



BEAM

Botanical Eradication and Management Machine

EEL 4914 | Senior Design I | Summer 2024 | Group 1

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Chapter 1 – Executive Summary

Chapter 2 – Project Description

2.1 Background and Motivation

The agriculture industry and all related industries in the US accounts for approximately the 5.6% of the Gross Domestic Product (GDP) and 10.34% of U.S employment [1]. Although, its significance might not seem much, production agriculture is the leading source of economic activity in numerous counties spread throughout the country, but they concentrate in the Great Plains states towards the Midwest. The Midwest is renowned for fertile soil, a temperate climate, and plenty of water resources like rivers and aquifers which are essential for irrigation and sustaining crop growth [2]. With our project, we aim to aid in the crop production yield of farms to fight the loss of direct employment and lower than average wage in rural areas, and to make it easier for farmers, both big and small, to diversify their production since research show that it has a direct correlation with a decrease in population [3].

In agriculture, one of the the largest inhibitors of plant growth are weeds. Weeds are plants that grow in places humans don't want them to grow. These invasive plants can spread rapidly through fields, becoming very tedious and difficult to remove. Weeds will often grow "too well", and outcompete desired crops for nutrients, water, and sunlight [4]. This can cause great economic loss for a farm. Monitoring and controlling weed growth can greatly benefit commercial crops, and there are only a few ways to handle this problem. So far, the strategies most used by commercial farmers are manual weeding, which is paying workers to pull weeds, mechanical weeding, using a machine pulled by a tractor to uproot weeds, or chemical weeding, using pesticides to kill weeds [5].

Chemical herbicides are one of the most common tools used to remove weeds, but along with the benefits of weed removal come disadvantages from their toxicity to the environment and human health. These herbicides can be extremely toxic to livestock, fisheries, natural predators, soil microbiomes, native plants, crops, and humans [6]. The many disadvantages of chemical herbicides should outweigh the benefits, but it is still a popular technique in many countries. Our project aims to revolutionize weed removal through a combination of object recognition and lasers. The use of light radiation to burn weeds is more environmentally friendly and will promote overall crop health, prevent the destruction of soil and water microbiomes, and decrease human contact with toxic chemicals.

2.2 Goals/Objectives

The goal of our project is to build a solar-powered vehicle-type robot that uses object detection to recognize weeds and then uses a laser to remove them. The main goals and objectives are listed below.

Overall Goals

- Build a robot that is suitable for navigating a field.
- Build a laser system capable of burning weeds.
- Provide farmers with an environmentally friendly weed control method that minimizes impacts on other vital plants.

Advanced Goals

- Keep track of number of weeds lasered.
- Have a reasonable data refresh rate for the application.

Stretch Goals

- Build on the application to add a user-friendly GUI used to monitor the robot's progress.

Robot Objectives

- Be able to navigate a field without getting stuck or becoming lost.
- Be able to charge the system battery using sunlight.
- Create a simple application that keeps track of weed statistics.

Laser System Objectives

- Achieve a high-power output from the laser diode to ensure efficient moisture evaporation, allowing for quick and effective weed control.
- Design the system to be lightweight, compact, and portable for the robot, allowing it to navigate various terrains and locations with ease.
- Integrate safety features into the robot's design to prevent accidents and ensure safe operation in proximity to humans and other objects.
- Achieve acute control of the laser position for weed removal.

2.2.1 Hardware Goals

These are the goals that we want to be able to accomplish with the BEAM's hardware setup. These goals are divided into basic, advanced, and stretch goals.

2.2.1.1 Basic Goal

Our project's overall engineering goal is to find and identify weeds using a vehicle robot that can navigate its surroundings without becoming lost or stuck. It is also essential that our robot does not become stuck in the wet soil while navigating its area. It will be designed for moderate to mild conditions, and not built for extremely muddy conditions to protect the hardware. To ensure that our robot does not become stuck in the soil or mud, we will equip the chassis with quality tires and strong motors.

2.2.1.2 Advanced Goal

An advanced hardware goal for the BEAM project is to add a sufficient cooling system for all the electronics on board. The robot will be operating outside in hot temperatures, and it is important to make sure that these components will remain in an appropriate temperature during their operation as this can negatively impact the performance of the electronics and inhibit the robot's overall performance.

2.2.1.3 Stretch Goal

The BEAM robot will be tested in Florida, where it is both hot and humid, and as such it is important that the components onboard are appropriately sheltered and protected from rapid changes in weather conditions. The hardware stretch goal of the BEAM project is to make the robot highly water resistant and create proper housing for each component and modify the chassis so that water does not penetrate the robot's infrastructure.

2.2.2 Software Goals

To obtain accurate weed identifications, we plan to feed our object detection system many images to compare real plants to. The data we use to train the system will be essential for correct identifications of crops vs weeds. The navigation system will use SLAM based mapping so that it does not get lost and wander aimlessly. We will use a lidar system to map out the area and use coding logic to help the robot make navigation decisions. The start-up method we want to use for the robot will be having it map out the entire area, and then it will proceed to start identifying weeds and note treated locations.

2.2.2.1 Basic Goals

The basic software goals for the BEAM project include building direct communication between the navigation system and the motors to pilot the robot where it needs to be. This also includes communication between the weed location sensors and the laser positioning system to accurately laser the correct areas beneath the robot.

2.2.2.2 Advanced Goals

An advanced goal of our project is to create a 3D active map model of the area the robot is in. This will not only help with navigation but allow for path planning and accurate location tracking for weed treatments. The 3D active map will allow for enhanced spatial awareness like obstacle detection and depth perception. This is important on a farm plot with uneven surfaces and crops in the way. Using simultaneous localization and mapping (SLAM) techniques, our robot will be able to build and update maps in real-time while monitoring its location. This will allow for improved route planning, and adaptability for changes in the environment such as terrain changes or moving objects.

2.2.2.3 Stretch Goals

An application for the robot would let users monitor the progress of weed removal in their field and document weed location so the user would know where problem areas are located. It would also show battery life and current location of the robot. The app would increase the amount of data provided to the user about their field, allowing them to make more informed choices about how to provide proper care for crops.

This application would let users navigate a graphical user interface allowing for easy user interaction between menus and systems. Additionally, the application will allow for real time monitoring to allow the user to track the robot in action. The application should allow for a reliable communication link between the robot and itself, allowing the user to momentarily take tele-present control remotely move the robot.

2.3 Description of Features and Functionalities

2.3.1 Navigation

LiDAR technique will be used to help the robot navigate by emitting laser pulses to create detailed 3D maps of their surroundings. This enables accurate environmental mapping, obstacle detection, and avoidance. The technique supports simultaneous localization and mapping. Allowing the robot to track its position while building maps. LiDAR data facilitates efficient path planning and dynamic path adjustments in real-time, ensuring safe and autonomous navigation in both indoor and outdoor settings.

2.3.2 Rechargeable Power System

Our outdoor robot is powered by a solar-charged power system, featuring solar panels connected to a high-capacity battery. Designed for field operations, this system uses solar energy to keep the robot charged and operational throughout the day, ensuring continuous performance without the need for external power sources or overnight charging.

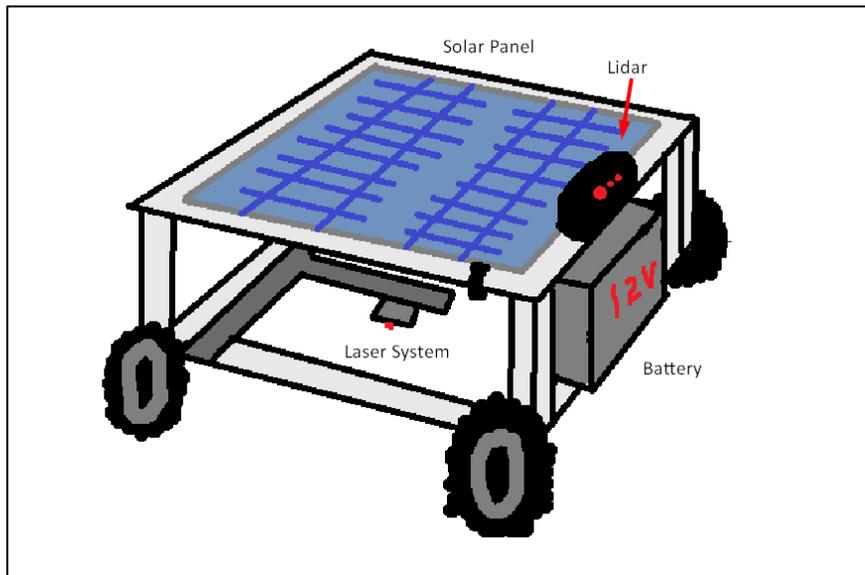


Figure 1 - Hardware Graphic

2.3.3 Weed Detection

The weed detection process begins with high-resolution cameras mounted on the robot capturing images of the field. These images are then processed using machine learning algorithms to identify weeds based on their visual characteristics. Machine learning models trained on weed and crop datasets classify the objects in the images. Weeds are identified by their size, shape, color, texture, and other features. Once the weeds are detected, their positions are calculated relative to the robot's location. This information is used to precisely target and activate the laser beam onto the detected weeds for effective weed-killing. By utilizing cameras and machine learning algorithms, the robot can accurately detect weeds in real-time, enabling targeted weed control without harming surrounding plants.

2.3.4 Weed Elimination

To eliminate weeds effectively, we are going to use laser diodes to evaporate the plant moisture. A lot of studies and experiments have been done on elimination of weeds by cutting their stems using lasers, but Mathiassen et al. [7] introduced another way to eradicate weeds by increasing the temperature of the moisture in the plant cells to eventually delay or stop its growth. Laser diodes with different wavelengths are going to be tested: blue, green, red, and infrared. Focusing on the objective of minimizing harm to essential plants and contamination to the environment, we aim to use high power laser that is strong enough to heat weeds. Laser diodes enable precise transfer of radiation energy, offering advantages for weed control such as weather-independent operation near crops, and customizable dosing capabilities [8].

2.3.5 Smartphone Application

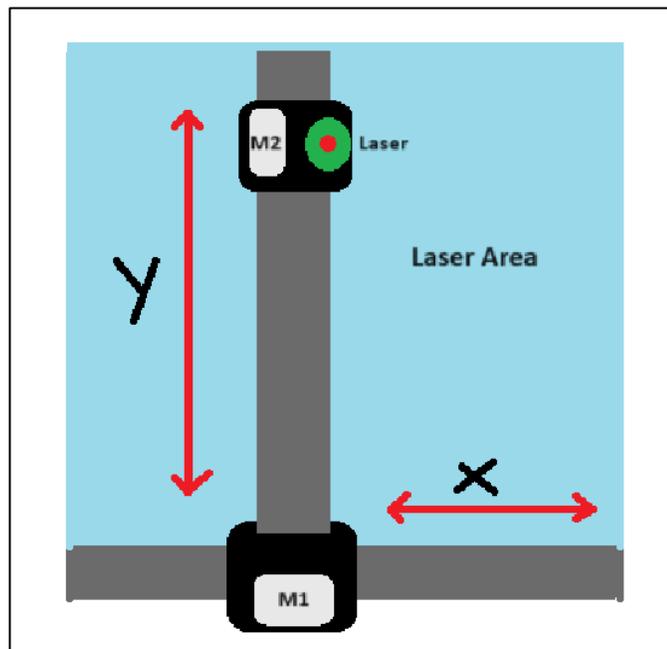


Figure 2 - Cartesian System for Laser Control

The application will provide users more information about weed treatment and problem areas in their field. This application will be hosted on a web interface that runs on a webserver. This server will allow the user to control the raspberry pi's GPIO pins and read information from sensors from a web browser. The code to read the data from the robot's external sensors will be read through a Python script interacting with the MCU. This information will then be displayed on the webserver through a user interface written in Java or HTML.

