THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

FARMBOT GROWROOM

by

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Bachelor of Engineering
in the field of Mechatronic Engineering

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Prof Amin Abbosh
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Dear Professor Abbosh,

In accordance with the requirements of the degree of Bachelor of Engineering in the division of Mechatronic Engineering, I present the following thesis entitled 'Farmbot Growroom'. This work was performed under the supervision of Dr. Matthew D'Souza.

I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at The University of Queensland or any other institution.

Yours sincerely,

Madison Beare

To me. Congratulations on all your hard work over the duration of your degree.
It's time to read a nice book. You deserve it.

Acknowledgments

Throughout the completion of this project, I have received a great deal of support and assistance.

I would first like to thank my supervisor, Dr. Matthew D'Souza, for both the guidance and equipment loan over the duration of the year.

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Finally, I'd like to thank my friends and family for always supporting me and the work I do. I truly appreciate each and every one of you.

Abstract

With food supply needing to increase by an estimated 60% by 2050 to meet global demand, food security has become an increasingly important issue [1]. Due to rising shortages in farmland, vertical farming solutions have been identified as the future of the agricultural industry. This provides an opportunity for AgTech to assist in these alternate applications.

This thesis provides a summary of the design and build of theMonarch - a robotic arm solution to integrate with the Growroom using the Universal Tool Mount. An analysis of key mechanical challenges paired with current robotic arm types resulted in a robotic scissor arm adaptation with a total workspace comprising of a torus with inner diameter of 172mm, outer diameter of 600mm and a depth of 710mm. The full mechanical build comprised of the arm mounted to a vertical axis consisting of a v-slot, a horizontal axis comprising of a c-beam and a turntable to provide rotational motion.

Before project deployment, future improvements need to be made regarding the turntable transmission system, slip ring placement, axis redundancy and full website deployment. The feasibility of a large scale model should also be investigated before a scale up of this design is produced.

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Chapter 1

Introduction

This section provides an overview of the motivation behind the FarmBot Growroom thesis, and the significance of providing a design solution. The aim and scope of the project are also summarised.

1.1 Motivations and Significance

With the Earth's population projected to reach 9 billion, food security has become an increasingly important issue [1]. To sustain this projection, predictions by the Food and Agriculture Organisation of the UN (FAO) estimate food supply will need to increase by 60% to meet global demand [1].

"With such high demand, land specialists such as agronomists, ecologists and geologists warn of rising shortages of farmland" [2]. With a potential for demand surpassing the ability to supply, recent advances in greenhouse technologies have looked towards alternate solutions to this impending global crisis.

Vertical farming represents a concept that minimizes spacial footprint, whilst maximising yield. This notion offers a sustainable and efficient alternate method for food production in heavily populated environments with little room for crop growth.

This concept presents a series of future opportunities for the agricultural industry in Australia. To further master the optimisation of agricultural yield, technology aims to assist in improved productivity and quality, reduce unnecessary wastage, increase sustainability, and assist farmers and growers with more informed decisions. The implementation of AgTech also offers a valuable opportunity to bring prosperity to both urban and rural communities.

1.2 Objectives

At a high level overview, the FarmBot Growroom thesis will focus on the implementation of AgTech in vertical farming and will investigate opportunities this project could provide.

To do this, a robotic arm must be designed to accompany the Growroom - a spherical planter structure designed by SPACE10. This robotic arm will be modeled after the FarmBot (a Cartesian gantry style robotic arm) - if possible. The end-effector of the system must be the Universal Tool Mount (UTM) of the FarmBot system design, and the primary objective of the arm is to provide farming assistance to all Growroom shelves using FarmBot tool heads.

1.3 Scope

The scope of the FarmBot Growroom is outlined in Table 1.1:

Table 1.1: Scope of FarmBot Growroom Thesis

In Scope	Out of Scope
Mechanical design and build of robotic arm	End-effector design
Electronic considerations and Printed Circuit Board (PCB) manufacture	Tool design
Preliminary interface implementation	Design and construction of Growroom
Component sourcing and selection	Fully established interface
Waterproofing and environmental considerations	
Integration with current FarmBot design (i.e. UTM)	

Chapter 2

Literature Review

This section provides an overview of background information relevant to the project, as well as a review of current solutions.

2.1 Growroom

The Growroom is a spherical greenhouse structure designed by SPACE10 that - in the full-scale version - consists of 5-tiered planter beds. The full-scale Growroom structure is 2.8m x 2.5m and has a small spatial footprint [3]. The Growroom is designed for cities, where space to grow traditional crops is lacking – tacking advantage of the area this vertical farm provides. Overlapping layers ensure water and light can reach vegetation, whilst sheltering visitors within [3].

The FarmBot Growroom thesis will focus on a small-scale version of this product, with dimensions of approximately 1.16m x 1.08m. This structure has 3 tiers and will be referred to as the Growroom from hereon after. The mechanical diagram of this structure can be seen in Appendix A.

2.2 FarmBot

2.2.1 Mechanical Structure

The FarmBot is a Cartesian or gantry style system that consists of 3-axis of movement over 3 different mechanical structures. These are listed below and illustrated in Appendix B.

1. **Tracks**. These consist of segments of aluminum v-slots attach to the grower's supporting infrastructure (i.e. garden bed). They allow for precise movement along the x-axis.

2. **Gantry & Cross-slide**. The gantry is the structural component that bridges the tracks and serves as the linear guide for the cross-slide [4]. The gantry moves along the x-axis through a belt and pulley drive system [4].

   The cross-slide moves along the y-axis using the gantry as it's linear support and provides the second degree of freedom for the system. This is the mounting location of the z-axis and movement is provided by a belt and pulley drive train.

3. **Z-axis**. The z-axis provides a mounting base for the UTM and all tools. Movement is provided via a lead screw.

2.2.2 Electronics

The electronics of the FarmBot consist of two major components: the Farmduino and a Raspberry Pi. The Farmduino uses Arduino architecture and communicates with the Raspberry Pi through language similar to G-code [5]. As it provides power and control to all electrical components, as well as stepper drivers, motors, UTM and peripherals, the board layout has been optimised for these specifications [5].

The Raspberry Pi monitors all software aspects of the system, including any machine learning, sequences, events and system settings. This includes responsibility and control over camera functionality, button observation and LED management.

2.2.3 Software

Software control for the FarmBot consists of communication between the Raspberry Pi and Farmduino and the Raspberry Pi to the FarmBot Web Application. A high level overview of the software application can be seen in Appendix C.

The FarmBot Web application allows for real-time control and logging as well as custom routines for the FarmBot to execute and drag-and-drop design, allowed for graphical garden bed design [6].

"The Raspberry Pi runs a custom operating system 'FarmBot OS' that synchronizes with the web application via the message broker" [6]. This allows for execution of scheduled events, communication over serial or USB connections, and uploading, reading and logging real-time and stored sensor data [6].

Physical operation of motors, tools, sensors and all electronics occurs from firmware flashed onto the Farmduino.

2.2.4 Universal Tool Mount

2.2.4.1 Head

The head of the UTM is designed such that tools are able to be automatically switched between. This component is made from Ultra Violet (UV) stabalised Acrylonitrile Butadiene Styrene (ABS) that mounts to the z-axis using M5 screws and tee nuts [7]. Components that make up the UTM head include:

- **Neodymium ring magnets**. Used to hold tools in place.
- **Passageways**. "This includes passageways for water, liquid amendments, and vacuum or compressed air" [7].
- **Pogo Pins**. This is used to establish electrical connections with tool mounts.

2.2.4.2 Tools

Farmbot Genesis tools include the following:

- **Seed Injector**. This positions seeds in a planter bed within millimeter accuracy. It is powered by a 24 volt vacuum pump [8].
- **Watering Nozzle**. Allows for plant watering.
- **Weeder**. Includes standard blades and spikes to remove weeds.
- **Soil Sensor**. This includes both a moisture and temperature sensor. Measures moisture content at each plant location to ensure precise feedback for accurate water requirements. Temperature sensor is used to help detect the risk of germination failure [8].
- **Camera**. Waterproof camera used to monitor plant growth, detect weeds and identify pests, disease and fruit ripeness [8].

2.3 Robotic Arm Types

2.3.1 Cartesian Robots

A Cartesian robot (commonly referred to as a rectilinear or gantry robot), has three linear axes, mounted perpendicular to one another [9]. This robot moves in three orthogonal axes X, Y and Z, according to the Cartesian coordinate system [10]. Occasionally, an end-effector will be attached to a wrist, providing rotational movement. Prismatic joins deliver linear motion along each respective axis [9]. Common applications of Cartesian robots include 3D printers and computer numerical control (CNC) machines. A simple schematic of a Cartesian robot can be seen in Appendix D

Advantages of Cartesian robots include their high rigidity that allows for the movement of heavy payloads, their high accuracy and high repeatability. Common applications suitable for this robot type include pick and place, stacking and part assembly [11].

2.3.2 Articulated Robots

Articulated robots are the most common types of industrial robots, as their ability to replicate the full range of movement of the human arm is significant [12]. These robotic arms consist of varying numbers of links, all with rotary joints that each provide a degree of freedom. A schematic example of this robot type (the ZETA 6 axis robot) can be seen in Appendix E.

The articulated robot structure typically starts with a base vertical to the ground containing the first joint referred to as the shoulder [10]. The main arm link is then connected to the base through this joint, with additional joints and links forming the robotic wrist and end-effector [10]. This is designed to closely mimic the human arm, providing an enhanced range of motion with a large work envelope.

The versatility the range of motion and workspace provides allows for these robots to be used in versatile applications from assembly lines, pick and place, packaging, and welding.

2.3.3 Selected Compliance Articulated Robot Arm

Selective Compliance Articulated Robot Arms (SCARA) is a type of robot designed to mimic the movement of the human arm through compliance in the X-Y axis and rigid in the Z-axis [13]. Appendix F shows the general configuration of the SCARA arm. The SCARA structure consists of two links/arms, a_1 and a_2 joined at their intersection q_2, with the base connected to a_1 through join q_1. Typically, motors situated at q1 and q2 use inverse kinematics to control the position of the end-effector, the final location being a factor of link length and joint angles. Key advantages of the SCARA robot consist of their high speed, accuracy and repeatability, making them optimal in pick-and-place or assembly operations [14].

2.3.4 Telescopic Robotic Arms

"At the most basic level, a telescoping structure consists of a sequence of nested units that can be extended and retracted" [15]. Appendix G illustrates 3 different types of telescoping robotic arms (where Figure G.1(a) represents an ideal thin telescopic arm [16]) that upon motion, result in linear extension. These potential solutions will be detailed in the following sections.

2.3.4.1 Telescopic Cylindrical Arm

Telescopic cylinders comprise of a series of tubes (typically steel or aluminum) with progressively smaller diameters nested within one another [17]. This can be seen in Appendix G, Figure G.1(b) The barrel is the largest base section of the nest, with the inner sleeves referred to as stages. Industry standard telescopic cylinders are typically kept to a maximum of 6 stages due to stability issues when this number is surpassed.

Telescopic cylinders are ideal in applications where a limitations on mounting or size of product occurs. The collapsed length of standard telescopic cylinders varies between 20 – 40% of the fully extended length [17]. Extending from largest to smallest means the largest stage will extend first and complete its movement, before the next stage begins to move. This procedure continues until all nested stages are fully extended. This works in reverse order when retracting, with the smallest diameter stage fully retracting before the next stage begins movement. This will continue until all stages are fully nested within the barrel.

To automate this process, hydraulic pressure is used to allow movement. Single-acting telescopic cylinders extended under this pressure, however, rely on gravity or external mechanical force for retraction when the fluid medium is removed [17]. This reaction force is typically the weight of the load subjected to gravity. Double-acting telescopic cylinders are powered hydraulically in both directions [17]. This is required in applications where a reliance on gravity or external mechanical force is not achievable. This adds complexity to the mechanical design with the addition of hydraulic seals and retracting piston faces to all stages [17].

2.3.4.2 Telescoping Slider Arm

Telescopic sliders are made up of an outer rail, fitted with one or more inner rails of smaller widths. These arms do not retract into one another, but instead fold underneath one another as shown in Appendix G, Figure G.1(c). This arm relies on balls or rollers to guide movement and are used in applications that require high rigidity and high load capacity over extended lengths [18]. These arms usually vary in material type, as each product may have differing budget, load, weight, and stiffness requirements.

The length of the arm is dependent on the overlap or stroke of each link, and the number of rails. As the total extension of the arm surpasses the link length itself, complications may arise with this over-extension such as tipping and lean, and often intermediate elements are required for stability [18].

Typically, this arm type is rigged to a pulley system, or directly coupled to actuators (in the case of only 2 rails) to allow for extension and retraction.

2.3.4.3 Robotic Scissor Arm

Robotic scissor arms consist of pairs of links typically known as scissors, that connect via rotational pivots. A scissor pair connects via this pivot when one scissor is placed directly over another, so they can be joined at their centers, creating a crisscross or ‘X’ pattern [19]. To build upon this, and create an arm, scissor pairs are coupled together by their ends. This can be seen in Appendix G, Figure G.1(d).

Typically one scissor of the base pair is mounted rigidly, with force applied to the other scissor in the pair. This causes the elongation of the coupled scissor, elongating the crisscross and adding length to the arm. This has a cumulative effect on each consecutive scissor pair in the system, as each is dependent upon the other.

To automate this process, hydraulic, pneumatic and mechanical power is typically used in industry applications (such as scissor lifts, lift tables) with elongation and retraction occurring due to this force. Hobby/commercial applications (pantograph mirror, scissor lamps) have consist of expansion due to mechanical or muscular force.

Chapter 3

Theory

This section will outline all theory required in the design process of this thesis. This includes formulae regarding arm lengths, torque calculations and transmission system requirements.

3.1 Scissors

3.1.1 Overview & Schematic

To facilitate the design of the robotic arm structure and determine the number of scissors (n) required for optimisation, calculations were completed based on the follow input data applied to Figure 3.1:

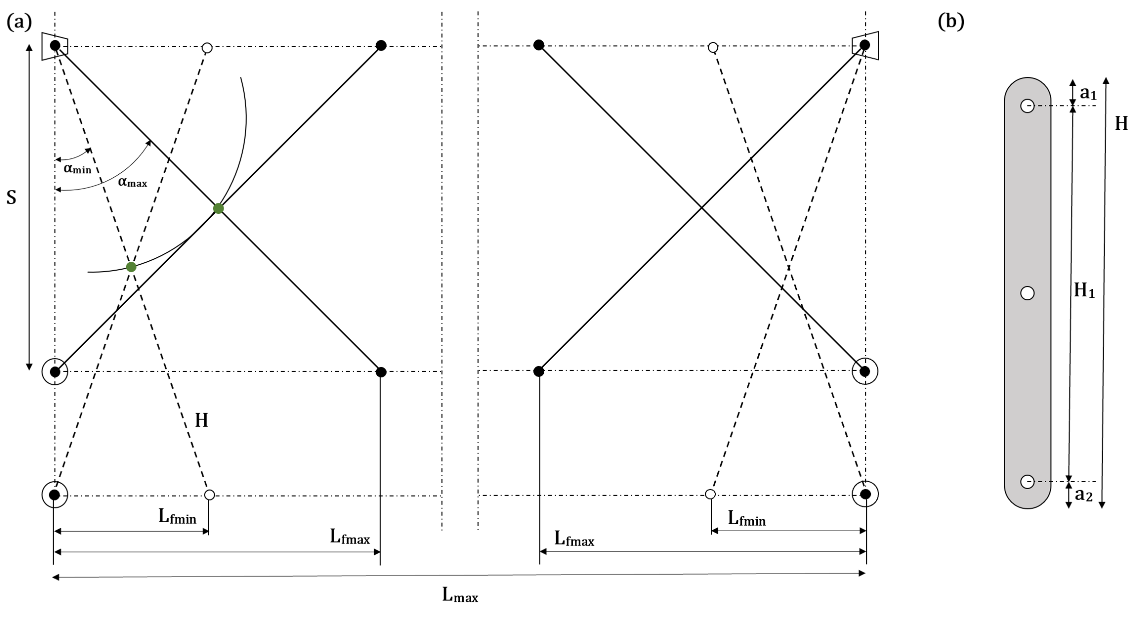

Figure 3.1: Scissor Schematic and Front View
(a) Schematic diagram of n scissors (b) Front view of scissor

- Maximum/open scissor angle: α_{max} (°)
- Minimum/folded scissor angle: α_{min} (°)
- Distance to pin joints: a_1, a_2 (m)
- Height of extended arm[1]: S (m)
- Height of scissor[2]: H (m)

To obtain:

- Number of scissors: n
- Total extendable length: L_{max} (m)
- Collapsed/folded length: L_{fmin} (m)

All length and height variables are measured in millimeters (mm), whilst angles are measured in degrees (°). The following formulas are computed using basic trigonometry functions and were adapted using [20].

