }
```

```
Block {
  BlockType           Outport
  Port             "1"
  OutMin              "[]"
  OutMax              "[]"
  Ports            [1, 1]
  Position            [290, 137, 385, 173]
  ZOrder              1
  LibraryVersion          "1.108"
  SourceBlock         "cstblocks/LTI System"
  SourceType          "LTI Block"
  sys              "G1"
  IC               "[]"
}
Block {
  BlockType           Scope
  Name             "Scope1"
  SID              "34"
  Ports            [1]
  Position            [570, 319, 600, 351]
  ZOrder              19
  Floating            off
  Location            [924, 379, 1309, 986]
  Open             off
  NumInputPorts       "1"
  List {
ListType        AxesTitles
axes1           "%<SignalLabel>"
  }
  List {
ListType        ScopeGraphics
FigureColor     "[0.5 0.5 0.5]"
AxesColor       "[0 0 0]"
AxesTickColor       "[1 1 1]"
LineColors      "[1 1 0;1 0 1;0 1 1;1 0 0;0 1 0;0 0 1]"
LineStyles      "-|-|-|-|-|-"
LineWidths      "[0.5 0.5 0.5 0.5 0.5 0.5]"
MarkerStyles        "none|none|none|none|none|none"
  }
  ShowLegends         off
  SaveName            "ScopeData1"
  DataFormat          "StructureWithTime"
  SampleTime          "0"
}
Block {
  BlockType           Scope
  Name             "Scope2"
  SID              "38"
  Ports            [1]
  Position            [570, 139, 600, 171]
  ZOrder              23
  Floating            off
  Location            [913, 147, 1361, 762]
  Open             off
  NumInputPorts       "1"
  List {
ListType        AxesTitles
```

```
axes1           "%<SignalLabel>"
  }
  List {
ListType        ScopeGraphics
FigureColor     "[0.5 0.5 0.5]"
ZoomFactor      "125"
Block {
  BlockType       Inport
  Name            "u"
  SID             "43"
  Position        [70, 38, 100, 52]
  ZOrder          26
  IconDisplay         "Port number"
}
Block {
  BlockType       Inport
  Name            "y"
  SID             "44"
  Position        [395, 88, 425, 102]
  ZOrder          27
  Port            "2"
  IconDisplay         "Port number"
}
Block {
  BlockType       Gain
  Name            "A1"
  SID             "45"
  Position        [115, 175, 145, 205]
  ZOrder          20
  Gain            "A-L*C"
  Multiplication      "Matrix(K*u) (u vector)"
  ParamDataTypeStr    "Inherit: Inherit via internal rule"
  OutDataTypeStr      "Inherit: Inherit via internal rule"
  SaturateOnIntegerOverflow off
}
Block {
  BlockType       Gain
  Name            "B2"
  SID             "46"
  Position        [155, 20, 190, 70]
  ZOrder          17
  Gain            "B"
  Multiplication      "Matrix(K*u) (u vector)"
  ParamDataTypeStr    "Inherit: Inherit via internal rule"
  OutDataTypeStr      "Inherit: Inherit via internal rule"
  SaturateOnIntegerOverflow off
}
Block {
  BlockType       Integrator
  Name            "Integrator1"
  SID             "47"
  Ports           [1, 1]
  Position        [115, 85, 145, 115]
  ZOrder          21
  BlockMirror         on
  NamePlacement       "alternate"
  InitialCondition    "x0"
```

```
}
Block {
  BlockType       Gain
  Name            "L"
  SID             "48"
  Points          [9, 0; 0, 22; -66, 0; 0, -12]
  DstBlock        "L"
  DstPort         1
}
Line {
  SrcBlock        "u"
  SrcPort         1
  DstBlock        "B2"
  DstPort         1
}
Line {
  SrcBlock        "Sum2"
  SrcPort         1
  DstBlock        "Integrator1"
  DstPort         1
}
Line {
  SrcBlock        "B2"
  SrcPort         1
  Points          [87, 0; 0, 50]
  DstBlock        "Sum2"
  DstPort         1
}
Line {
  SrcBlock        "A1"
  SrcPort         1
  Points          [132, 0; 0, -75]
  DstBlock        "Sum2"
  DstPort         3
}
  }
}
Line {
  SrcBlock            "LTI System"
  SrcPort             1
  Points              [105, 0]
  Branch {
DstBlock        "Scope2"
DstPort         1
  }
  Branch {
DstBlock        "observer"
DstPort         2
  }
}
Line {
  SrcBlock            "observer"
  SrcPort             1
  Points              [0, 15]
  Branch {
Points          [0, 20]
DstBlock        "Gain"
```

```
    DstPort         1
      }
      Branch {
    DstBlock        "Scope1"
    DstPort         1
      }
    }
    Line {
      SrcBlock            "Step"
      SrcPort             1
      DstBlock            "Sum"
      DstPort             1
    }
    Line {
      SrcBlock            "Sum"
      SrcPort             1
      Points              [41, 0]
      Branch {
    Points          [0, 73; 244, 0]
    DstBlock        "observer"
    DstPort         1
      }
      Branch {
    Points          [30, 0]
    Branch {
      Points          [0, -120]
      DstBlock        "Scope3"
      DstPort         1
    }
    Branch {
      DstBlock        "LTI System"
      DstPort         1
    }
      }
    }
    Line {
      SrcBlock            "Gain"
      SrcPort             1
      Points              [-120, 0]
      DstBlock            "Sum"
      DstPort             2
    }
  }
}
```