2.4 Block Diagrams

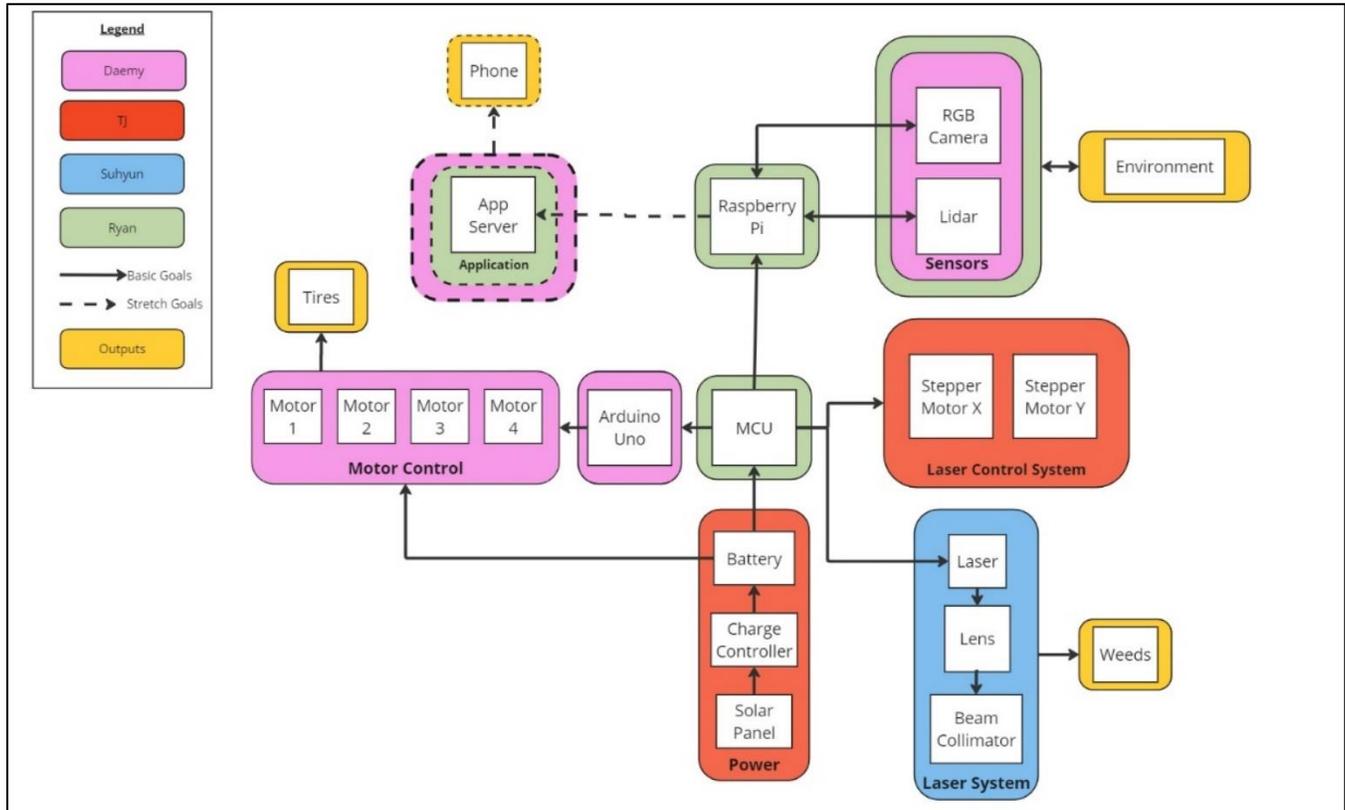


Figure 3 - BEAM hardware diagram

2.4.1 Hardware

The BEAM project is divided into 6 sections: Motor control, Power management, sensors, laser system, laser control system, and the application. Daemy and Ryan will work together on the motor control system and sensors, along with the communication pathway between the raspberry pi, MCU, sensors, and application. TJ will work on the power management system involving the solar panel, charge controller, and battery that will power the robot. TJ will also be working closely with Suhyun to calibrate the laser system and laser control to effectively target and lase weeds. Suhyun will design the laser system to find the most efficient way to evaporate water from the leaves of the weeds. As the main components of the BEAM system come together, we will begin to work on the communication pathway between the application and the server.

2.4.2 Software

As shown in Figure 4, the software portion of the BEAM project can be divided into mapping and location, laser control system coordination, and application information transfer. The system will first figure out if needs to map an area, and then proceed to

recording location information for mapping if it is in a new area. Once the mapping is complete, visual sensors like the RGB camera will be used via the Raspberry Pi to detect weeds underneath the robot. The Raspberry Pi will then transfer the coordinates of the weeds to the Arduino Uno so the laser control system can reposition itself to lase them. As part of our application, the weed location data will correspond to a location on the robot's mapping system so the user can track treated areas. The Raspberry Pi will function as a server for an application to connect to. This will allow data to be quickly transferred between the robot and the application.

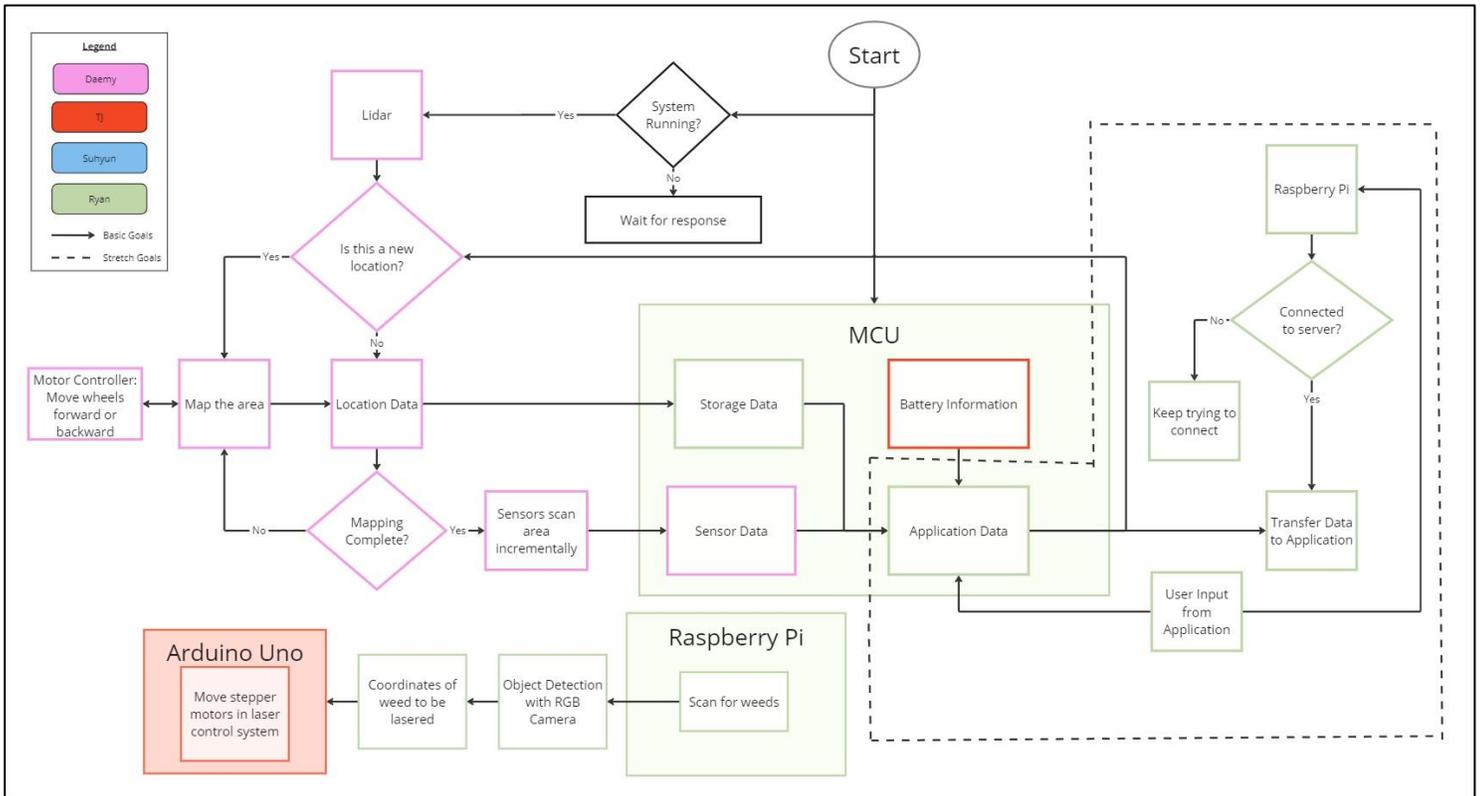


Figure 4 - BEAM software diagram

2.5 Engineering Requirements Specifications

Demonstratable specifications are highlighted in yellow.

BEAM Engineering Requirements	
Chassis	
Length x width x height	TBD
Weight	TBD
Material	Aluminum
Solar Panel	
Max Power	6 W
Maximum Voltage	15 V
Battery	
Maximum Lifespan	10 Ah
Maximum Voltage	12.8 V
Laser Source	
Wavelength Range	450 – 550 nm
Optical Power	1000 – 5500 mW
Laser System	
Location accuracy	≤ 1 cm
Weed Treatment	
Treatment Time	20 – 30 seconds
Treatment Distance (Laser Pointer End to Plant)	5 – 10 cm
Identification Efficiency	Expected at 70-85%

Table 1- Engineering requirements and specifications

Marketing Requirements
<ol style="list-style-type: none"> 1. The Rover should not exceed the proposed object (not including replacements). 2. The Rover should accurately identify weeds. 3. The Rover should be easy to use. 4. The Rover should withstand weather changes. 5. The Rover should have low maintenance. 6. The Rover should have high performance. 7. The Rover should have moderate power consumption.

Table 2 - Marketing requirements

2.6 Past and Existing Projects' Comparison

Previously existing products and related work, like our project, include:

Carbon Robotics is a leading organization within the agricultural technology industry. Their particular niche is laser weeding technology. Their autonomous robot weeder is diesel-powered and equipped with multiple high-resolution cameras and an AI-powered

computer to aid in autonomous features. The robot is estimated to eliminate around 200,000 weeds per hour without disrupting the soil. [9]

EcoRobotix is a Swiss corporation that has developed a solar-powered weeding robot that uses cameras and GPS guidance to navigate and detect weeds. Instead of a laser, the robot targets and applies microdoses of herbicides to the individual identified weeds. The idea is to use these precisely targeted microdoses to significantly reduce overall chemical usage. This robot adapts its operation speed to the size of the field it is working on as well as the overall weed density in a given area, allowing it to remain power-efficient in most situations. [10]

LettuceBot, created by Blue River Technology, uses computer vision and image recognition to identify weeds and spray them with a precision dose of herbicide. The idea is similar to that of the EcoRobotix robot, if the weeds can be found much easier and sprayed with much higher precision with much less use of these herbicides, reducing the overall impact over time. [11]

WeedBot, based in Lavata, is planning to launch its own laser weeding robots. These aim to provide a less harmful alternative to traditional herbicides, offering precise weed control using an AI-backed algorithm for weed and crop recognition. After detection, the weeds are quickly eliminated with minimal disruption of other organic material and soil. [12]

Autonomous Diode Laser Weeding Robot, A project led by the West Central Research and Outreach Center collaborated with the University of Minnesota to develop a laser weeding robot designed specifically for use in cotton fields and to utilize deep learning for weed detection. Combining a GPS-based navigation system with visual serving allows the robot to precisely target and eliminate weeds using diode lasers. Another project aims to reduce the reliance on chemical herbicides as well as improve overall sustainability. [13]

The Tertill Weeding Robot, produced by the company Tertill and developed by the inventor of Roomba, is a small weeding robot made for gardens. It is solar powered and



Figure 5 - Carbon Robotics LaserWeeder [9].

weather resistant and uses specially designed wheels to kill emerging weeds. It also comes with a small trimmer to chop sprouted weeds and an app for users to monitor their weeding bot. [14]



Figure 6 – Tertill Weeding Robot [14]

2.7 House of Quality

The house of quality takes the information from the engineering requirements (Table 1- Engineering requirements and specifications) and the marketing requirements (Table 2)

Correlation Matrix	
↑↑	Strong Positive
↑	Positive
↓	Negative
↓↓	Strong Negative
	Not Correlated
Positive Polarity	+
Negative Polarity	-

Figure 7 - House of quality correlation matrix

from the section 2.5 and provides matrices of correlation between them. Below there's a legend that describes what each correlation means and their polarity.