3.1.2 Number of Scissors

The number of scissors required is determined by the relation:

$$n = \left\lceil \frac{L_{max}}{2 \cdot H \cdot \sin(\alpha_{max})} \right\rceil \tag{3.1}$$

3.1.3 Maximum and Minimum Arm Length

Using Equation 3.1 the total extendable/open and retractable/folded length (L_{max}) and (L_{min}) can be calculated:

$$L_{max} = 2n \cdot H \cdot \sin(\alpha_{max}) \tag{3.2}$$

$$L_{min} = 2n \cdot H \cdot \sin(\alpha_{min}) \tag{3.3}$$

3.1.4 Lead Screw Length

The length of the lead screw required in the arm design is directly proportional to the difference between the length of the folded arm and the length of the fully extended arm.

These distances are shown in Figure 3.1 and are shown as L_{max} and L_{fmin}.

[1] Calculated based on height of shelves in Growroom, UTM height and tool lengths
[2] Calculated using trigonometric functions using α_{min} and S

The equation to determine the length of the lead screw is as follows:

$$Lead\ Screw\ Length = L_{max} - L_{fmin} \tag{3.4}$$

Where:

$$L_{max} = H \cdot sin(\alpha_{min}) \tag{3.5}$$

$$L_{fmin} = H \cdot sin(\alpha_{max}) \tag{3.6}$$

3.2 Torque Requirements

3.2.1 Horizontal Lead Screw Torque

Figure 3.2 shows a basic layout of the horizontal lead screw formation.

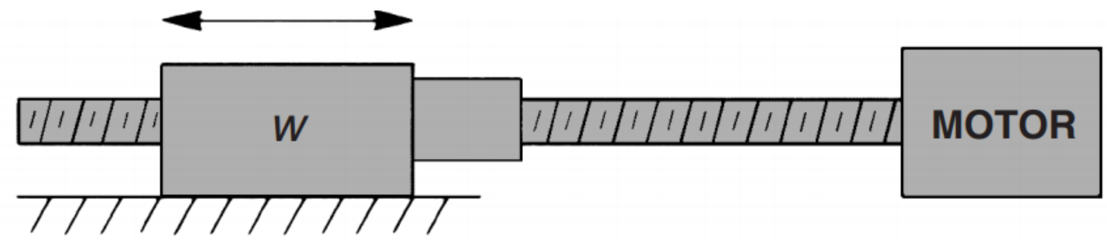

Figure 3.2: Horizontal Lead Screw Diagram
Source: [21]

To calculate the torque necessary to accelerate the load horizontally, the motor is required to [22]:

1. Accelerate the load;
2. Rotate the lead screw;
3. Accelerate the motor rotor and
4. Overcome frictional forces.

3.2.1.1 Accelerating the Load

To accelerate the load the following relation can be used:

$$J_{load} = m \cdot l^2 \cdot \left(\frac{1}{2\pi}\right)^2 \tag{3.7}$$

Where:

- Inertia of the load: J_{load} (mkg^2)
- Mass of load: m (kg)
- Lead: l (m)

"This converts linear mass into rotational inertia as reflected to the motor shaft by the screw" [23].

3.2.1.2 Rotating the Screw

To inertia of the lead screw can be calculated by:

$$J_{screw} = \frac{\pi L \rho R^4}{2} \tag{3.8}$$

Where:

- Inertia of the screw: J_{screw} (mkg^2)
- Length of lead screw: L (m)
- Radius of lead screw: R (m)
- Density of lead screw material: ρ (kg/m^3)

3.2.1.3 Accelerating the Motor Rotor

This refers to the inertia of the motor (mkg^2), and will be located on the motor data sheet.

$$J_{motor} = implementation\ dependent \tag{3.9}$$

3.2.1.4 Overcoming Frictional Forces

The following relation calculated the torque due to friction acting upon the system:

$$\tau_{friction} = \frac{\mu m g}{2\pi p \eta} \tag{3.10}$$

Where:

- Torque due to friction: $\tau_{friction}$ (Nm)
- Coefficient of friction: μ

- Mass of load: m (kg)
- Acceleration due to gravity: g (m/s^2)
- Pitch: p (revs/unit length)
- Efficiency of lead screw: η

3.2.1.5 Total Torque

The total torque required to accelerate the system can be calculated using the following relation:

$$\tau_{total} = (J_{load} + J_{scew} + J_{motor}) \left(\frac{\Delta v}{\Delta t}\right) \left(\frac{2\pi}{s_{rev}}\right) + \tau_{friction} \tag{3.11}$$

Where:

- Total torque: τ_{total} (Nm)
- Steps per second: Δv (steps/second)
- Acceleration time: Δt (seconds)
- Steps per revolution: s_{rev} (steps/rev)

All other variables are references to Equations 3.7, 3.9, 3.8 and 3.10.

3.2.2 Vertical Lead Screw Torque

The first vertical transmission system within this application consists of a lead screw required to raise and lower a load. Figure 3.3 (a) shows a lead screw with [21]:

- Mean diameter: d_m (m)
- Pitch: p (revs/unit length)
- Lead angle: λ (deg)
- Helix angle: ψ (deg)

Loaded by the:

- Compressive force: F (N).

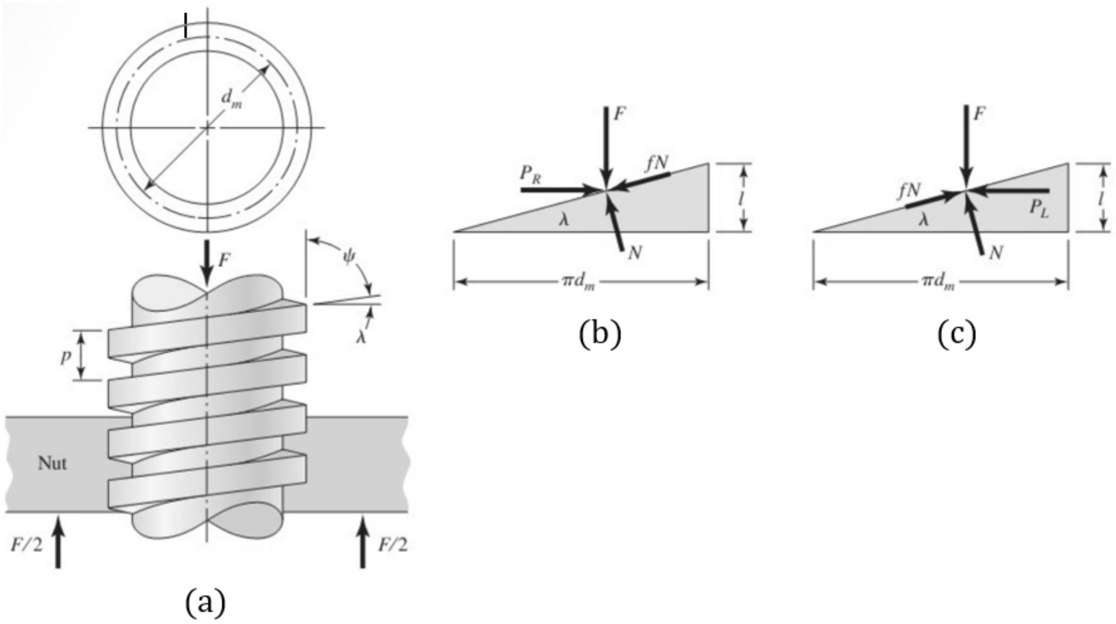

Figure 3.3: Lead Screw Segment & Free Body Diagram
(a) Lead screw portion. Force diagram of (b) Lifting load (c) Lowering load
Source: [21]

Figure 3.3 (b) and (c) show the free body diagrams used to find the expressions for torque. In these diagrams, a thread is unrolled for a single turn. This forms the hypotenuse of a right angle triangle while the other two sides comprise of the base (equal to the circumference of the mean thread diameter circle (πd_m)) and the height (equal to the lead of the screw (l)) [21].

The following parameters are also required to determine the torque:

- Force to raise the load: P_R (N)
- Force to lower the load: P_L (N)
- Normal force N (N)
- Coefficient of friction: f.

The normal force is eliminated when completing these equations as it is not required. Thus from the free body diagrams we are able to obtain:

$$P_R = \frac{F[l/\pi d_m + f]}{1 - (fl/\pi d_m)} \tag{3.12}$$

$$P_L = \frac{F[f - l/\pi d_m]}{1 + (fl/\pi d_m)} \tag{3.13}$$

Noting torque is the product of the force P and mean radius πd_m we can calculate the torque required to raise the load and overcome thread friction [21]. This can obtained using the relations:

$$\tau_{raise} = \frac{F d_m}{2}\left(\frac{l + \pi f d_m}{\pi d_m - f l}\right) \tag{3.14}$$

The torque required to lower the load can be obtained using the relation:

$$\tau_{lower} = \frac{F d_m}{2}\left(\frac{\pi f d_m - l}{\pi d_m + f l}\right) \tag{3.15}$$

These formula were obtained using [21].

3.2.3 Vertical Transmission Torque

The second vertical transmission system comprises of a belt and pulley system required to raise and lower the load of the arm. To determine the torque requirements, parameters outlined in the following section must be known or assumed. Figure 3.4 is used as a reference to complete this calculation.

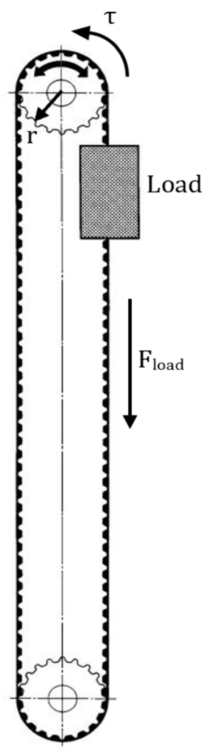

Figure 3.4: Vertical Pulley System Schematic
Source: [24]

Parameters:

- Holding torque: $\tau_{holding}$ (Nm)

- Torque: τ (Nm)
- Force due to load: F_{load} (N)
- Force due to acceleration:n F_a (N)
- Mass of load: m (kg)
- radius of drive pulley: r (m)
- Acceleration of load: a (m/s^2)
- Acceleration due to gravity: g (m/s^2)
- Efficiency of system: η

To calculate the torque required of the system, first we can calculate the holding torque. This will be the minimum torque required to hold the load stationary. This is determined by the relation:

$$\tau_{holding} = \frac{F_{load} \cdot r}{\eta} \tag{3.16}$$

Where:

$$F_{load} = m \cdot g$$

Therefore,

$$\tau_{holding} = \frac{m \cdot g \cdot r}{\eta} \tag{3.17}$$

To find the torque at a specified acceleration, the following relation is used:

$$\tau = \frac{(F_{load} + F_a) \cdot r}{\eta} \tag{3.18}$$

Where:

$$F_{load} = mg \text{ and } F_a = ma$$

Therefore,

$$\tau = \frac{(mg + ma) \cdot r}{\eta} \tag{3.19}$$

3.2.4 Turntable Torque

To determine the torque required for turntable actuation, two formulas were required. Again, specific perimeters were required to be known or assumed. These parameters are as follows, with Figure 3.5 showing a simple schematic to accompany these equations.

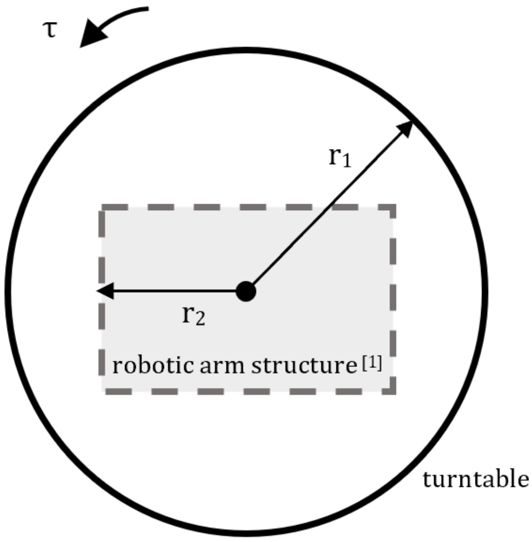

Figure 3.5: Turntable System Schematic
[1]Robotic arm structure footprint not to scale

Parameters:

- Total torque: τ (Nm)
- Turntable torque: τ_{table} (Nm)
- Arm torque: τ_{arm} (N)
- Mass of arm: m_{arm} (kg)
- Mass of turntable top m_{table} (kg)
- Drive speed: N_{RPM} (RPM)
- Radius of turntable: r_{table} (m)
- Radius of arm center of mass: r_{arm} (m)
- Moment of inertia of turntable: I_{table} (kgm^2)
- Moment of inertia of arm: I_{arm} (kgm^2)

- Angular acceleration: $\alpha_{table}/\alpha_{arm}$ (rad/s^2)
- Acceleration time: t (seconds)

The torque of the turntable is given by:

$$\tau_{table} = I_{table} \cdot \alpha_{table} \tag{3.20}$$

The torque of the arm is given by:

$$\tau_{arm} = I_{arm} \cdot \alpha_{arm} \tag{3.21}$$

Where the moment of inertia's are given by:

$$I_{table} = \frac{(m_{table}) {r_{table}}^2}{2} \tag{3.22}$$

$$I_{arm} = m{r_{arm}}^2 \tag{3.23}$$

and [25]

$$\alpha = \frac{2\pi \cdot N_{RPM}}{60 \cdot t} \tag{3.24}$$

The total torque of the system is given by:

$$\tau_{total} = \tau_{table} + \tau_{arm} \tag{3.25}$$

3.3 Transmission System Requirements

The number of revolutions a stepper motor completes will dictate the linear distance traversed, and the angle the arm travels through. As three different transmission types are being used in this application, distance calculations for each must be calculated.

3.3.1 Timing Belt Transmission

To determine the steps per linear distance, the following parameters must be known:

- Steps per revolution: S_{rev}
- Micro-step factor: f_m
- Pitch: p (revs/unit length)
- Number of pulley teeth: N_t
- Distance to traverse: d_{trav} (mm)

The steps per millimeter is given by the following relation [26]:

$$Steps\ per\ mm = S_{rev}\left(\frac{d_{trav} \cdot f_m}{p \cdot N_t}\right) \tag{3.26}$$

3.3.2 Lead Screw Transmission

To determine the steps per linear distance, the following parameters must be known:

- Steps per revolution: $S_{rev}(steps/rev)$
- Micro-step factor: f_m
- Pitch: p (revs/unit length)
- Number of starts: s
- Distance traverse: d_{trav} (mm)

The steps per millimeter is given by the following relation:

$$Steps\ per\ mm = S_{rev}\left(\frac{d_{trav} \cdot f_m}{p \cdot s}\right) \tag{3.27}$$

3.3.3 Direct Coupling

In the turntable application, a stepper motor is directly coupled to the load. The angle turned through and thus the number of steps must be calculated from the following known parameters using Figure 3.6:

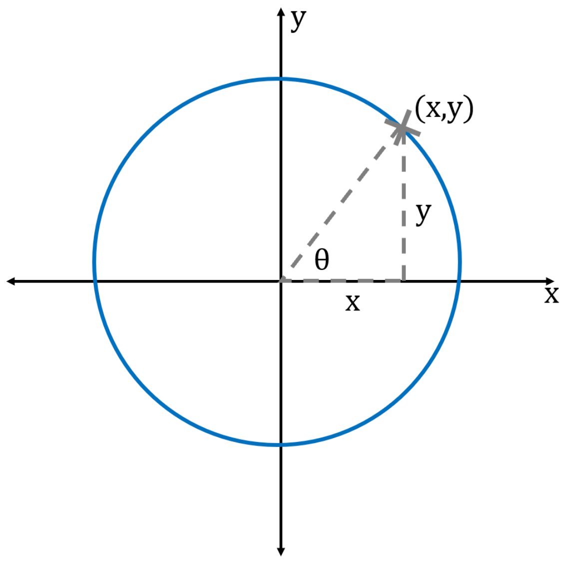

Figure 3.6: Calculating θ from (x,y)

- Steps per degree[3]: S_{degree} (steps/°)
- x co-ordinate: $x_{coord}(mm)$
- y co-ordinate: $y_{coord}(mm)$

[3]Calculated from steps per revolution of motor data sheet

The number of steps required is given by the following relation pertaining to Figure 3.6:

$$steps = S_{degree}\left(\tan^{-1}\left(\frac{y_{coord}}{x_{coord}}\right)\right) \tag{3.28}$$

Chapter 4

Methodology and Design

This section will outline the steps taken to complete the design process, as well as the design itself. This will include key challenges identified in the mechanical, electrical and software designs, preliminary analysis for component selections and a justification and explanation of the final design.