Engineering Specifications		Marketing Requirements							
		Set up Time	Response Time	Product Size	Battery Life	Light Source Reliability	Beam Accuracy	Mapping Accuracy	Cost
		-	+	-	+	+	+	+	-
Ease of Use	+	↑↑	↑	↑		↑	↑	↑	
Durability	+			↑		↓↓	↓↓		↓↓
Low-maintenance	+					↓↓	↓↓	↓↓	↓
Power Consumption	-	↑		↓	↑↑	↑	↑↑		↓
Data Accuracy	+		↑↑			↑	↑	↑↑	↓
Cost	-		↓	↓	↓	↓↓	↓↓	↓↓	↑↑
High Performace	+	↑↑	↑↑		↑	↑↑	↑↑	↑↑	
Targets for engineering Requirements		≤ 15 seconds	≤ 5 seconds	1ftx1ftx2ft	≥ 10 hours	808-1064 nm	237-1400 J	80-90%	≤ \$677

Figure 8 - House of quality

Chapter 3 – Technology Research and Part Selection

3.1 Technologies

3.1.1 Microcontrollers

3.1.1.1 MCU

Microcontroller Units (MCUs) are circuit chips designed to execute on specific control tasks within integrated embedded systems. They usually consist of a CPU, memory, as well as programmable I/o peripherals and ports. They are used widely in various applications due to their overall low cost, ease of use, availability, and energy efficiency.

Most MCUs are designed for low power consumption making them the ideal choice for systems that need to be battery operated. They offer a myriad of power options to allow for sleep, standby, or various other low power modes tailoring to the users' needs whenever necessary. [15] MCU's typically support multiple communication protocols and come equipped with integrated peripherals like ADCs and DACs as well as supporting I2C, UART, and other types of communication interfaces. MCUs are generally much lower cost, and compact, which is very beneficial to people looking for low cost and cost-efficient solutions for various applications it would benefit. [16] MCUs are known to support real-time processing, however it should be noted that their capabilities are limited in comparison to FPGAs, while this is the case MCUs are able to support and are suitable for many real time control applications. Most industrial MCUs are available and usable for applications requiring operating the robot or MCU in various harsh environments, obviously greater shielding and placement withing the robot may further befit an MCU. MCUs are much easier to develop for and program with then FPGAs, this is due to the use of higher-level programming languages like C or C++, this also allows for a much greater amount of support, as these languages are much more popular and have more documentation, allowing for greater ease in troubleshooting then with any FPGA. [17] Some of the advantages an MCU would help serve our purposes are the overall ease of use and cost effectiveness compared to most other FPGAs, as well as the compact size, On-Chip integrated peripherals, as well as its low power consumption make it an easy choice for our purposes. An MCU will most likely be the type of processor we use as the main brain of the robot. However, some disadvantages we would need to tackle would be the overall lack of flexibility in customization and various optimizations that FPGAs are overall better at achieving. As well as the overall limited processing power, we will need to make adjustments in the code in order to overcome these limitations.

3.1.1.2 FPGA

Field Programmable Gate Arrays or FPGAs are devices that consist of an array of logic blocks that are programmable and interconnected by routing resources. One of the key

characteristics of FPGAs that differentiate them from MCUs is the ability to excel in parallel processing. Along with an overall higher performance than an MCU, this makes them very suitable for handling real time data and complex calculations. [18] These gate arrays are highly customizable, enabling them to be tailored for a myriad of applications. With the proper protection, they are suitable for industrial applications and can be configured to perform a wide variety of tasks, making them a versatile and powerful tool. Many applications that FPGAs are used for are in industrial automation. FPGAs are also widely used in the telecommunications industry as they typically require high speed data processing and transfer. [19] They are great for industrial automation applications that require custom hardware and fast performance and are beneficial to advanced robotics applications that require real time control. This also includes other weed killing robots in the industry.

FPGAs are ideal for tasks that have excessive parallelism as well as require high speed processing, as well as data encryption. FPGAs would potentially suit our purposes better than an MCU, however due to certain flaws, they are unlikely to be applicable to this project. While it has been established that FPGAs have much higher processing speeds and are well suited to applications in real time systems, this comes at the expense of much higher power consumption than MCUs, making them less suited to battery operated robots or other applications. [20] Additionally, FPGAs have a much more complicated programming and development cycle than an MCU. Requiring an expertise in HDLs and other specialized development tools would prove to be complicated and stop us from taking full advantage of these resources. Another major disadvantage our project would incur if we decided to use an FPGA would be its much higher initial cost in hardware. These processors usually take up more space, which would affect our PCB design as we would need to compensate for the space somewhere in the design. The increase in the cost alone would normally disqualify it from use from our project, and especially considering a lot of the other disadvantages, FPGAs while incredibly useful, would not be the right processor for the BEAM project.

3.3.1.2 MCU vs FPGA:

When deciding on the specifications of a project's hardware, it is likely that the discussion between FPGAs and MCUs and their corresponding advantages and disadvantages take place. Without this context, the reason for deciding between the two may become muddled and confusing. To start, one of the main advantages FPGAs have over MCUs is their ability to do parallel processing. This makes tasks that would otherwise take a much longer time easily processed in a much faster time than a regular MCU would be able to. Additionally, the FPGA's must use more complicated programming languages like Verilog, which provide quite a steep learning curve. This is directly opposed to the MCU's ease of use in programming languages such as C or C++. [20] While these are not easy to program with, the documentation and resources available to help navigate difficult debugging questions

are much easier to describe and diagnose than with another less documented and more complicated programming language, such as Verilog.

Another major comparison between the two would be the power consumption of both processor types. Generally, the power consumption of the FPGA is much higher than that of the MCU. This is due to the parallel processing mentioned before; the FPGAs have high-speed clocks and can often operate at much higher frequencies, which typically results in decreased overall power consumption. [21] This may be advantageous for certain applications, due to the limited power supply as well as the dynamic power generated by the solar panels. It may be better for our purposes to use an MCU, as the MCU was designed for more portable, battery-powered machines. This is due to its overall power efficacy, offering low power modes and dynamic power management features. For these reasons, we feel as if an MCU would be a better choice of processor than the FPGA alternatives. Some qualities to consider when picking out the correct MCU needed for the job go as follows: processing power, overall complexity, peripheral support, memory, communication interfaces, environmental tolerances, and real-time processing. These are the metrics to which the MCUs will be compared and contrasted; multiple tables will be provided at the end for viewing convenience.

MCU Vs FPGA [22]		
Parameter	MCUs	FPGAs
Processing Power	Moderate, typically up to 480 MHz	High, excellent for parallel processing and high-speed tasks
Power Consumption	Low, suitable for battery-operated devices	Higher, generally higher power consumption
Peripheral Support	Extensive integrated peripherals (ADC, DAC, timers, communication interfaces)	Highly customizable, flexible peripheral integration
Memory	Varies (e.g., up to 2 MB Flash, 1 MB RAM)	Depends on design, typically large capacity
Communication Interfaces	Supports multiple protocols (I2C, SPI, UART, CAN)	Supports multiple protocols, customizable
Environmental Tolerance	Industrial-grade versions available	Suitable for outdoor use with appropriate enclosures
Real-time Processing	Limited real-time processing capabilities	High, ideal for minimal latency and precise control
Development Complexity	Easier to program (C/C++), extensive development tools and libraries	Complex to program (HDLs like VHDL or Verilog), steeper learning curve
Cost	Lower cost	Higher initial cost, both in hardware and development

Size	Typically smaller in size, beneficial for compact designs	Often larger in size, can be a drawback for compact designs
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Table 3 - MCU Vs FPGA Comparison

3.1.2 Motors

A motor is a machine that converts electric energy into mechanical energy by the interaction of the field current and the magnetic field, making the armature rotate (this will be joined to the wheels). There are several different types of motors that can be subdivided into many categories, however, to decide which one is better suited for our project we must look into distinct aspects such as weight capacity, size, torque, etc.

The first step was to calculate some of the motors' specifications, RobotShop Community [23] offers a tool designed to give you some of the basic outputs desired for your motor depending on the following:

Input	Outputs
a = acceleration = 0.2 m/s^2	T = total Torque
g = acceleration due to gravity = 9.8 m/s^2	W = angular velocity
θ = degrees on the incline = 20°	P = total power
M = total mass of the robot = 9.071 kg	I = Maximum current
R = radius of wheels = 0.0635 m	c = battery pack capacity
N = number of drive motors = 4	
v = speed = 0.2 m/s	

They take the inclined plane formula, torque formula, and calculate for the total Torque.

$$T = \frac{(a + g * \sin(\theta)) * M * R}{N}$$

(1) Total Torque Formula

$T = \frac{(.2+9.8*\sin(20^\circ))*9.071*0.0635}{4} = 511.466 * 10^{-3} Nm$ This answer provides the torque at a 100% efficiency, however, motors can't work at full efficiency so we that took into account. According to the figure below, a motor working at optimum efficiency can range from 60 to 80 %, so we chose to calculate the total torque of each motor at 65% efficiency to have little room to spare when it comes to the workload or mass of the motor.

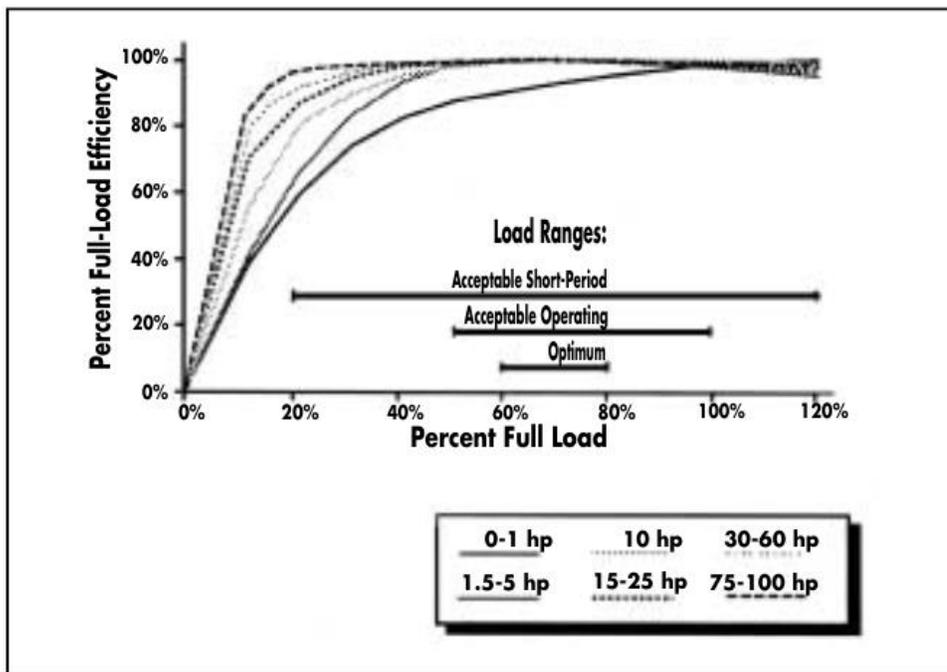


Figure 9- Motor Part-Load Efficiency [24]

At 65% efficiency $T = (100/65)(511.466 * 10^{-3}) = 786.871 * 10^{-3} Nm$.

$$\omega = \frac{v}{r}$$

(2) Angular Velocity Formula

The angular velocity obtained with the formula was be used to calculate the angular velocity, $\omega = \frac{0.2}{0.0635} = 3.1496 \text{ rad/s}$.

$$P = T * \omega$$

(3) Power Formula for Rotational Motion

Afterwards, we took the torque and angular velocity previously calculated to determine the power needed. $P = 786.871 * 10^{-3} * 3.1496 = 2.4783 \text{ W}$.

$$I = \frac{P}{V}$$

(4) Current Formula

From the power calculated, we can divide it by the supplied voltage to get the maximum current allowed, $I = \frac{2.4783}{12} = 0.2065 A$.

$$c = I * t$$

(5) Battery Capacity Formula

We used the battery capacity formula to calculate the minimum battery pack capacity per motor needed with our specifications, $c = 0.2065A * (3h * 4) = 2.478 Ah$.

3.1.2.1 DC Brushed Motors

DC motors have two main types, brushed and brushless, a brushed motor consists of a rotor containing current-passing coils, which is encapsulated by a permanent magnet or electromagnet. To keep rotation, it is imperative that the current is constantly reversed, this is achieved by the use of mechanical brushes and a commutator that switch the current direction in the windings, transferring electrical power from the brushes to the windings which generates the magnetic field necessary for motion. DC Brush motors are one of the most commonly used types of motors, they are characterized by a simple design that doesn't require a high initial cost for its construction, they also have a higher reliability compared to other types of motors, offer a simple motor speed control, and they have higher torque characteristics. However, they tend to have a higher maintenance due to the use of brushes, which require the change of the worn out brushes, they also have a lesser efficiency rate due to the loss of energy from friction and heat because of the brushes and commutator, and they have a higher noise production making them not ideal for certain applications.

3.1.2.2 Brushless DC Motors

As opposed to brushed motors, in a brushless DC motor, instead of using brushes and a commutator, the permanent magnet is attached to the rotor while the coils are fixed in the outer shell, since the permanent magnet is the one that is constantly rotating it makes the use of brushes unnecessary. Advantages of brushless DC motors include higher efficiency due to reduced energy loss from friction and heat, a longer lifespan and lower maintenance due to the lack of brushes, and a reduced noise production. Although they provide many benefits, they have a higher initial cost in comparison with other types of motors since they implement the use of a controller to monitor different axes, in addition, they have a generally more complex speed control, and require more sophisticated algorithms for better performance.

3.1.2.3 Gear Motors

Gear motors is a term used to refer to the combination of a gearbox and an electric motor, which can use either AC or DC as a power supply, it serves as speed reducer and a torque multiplier to the output shaft, making them enticing when needed to reduce power for a heavier load. Different combinations are possible depending on intended use, all aspects are needed to be known to maximize the operation and are customizable. They also offer a precise and optimal speed control, a high torque, higher efficiency, and are adaptable to different environments and load conditions given the proper gear ratio is selected.

A couple of drawbacks are the higher complexity on design, the larger size in comparison with simpler motors making them have limited applications due to size constraints, the high initial cost of the specific design, and that performance is affected by different factors such as housing design, lubrication, gear type, bearings.

3.1.2.4 AC Motors

AC motors are electric machines that converts alternating current to mechanical power, similar to DC motor, they can be brushed or brushless, but most of them are brushless. They offer a high versatile range of applications from industrial to residential that can be further specified by their different types, such as induction or synchronous motors. AC motors are characterized by their robust and reliability making them suitable for various environments, they have a longer lifespan than DC motors, they have a lower maintenance since most models are brushless, they have a lower cost due to their standardized manufacturing processes and have a higher efficiency particularly when operating at their rated load [25]. Some of their disadvantages include a low starting torque compared to DC motors or other types of motors, these motors have a more complex speed control for adjustments, they tend to have fluctuations in voltage and frequency that affects their performance when not regulated, and they suffer a slowing down due to the Back-Electromagnetic Field, not practical for portable applications [26].

3.1.2.5 Stepper Motors

They are electrical motors that are characterized by moving in precise steps and to facilitate this they convert digital pulses into motions. They are mostly used in applications that require accurate positioning and control without the need of feedback since they moved in a fixed number of degrees counting the number of steps taken. They can not only move continuously in a forward or reverse direction like most motors, but they can also rotate in steps and hold its position, offering a higher precision control. Some of their advantages include precise positioning without the use of sensors, higher torque at low speeds, high mechanical stability making them more useful in automation. However, the selected torque must be precise since having it too high or too low can make it miss a step, meaning it can no longer accurately count the steps to know the position of the motor. These motors have

generally low torque, emit a higher noise than other types of motors at high speeds, they're more complex when it comes to a smooth motion control that requires a specific algorithm. Stepper motors also have a higher power consumption because of high currents draws at high speeds, and they can be heavier than other types of motors and can also overheat while providing low efficiency [27]. While stepper motors are not the best option for movement control for the BEAM navigation system, it is a great option for the controlling the precise movements of the weeding laser, which is discussed in more detail later in section 3.1.8 Laser Control System.

3.1.3 Motor Controllers

3.1.4 Batteries

The difference between charging capabilities of primary and secondary batteries needs to be explained before delving into the various types of batteries. Primary batteries are “single use” and cannot be recharged and must be discarded after they runs out of energy. Meanwhile, secondary batteries are rechargeable and reduce the need for frequent replacements. Typically, secondary batteries more expensive than primary ones because of the cost of materials, safety features, and performance [28]. The BEAM robot will use a secondary battery because it needs to be able to recharge itself using solar energy while it navigates its target region. There are many specifications for secondary batteries that need to be considered, such as specific energy, cycle life, charge time, overcharge tolerance, charge/discharge temperature, maintenance requirements, and more. The necessary values we need to compare are explained in Table below.

Battery Terminology		
Terms	Definition	Significance
Specific Energy	The amount of energy a battery can store per unit weight (watt-hours per kilogram).	Higher specific energy means the battery can store more energy for its weight.
Cycle life	The number of complete charge and discharge cycles a battery can complete before its charge capacity starts to decrease.	Longer cycle life means a more durable battery and less battery replacement.
Charge/Discharge Temperature	The optimal range within which a battery can be charged and discharged safely.	Batteries need to operate in specific temperature ranges to maintain performance and safety.

Table 4 - Battery Terminology [29]

Battery Comparison						
Specifications	Lead Acid	NiCd	NiMH	Li-Ion	Cobalt Phosphate	Manganese
Specific Energy (Wh/kg)	30-50	45-80	60-120	150-250	100-150	90-120
Cycle Life	200-300	1000	300-500	500-1000	500-1000	1000-2000
Charge Time	8-16h	1-2h	2-4h	2-4h	1-2h	1-2h
Self-discharge per month	5%	20%	30%	<5%		
Cost (per kWh)	\$150-200	\$300-500	\$400-800	\$100-300		

Table 5 - Battery comparison [30]

3.1.4.1 Lithium Ion

Lithium-ion (Li-ion) batteries use ions to store energy and create electric potential differences between two poles. They are widely used in consumer and commercial electronics, and are well renowned for their recharge capacity, charge storage, and size. These batteries also vary in the materials used, such as lithium cobalt oxide and graphite, lithium manganese oxide, and lithium phosphate oxide. Li-ion batteries are one of the highest energy dense batteries in commercial use and can come close to 300 Wh/kg depending on the type [31]. These batteries also vary in size and can be small, like smartphone batteries, or large, like batteries in vehicles or ships.

There are several advantages that make lithium-ion batteries a great choice for the BEAM robot. Two of the main benefits are the high energy density and cycle life. BEAM will be a moderate-energy consuming robot that will need a lightweight, yet powerful battery to navigate its difficult terrain. The battery needs to be able to be charged and discharged whenever necessary, so having a high cycle life will be very advantageous as it will contribute to the overall cost-effectiveness over time. Li-ion batteries also have a very low self-discharge rate which allows them to retain charge when not being used. This will be very beneficial to the battery life during and after scheduled weed treatments.

Li-ion batteries do have some disadvantages that should be noted. They can be sensitive to temperature extremes, which can impact their operation and durability. This battery is almost always manufactured with protection circuits to maintain safe operation because overcharging, extreme discharging, and high temperatures can cause the battery to give off immense heat and possibly catch fire. Li-ion batteries are often still the most expensive type of battery when compared to other commercial batteries [32].

3.1.4.2 Lead-Acid

The lead-acid battery was the first secondary battery to be invented for commercial use. It is still very popular today and in wide use as a cost-effective battery for vehicles, backup power supplies, and energy storage systems. The lead battery uses a combination of lead alloy and sulfuric acid to charge and discharge, and it is heavy and bulky due to the lead content.

Lead-acid batteries have several advantages when compared to other batteries on the market. They are cost-effective, often cheaper than NiCd, NiMH, and Li-ion batteries, they can deliver high surge currents for more power, they can operate in a wide span of temperatures, and they are very reliable having been in use for over a century. Though with these advantages come several disadvantages such as the battery having a shorter cycle life, the charge time is very long (8-16h), the battery has a smaller specific energy, and the lead is also very toxic to humans and the environment [33].

For the intended purpose of the BEAM robot, the specific energy and cycle life of the lead-acid battery does not suit the project's needs. The battery is very heavy, and not intended to be recharged constantly and at multiple intervals. While some of the advantages are appealing, like the cost and operational temperature range, the lead-acid battery would not be the most efficient power storage unit for this project.

3.1.5 Charge Controllers

Charge controllers are a necessary component of a solar power system, providing electrical protection for both the battery and solar panel. They perform three main functions: supplying adequate voltage for the battery, regulating charging current, and preventing battery overcharge [34]. In addition, depending on the charge controller, it can also regulate voltage differences between the solar panel and battery. There are several factors to consider when choosing a charge controller, such as voltage compatibility, maximum current rating, display monitoring, temperature compensation, efficiency, and cost.

Charge Controller Comparison		
Specifications	PWM	MPPT
Voltage Compatibility	Fixed voltage Battery = Panel	Wide range of voltages
Displays	Basic LCD or LEDs	Advanced displays and detailed monitoring
Efficiency	70-85%	95-99%
Cost for small systems	\$10-60	\$100-200

Figure 10 – Charge controller comparison

3.1.5.1 Pulse-Width Modulation (PWM)

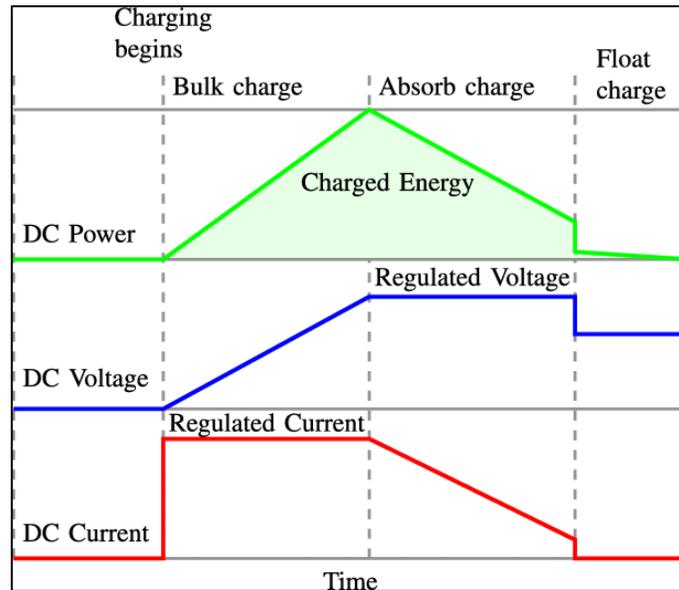


Figure 11 - Battery 3-stage charging (bulk, absorb, float) [37]

Pulse-width modulation is a method of representing a signal as a square wave for a certain frequency per duty cycle. This method is used in the algorithms inside some solar charge controllers, which is why they are called PWM solar charge controllers. Batteries need to be charged with the right level of voltage, and a PWM charge controller helps facilitate this by modifying the voltage that exits the solar panel and preparing it to be absorbed by the battery input [35]. This controller can help prevent a battery from overcharging by decreasing the current that flows into it as the charge increases. There are three main charging stages for PWM controllers on lead-acid batteries: bulk charging, absorption charging, and float charging. Bulk charging is the initial stage in a battery where the charge controller fully opens the connection between battery and solar panel and allows the maximum current to leave the panel and enter the battery. This stage is meant to bring the battery up to 80-90% charge and is usually used when the battery is low or close to zero charge. The next stage is absorption charging, where the charge controller starts to slowly decrease the current flow so the battery can start to approach full capacity at 98% or higher. Usually during this stage, the voltage is constant and regulated as to prevent the battery from overcharging. The final stage is float charging, where the PWM further reduces the current to an extremely low level. This current only provides enough power to keep the battery full, and to compensate for any self-discharged energy. The voltage in the float stage is typically lowered even more so than the absorption voltage to ensure that the battery does not overcharge [36] [37].

The three charging stages for lead-acid batteries are slightly different when it comes to PWM charge controllers and lithium batteries. Lithium-ion batteries still go through the bulk and absorption charging phases, but both the bulk and absorption voltages are usually

lower for Li-ion during these stages. As for the float stage, Li-ion batteries do not require this stage because it can be detrimental to the battery to leave it at a constant high voltage. Typically, if a PWM charge controller has adjustable settings for lithium batteries, it will stop charging once the battery reaches full charge. This is due to the lithium batteries having an extremely low (close to zero) self-discharge rate [38].