4.1 Key Challenges

To successfully design and build a robotic arm structure, key challenges regarding the mechanical, electrical and software components of the system were identified. These highlighted all restrictions, potential complications or design considerations to account for.

4.1.1 Key Mechanical Challenges

Key mechanical challenges included identifying any problematic requirements associated with the robotic workspace required. This meant examining the Growroom. Figure 4.1 highlights the 4 key challenges identified with this design.

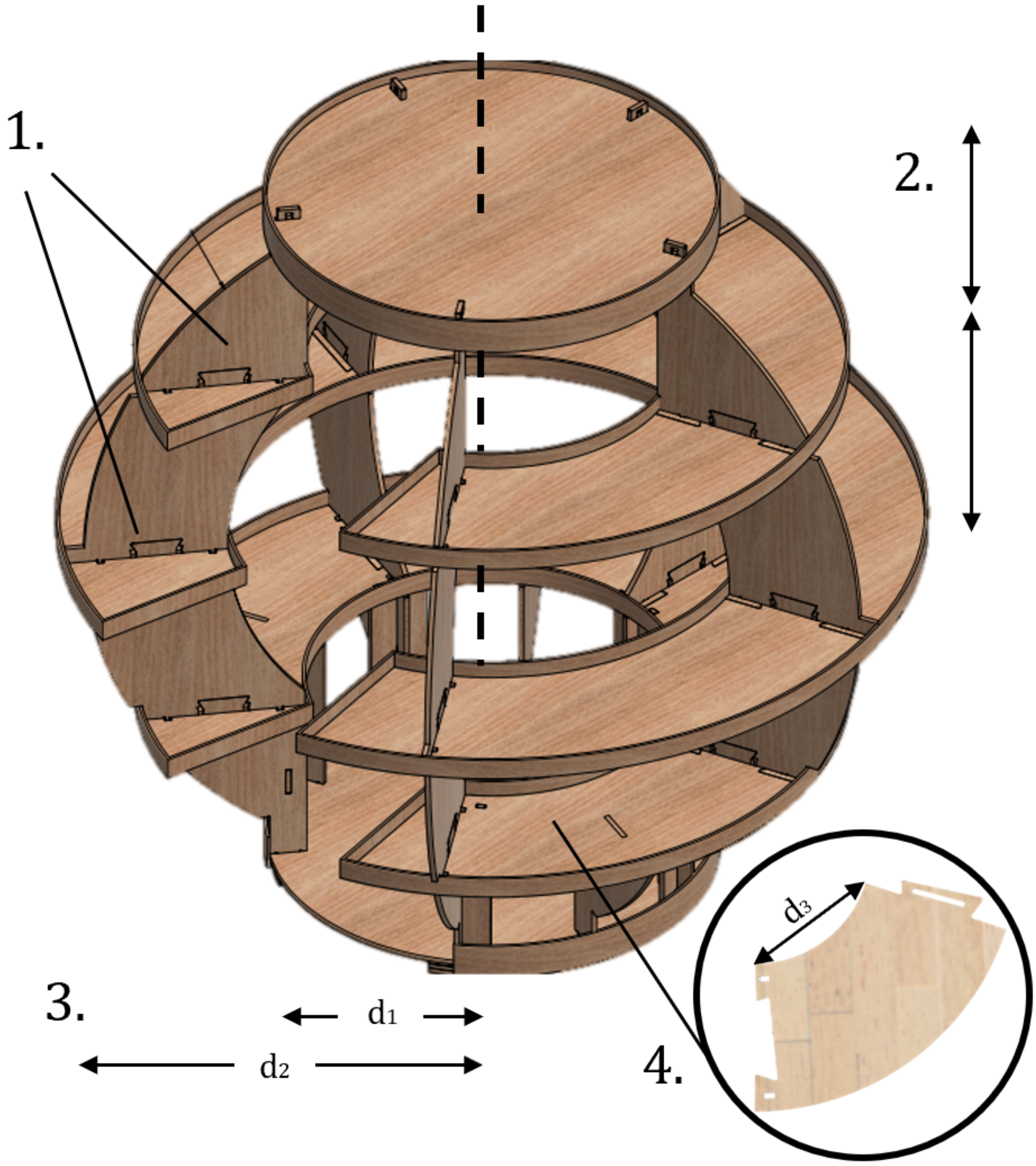

Figure 4.1: Key Mechanical Challenges
Growroom render: [27]

The key challenges were as follows:

1. **Supporting structure**. These supports acted as dividers, segmenting shelves. This meant the arm design must be able to maneuver in and around these supporting structures.
2. **Distance between shelves**. The UTM had a maximum height of 120mm (including the seeding tool) and thus the arm was required to fit within the shelves with this head in place.

3. **Difference in shelf diameter**. The arm must be able to reach both d_1 and d_2.

4. **Shelf aperture**. The arm was required to fit within the minimum shelf opening distance d_3.

It is also worth noting that the design was also restricted due to the mechanical strength of the Growroom. This design was construction from 6mm plywood, and thus mounting anything from the ceiling of this structure was deemed unfeasible.

4.1.2 Key Electrical Challenges

Taking into account the potential degrees of freedom and operational axes requirements, key challenges for the electrical design comprised of:

1. **Cable management**. This referred to all wiring, storage and placement of cables.

2. **PCB optimisation**. This included optimising board layout for peripherals and motor requirements whilst minimising board size.

3. **Power supply location**. With rotational movement hindering direct coupling, how power will be supplied to the system had to be considered.

4. **Pin requirements**. This referred to ensuring the chosen micro controller had sufficient capability to run all required devices.

5. **Waterproofing**. As this implementation will include outdoor and water usage, sufficient waterproofing was required.

4.1.3 Key Software Challenges

Software challenges include:

1. **Interfacing with FarmBot**. This referred to adapting the design such that it could easily integrate with the current FarmBot solution, or adapting a similar approach/solution.

4.2 Mechanical Design Process

This section will outline all analysis and processes taken to obtain the final mechanical design.

4.2.1 Arm Type

This section will include the analysis and selection of the arm type and components. Section 2.3 outlines current arm types. Table 4.1 compares the ability of these arms to achieve the key mechanical challenges.

Table 4.1: Arm Type vs. Key Mechanical Challenges

Arm Type	Key Challenge 1	Key Challenge 2	Key Challenge 3	Key Challenge 4
Cartesian	✗	✓	✓	✓
Articulated	✓	✗	✓	✓
SCARA	✓	✓	✗	✗
Telescopic Cylindrical	✓	✓	✓	✓
Telescoping Slider	✓	✗	✓	✓
Scissor	✓	✓	✓	✓

From Table 4.1 it is evident that only two current arm types meet all key challenges: Telescopic Cylindrical and Scissor. Although both of these designs have operational potential, there are a number of advantages and disadvantages to each design.

The telescopic cylindrical arm is more robust in terms of stability. As each stage nests inside the next, a strong base will be formed. This will be advantageous in undesirable weather. This design is also more aesthetically pleasing as the entire arm (excluding the end effector) would be a simple, compact cylinder when retracted. Disadvantages of this design include the potential for insufficient lifting ability when the load of the end-effector is applied. This point mass may be too significant based on the size of the telescopic base, and the number of stages. This design will also require an actuation force. Industry applications typically use hydraulic pressure to allow movement. This is likely unfeasible for this application, and if actuators were used, the number of actuators would be proportional to the number of stages. This could potentially cause overloading at joints, and cause stability issues due to bending moment stress.

The scissor arm application is advantageous as it is simpler to implement and build. While industry applications use hydraulic and pneumatic pressure to power the extension of this arm, mechanical actuation is also possible. This design would require only one actuator for extension of the entire arm. Disadvantages of this design include bending and droop if over-extension of joints occur, or if end-effector mass is too great. Stability of the design may also be a disadvantage in undesirable weather if ideal scissor thickness and material selection is unfeasible for the application.

From this, the robotic scissor arm type was selected. This was primarily due to the feasibility of implementation and performance ability requirements being met.

4.2.2 Linear and Rotational Actuation

After the selection of arm type was finalised, the axes required to implement this design could be selected.

4.2.2.1 Vertical Axis (y-axis)

To reach each shelf in the Growroom with a scissor arm, the vertical axis was required to traverse the height of the Growroom to allow this reach to occur. To feasibly do this, a long structure was required and to optimise the limited internal space, compact solutions were desired.

A decision matrix was completed to identify the most feasible linear actuation option between a lead screw, ball screw, timing belt and rack and pinion. Table 4.2 provides a summary of the type of linear actuation with the weighted total (where a lower weighted total indicates a more ideal solution). Full decision matrices and weighted tables can be seen in Appendix H.

Table 4.2: Summary of Weighted Linear Actuation: Vertical Axis

Linear Actuation	
Type	**Weighted Total**
Lead Screw	2.5
Ball Screw	2.2
Timing Belt	2.0
Rack and Pinion	2.4

From this, a timing belt was the most ideal solution, where accuracy, size and stability were the three parameters with the strongest weighting. A v-slot beam was chosen to be used with a timing belt as the vertical axis due to it's small size, and use in the FarmBot system.

4.2.2.2 Horizontal Axis (x-axis)

At current, the design consists of an arm extended from the vertical v-slot centered inside the Growroom. A horizontal axis will be incorporated in the design, although it provides a redundancy (moves in the same direction as the arm). Fixing the arm in a central position results in a neutral COM, and adds to aesthetics. This redundancy allowed key challenges 2 and 3 to be met.

A decision matrix was completed to identify the most feasible linear actuator for this axis. The same actuation types as Section 4.2.2.1 were considered. Table 4.3 provides a summary of findings with full decision matrices, rankings and weighted tables can be seen in Appendix I.A lower weighted total indicates a more ideal solution.

Table 4.3: Summary of Weighted Linear Actuation: Horizontal Axis

Linear Actuation	
Type	**Weighted Total**
Lead Screw	1.8
Ball Screw	1.9
Timing Belt	2.2
Rack and Pinion	2.4

Table 4.3 shows that the lead screw is the ideal implementation for this axis. This was based on significant weights on cost, accuracy and stability parameters. A c-beam was selected to be paired with a lead screw as stability was of extreme importance.

4.2.2.3 Rotational Axis

To rotate the structure to achieve accurate positioning, there were three options:

1. Rotate only the arm;
2. Rotate the vertical axis or
3. Rotate the entire structure.

Although rotating only the arm or rotating the vertical axis would allow the base of the structure to be rigidly fixed in place, both also introduce issues. The main includes how they would be fixed to their mounting components (arm to vertical axis and vertical axis to c-beam). Rotating the entire device will be simpler, but will also be a significant feat as the entire system weight must be rotated.

Ultimately, the rotational axis was decided to encompass the entire structure. This was due to simplicity and the potential instability and mounting issues associated with the other two options. To rotate the entire structure, a turntable will be used.

4.2.3 Motor Selection

To determine the motors used in these applications, torque calculations were completed. These used equations in Section 3.2. Table 4.4 provides a summary of the torque required for these applications, with parameters and equations used specified in Appendices K, L, M, N.

Table 4.4: Summary of Torques Required

Subsystem	Torque Required (Nm)
Arm	0.035
Vertical Axis	0.166
Horizontal Axis	0.230
Turntable	0.355

Once the torques required were obtained, a decision matrix on motor type was completed. Ideally, all of the same type of motor would be used, however this may not be possible due to specific implementation requirements. Thus Table 4.5 was completed with two columns regarding implementation dependencies. The torque and size requirements for each subsystem varies and as such, these requirements will require further analysis to make an informed decision.

Table 4.5: Motor Type Selection Summary

Motor Type Selection					
Motor	**Precision/Control**	**Torque Capability**	**Size/Weight**	**Cost**	**Total**
AC	5	Implementation Dependent	Implementation Dependent	4	9
DC Brushed	5			3	8
DC Brushed with Encoder	1			4	5
DC Brushless	5			2	7
DC Brushless with Encoder	1			4	5
Servo Motors	2			1	3
Stepper Motors	1			2	3

4.2.3.1 Arm Motor

From Table 4.4 the arm motor requires only 0.035Nm of torque. From Table 4.5, the most ideal motor is a stepper motor based on the precision and cost. The arm requires a small motor that is easily mountable on a rectangular platform. For this reason a stepper motor was chosen, more precisely, the Nema 17 Bipolar 1.8deg 16Ncm (SKU: 17HS08-1004S) [28]. This has a short body length (20mm), a square face, and is was the most cost effective stepper motor found that met the torque requirements.

4.2.3.2 Vertical Axis Motor

From Table 4.4 the arm motor requires only 0.166Nm of torque. From Table 4.5, the most ideal motor is a stepper motor based on the precision and cost. This axis makes use of a v-slot beam. These beams are made specifically for stepper motor integration, and thus a stepper motor was chosen. More specifically, the Nema 17 Bipolar 1.8deg 26Ncm (SKU: 17HS13-0404S1) [29]. This motor type was the type recommended for integration, and was the most cost effective motor that met the torque requirements with a sufficient safety factor of at least 20% [30].

4.2.3.3 Horizontal Axis Motor

From Table 4.4 the arm motor requires 0.23Nm of torque. This axis makes use of a c-beam, in which previous solutions exist for mounting solutions with stepper motors. Thus, a stepper motor was chosen. This aligns with the aims of the project in keeping the implementation in line with the FarmBot. The motor selected was the Nema 17 Bipolar 1.8deg 26Ncm (SKU: 17HS13-0404S1) [29]. This motor type was the type recommended for integration, and was the most cost effective motor that met the torque requirements.

4.2.3.4 Turntable Motor

From Table 4.4 the arm motor requires 0.335Nm of torque. This motor will be directly coupled to the turntable. For this implementation, a stepper motor was also selected. A brushed DC motor with encoder was also considered. These motors have significantly greater torque capabilities as often, they are geared, whereas stepper motors have low torque capability. Ultimately, a stepper motor was selected for implementation, although the cost of this motor was greater. This motor type was chosen primarily based on the ease of integration with the FarmBot system, and for mechanical, electrical and software design consistency. More precisely, the Nema 23 Stepper Motor 1.26N.m (SKU: ELEC-NEMA23-635-B) was chosen [31]. This motor was one of the most cost effective that met the torque requirements and allowed for a sufficient safety factor of at least 20%.

4.3 Electrical Design Process

The electrical design process consisted of primary focus on the power supply location, communication requirements, microcontroller considerations and power requirements.

4.3.1 Power Supply Considerations

As the robotic arm structure consists of a turntable that provides rotational movement, two PCBs will be required. One for the turntable, and another for the arm structure. This is because the power pack will not be able to supply only one PCB due to wire complications (twisting) that will arise due to rotation.

Once this was discovered, it was evident that a wireless communication method between systems or to the web interface would be required to obtain data.

4.3.2 Wireless Communication Protocol

To wireless obtain data from the interface, Wi-Fi was used. This was chosen chosen in alignment with the current FarmBot implementation and provided a simple connectivity method to the retrieve data directly from the web interface. Microcontroller selection will be further explored in the following section, when pin requirements are identified

It was decided that instead of both subsystems accessing the web interface directly, one system would retrieve the information and send the required information onto the next. This was done primarily to avoid interference and noise issues with obtaining the data from the same access point. To wireless communicate between each other, radio frequency (RF) was chosen. This method was favored due to its range, availability, cost and independence from any wireless bandwidths and systems. More specifically the SparkFun Transceiver Breakout - nRF24L01+ was selected [32].

4.3.3 Microcontroller Selection

Once the wireless communication methods were selected the total required pins for each subsystem were calculated. These are outlined in Table 4.6.

Table 4.6: Full System Pin-out Requirements

Arm System Pin-out Requirements			
Component	**Units**	**Unit Pins Required**	**Total Pins Required**
Stepper Motors	3	2	6
Microswitches	6	1	6
nRF Transeiver	1	5	5

Turntable Pin-out Requirements			
Component	**Units**	**Unit Pins Required**	**Total Pins Required**
Stepper Motors	1	2	2
Microswitches	1	1	1
nRF Transeiver	1	5	5

From this, is is evident that the arm system will require at least 17 pins, while the turntable will require at least 7 pins.