Lithium batteries are more widely used with MPPT solar chargers, but it is possible to use them with PWM chargers if a Li-ion compatible charger is used. There are several factors to take into consideration when choosing a PWM controller for a Li-ion battery, such as voltage range, current rating, safety features, and more. If a noncompatible PWM charger is used with a Li-ion battery, it could cause the battery to fail or overheat and catch fire. It is important to use a PWM that has a temperature monitor to adjust charge rates, charge current selection to reduce excess heat generation, and voltage monitoring to prevent overcharging. These safety measures are essential when choosing a PWM charge controller that will provide efficient power transfer between the BEAM solar panel and battery, and also protect both components from damage [39] [40].

3.1.5.2 Maximum Power Point Tracking (MPPT)

Maximum power point tracking is another algorithm used in photovoltaic systems that help account for factors that impact solar panels like variable sunlight, temperature, and battery load [41]. The “maximum power point” (MPP) is the point where current and voltage production is maximized for a solar panel. This point varies based on sunlight intensity and temperature, and it is monitored by the MPPT algorithm by varying the resistance seen by the panel then measuring the power output [42]. MPPT charge controllers adjust the current leaving the solar panel to keep the system running close to peak power point of the panel.

An important part of the MPPT system is the buck/boost DC-DC conversions that allow the system to convert between higher and lower currents and voltages. The boost conversion will increase the power from the solar panel to match that of the battery, so if the panel outputs 6V and the battery needs 12V, the boost converter will increase the voltage exiting the panel to 12V. This is the opposite for the buck conversion which decreases the voltage from the panel to match the battery. If the panel outputs 24V and the battery needs 12V, then the buck converter will decrease the panel output to 12V. This buck/boost conversion allows for high power transfer, compatibility between different panels and batteries, and flexibility in panels for different applications [43].

When considering MPPT charge controllers for the BEAM project we must take into consideration the type of battery and solar panel that would suit the project the best. However, the type of battery typically takes precedence when considering what type of charge controller to use, so in this case we will focus on how the MPPT charge controller could benefit our project when used in combination with a lithium-ion battery. MPPT charge controllers can provide more power during varying weather conditions, voltage

match and compensate for inconsistencies between battery and panel and provide more precise charge control to prevent overcharging the battery. MPPT charge controllers are also more widely used with lithium-ion batteries because of their ability to precisely regulate the voltage and current between panel and battery. A lithium-ion battery needs to have stable and constant charge to achieve peak performance, so a MPPT charge controller is a great choice over PWM for this project.

3.1.6 Voltage Regulation

The BEAM power system needs a voltage regulator to step down the battery's 12V to 5V to power the electronics guiding the system. The Raspberry Pi 4 needs 5V/3A to operate, and the Arduino can handle 7-12V/1A, so our system needs to be able to bring down the voltage to prevent damage to these components. The two options for a voltage regulation system are a linear regulator or a buck converter. Both options are cost effective, reliable circuits that have been tested and compared by reputable companies such as Texas Instruments.

Voltage Regulator Comparison		
Specifications	Linear Regulator	Buck Converter
Cost	\$2-5	\$5-15
Voltage Output Ripple	1-50 mV	10-100mV
Full-Load Efficiency	15-20%	65-80%
Circuit Complexity	3-5 Components	6-11 Components
Power Loss ¹	2W	0.1W

Table 6 - Voltage Regulator Comparison [44]

3.1.6.1 Linear Regulator

Linear regulators are very reliable and have been in production for over 50 years. They have been widely used in industrial circuits because they are simple and can provide voltage conversions for a wide range of voltages. These regulators are typically less complex, requiring less components, but they often require more space to provide proper thermal relief. This regulator works by using a voltage-controlled current source to set a fixed voltage across a load resistor. This load resistance is connected to the voltage output of the regulator, and so sets the output to the desired voltage. A control circuit/feedback loop is used to monitor the voltage output and adjusts the current source based on the load to keep the voltage consistent [45]. For large voltage differences, the linear regulator tends

¹ The power loss shown in the table comes from a study completed by Texas Instruments [44]. Its purpose in the table is to show that linear regulators typically have a very large power loss when compared to buck converters.

to have large power losses that ends up dissipating as heat in the system. This is because of the power dissipated, given by Equation (6) - Linear Regulator Power Dissipation, where if V_{in} is larger than V_{out} and the current needed across the load is also large, then P will also be quite large.

$$P_{dissipated} = (V_{in} - V_{out}) * I_{Load}$$

(6) - Linear Regulator Power Dissipation

This power loss also leads to the linear regulator having poor power efficiency because over half of the power going into the circuit is wasted as heat energy. This would force us to design a circuit that provides maximum heat dissipation and invest in heat sinks or cooling fans.

A benefit of the linear regulator is the low voltage ripple, which leads to overall less noise in the system. This would be beneficial to prevent disturbances in signal integrity for our sensing equipment. Another benefit is the low cost of a linear regulator, when reviewing a report written by Texas Instruments (TI), they found out that a linear regulator circuit (\$0.32) cost more than five times less than a buck converter circuit (\$1.80) [44]. This decrease in cost would allow us to spend more towards a cooling system, potentially making the linear regulator a viable option for a voltage regulator.

3.1.6.2 Buck Converter (Switching Regulators)

Buck converters, also known as switching regulators, are newer than linear regulators and widely used in industrial voltage regulation systems for its efficiency and simplicity. The buck converter controls voltage transfer through switches, inductors, diodes, capacitors, and sometimes MOSFETs. The switches are used to control the flow of current through the inductor which charges the output capacitor and powers the load. When the switches are turned off, the stored energy is released and current continues to flow into the load. Similarly to the linear regulator, the output voltage is monitored using a feedback system that compares the output to a voltage reference [46]. Buck converters are typically more complex than linear regulators because they use more external components and can be more complicated to design. Unlike linear regulators though, buck converters can take up less space because they do not need to spread out components for adequate heat dissipation. Buck converters are extremely efficient when compared to linear regulators, and have very minimal power loss, resulting in little heat generation. These regulators even excel at preventing power loss when using increased load currents and tend to perform better with higher currents over 1A [44].

There are some manageable downsides to using buck converters, such as higher voltage ripple and noise production. These regulators generate more noise and voltage ripple due to switching on and off to regulate the output voltage, which can lead to interference in sensitive digital circuits. If this regulator is implemented, proper circuit design and filtering

would need to be used to mitigate interference with other sensitive components [47]. With proper implementation, the benefits of using the buck converter outweigh the disadvantages. The buck converter has many benefits over the linear regulator that are desirable for the BEAM project, such as low heat generation for large voltage conversions, high power efficiency for large load currents, and less design space required for circuit board layouts.

3.1.7 Solar Panels

For the BEAM project, solar panels will be used to power the electronics on board and keep the system's battery charged. There are three popular types of solar panels used for industrial, residential, vehicular, and personal applications: monocrystalline, polycrystalline, and thin-film photovoltaics. It is important to compare the specifications between these three panels, specifically cost, energy efficiency, and temperature performance. The BEAM project will require a solar panel with high energy efficiency, low temperature performance, and at a reasonable cost.

Solar Panel Comparisons			
Specifications	Monocrystalline	Polycrystalline	Thin-Film
Efficiency	$\geq 23\%$	$\leq 20\%$	7-18%
Cost per Watt [48]	\$1 – 1.50	\$0.90 – 1.50	\$0.50 – 1.50
Color Hue	Black	Blue	Blue
Temperature Performance [49]	0.38 - 0.44%	0.44 - 0.50%	0.20%
Lifespan (years) [50] [51]	25+	25+	10-20

3.1.7.1 Monocrystalline

Monocrystalline solar panels, also known as single-crystal panels, are made from a single silicon crystal that is then divided into wafers. Monocrystalline panels can reach power efficiencies of over 23% [51]. The efficiency of these cells are due to the increased electron flow of the single crystal. While these panels are well-known for being the most efficient in power collection, they are also the most expensive. The monocrystalline panels have a good performance in high temperature conditions due to the single crystal and with proper housing can be waterproof. The lower temperature coefficient, high energy efficiency, and durability make the monocrystalline solar panel a great option for the BEAM robot. While the monocrystalline solar panels are typically the most expensive, they have also been very popular in personal applications. There are several affordable and reasonably sized panels available that would meet the BEAM project's needs.

3.1.7.2 Polycrystalline

Polycrystalline solar panels are made from multiple silicon crystals melted together. This process of creating wafers is less complex than that of the monocrystalline wafers, making these solar panels have a cheaper price, but also a lower efficiency [51]. Polycrystalline solar panels also have a higher temperature coefficient when compared to monocrystalline because of the structure of the wafer, making it less desirable than the single-crystal panels. While both polycrystalline and monocrystalline panels are widely available on the market at various voltages and power ranges, a polycrystalline panel would be a less suitable choice when compared to monocrystalline.

3.1.7.3 Thin-Film

Thin-film panels are created by placing layers of photovoltaic material onto a conductive substrate, allowing them to be lightweight and flexible. Solar cells for thin-film panels can be made from amorphous silicon (a-Si), cadmium telluride (CdTe), or copper indium gallium selenide (CIGS). These panels can be the same thickness as silicon-based mono/polycrystalline panels, or up to 350 times thinner [50]. A great benefit of thin-film panels is that they are extremely insensitive to high temperatures and even resilient against moisture, making them great for humid climates. This could prove extremely beneficial to the BEAM project because it will be tested and conditioned to work in Florida, which is both humid and hot. Another benefit of thin-film photovoltaics is the cost when compared to crystalline panels. Thin-film is lighter because of how it is manufactured, and requires less material, and so is less expensive. Thin-film would not be the best option for the BEAM project because the energy efficiency is very low when compared to other photovoltaic panels. There are also not many thin-film solar panels available on the market at specific voltages and powers, whereas compared to the more popular crystalline panels, there are many options to choose from. It could be more expensive to request a custom thin-film panel from a manufacturer than find an available crystalline one on the market.

3.1.8 Laser Control System

3.1.8.1 Stepper Motors

As previously discussed in section 3.1.2.5 Stepper Motors, these motors are used in applications that require accurate positioning and control without the need of feedback since they moved in a fixed number of degrees counting the number of steps taken. This is extremely useful for fixed cartesian systems because it eliminates the need for limit switches if the length and height of the plane are known.

3.1.8.2 Stepper Motor Drivers

3.1.9 Laser Diode

Lasers are considered one of the most effective light sources for targeting weeds [52]. Laser is an acronym for "light amplification by stimulated emission of radiation," which refers to a device that emits light through the optical amplification process, which is based on the stimulated emission of electromagnetic radiation. Prior to detailed information about laser diode, Table 7 explains some important optics terms, such as wavelength, refractive index, stimulated emission, spontaneous emission, polarization, and waveguide.

They will help readers gain a better understanding of different optical concepts.

Optics Terminology		
Terms	Definition	Significance
Wavelength	The distance between corresponding points of two consecutive waves	It directly relates to several key properties of waves: frequency, wave behavior, wave types, and wave propagation
Refractive Index	The measure of the bending of a ray of light when passing from one medium to another	Higher refractive index indicates stronger light bending and slower light speed in the material
Stimulated Emission	The amount of energy a battery can store per unit weight (watt-hours per kilogram).	Higher specific energy means the battery can store more energy for its weight.
Spontaneous Emission	The number of complete charge and discharge cycles a battery can complete before its charge capacity starts to decrease.	Longer cycle life means a more durable battery and less battery replacement.
Polarization	Characteristic of certain electromagnetic radiations where the direction and magnitude of the oscillating electric field are correlated in a defined manner	It defines how the electric field vector of an electromagnetic wave oscillates in space – whether it oscillates in a single plane (linear polarization), in a circular manner (circular polarization), or in an elliptical path (elliptical polarization)
Waveguide	Any device that confines and directs the propagation of electromagnetic waves, including radio waves, infrared rays, and visible light	Waveguides come in various shapes and forms, such as hollow metallic tubes, coaxial cables, and optical fibers

Table 7 - Optics Terminology

A laser diode emits a beam from an active layer located either on the surface or embedded within a non-active bulk material. The active layer has two facets: front and back. The front facet of the active layer is uncoated with a natural approximate reflectivity of 0.3 while the back facet is high-reflection (HR) coated. A lasing cavity is created by these two facets. A laser diode with this type of cavity is referred to “Fabry-Perot” laser diode, which differs from laser diodes with other types of cavities. The refractive index of the active layer is higher than that of the bulk inactive material around the layer and it serves as a waveguide. Upon the injection of electrical current into the active layer, electrons and holes combine together, resulting in photon emission. The photons emitted here bounce back and forth between the two facets of the active layer. This process is called lasing. Since the active layer has an indirect relationship with the lasing efficiency, it has a thickness of only a few microns to maximize the efficiency. Only a minor portion of the laser energy is confined within the active layer, and part of this laser energy is called the confinement factor. The active layer can be widened to several hundred microns to enhance the laser power output [53].

3.1.9.1 Laser Diodes VS LED

Another optical energy source used for weed control is LED, which stands for light-emitting diode. Table 8 shows comparison data over some key parameters of LEDs and laser diodes. Unlike lasers, LED is an incoherent light source and operates based on spontaneous emission of photons. LEDs can typically be operated at higher currents, are more cost-effective, consume less power, feature larger emitting areas, and have longer lifespans. Unlike LEDs, lasers do not operate below a threshold current; they only begin lasing once this threshold current is reached. Both LEDs and laser diodes are sensitive to temperature, affecting their overall lifetime. For instance, operating a laser diode just 10°C above its rated temperature can halve its lifespan, and lasers typically cease functioning at 100°C.

Comparison of LED and Laser Diode		
Specifications	LEDs	Laser Diodes
Particle Phase	Incoherent	Coherent
Radiative Recombination	Spontaneous Emission	Stimulated Emission
Polarization State	Randomly Polarized	Linearly Polarized
Direction	Random	Linear
665 nm	GaAsP	GaAlAs
800-930 nm	$Ga_{1-x}Al_xAs$	$Ga_{1-x}Al_xAs$
1300, 1550 nm	InGaAsP	InGaAsP
Output Power	10 – 50 μ W	1 – 1000 mW
Rise Time	1 to 100 ns	< 1 to 10 ns

Temperature Effects	Increases wavelength by .6 nm/ °C	Wavelength varies by .25 nm/ °C Threshold current rises by .5mA/ °C
Significant Parameters	BW vs Power BW increases at the expense of power	Threshold current, Index guided: 10 to 30 mA Gain guided: 60 to 150 mA

Table 8 – Comparison of LEDs and Laser Diodes (reprinted with permission) [54]

Although LEDs are more affordable, have lower power consumption, and have longer lifespan, laser diodes will be utilized in this project based on some considerations.

First, laser diodes are capable of operating at higher intensities. High-power lasers provide the necessary energy to effectively target and destroy weeds. They can penetrate deep into plant tissues, causing thermal damage that leads to the immediate death of the weed or severely hinders its ability to recover and grow. This ensures that the treatment is both rapid and effective, reducing the likelihood of regrowth [7]. Moreover, the precision of high-power lasers allows for targeted weed control. This means that the robot can selectively target weeds without damaging the surrounding crops, which is particularly beneficial in mixed or densely planted fields. This level of precision minimizes collateral damage and helps maintain the health and productivity of the crops [52]. High-power lasers also offer the advantage of reducing the need for chemical herbicides [7]. By providing a non-chemical method of weed control, the robot can help mitigate the environmental impact associated with herbicide use, such as soil and water contamination and harm to beneficial insects and other wildlife. Additionally, the use of high-power lasers can enhance the efficiency and speed of weed control operations. Lasers can operate continuously and effectively in various weather conditions, unlike some mechanical or chemical methods that may be hindered by rain or wind. This reliability ensures consistent weed management and can lead to a reduction in labor costs and time spent in the field. In overall, to eliminate weeds effectively by raising their temperature, a high-power light source is necessary. In his research group, Rakhmatulin built a weed controlling device that uses laser beams and showed a laser with power less than 1W was not enough to damage crop plants in a short time [55].

Another consideration is that using laser diodes reduces treatment time. The project utilizes a chassis with four wheels for traversing the wide field. Consequently, minimizing treatment time significantly enhances efficiency, allowing it to cover larger areas in a shorter period. This is especially important in agricultural settings where timely weed control is essential to prevent competition for resources between weeds and crops. By minimizing the treatment time, the robot can address weed growth more effectively and promptly, reducing the likelihood of weeds reaching a stage where they can severely impact crop yield. Additionally, shorter treatment times mean that the robot can operate more frequently or attend to multiple fields within a given timeframe, thereby maximizing

the utility and cost-effectiveness of the technology. Faster operations also reduce the energy consumption per unit area treated, contributing to the sustainability of the farming practices. Moreover, by quickly eliminating weeds, the robot helps maintain optimal growing conditions for crops, which can lead to better crop health and higher productivity. Overall, short treatment times enhance the robot's effectiveness in managing weeds, supporting agricultural productivity, and ensuring more efficient use of resources.

An experiment conducted at University of Georgia had two types of weeds growing in the pots that underwent laser treatment using laser diodes placed approximately 5 cm away and perpendicular to the weed stems to minimize the treatment time. This experiment followed a factorial design involving 2 laser output powers, 3 treatment durations, and 2 weed species, resulting in a total of 12 treatments. Each treatment combination was replicated 5 times. The laser powers were 5.1 W and 6.1 W, respectively, while treatment durations varied between 0.5, 1, and 1.5 seconds. As a result the 5.1 W diode laser showed an overall effectiveness of 66.67% (kill/stunt) across all treatment durations. On the other hand, the 6.1 W diode laser exhibited 80% effectiveness for treatment durations of 0.5 s and 1 s, and 100% effectiveness for the 1.5 s duration [52]. This experiment presents a direct relationship between laser power and treatment time. Applying the experimental findings to our project, we intend to utilize a high-power laser while minimizing treatment duration. However, considering laser safety concerns, it's crucial to note that when a laser beam contacts a surface, it converts into heat energy. High-energy lasers have the potential to ignite materials and inflict thermal injuries [56]. Employing diode lasers with lower output power has fewer operational risks compared to high-powered CO₂ and fiber lasers, which are more complex. However, even low-output diode lasers can pose risks to the eyes upon exposure, necessitating the use of protective eyewear [56]. Therefore, we plan to still maintain high laser power and low treatment intensity while ensuring optimal safety measures.

Furthermore, laser diodes have narrow beams, which are critically important for a weed control robot because they significantly enhance precision, safety, and energy efficiency in the weed control process [8]. By focusing the laser energy on a very small, specific area, narrow beams allow the robot to target weeds with high accuracy, ensuring that only the unwanted plants are affected and minimizing the risk of damaging valuable crops [52]. This precise targeting is especially beneficial in fields where crops and weeds are closely spaced. Additionally, the concentrated energy of narrow beams maximizes the intensity at the target point, leading to more efficient use of power and reducing overall energy consumption, which extends the robot's operational time. Furthermore, the focused heat minimizes the spread of thermal damage to surrounding areas, protecting nearby crops and soil microorganisms from unintended harm [52]. Narrow beams also provide better control over the depth and extent of laser penetration into the weed tissues, allowing for effective destruction of various types of weeds without unnecessary damage to the soil. Moreover, the precision of narrow beams enhances safety by reducing the risk of accidental exposure to humans, animals, or unintended parts of the field [8]. For robots equipped with advanced machine vision systems, narrow beams complement high-resolution imaging and

identification, enabling the targeting of even the smallest weeds at an early growth stage. Overall, narrow beams are essential for achieving efficient, effective, and safe weed control, significantly improving the performance and reliability of the weed control robot in agricultural fields.

3.1.9.2 Laser Wavelength

Choosing the correct laser diode wavelength is critical for weed control because different wavelengths affect how quickly the temperature of the plant leaves rises or how efficiently they dry out. Essentially, the wavelength of light plays a vital role in how plants absorb light. To effectively remove moisture from plants, it's necessary to use a laser with the right wavelength. To gain a rough idea of which wavelengths are most effective in this regard, we need to understand how plants derive their energy and absorb light.

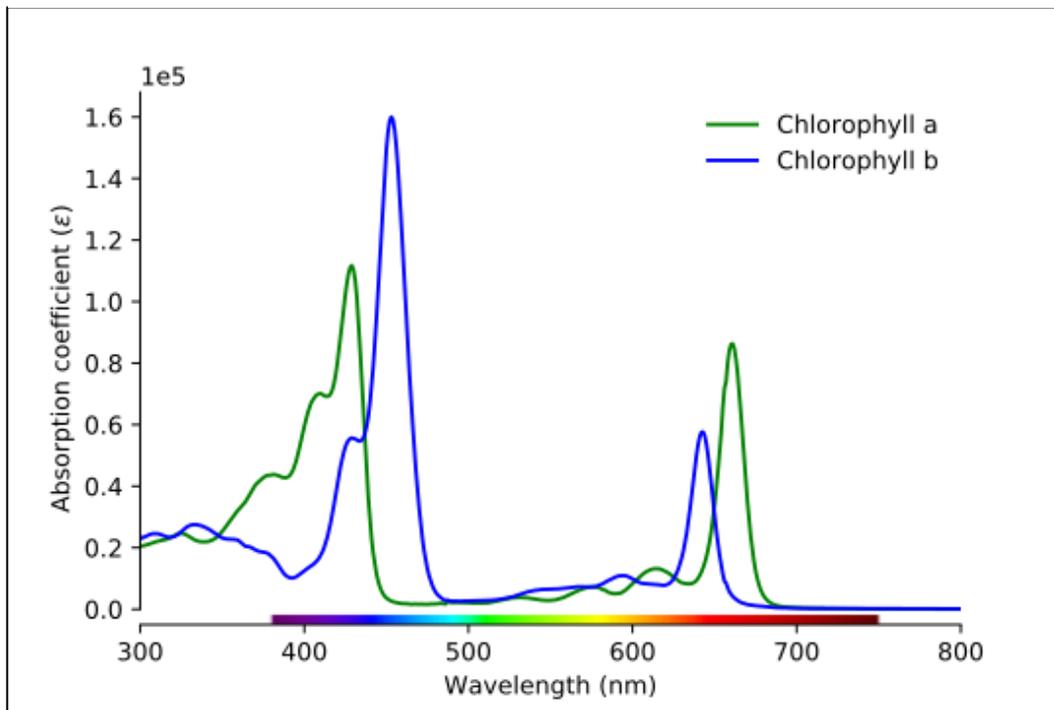
Plants perform photosynthesis, which is the major function of converting solar energy into chemical energy to synthesize their food source and storing that chemical energy for later use. (The important role of photosynthesis, 4/9, 2013, Michigan State university Extension, Bill Cook) Photosynthesis occurs in specialized regions of the cell known as chloroplasts. Photosynthesis relies on light sources, with the intensity and spectral distribution of light exposure significantly impacting the rate of photosynthesis. The spectrum characteristics of light, including light quality, play a crucial role in the rate of photosynthesis [57].