From this, microcontrollers were selected. Keeping with the aims of the project, the FarmBot system was again looked at and adapted from. The FarmBot utilises a Farmduino as one of their primary controllers. Due to this, an Arduino was selected as the microcontroller for the arm system. The Arduino Uno has only 14 digital pins, however it has 6 analogue inputs, all of which can read inputs and be used for digital writing. This gave a total of 20 total pins for usage, ensuring this was sufficient for the required application.

An Arduino Uno did not meet the sufficient requirements for the turntable microcontroller as it had no WiFi capabilities. The Arduino Uno WiFi Rev2, has an integrated ESP8266WiFi module. A cheaper version of a similar board, the WeMos D1 ESP8266 WiFi was selected. This used the same WiFi module, and uses the Arduino layout. This was selected as it had a sufficient amount of digital I/O pins (11), and similar WiFi capabilities at a cheaper price [33].

4.3.4 Power Requirements

To supply a sufficient amount of power to both systems, the power requirements of all components was identified. Table 4.7 shows a summary of the power requirements, with a full breakdown shown in Appendix O.

Table 4.7: Power Consumption Summary

PCB	Power Consumption (W)
Arm System	19.52
Turntable	10.3

From these values, two 12V, 3A power packs were selected. These met all requirements with a sufficient safety factor accounted for, allowing for design flexibility.

Identical power packs were purchased for simplicity, and to serve as reinforcements for each other if issues arose. The only other specifications for power packs were a tip size of 2.1 or 2.5mm, as power jacks of this size were available at the Engineering & Technical Support Group (ETSG) store. The power supply purchased was a Wagner 12 Volt 3A Switch-Mode (Item No: SMP12V-3A-21P) [?].

4.4 Software Considerations

Software considerations consisted only of interface implementation.

FarmBot use a web-based application that enables a user to obtain real-time data, control systems and design gardens. Similar to this, the interface designed was a preliminary model that consisted of a basic web page design in which the system read co-ordinates from. This relies on user input in the form of a text file containing the specified co-ordinates.

Chapter 5

Results and Discussion

The final subsystem comprises of the arm structure (theMonarch) and the turntable. From this point onwards, the arm structure will be referred to as theMonarch, with subsequent subsection consisting of: the arm, the vertical axis (v-slot) and the horizontal axis (c-beam). The turntable is considered a separate entity and will be referred to accordingly.

This section will show the completed assembly of theMonarch and the turntable. It will display the minimum and maximum reach of the arm, and the parameters used to obtain these values. This section will also include PCB schematics and layout, and a high level overview of the software design. A summarised budget breakdown and bill of materials (BOM) will also be discussed, as will future improvements to the current design.

5.1 theMonarch

Figure 5.1 shows the full assembly of the final arm design. This design incorporates the use of a lead screw to raise and lower the arm, extending and retracting the end-effector respectively.

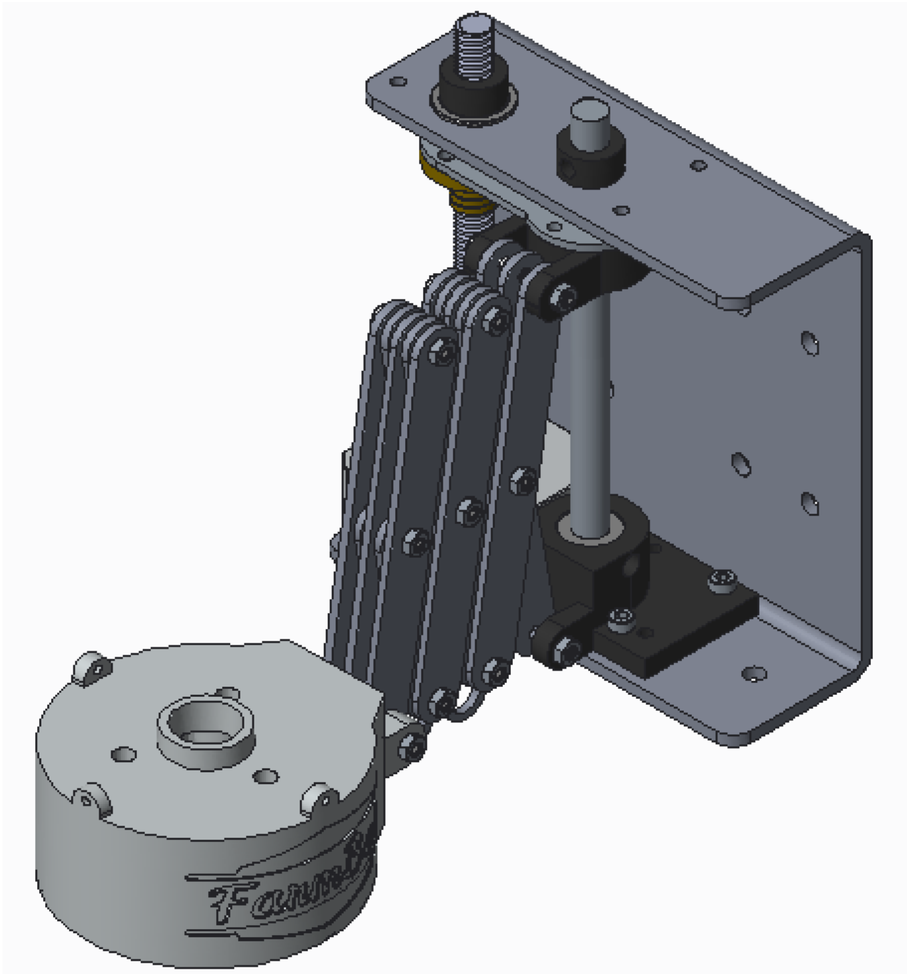

Figure 5.1: theMonarch: Arm Assembly

Table 5.1 provides the different extension lengths of the arm, as the lead screw is moved and α_{max} is increased. This table is calculated using Equations 3.2, 3.4 and 3.5, from Section 3.1. The number of scissors required for adequate extension was 3. This was calculated using Equation 3.1 from Section 3.1. For full list of variables used, please refer to Appendix P.

Table 5.1: Extended Arm Lengths with Varying α_{max} Values

α_{max}**(degrees)**	**Extended Arm Length (mm)**	**Lead Screw Distance to Travel (mm)**
20	151	4.5
30	234	11.8
40	254	21.9
50	320	34.2
60	374	48.5

From Appendix P we know that the maximum extension length required L_{max} was 302mm. Therefore, extending to an angle of $\alpha_{max} = 50°$ will meet this requirement.

The length of the closed arm came to 172mm (L_{min}) from Appendix P. This meant the robotic workspace of theMonarch was a tarus with an inner radius of approximately 172mm, an outer radius of 600mm and a depth of approximately 710mm (length of v-slot the platform can traverse (referenced from Appendix Q). A topology view of this can be seen in Figure 5.2.

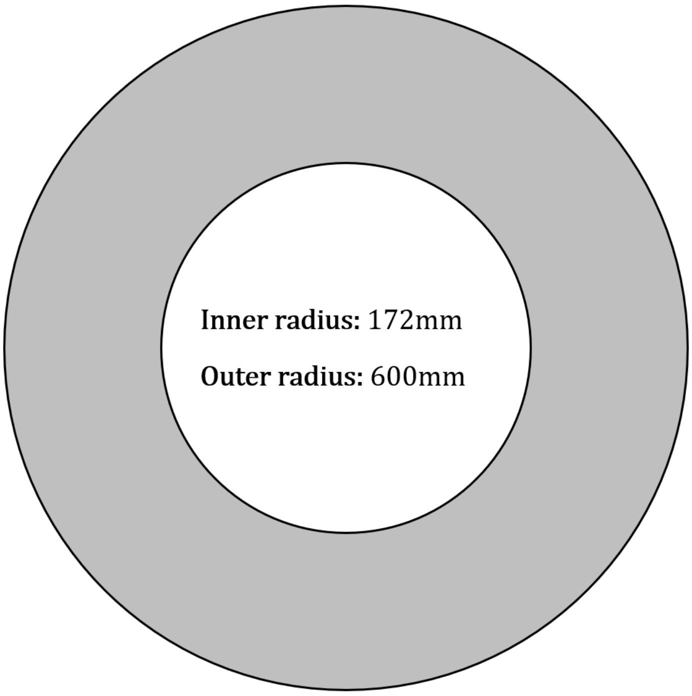

Figure 5.2: Robotic Workspace (Topology View)

5.2 Full Assembly

A full assembly of theMonarch and turntable system can be shown in Figure 5.3. Figure 5.4 shows this assembly within the Growroom. Additional view of the full system can be seen at:

Additional Renders

Figure 5.3: Full Assembly: theMonarch and Turntable
CAD Render by: [27]

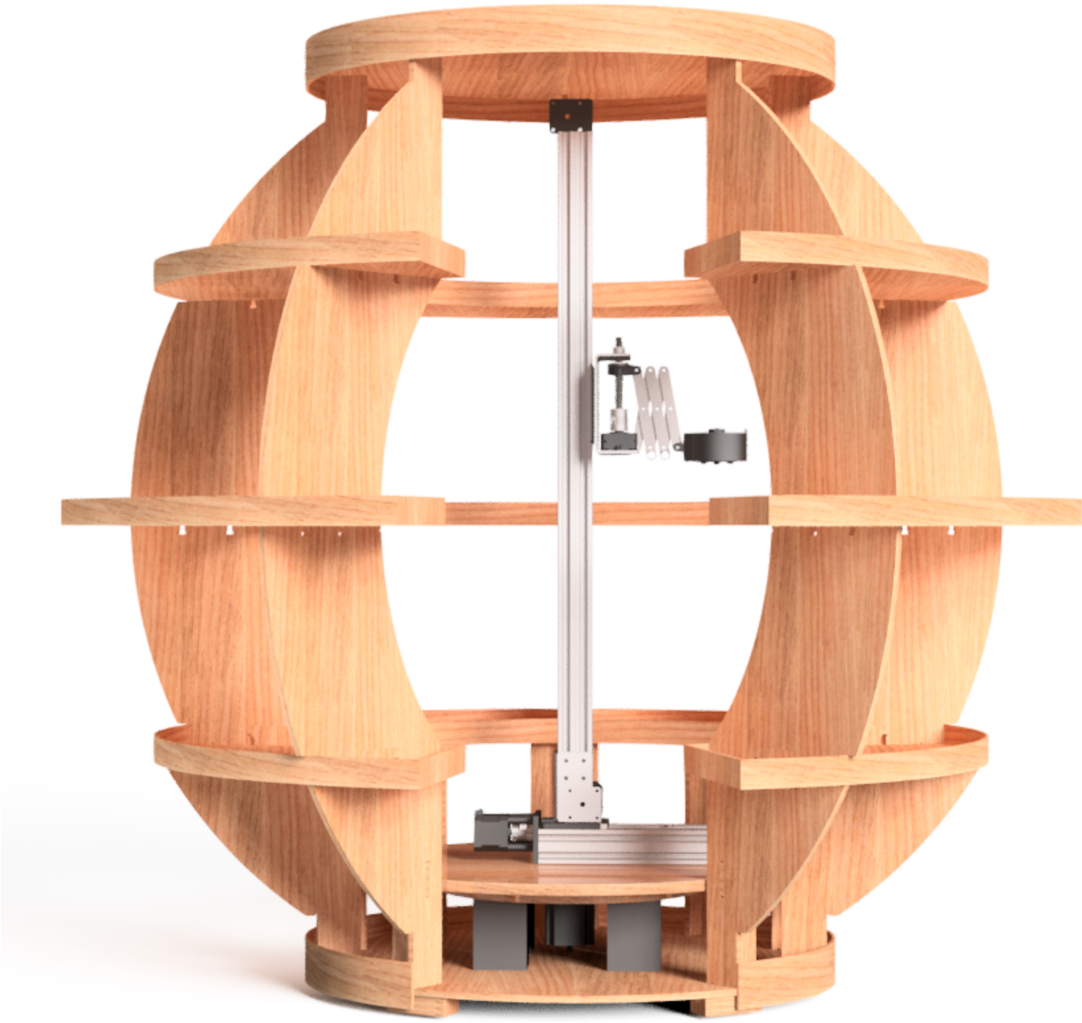

Figure 5.4: Full Assembly Within Growroom
CAD Render by: [27]

For all mechanical part and assembly files, please refer to Section R.1 in Appendix R.

5.3 PCB Design

The 3D layout mode of theMonarch PCB is shown in Figure 5.5, and the 3D layout mode of the turntable PCB is shown in Figure 5.6. Full schematic diagrams are shown in Appendix S. Both PCBs comprise of 4 layers, with one internal ground plane and one internal power plane (3.3V). Each PCB board has layout and headers that have been optimised for each systems individualised peripherals and motor requirements.

The dimensions of the PCBs are as follows:

- **theMonarch PCB:** 97.41mm x 52.96mm
- **Turntable PCB:** 50.42mm x 40.89mm

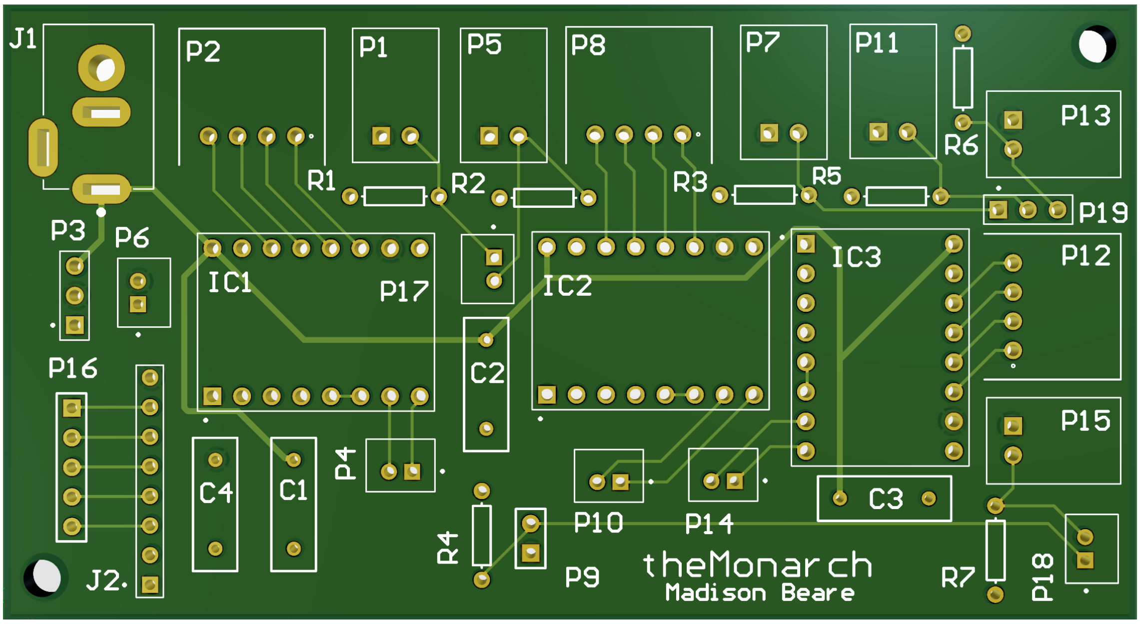

Figure 5.5: theMonarch PCB: 3D Layout Mode

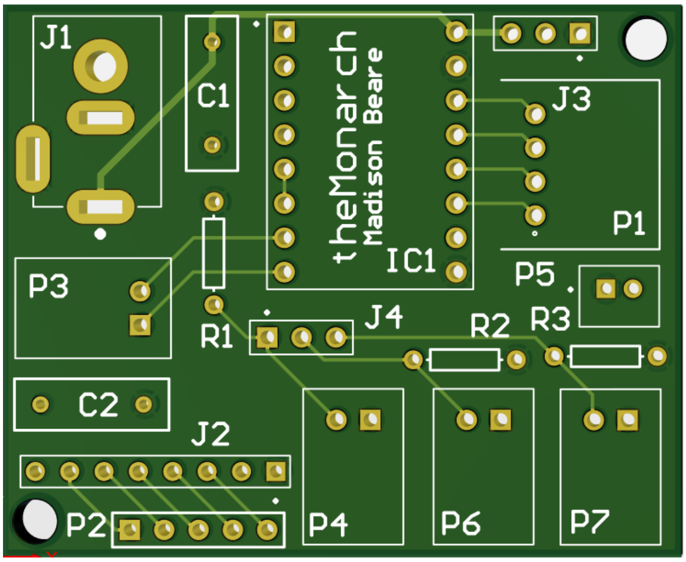

Figure 5.6: Turntable PCB: 3D Layout Mode

For all PCB project files and manufacturing files, please refer to Section R.2 in Appendix R.

5.4 Software Overview

Figure 5.7 shows a high level overview of the full system design. This shows the software interactions between a user, the web interface, the turntable (Wemos D1 ESP8266), theMonarch (Arduino Uno), RF transceiver communication (connected to theMonarch and the turntable) and the read and writing of stepper motors and microswitches.

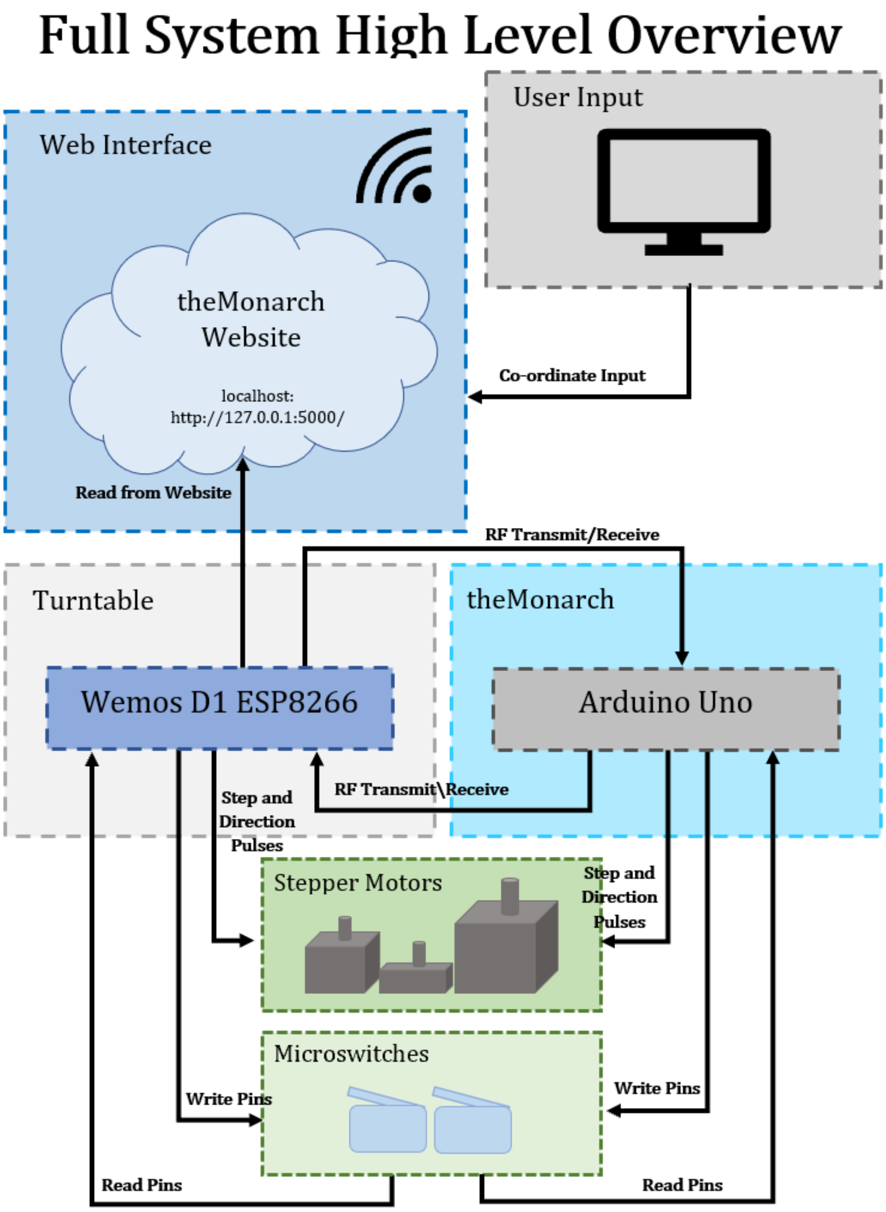

Figure 5.7: Full System Software Application: High Level Overview

The web interface of for this implementation is shown in Figure 5.8. For this implementation, the website was deployed on localhost using Flask and CodeIgniter templates. The navigation bar at the top right of the web page links to different pages that contain the coordinates to traverse to as well as shelf information. These web pages are what the Wemos D1 ESP8266 accesses in order to retrieve these coordinates. Ideally, this will be updated in future works to have a more sophisticated user interface similar to the FarmBot web interface.

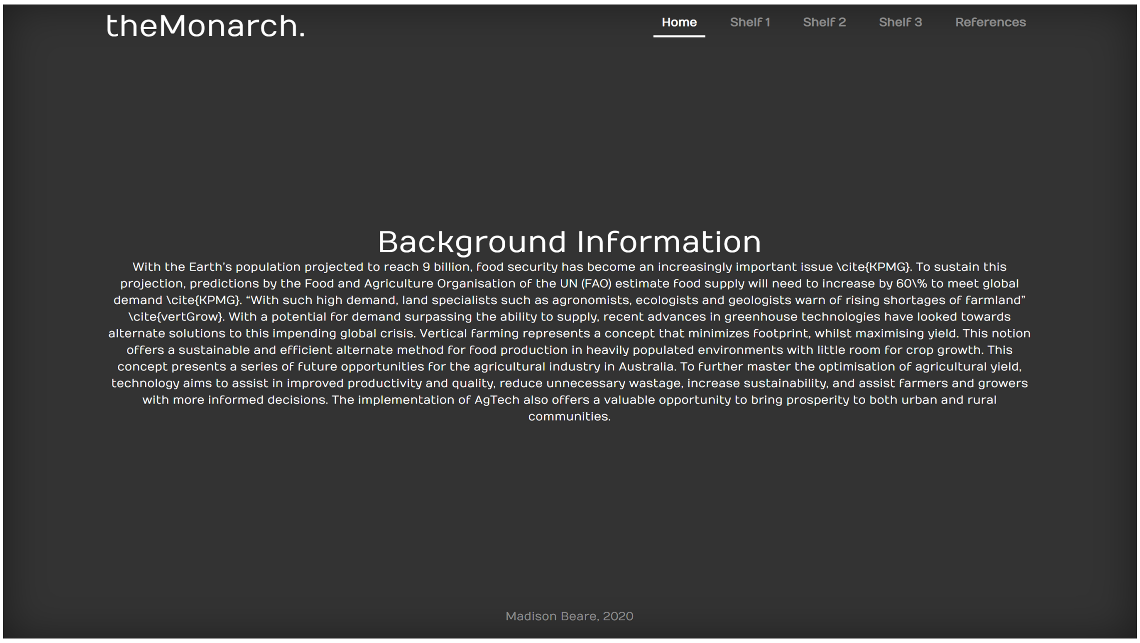

Figure 5.8: theMonarch Website Interface

5.5 Bill of Materials

The final cost of the project is summarised in Table 5.2, with full Bill of Materials (BOM) located in Appendix T.

Table 5.2: Total Project Cost

System	Total Cost ($AUD)
Mechanical Build	363.56
Electrical Build	218.40
Total Project Cost	**581.96**

This summary assumes no components were owned before the commencement of this build. While this was not the case for this project, this breakdown gives an accurate representation of what the project costs would be for external parties. As shown, this build would not comply with the thesis project budget $250 AUD if components were not preowned or sourced from countries other than Australia.

5.6 Future Improvements

This section will outline improvements to the project that should be made before product deployment.

5.6.1 Turntable Transmission

Currently, the turntable drivetrain consists of the Nema23 motor directly coupled to the turntable top. This solution would be unfeasible for the final product deployment as it was not robust. Due to direct coupling, the turntable shaft needed to be exactly aligned with the motor shaft so that decoupling would not occur. If these two were offset even marginally, significant frictional forced occurred due to the misalignment and the turntable would not rotate. There was also a significant inaccuracies with stopping accuracy. As the turntable rotated on a bearing, when coming to a stop the stepper motor shaft did not have enough torque to prevent additional rotation. This led to incorrect location traversal, which was an issue due to the potential for collisions to occur. To ensure accurate traversal occurs with negligible additional rotation, either a drivetrain should be installed, or a different motor type selected, or both.

There are multiple options for drivetrains, inlcuding geared or pulley system. By incorporating a drivetrain, decoupling risk would be significantly lowered as a direct connection between the motor and load would not be present. Incorporating a drivetrain would also aim to reduce the additional rotation. This would be done by ensuring the transmission system elements provide enough torque to withstand the momentum of the table after the motor ceases movement.

A different motor type could be selected. A stepper motor was currently used in the implementation primarily for consistency in this system and to align with the FarmBot implementation. An improvement to the current design would be to select a motor that is internally geared, or one with a large amount of torque to enhance the previous solution of adding a drivetrain.

5.6.2 Relocation of Motor

As shown in Figure 5.9, the arm is not directly attached to the lead screw nut. Instead it is attached via an aluminum bridge attachment. This design should be altered to incorporate this change. As the bridge attachment is being pulled/pushed, at times it would scrape against the linear rod, as it did not remain flush in travel (often one side was higher than the other). This caused jamming issues, and also caused slight height discrepancies at either end of the bridge attachment. This meant the lead screw nut was always slightly higher or lower than the attached scissors. Relocating the motor so that the arm is directly coupled to the lead screw nut should remove these issues.

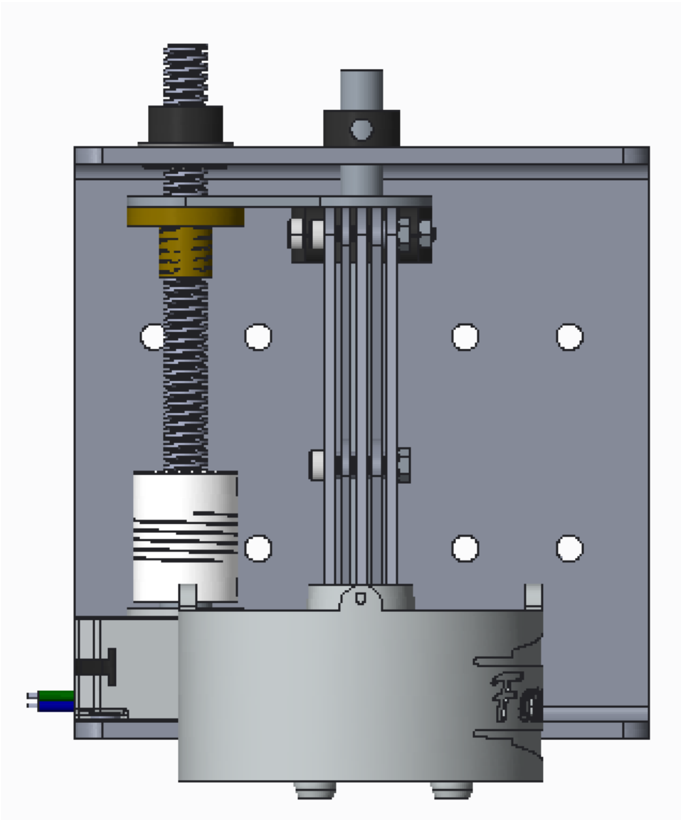

Figure 5.9: theMonarch Arm: Front View

5.6.3 Communication Protocol

At current, the turntable PCB communicates via WiFi to obtain coordinates from user input. It then transfers the required coordinates to the turntable via RF communication. A more robust solution would be to have both theMonarch and the turntable read directly from the web interface. This was not currently implemented due to budgetary constraints and potential issues in reading from the same source concurrently. Implementing this alternate method would reduce the potential for lost information over RF and would also eliminate the need for RF completely. This would enhance the robustness of the system.

5.6.4 Website Completion

Currently, only a preliminary website has been deployed. This implementation relies on users to input coordinates that are within the range theMonarch can traverse.

Relying solely on user input introduces multiple vulnerabilities to the system. Updating the user interface to ensure only feasible coordinates can be selected would be paramount in moving forward.

5.6.5 Slip Ring Requirement

The full scale assembly is shown in Figure 5.3. In the current design, there is no way to incorporate power to the full system. This is due to the rotational movement the turntable provides. A slip ring is a device that allows electrical connection from a stationary object to a rotating assembly [34]. To allow for system power, a slip ring would need to be incorporated. This could be incorporated into the top of the Growroom, or at any feasible location.

5.6.6 Axis Redundancy

The system currently has a redundant axis, that is, movement occurs in the same direction at two different locations. This occurs when the arm structure moves across the turntable via the c-beam, and when the arm extends out. The current reason for this is that the arm must fully extend on every occasion. This is due to the UTM being rigidly fixed in place. To ensure the UTM remains parallel to the ground on every iteration, the extension is necessary.

Due to this extension requirement a redundant axis was necessary. To remove this redundancy, the number of scissors required in the arm implementation would need to be increased, and the arm would require offsetting (meaning the COM would not lie in the center of the Growroom). This would also require dynamic movement of the UTM as it would not be possible to have this rigidly fixed in place. Overcoming these issues may not be feasible, however it is worth further investigation as removing the horizontal axis will remove significant weight and an entire linear actuation component.

Chapter 6

Conclusion

6.1 Summary and Conclusions

By analysing current robotic arm systems and drawing inspiration from the current FarmBot design, this thesis has outlined a solution that combines technology with a vertical farming system. This system - theMonarch - has shown how AgTech can be incorporated in the agricultural industry to assist with optimising crop yield.

By identifying the key challenges associated with the mechanical, electrical and software requirements, a robotic arm structure was designed in conjunction with the Growroom. These key challenges led to calculations regarding the arm type, number of scissors required for the robotic scissor arm, linear transmission analysis, motor selection, power requirements and torque calculations.

theMonarch consisted of a robotic scissor arm driven by a lead screw, a vertical axis comprising of a v-slot and timing belt, and a horizontal axis comprised of a lead screw transmission system. This was integrated with a turntable that provided rotational motion.

The arm was required to have a maximum extension length of 302mm, and the current solution allowed for an extension of 320mm. Two PCBs were designed, one for theMonarch system and one for the turntable. This was required due to rotational motion. A preliminary interface was designed and deployed to localhost. This required user input for coordinate traversal. The current project costs came to a total of $581.96 AUD.

Future work should include implementing all future improvements before project deployment, with further research needed to determine alternate turntable transmission types, the best placement of slip rings, and whether or not the current axis redundant is required.

6.2 Full Scale Model

The biggest difference between the current Growroom and the full-scale model aside from the larger size is the increased number of shelves and greater shelf depth. While theMonarch and turntable have the potential to be scaled up, the key challenges of the larger Growroom will be different due to these changes. This means that an alternate solution may be more ideal. Further investigation into this must be completed.

In terms of the full-scale design, it may be worth revisiting the scope and purpose of this project. As the shape of the Growroom is not optimised for crop yield, it was assumed that the design was created primarily for aesthetic purposes. Creating a robotic arm system that fits inside a pre-existing structure based purely around visual impact is not ideal, as the feasibility of robust integration between the two is low.

It is worth contemplating why an additional arm structure is needed in the full-scale design, as adding a robotic arm will retract from the aesthetics of the Growroom. Alternate options to a robotic arm structure that align with the creation of the Growroom and the scope of this project include the addition of hydroponics, automatic sprinkler systems, or smaller robotic systems created within shelves.