Two primary pigments located in chloroplasts are involved in plants' photosynthesis: Chlorophyll A and B. For this project, we are going to target these pigments since they are parts that allow plants to absorb light to provide for their energy. Chlorophyll A is the green pigment responsible for absorbing light and providing energy for oxygenic photosynthesis. It is present in all plants, green algae, and cyanobacteria, and plays a pivotal role in photosynthesis by acting as the primary electron donor in the electron transport chain. On the other hand, chlorophyll B collects light energy and transfers it to chlorophyll A. The structure of Chlorophyll B closely resembles chlorophyll A. Chlorophyll B is present in plants and green algae. Figure 7 shows the absorption spectrum of chlorophyll A and B. Observing, the peak absorption coefficient for each chlorophyll, chlorophyll A most effectively absorbs light at wavelengths of 429 nm and 659 nm, corresponding to the violet-blue and orange-red parts of the spectrum, respectively while chlorophyll B absorbs light most effectively at wavelengths of 455 nm and 642 nm, corresponding to violet and red colors, respectively, and reflects a yellow-green color. [58]

Difference Between Chlorophyll A VS B		
	Chlorophyll A	Chlorophyll B
Role	The main pigment that absorbs sunlight	The auxiliary pigment that captures sunlight and transfers it to chlorophyll A
Absorbed Light Wavelength	430 – 660 nm	450 – 650 nm
Absorption Peak	430 nm & 662 nm	470 nm
Absorbed Light	Violet-blue & Orange-red	Orange-red
Color Reflected	Blue-green	Yellow-green
Organism Types	all plants, algae, and cyanobacteria	All plants and green algae
Proportion in Total Chlorophyll in Plants	$\frac{3}{4}$	$\frac{1}{4}$

Table 9- Difference between Chlorophyll A VS B [58]

Figure 12 - © Wikimedia Commons / Daniele Pugliesi, M0tty



3.1.9.3 Laser Temperature

Setting the right temperature for a laser and considering the environmental temperature are crucial for effective weed control. Heat stress impacts plant growth at all stages of development, though the heat threshold level varies significantly across these stages. For example, high temperatures during seed germination can slow down or completely inhibit the process, depending on the plant species and the intensity of the heat stress. In later stages, high temperatures can negatively affect photosynthesis, respiration, water relations, and membrane stability, as well as alter hormone levels and the production of primary and secondary metabolites. Additionally, throughout a plant's development, increased expression of various heat shock proteins, other stress-related proteins, and the production of reactive oxygen species (ROS) are key responses to heat stress [59]. The laser temperature needs to be high enough to cause fatal damage to the weed's tissues, ensuring that the plant is killed efficiently. If the laser temperature is too low, it may only stress the plant without killing it, allowing it to recover and continue growing. On the other hand, if the laser temperature is too high, it could lead to unintended damage to surrounding plants, soil, or beneficial organisms. Additionally, environmental temperature plays a significant role in the effectiveness of the laser treatment. In hotter conditions, the initial temperature of the weeds is higher, meaning less energy is required to reach a lethal temperature. Conversely, in cooler conditions, more energy might be needed, which could affect the efficiency and speed of the treatment. Understanding and adjusting for these factors ensures that the laser weed control method is both effective and environmentally safe.

An experiment conducted at the Department of Plant Biology at Carnegie Institution of Washington measured the amount of emitted fluorescence at 77 K (-196 °C) from *Siratro* and found out that the plant exhibits a special protective mechanism called paraheliotropic leaf movement (PLM) to reduce exposure to intense sunlight when the water shortage becomes severe. Chlorophyll fluorescence is a technique used to measure the efficiency and health of photosynthetic systems. By measuring fluorescence emission kinetics at 77 K (a very low temperature), researchers can assess how well the photosynthetic machinery is functioning under stress conditions. The experiment further showed that the photosynthetic system of the plant started to get damaged even in darkness when the leaves were exposed to a temperature exceeding 42°C and leaf death was observed at 48°C. Heat damage severity increased with increased time exposure between 42°C and 48°C, although moderate damage recovery took several days. As the temperature range ideal for plant growth increased, the threshold temperature for direct heat damage increased, regardless of water-stress history or current leaf hydration levels. Below 42°C, there was no direct heat damage. However, plants that had inadequate water availability or drought conditions experienced more suppression in their photosynthesis between 31–42°C of leaf temperature with increasing photon flux density up to values equivalent to full sunlight [60].

Similarly, for effective weed control specifically in Orlando, we will examine a climate graph displaying monthly temperatures in the area. Understanding Orlando's climate conditions is crucial for targeting plants that grow there, as it helps identify the optimal temperatures for plant eradication as the information given above for Siratro and informs our laser settings. Additionally, because temperatures vary across different seasons and months, we aim to develop a solution that accounts for these changing conditions. Based on the average monthly data on the temperature of Orlando from 1991 to 2021, it is noticeable that Florida experiences less temperature fluctuation throughout the year compared to other regions, with average temperatures ranging from 50 to 80°F. From January to February, temperatures typically remain below 65°F, which is relatively cool compared to other months. This trend continues into March, with temperatures still below 70°F. By April, temperatures begin to rise, marking the transition to the peak season (May - September), where temperatures range from 75 to 80°F. In October, temperatures start to cool as the cold season begins, typically falling below 70°F.

For the experiment, we have been given August to November as our timeframe, which we consider optimal since this period allows us to conduct treatments during the peak temperatures of 87 to 90°F in August and September, followed by the transition season in October as temperatures begin to cool. We will observe the effects of the treatment during November, which represents the onset of the colder season.

	Average Temperature (°F)	Min Temperature (°F)	Max Temperature (°F)
January	59.5	51.8	69.6
February	62.6	54.7	72.7
March	66.6	57.8	77.1
April	71.7	62.8	81.9
May	76.7	68.1	86.4
June	79.9	73.6	88.2
July	80.8	75.1	88.6
August	80.9	75.5	88.5
September	78.8	73.7	86
October	74	67.8	81.8
November	67.2	60.2	76.2
December	63	56	72.4

Figure 13 - Orlando Monthly Temperature [61]

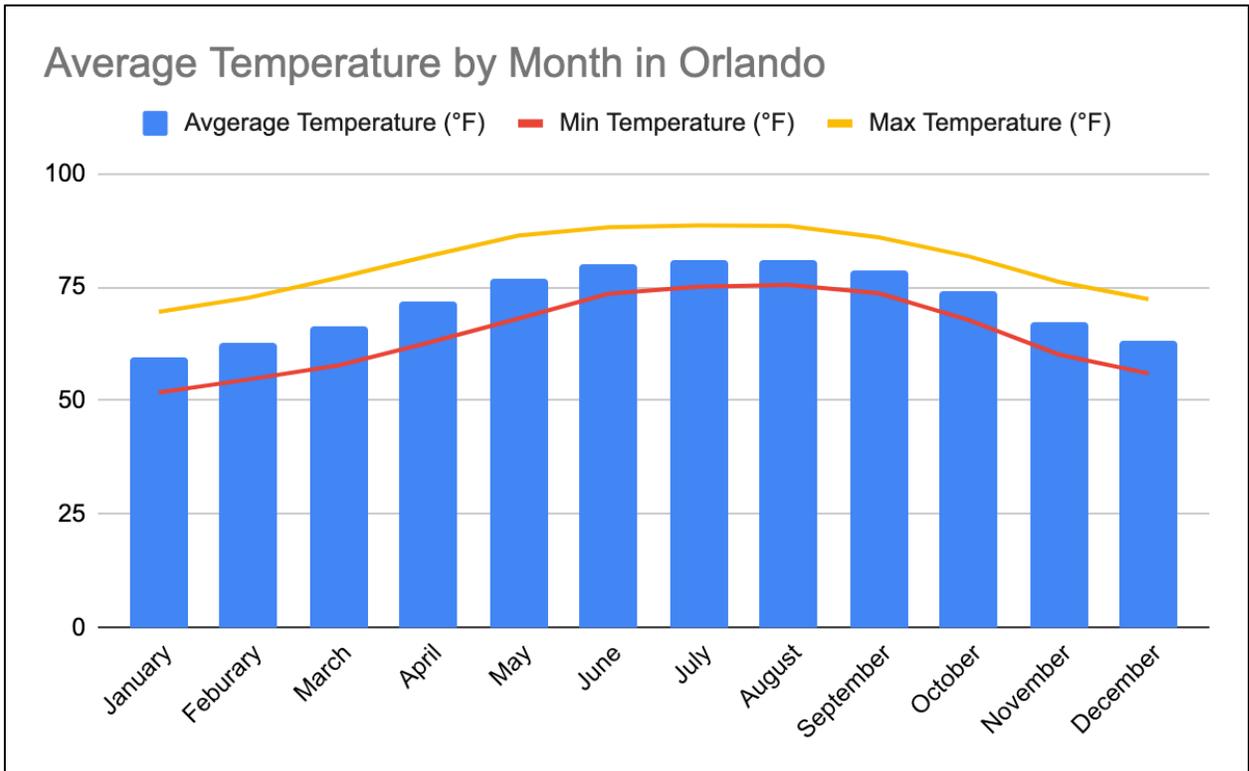


Figure 14 - Average Temperature by Month [61]

For other consideration factors, there are humidity, rain days, precipitation depth, and average sun hours. Analyzing the climate data for Orlando, we observe that humidity levels vary throughout the year, with the highest levels recorded in July and August at 80%. These months, coupled with June and September, also experience the highest rainfall, ranging from 142 mm to 170 mm, and have the most rain days (14-17 days). Conversely, the humidity is lowest in April and May at 64-65%, and these months, along with November, have the least rainfall (36 mm to 70 mm) and fewer rain days. Sunlight hours peak in May and June, averaging around 10.2 to 10.3 hours per day, providing the most sunlight exposure, while the shortest sunlight hours occur in December with 6.5 hours.

For the project, which involves using high-power lasers to dry and kill weeds, the ideal periods would be April, May, October, and November. During these months, the combination of lower humidity, moderate rainfall, and adequate sunlight hours enhances the effectiveness of the laser drying process. In contrast, the months from June to September pose significant challenges due to high humidity, frequent rainfall, and slightly reduced sunlight hours, making these periods less suitable for the weed control method. Therefore, targeting the drier and sunnier months will maximize the efficiency of the laser treatment, while the rainy and humid summer months may hinder its performance.

	Humidity (%)	Rain days (d)	Precipitation / Rainfall (mm)	Average Sun Hours (hours)
January	71	5	58	6.9
February	68	5	52	7.1
March	65	5	64	8.5
April	64	5	55	9.5
May	65	7	70	10.2
June	75	14	157	10.3
July	79	16	158	10.3
August	80	17	170	9.6
September	80	14	142	8.7
October	73	8	69	7.9
November	71	4	36	7.1
December	73	4	51	6.5

Table 10 - Weather Factors in Orlando [62]

1W Blue Laser Diode Specifications		
Model	GH04C01C2G [63]	SLD105VL-52 [64]
Output Power	1000 mW (50°C)	1000 mW
Min Peak Wavelength, λ_p	440 nm	445 nm
Peak Wavelength, λ_p	450 nm	447 nm
Max Peak Wavelength, λ_p	465 nm	450 nm
Operation Power, P_{op}	-	-
Operation Temperature, T_{op}	-10 ~ +50 °C	-10 ~ +60 °C
Min Operation Current, I_{op}	-	-
Operation Current, I_{op}	680 mA	-
Max Operation Current, I_{op}	850 mA	44.99 mA
Min Threshold Current, I_{th}	-	-
Threshold Current, I_{th}	100 mA	-
Max Threshold Current, I_{th}	200 mA	-
Min Operation Voltage, V_{op}	-	-
Operation Voltage, V_{op}	4.3 V	1.9 V

Max Operation Voltage, V_{op}	5.6 V	2.5 V
Forward/Reverse Voltage	2V (Reverse)	-
Module Diameter	5.6 mm TO-18	5.6 mm TO-18
Min Slope Efficiency, η_d	1.5 W/A	-
Slope Efficiency, η_d	2 W/A	
Max Slope Efficiency, η_d	-	-
Cost	\$21.61	\$56.32

Table 11 - 1W Blue Laser Diode Specifications [63] [64]

For Model PLPT9 450LB, given with output power, operation current, I_{op} , and threshold current, I_{th} , we can use the equation below to calculate the expected output power.

$$\eta_s = \frac{P_{out}}{I_{op} - I_{th}}$$

Hence, we get

$$\eta_s = \frac{5}{3 - 0.29} = 1.845 \text{ W/A}$$

5W Blue Laser Diode Specifications			
Model	LT-LD-455-5000M-C [65]	PLPT9 450LB [66]	GH04C05B9G [67]
Output Power	5000 mW	5000 mW	5000 mW
Min Peak Wavelength, λ_p	448 nm	440 nm	430 nm
Peak Wavelength, λ_p	455 nm	450 nm	440 nm
Max Peak Wavelength, λ_p	462 nm	455 nm	450 nm
Operation Power, P_{op}	-	-	5 W
Min Operation Current, I_{op}	-	-	-
Operation Current, I_{op}	-	3 A	2.24 A

Max Operation Current, I_{op}	-	3.8 A	2.28 A
Min Threshold Current, I_{th}	220 mA	-	-
Threshold Current, I_{th}		0.29 A	0.25 A
Max Threshold Current, I_{th}	420 mA	0.45 A	0.33 A
Min Operation Voltage, V_{op}	3.6 V	-	4.8 V
Operation Voltage, V_{op}	-	-	5.2 V
Max Operation Voltage, V_{op}	4.8 V	-	5.6 V
Forward/Reverse Voltage	-	4.3V~5V (Forward)	
Module Diameter	-	9mm TO-5	9.0 mm
Min Slope Efficiency, η_d	-		1.5 W/A
Slope Efficiency, η_d	1.8 W/A	1.845 W/A	2 W/A
Max Slope Efficiency, η_d	-		-
Cost	\$42.00	\$48.32 (Amount:2)	\$29.50

Table 12 - 5W Laser Diode Specifications

3.1.10 Movement Control Sensors

3.1.10.1 Lidar

3.1.11 Weed Identification Sensors

3.1.11.1 RGB Camera

3.4 Part Selection

Peak Power Information per Component			
Components:	Quantity	Voltage (V)	Peak Power (W)
Motor Controller	1		
Arduino Uno	1		
Raspberry Pi 4	1		

Laser Diode	3		
Lidar	1		
RGB Camera	1		
MCU	1		

Table 13 - Peak Power Information per Component

3.4.1 Lithium Ion Battery

The BEAM robot requires a secondary battery to power all electronics and motors onboard. This battery needs to be lightweight, compatible with a MPPT charge controller, have good temperature ratings, be 12-12.8V and have at least 10-amp hours.