Appendix A

Growroom

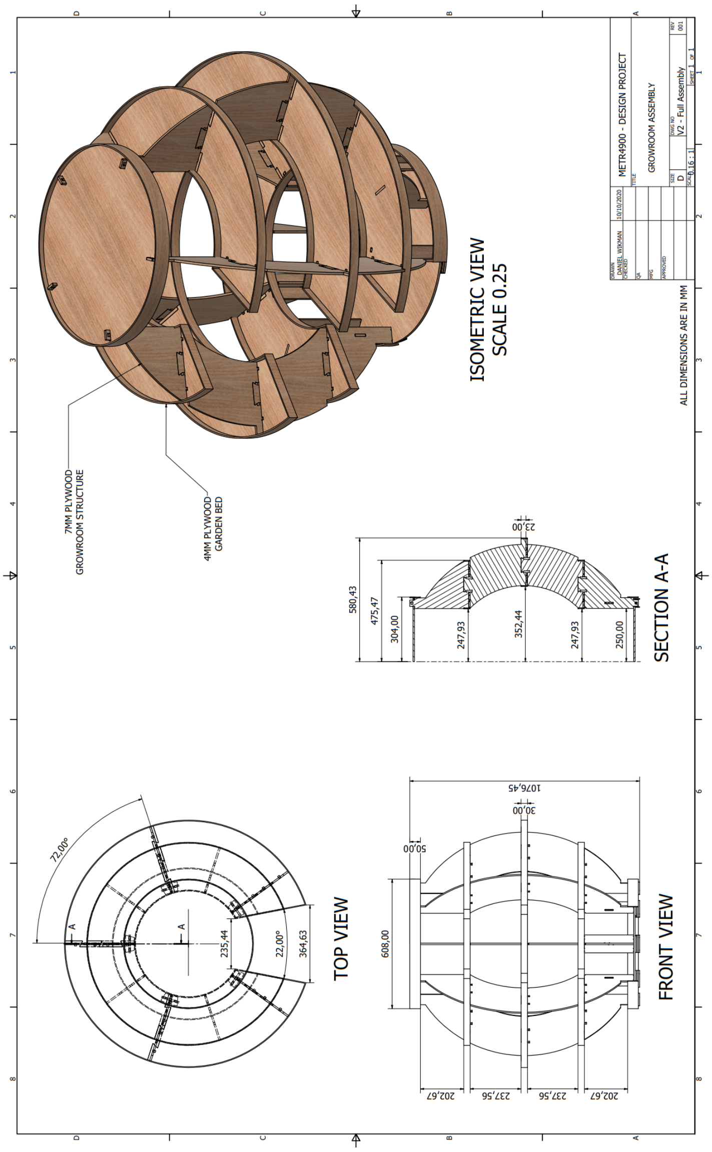

Figure A.1: Mechanical Drawing of Growroom
Source: [35]

Appendix B

FarmBot Mechanical Structure: High Level Overview

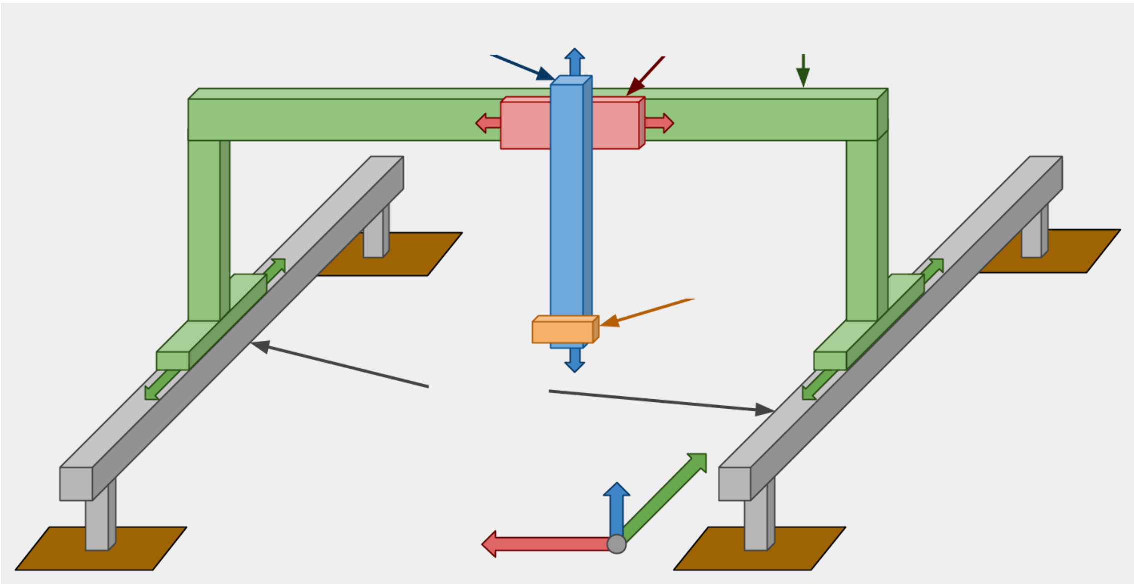

Figure B.1: High Level Overview of FarmBot Mechanical Structure
Source: [4]

Appendix C

FarmBot Software: High Level Overview

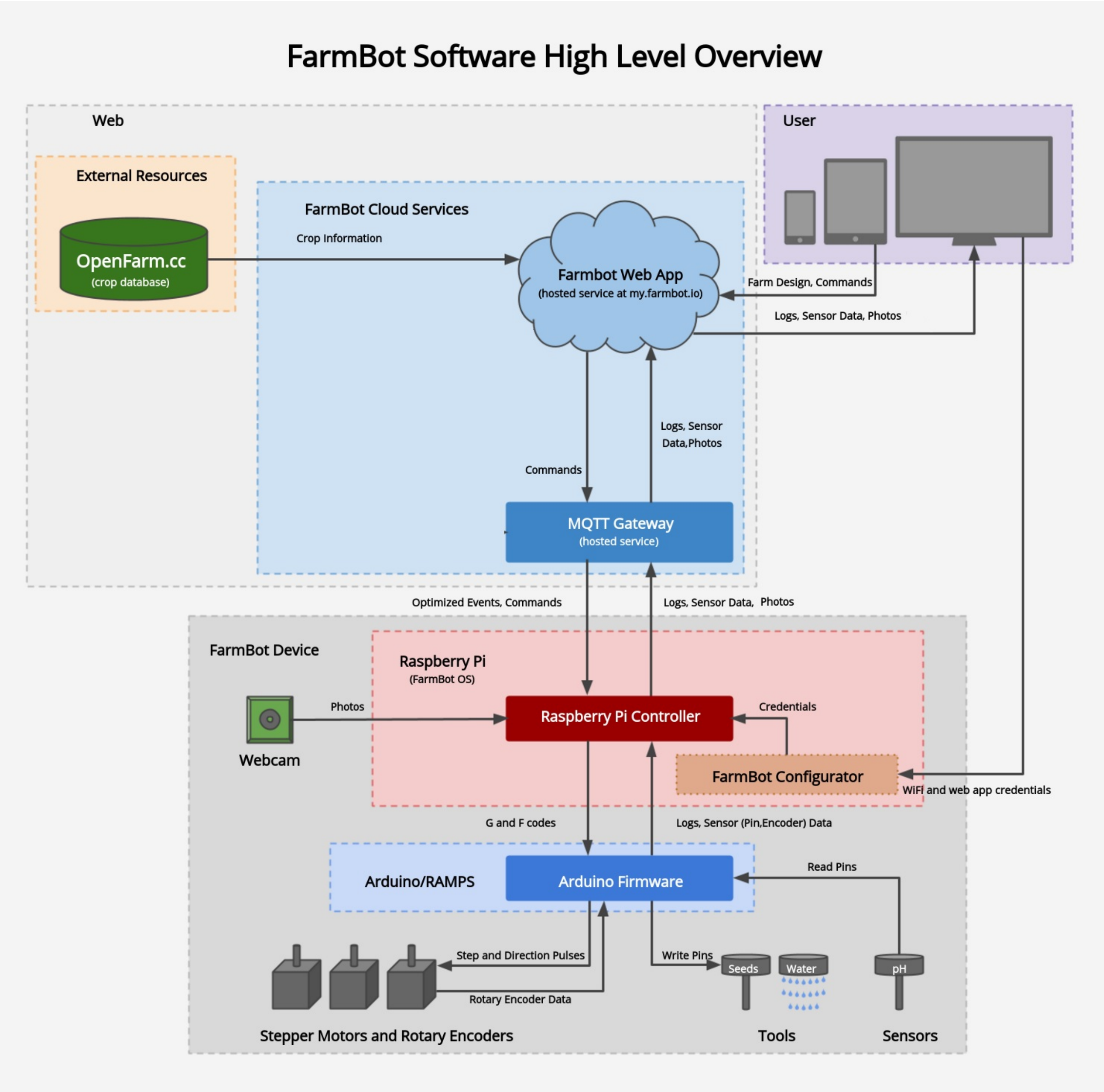

Figure C.1: FarmBot Software: High Level Overview.
Source: [6]

Appendix D

Cartesian Robot Arm

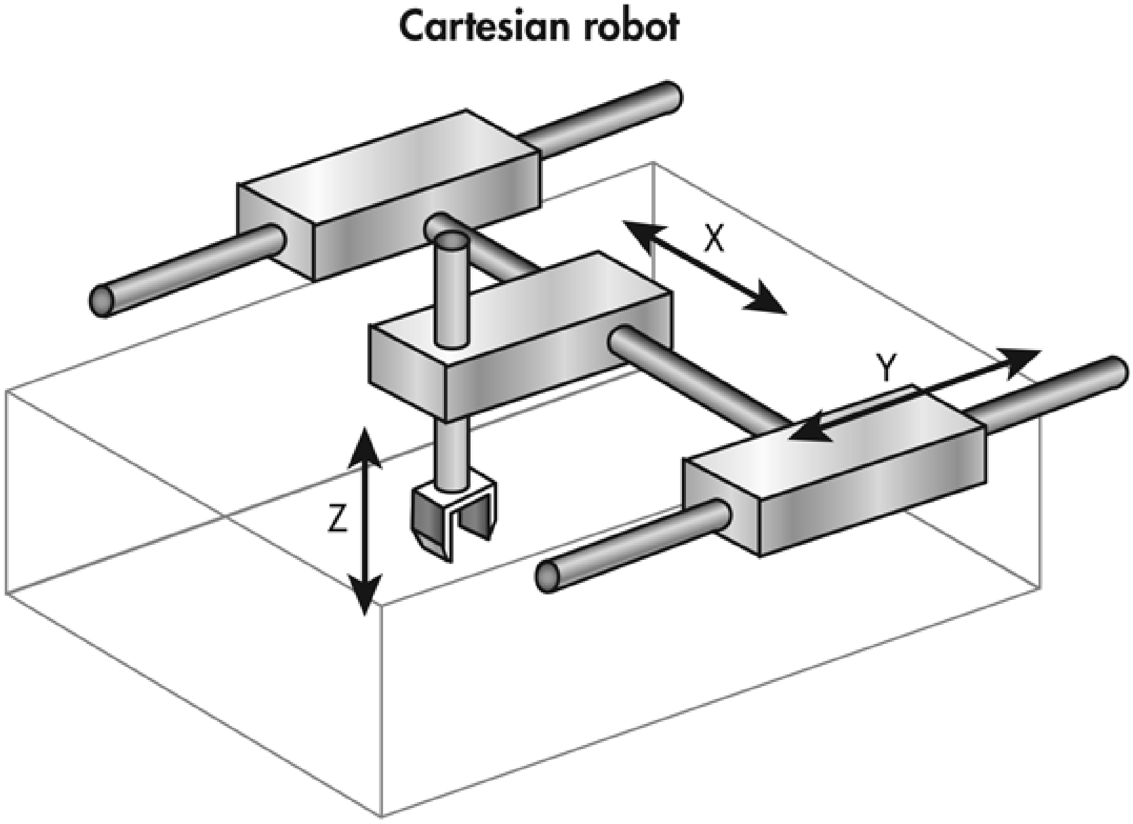

Figure D.1: Schematic Diagram of Cartesian robotic arm.
Source: [36]

Appendix E

Articulated Robot Arm

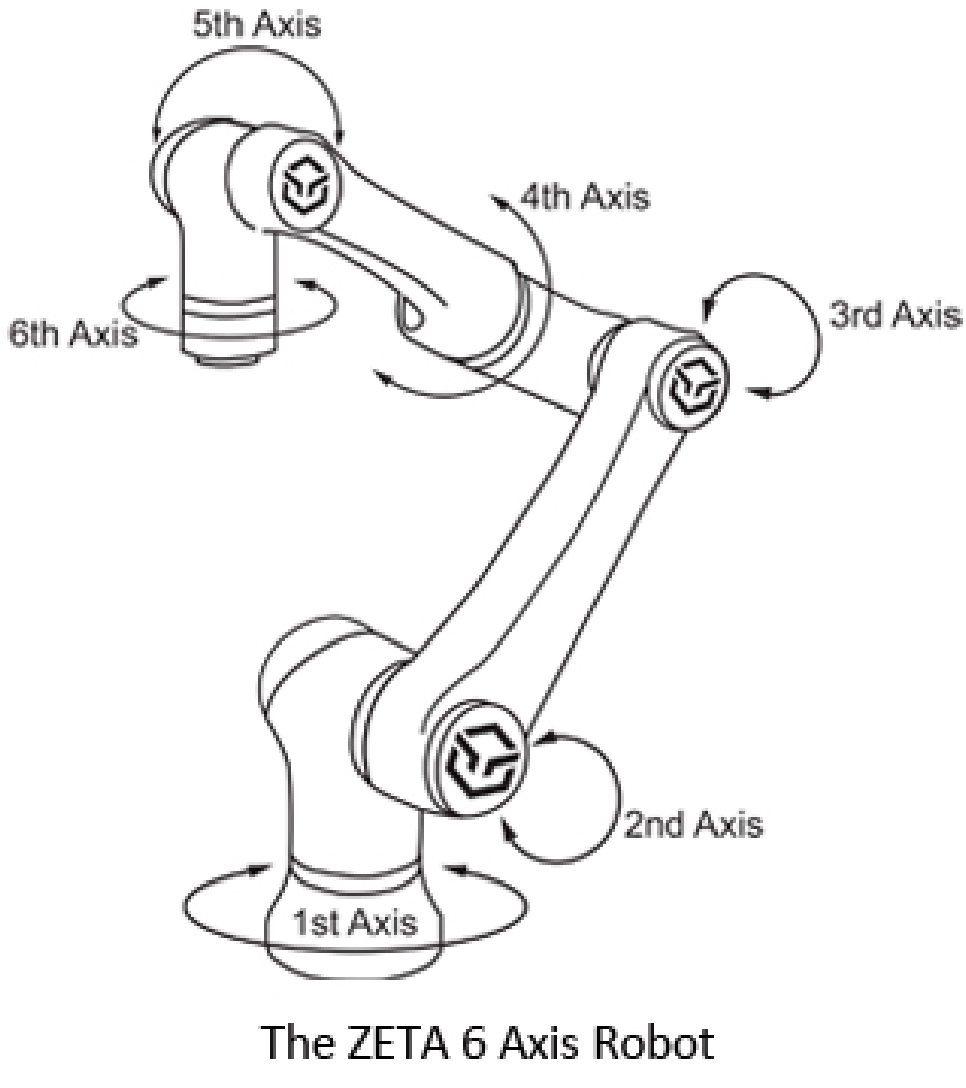

Figure E.1: Schematic Diagram of the ZETA 6 axis robotic arm.
Source: [37]

Appendix F

SCARA Robot Arm

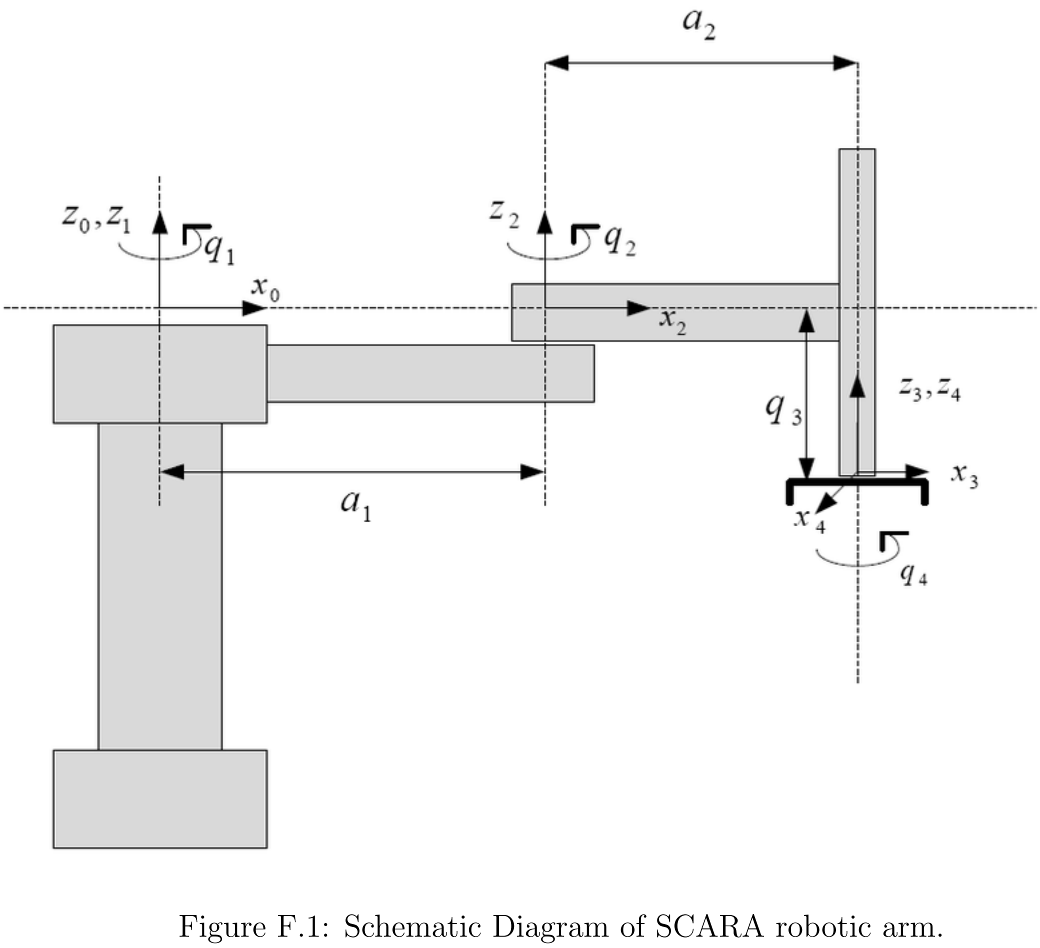

Figure F.1: Schematic Diagram of SCARA robotic arm.
Source: [38]

Appendix G

Telescoping Robotic Arms

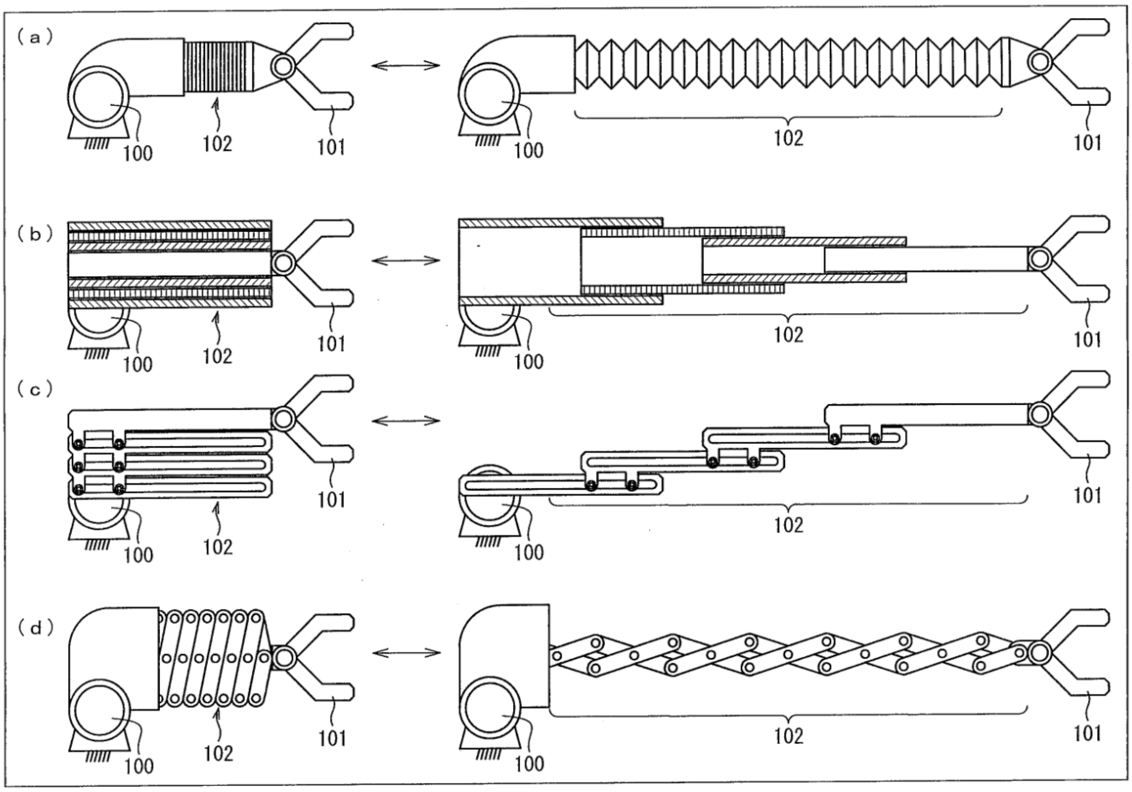

Figure G.1: Types of telescoping robotic arms.
Source: [16]

Appendix H

Linear Actuation: Vertical Axis

Table H.1: Linear Actuation Types and Specifications
Source: [39] [40] [41] [42]

Linear Actuation						
Type	**Cost**	**Accuracy**	**Size**	**Stability**	**Availability**	**Total**
Lead Screw	4	1	4	1	1	13
Ball Screw	5	1	4	1	1	12
Timing Belt	2	3	1	2	1	9
Rack and Pinion	5	1	2	2	5	15

Figure H.1: Matrix Rankings

Parameter	**Transmission System Rank**				
	1	**2**	**3**	**4**	**5**
Cost	\$0-\$24	\$25-\$49	\$50-\$74	\$75-\$99	\$100+
Accuracy/Repeatability	Extremely accurate with low potential for inaccuracies to occur	Accurate with minimal potential for inaccuracies to occur	Moderately accurate with moderate potential for inaccuracies to occur	Moderately accuracy with high potential greater inaccuracies will occur	Inaccurate
Size/Weight	Lightweight and compact size, no hinderance on design	Size/weight will not impact design and can be feasibly implemented	Size/weight adequate for design and few (1-3) changes required to accommodate	Size/weight of design is large and design changes will be required to accommodate this option	Size/weight of this option is unfeasibly large and will be too large to incorporate in design
Stability	No/negligible chance of movement in platform/arm	Little chance of movement in platform/arm	Some chance of movement in platform/arm	Large potential of movement in platform/arm	Unfeasible stability. Will case large inaccuracies
Availability (includes design time if required)	Can obtain part in 0-1 working days	Can obtain part in 2-3 working days	Can obtain part in 3-4 working days	Can obtain part in 4-5 working days	5+ working days

Table H.2: Linear Actuation Rankings: Vertical Axis

		A	**B**	**C**	**D**	**E**
		Cost	**Accuracy**	**Size**	**Stability**	**Availability**
A	Cost		B	AC	D	A
B	Accuracy			B	BD	B
C	Size				CD	CE
D	Stability					D
E	Availability					

Table H.3: Weighting Table: Vertical Axis

Rankings	No. of Ranking	Weighting
A	2	0.14
B	4	0.29
C	3	0.21
D	4	0.29
E	1	0.07

Table H.4: Weighted Linear Actuation: Vertical Axis

Linear Actuation						
Type	**Cost**	**Accuracy**	**Size**	**Stability**	**Availability**	**Weighted Total**
Lead Screw	0.71	0.57	0.86	0.29	0.07	2.5
Ball Screw	0.71	0.29	0.86	0.29	0.07	2.2
Timing Belt	0.29	0.86	0.21	0.57	0.07	2.0
Rack and Pinion	0.71	0.29	0.43	0.57	0.36	2.4

Appendix I

Linear Actuation: Horizontal Axis

This uses Appendix H Table H.1 for preliminary types and specifications. Rankings and weightings are performed on this table.

Table I.1: Linear Actuation Rankings: Horizontal Axis

		A	B	C	D	E
	Parameters	Cost	Accuracy	Size	Stability	Availability
A	Cost		B	A	D	A
B	Accuracy			B	BD	B
C	Size				D	CE
D	Stability					D
E	Availability					

Table I.2: Weighting Table: Horizontal Axis

Rankings	**No. of Rankings**	**Weighting**
A	2	0.17
B	4	0.33
C	1	0.08
D	4	0.33
E	1	0.08

Table I.3: Weighted Linear Actuation: Horizontal Axis

Linear Actuation						
Type	Cost	Accuracy	Size	Stability	Availability	Weighted Total
Lead Screw	0.67	0.33	0.33	0.33	0.08	1.8
Ball Screw	0.83	0.33	0.33	0.33	0.08	1.9
Timing Belt	0.33	1.00	0.08	0.67	0.08	2.2
Rack and Pinion	0.83	0.33	0.17	0.67	0.42	2.4

Appendix J

System Weights

Table J.1: System Weights

Component	Component Weight	Cumulative Weight
Arm	0.7	0.7
UTM	0.04	0.74
V-slot	0.58	1.32
Misc. (PCBs, wiring, etc.)	0.2	1.52
C-beam	1.76	3.28
Turntable	3.48	6.76

Appendix K

Horizontal Lead Screw Torque

The following will complete the steps outlined in Section 3.2.1 with the system weights specified in Appendix J.

Using Equation 3.7 with the following parameters:

- m = 1.52kg
- l = 0.008m

$$J_{load} = 2.4{\times}10^{-6} kgm^2$$

Using Equation 3.8 with the following parameters:

- L = 0.152m
- R = 0.004m
- ρ = 7700 g/m^3

$$J_{lead} = 4.7{\times}10^{-7} kgm^2$$

Using Equation 3.9 we add this total after a motor is selected. We will use the torque of a Nema17 Stepper motor ([29]). This gives:

$$J_{motor} = 380{\times}10^{-6} \text{ kg-}m^2$$

In this implementation, friction is negligible due to the small load.

$$T_{friction} = 0$$

Using Equation 3.11 with the following parameters:

- ω = 3800 steps/sec
- t = 0.2 seconds

$$J_{total} = 0.23 \text{ Nm}$$

Appendix L

Vertical Lead Screw Torque

To determine the torque required to raise and lower the load using a lead screw, Equations 3.14 and 3.15 were used with the follow parameters:

- F = mg = 6.867N
- d_m = 0.008m
- l = 0.008 m
- f = 0.19

$$T_{raise} = 0.035 \text{ Nm}$$

$$T_{lower} = 0.0094 \text{ Nm}$$

Appendix M

Vertical Transmission Torque

To determine the torque required to raise and lower the load using a belt and pulley system, Equations 3.17 and 3.19 were used with the follow parameters:

- m = 0.7kg
- g = 9.81 m/s^2
- a = 0.01 m/s^2
- r = 0.016m
- η = 0.8

This gives:

$$\tau_{holding} = 0.165 \text{ Nm}$$

$$\tau = 0.166 \text{ Nm}$$

Appendix N

Turntable Torque

- $m_{arm} = 3.28\text{kg}$
- $m_{table} = 2\text{kg}$
- $N_{RPM} = 10\text{RPM}$
- $r_{table} = 0.225\text{m}$
- $r_{arm} = 0.02\text{m}$
- $I_{table} = 0.051 \text{ kg}m^2$
- $I_{arm} = 0.0031 \text{ kg}m^2$
- t = 0.3 seconds
- N = 20 RPM

$$\tau_{arm} = 0.0046 \text{ Nm}$$
$$\tau_{table} = 0.35 \text{ Nm}$$
$$\tau_{total} = 0.355 \text{ Nm}$$

Appendix O

Power Requirements

All laboratory measurements include a 20% safety factor to account for worst case current draw.

Table O.1: Component Power Consumption

Arm Subsystem PCB						
Component	**Unit/s**	**Current (A)**	**Voltage (V)**	**Unit Power Consumption (W)**	**Total Power Consumption (Worst Case)**	**Reference**
Logic Power Consumption						
Ardunino Uno						
Atmega328	1	0.042	3.3	0.1386	0.1386	[43]
LED (1k ohm)	1	0.02	3.3	0.66	0.066	[44]
Stepper driver logic	3	0.008	3.3	0.0264	0.0792	[45]
Limit switch when engaged	6	negligible	3.3	0	0	
nRFL01+	1	0.0135	3.3	0.04455	0.04455	[46]
Actuator Power Consumption						
Nema 17 42 x 42 x20	1	0.4	12	4.8	4.8	laboratory testing
Nema 17 42 x 42 x34	2	0.6	12	7.2	14.4	laboratory testing
				Total	**19.52**	
Turntable PCB						
Component	**Unit/s**	**Current (A)**	**Voltage (V)**	**Unit Power Consumption (W)**	**Total Power Consumption (Worst Case)**	**Reference**
Logic Power Consumption						
Wemos D1 ESP2866						
ESP-8266EX	1	0.17	3.3	0.561	0.561	[47]
LED (1k ohm)	1	0.02	3.3	0.66	0.066	[44]
Stepper driver logic	1	0.008	3.3	0.0264	0.0264	[45]
Limit switch when engaged	1	negligible	3.3	0	0	
nRFL01+	1	0.0135	3.3	0.04455	0.04455	[46]
Actuator Power Consumption						
Nema 23	1	0.8	12	9.6	9.6	laboratory testing
				Total	**10.30**	

Appendix P

Arm Calculations: Extension and Maximum Height

P.0.1 Maximum Arm Height

To determine the maximum arm height, the height of the UTM with the longest tool was required to be known. These values are outlined in Table P.1.

Table P.1: Maximum UTM Measurements

UTM Measurements		
Component	**Height**	**Units**
UTM Depth	16.25	mm
Seeder/Watering/Vacuum	15	mm
Seeder Nozzle	61	mm
Total	**92.25**	**mm**
	0.09225	**m**

From these values, the maximum height restriction on the arm is:

$$Max\ Arm\ Height(S) = Min\ Shelf\ Height - Max\ UTM\ Height$$
$$Max\ Arm\ Height(S) = 0.11m$$

Where:
Min Shelf Height = total from Table P.1 = 0.092m
Min Shelf Height = Shelf 3 Height (from Appendices A and Q) = 0.202m.

P.0.2 Arm Extension

The required arm extension length was determined as:

$$Extension\ Length = R_{max} - x_{UTM} - T_d$$

Where: R_{max} = max radius of the Growroom
x_{UTM} = UTM reach
T_d = horizontal axis length

Parameters used for these calculations are seen in Table P.2.

Table P.2: Arm Parameters

Parameters Determined By Structure:			
Parameter	**Symbol**	**Value**	**Units**
Max Height	S	0.11	m
Max Radius	R_{max}	0.58	m
Max Extension Length	S	R_{max} - T_d - x_{UTM}	
	L_{max}	0.302	m
Distance to Pins	d	0.01	m
Distance Between Pins	$h_1 + h_2$	0	m
Min/Folded Angle	α_{min}	10	degrees
Max/Open Angle	α_{max}	50	degrees
Distance to End of TT	T_d	0.2	m
UTM Reach	x_{UTM}	0.078	m

Using these parameters, a closed scissor extension length ($\alpha_{min} = 10°$) was calculated:

$$\alpha_{min} = 172\text{mm}$$

Appendix Q

Height Calculations

To calculate the height of the v-slot that comprised of theMonarch's vertical axis, the height of all components needed to be subtracted from the height of the Growroom.

Figure ?? shows the height of all sub-components, and the calculations done to determine the height of the v-slot. Figure Q.2 heights of each shelves relative to both the ground and the v-slot.

Table Q.1: Sub-system Heights and V-slot Height Calculation

	Add to Height	**Subtract from Height**
	Height (mm)	**Height (mm)**
Total Height of Growroom		
Growroom	1076.45	
Heights of Subitems		
Base Height Above Ground		28
Turntable Feet		80
Turntable Bottom		12
Turntable Bearing		7
Turntable Top		12
C-beam		40
C-beam plate		6
Bottom Motor Connector		40
Top Idler connection		40
Roof Depth		50
Clearance		10
Length of V-slot		**751.45**

Table Q.2: Shelf Heights

Shelf	**Shelf Height (mm) (from ground)**	**Marked Height (mm) (relative to v-slot)**
Base	28	
Shelf 1	224.67	27.67
Shelf 2	492.23	295.23
Shelf 3	759.29	562.79
Roof	997.35	

Appendix R

Repository Links

This Appendix provides GitHub repository links for the specified sections. All have a README file included for information regarding the content of each. The full repository can be found at:

Link: Full FarmBot Growroom Repository

R.1 Mechanical Components & Designs

Link: Mechanical Repository

R.2 PCB Design

Link: Electrical Repository

R.3 Software Implementation

Link: Software Repository

Appendix S

PCB Schematics

This Appendix includes the schematic diagrams for both PCBs. For full documentation refer to Section R.2 in Appendix R.

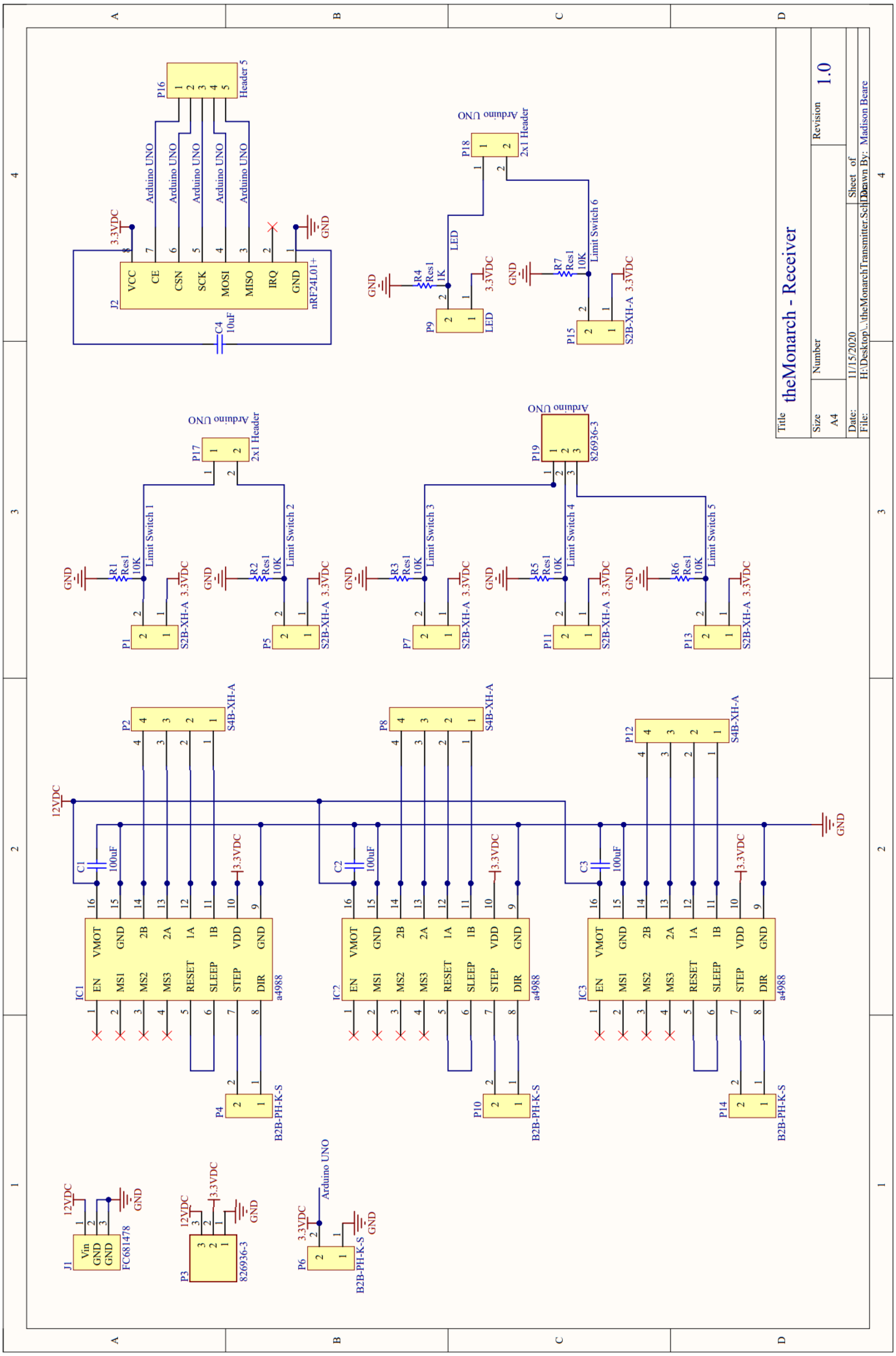

Figure S.1: theMonarch PCB Schematic

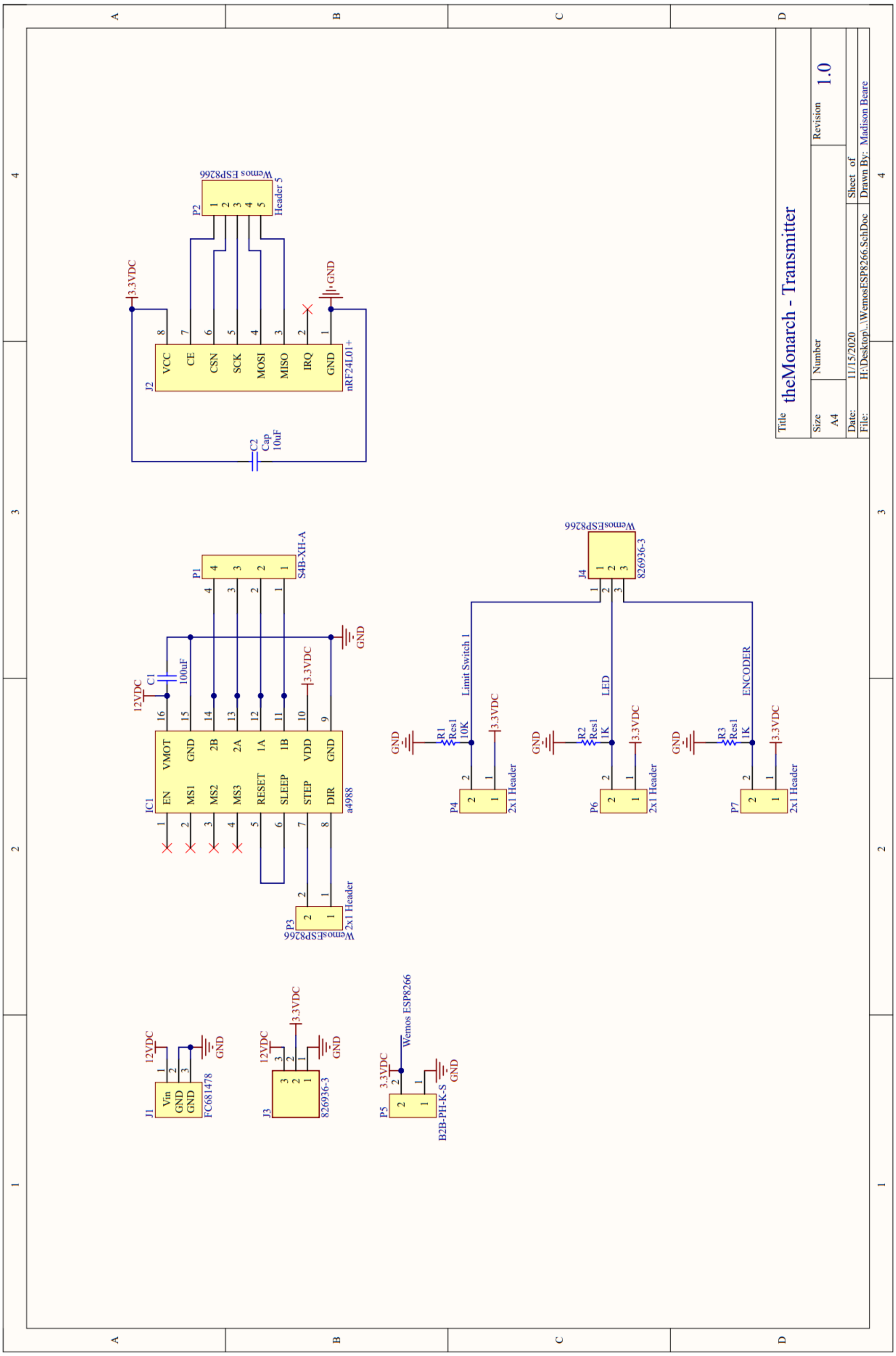

Figure S.2: Turntable PCB Schematic

Appendix T

Bill of Materials

T.1 Electrical BOM

Table T.1: Electrical BOM

The Monarch Receiver PCB								
Part Number/Name	**Description/Value**	**Designator**	**LibRef**	**Quantity**	**Unit Price**	**Total Price**	**Source**	**Ref/Bin Number**
theMonarchReceiver PCB	PCB			5	1.954	9.77	JLCPCP	
Arduino Uni	microcontroller			1	0	0	preowned	
Capacitor	10uF	C4	Cap	1	1.59	1.59	ETSG	07-68-03
Capacitor	100uF	C1,C2,C3	Cap	3	0.48	1.44	ETSG	07-58-03
Resistor	1K	R4	Res1	1	0.03	0.03	ETSG	02-25-02
Resistor	10K	R1, R2, R3, R5, R6, R7	Res1	6	0.03	0.18	ETSG	02-33-02
A4988	Stepper Driver	IC1, IC2, IC3	a4988	3	6.5	19.5	Makerstore	
FC681478	Power Jack	J1	FC681478	1	2.31	2.31	Element14	
8 Pin Header	8 Pin Header	IC1, IC2, IC3, J2	WRL-00691	7	1.72	12.04	ETSG	03-38-03
S2B-XH-A	2 Pin Header (right-angle)	P1, P5, P7, P11, P13, P15, P17, P18	S2B-XH-A(LF)	8	0.27	2.16	ETSG	08-52-03
S4B-XH-A	4 Pin Header (right-angle)	P2, P8, P12	4B-XH-A(LF)(SN)	3	0.69	2.07	ETSG	08-53-01
826936-3	3 Pin Header	P3, P19	826936-3	2	0.86	1.72	ETSG	08-34-01
B2B-PH-K-S	2 Pin Header	P4, P6, P10, P14	B2B-PH-K-S(LF)(SN)	4	0.151	0.604	Element14	
HDR1X5	5 Pin Header	P16	HDR1X5	1	0.63	0.63	ETSG	03-38-01
LED	LED (green)	P9	LED	1	0.08	0.08	ETSG	04-49-01
DB1C-A1LB	Micro Switch	-	-	6	2.81	16.86	ETSG	04-91-03
nRF24L01+	Transceiver	J2	WRL-00691	1	20.95	20.95	Sparkfun	
K143 Crimps	JST Crimps			40	0.02	0.8	ETSG	08-50-03
JST PHR-2	JST Terminal Housing (2 Pin)			10	0.07	0.7	ETSG	08-49-01
JST PHR-4	JST Terminal Housing (4 Pin)			3	0.09	0.27	ETSG	08-49-02
Nylon Screw	M3.0 x 6mm Nylon Bolt			2	0.13	0.26	ETSG	10-34-01
Nylon Hex Nut	M3.0 Nylon Nut			2	0.11	0.22	ETSG	10-38-01
SMP12V-3A-21P	Power Pack			1	24.95	24.95	Wagner	
					theMonarchReceiver PCB Cost:	**119.134**		
Turntable PCB								
Turntable PCB	PCB			5	1.396	6.98	JLCPCP	
Wemos D1 ESP8266	microcontroller			1	19.99	19.99	Ebay	
Capacitor	10uF	C2	Cap	1	1.59	1.59	ETSG	07-68-03
Capacitor	100uF	C1	Cap	1	0.48	0.48	ETSG	07-58-03
Resistor	1K	R2, R3	Res1	1	0.03	0.03	ETSG	02-25-02
Resistor	10K	R1	Res1	2	0.03	0.06	ETSG	02-33-02
A4988	Stepper Driver	IC1	a4988	1	6.5	6.5	Makerstore	
FC681478	Power Jack	J1	FC681478	1	2.31	2.31	Element14	
8 Pin Header	8 Pin Header	IC1, J2	WRL-00691	3	1.72	5.16	ETSG	03-38-03
S7036-ND	3 Pin Header	J3, J4	826936-3	2	0.86	1.72	ETSG	08-34-01
S4B-XH-A	4 Pin Header (right-angle)	P1	4B-XH-A(LF)(SN)	3	0.69	2.07	ETSG	08-53-01
HDR1X5	5 Pin Header	P2	HDR1X5	1	0.63	0.63	ETSG	03-38-01
S2B-XH-A	2 Pin Header (right-angle)	P3, P4, P6, P7	S2B-XH-A(LF)(SN)	4	0.27	1.08	ETSG	08-52-03
B2B-PH-K-S	2 Pin Header	P5	B2B-PH-K-S(LF)(SN)	1	0.151	0.151	Element14	
LED	LED (green)	P9	LED	1	0.08	0.08	ETSG	04-49-01
DB1C-A1LB	Micro Switch	-	-	1	2.81	2.81	ETSG	04-91-03
nRF24L01+	Transceiver	J2	WRL-00691	1	20.95	20.95	Sparkfun	
K143 Crimps	JST Crimps			40	0.02	0.8	ETSG	08-50-03
JST PHR-2	JST Terminal Housing (2 Pin)			5	0.07	0.35	ETSG	08-49-01
JST PHR-4	JST Terminal Housing (4 Pin)			1	0.09	0.09	ETSG	08-49-02
Nylon Screw	M3.0 x 6mm Nylon Bolt			2	0.13	0.26	ETSG	10-34-01
Nylon Hex Nut	M3.0 Nylon Nut			2	0.11	0.22	ETSG	10-38-01
SMP12V-3A-21P	Power Pack			1	24.95	24.95	Wagner	
					Turntable PCB Cost	**99.26**		
					Total Cost	**218.40**		

T.2 Mechanical BOM

Table T.2: Mechanical BOM

Mechanical BOM					
Component	**Part Nunber/SKU**	**Quantity**	**Unit Cost ($AUD)**	**Total Cost ($AUD)**	**Supplier**
Turntable					
Flexible Coupling (6.25mm x 8mm)	HARD-COUP-635X8	1	9.75	9.75	Maker Store
CustomWood MDF 1200 x 600 x 12mm	0590090	1	14.00	14.00	Bunnings
Adoored 40 x 40 x 80mm Square Cab Black Plastic Leg Furniture	0173177	4	2.50	10.00	Bunnings
Adoored 75mm 90kg Lazy Susan Bearing Plate	0080820	1	3.40	3.40	Bunnings
Nema 23	ELEC-NEMA23-635-B	1	12.09	12.09	Maker Store
			Total Tuntable Cost	**$49.24**	
Central Transmission System (v-slot + c-beam)					
GT2 (2mm) Aluminum Timing Pulley 20	BELT-GT2-TP20	1	5.95	5.95	Maker Store
Metric Aluminium Spacer (30mm)	SHIM-SPAC-30MM	8	0.95	7.60	Maker Store
Metric Aluminium Spacer (3mm)	SHIM-SPAC-3MM	2	0.50	1.00	Maker Store
Smooth Idler Pulley Kit	WHEEL-PULLEY-KIT	1	6.06	6.06	Maker Store
Actuator Pulley Plate	PLATE-ACTUATOR-PULLEY	2	8.00	16.00	Maker Store
100mm V-Slot Gantry Plate	PLATE-100MM-GANTRY-VSLOT	1	14.95	14.95	Maker Store
Solid V Wheel Kit	WHEEL-SOLIDV-KIT	4	6.00	24.00	Maker Store
Metric Aluminium Spacer (6mm)	SHIM-SPAC-6MM	2	0.50	1.00	Maker Store
Eccentric Spacers – 8mm Hex – 6mm Height	SHIM-ECCENTRIC-8-6	2	3.50	7.00	Maker Store
V-slot 20 x 40 x 1000mm	LR-2040-S-1000	1	18.60	18.60	Maker Store
GT2 (2mm) Timing Belt (per meter)	BELT-GT2-1M	3	3.95	11.85	Maker Store
Belt Crimp Clamp	BELT-CLAMP	2	2.15	4.30	Maker Store
M3 Button Head Screws – 35mm (10 pack)	SCREWS-M3-BH-35	1	1.60	1.60	Maker Store
M5 Low Profile Screws – 8mm (10 pack)	SCREWS-M5-LP-8/10	2	1.60	3.20	Maker Store
Tee Nuts – 1 Piece (25 pack)	HARD-TNUT-PACK25	1	4.95	4.95	Maker Store
8mm Metric Lead Screw / ACME	HARD-ACME-8-290	1	14.3	14.30	Maker Store
M5 Low Profile Screws – 25mm (10 pack)	SCREWS-M5-LP-25/10	1	2.00	2.00	Maker Store
Nema 17	17HS13-0404S1	2	12.09	24.18	Maker Store
C-Beam Gantry Bundle	BUN-CBEAM-GANTRY	1	41.00	41.00	0
Manufactured Bracket		1	5	5	UQ Innovate
3D Print		1	34.50	34.50	UQ Innovate
			Total Centre Beam Cost	**$249.04**	
Arm					
Ball Bearing 625 2RS	BEAR-6252RS	1	2.19	2.19	Maker Store
Belt Crimp Clamp	BELT-CLAMP	2	2.15	4.30	Maker Store
Nema 17 Stepper Pancake	17HS08-1004S	1	12.09	12.09	Stepper Online
Flanged 688ZZ Ball Bearing	BEAR-F688ZZ	1	2.95	2.95	Maker Store
8mm Metric Lead Screw / ACME	HARD-ACME-8-290	1	14.3	14.30	Maker Store
8mm Smooth Rod	HARD-ROD-8-300	1	3.5	3.50	Maker Store
Flexible Coupler 5x8	HARD-COUP-5X8	1	9.75	9.75	Maker Store
Manufactured Bracket		1	5	5	UQ Innovate
3D Print		1	11.2	11.2	UQ Innovate
			Total Arm Cost	**$65.28**	
			Total Cost	**$363.56**	

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