Battery Selection Comparison			
Brand	Eco-Worthy [68]	Nermak [69]	XZNY [70]
Voltage	12.8V	12.8V	12.8V
Amp Hours	10Ah	10Ah	10Ah
Battery Type	LiFePO4	LiFePO4	LiFePO4
Discharge Temperature Rating	-20 – 55°C	-20 – 60°C	-20 – 60°C
Weight	2.46 lbs	2.64 lbs	2.43 lbs
Dimensions	5.9 x 2.6 x 3.7 in	5.94 x 2.56 x 3.71 in	5.94*2.56*3.7 in
Price	\$49.99	\$35.99	\$36.99
Charging Requirements	14.4 – 14.6V	14.4 – 14.6 V	14.6V
	CC, ≤10A	CC, ≤6A	CC, ≤10A
	Yes BMS	Yes BMS	Yes BMS

Table 14 - Battery Selection Comparison

3.4.2 MPPT Charge Controller

The BEAM robot needs an MPPT charge controller that is lithium battery compatible. It is important that the charge controller has 14.4–14.6V output for charging the lithium battery, accepts solar power input DC 15–30V, has an output current of 8-12A for rapid charging, and that it offers protections from over charging, over voltage, over temperature, etc. It would also benefit the robot’s mobility if the charge controller was light weight and benefit durability if it was somewhat water resistant.

MPPT Charge Controller Selection Comparison			
Brand	Powerwerx [71]	Bateria Power [72]	Voltset [73]
Input Voltage	16-25 V	15-30 V	≤ 30 V
Output Current	12 A	10 A	10 A
Max Power	150 W	144 W	144 W
Price	\$29.99	\$36.99	\$39.99
Protections²	SC, OT	OC, OT, OV, SC	OC, OT, OV, SC
Operating Temperature	N/A	-20—45°C	N/A
Weight	0.25 lbs	0.32 lbs	0.375 lbs
Dimensions	2.3 x 1.6 x 0.9 in	3.75x2.42x1.06 in	6.69"L x 4.72"W x 1.3"H
LCD	No	Yes	Yes

Table 15–MPPT Charge Controller Selection Comparison

3.4.3 Buck Converter (Switching Regulator)

3.4.4 Monocrystalline Solar Panel

3.4.5 Motors

AC motors have a lower initial cost and high efficiency rates compared to other types of motors; however, they present certain trade-offs, factors such as a lower starting torque and the need for adjustments due to their complex speed control were carefully considered. Because of the commonness of brushless motors in AC configurations, they have a low maintenance which makes them ideal for outdoor applications, however, the need of alternating current to be powered, whether single-phase or three-phase, presents a challenge as our project setup doesn't accommodate this. Since gear motors are characterized for their optimal speed control, they initially seemed to be a good addition to our project, however, the high initial cost coupled with the fact that this project has a low use demand for heavy load makes the implementation of gear motors unfavorable. Stepper motors would be a great addition to the project when it comes to the navigation system of the robot because of their inherent ability for counting steps which makes them not require feedback to know their position at all times, despite their advantages, we ended not going this route because they tend to have a low torque and require a specific algorithm for motion control. The low maintenance of the brushless DC motors and its high efficiency makes it a great candidate to implement it in our project, however, its high cost and the complexity associated with its speed control made us ultimately not select it as an option. Although

² Overcharge (OC), Over Temperature (OT), Over Voltage (OV), Short Circuit (SC)

Brushed DC motors require a higher maintenance in comparison to brushless motors and have a lower efficiency rate, we ended up choosing them for the navigation system because of their low initial cost, high reliability, and simple motor control system.

When it comes to choosing a motor, we referred to the values for Torque, angular velocity, power, current, and battery capacity previously calculated on section 3.1.2 Motors to serve as initial criteria for researching the specifications for brushed DC motors.

Brushed DC Motors Comparison				
Motor	E-S Motor 555 Size DC [74]	Mabuchi RS-555SH [75]	E-S Motor 775 DC Motor [76]	OSEPP Electronics R540 6-12V [77]
Nominal Voltage	12 V	12 V	12 V	6 V
Torque	400 g-cm	420 g-cm	2 kg-cm	-
Dimensions	77mm x 36mm ³	3.035”x1.48” ³	91mm x 42mm ³	50mm x 35.8mm ³
No-load Speed	8000 RPM	5100 RPM	4000 RPM	16700 RPM
Weight	-	0.45 lbs.	-	160g
Cost	\$14.50	\$9.99	\$11.78	\$14.25
Rated Current	3.5 A	2.83 A	1.5 A	2.5 A

Table 16-Brushed DC Motors Comparison

The first motor we compared was an E-S motor that features integrated a cooling blade and a dual-channel encoders with hall power of $\pm (5 \text{ V}/3.3 \text{ V})$, it has high torque and when tested it proved to last more than 1000 operational hours, in addition, it has stable power and balanced heat dissipation. The second one is a Mabuchi motor that has as key features high torque with high-efficiency, a wrap-around shield that reduces electrical interference, and a speed of 5100 RPM. The third motor is also an E-S Motor that offers high torque and low noise, it has a cooling fan and five group winding at voltages 6/12/24 V.

³ Motor Dimensions include shaft Dimensions.

Chapter 4 – Design Constraints and Standard

4.1 Design Constraints

4.1.1 Environmental Constraints

The efficiency and effectiveness of the laser in dehydrating weed leaves are highly dependent on factors such as humidity, temperature, and precipitation. High humidity levels, especially in Orlando's summer months, can reduce the laser's efficiency as the increased moisture content in the air and plants requires more energy to achieve the desired drying effect. Similarly, extreme temperatures, whether too low or too high, can impact the robot's components, leading to potential malfunctions or reduced operational life. Cold temperatures can cause materials to contract and affect battery efficiency, while higher temperatures can lead to overheating and increased wear and tear on mechanical parts. In this regard, understanding these environmental conditions helps in planning and scheduling the robot's operation and during periods when the weather is most conducive to its function. Furthermore, operating within defined environmental parameters helps in minimizing the ecological impact, ensuring the robot's activities do not inadvertently harm non-target plants or wildlife and maintain compliance with local environmental regulations.

As we can see in Figure 15, Orlando's monthly humidity data reveals a clear pattern of fluctuation throughout the year, reflecting the seasonal climatic changes typical of a subtropical region. The humidity levels are at their lowest during the spring months, with March and April recording 65% and 64%, respectively. This dip in humidity suggests a drier period, which might be favorable for the laser-based weed drying method as the reduced moisture in the air could enhance the efficiency of the laser in dehydrating the weeds' leaves. As summer approaches, the humidity begins to climb, peaking in the late summer months. June shows a significant increase to 75%, followed by July and August, which are the most humid months with 79% and 80%, respectively. September maintains this high humidity at 80%, indicating a prolonged period of moist conditions. These high humidity levels could pose challenges for the laser method, as the increased moisture content in the air and plant leaves may reduce the effectiveness of the drying process.

The fall months see a gradual decline in humidity, with October dropping to 73%, and November stabilizing at 71%, similar to January. This period might offer slightly better conditions than the peak summer months but still represents a relatively high moisture environment. December, at 73%, marks the beginning of the cooler, less humid winter season, transitioning into January, when the humidity starts at 71%.

Overall, the spring months of March and April, with their lower humidity levels, emerge as the optimal periods for employing high-power lasers to dry weeds in Orlando. Conversely, the summer months, particularly July through September, with their peak

humidity, present the most challenging conditions for this method. The robot should operate optimally within a humidity range of 60-70% for maximum efficiency in drying weeds. This range is typically observed during the spring months (March and April) in Orlando []

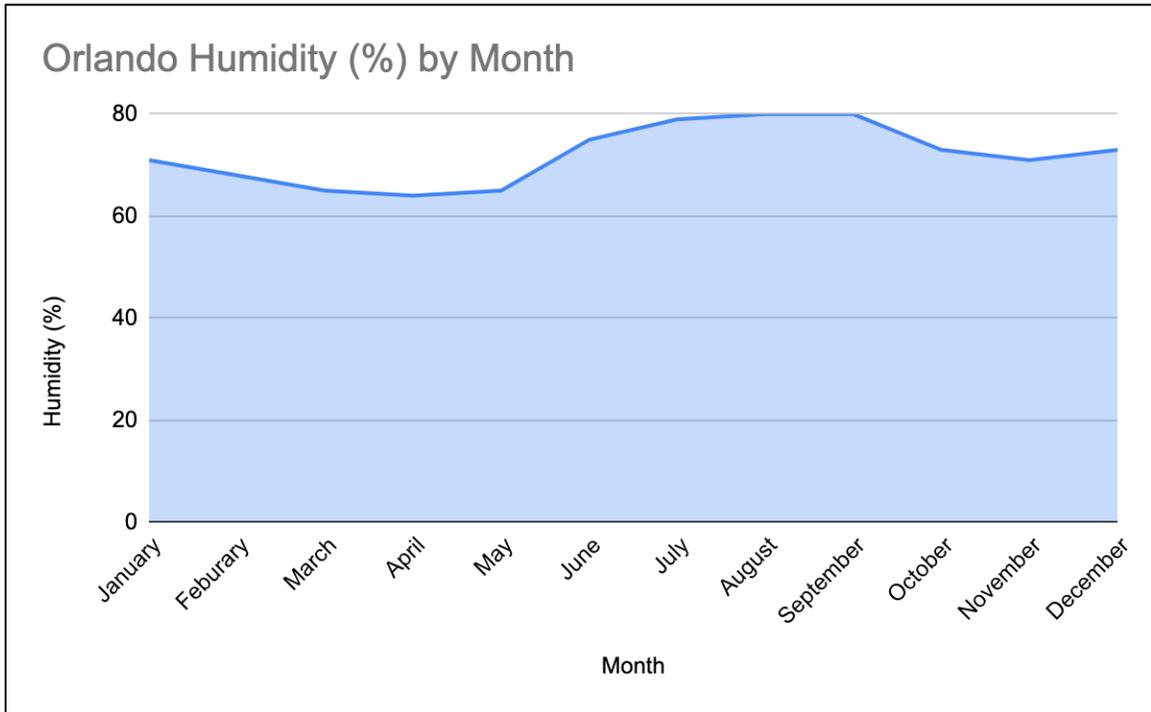


Figure 15 - Orlando Humidity by Month []

Other factors such as rainy days and precipitation patterns present varying conditions for operating a robot that uses lasers to dry weeds' leaves. Referencing Table 10 - Weather Factors in Orlando , the month of January experiences only 5 rain days and 58 mm of precipitation, making it a relatively good period for laser operation since the dry conditions would facilitate efficient weed drying. Similarly, February's 5 rain days and 52 mm of rainfall are conducive to this method. March maintains this favorable trend with 5 rain days and slightly higher precipitation at 64 mm, though still manageable for the laser's effectiveness. April, with 5 rain days and 55 mm of rain, continues to provide suitable conditions for the laser-based weed drying approach. May, however, introduces more challenges with an increase to 7 rain days and 70 mm of precipitation. This uptick indicates the beginning of more frequent rain, which could intermittently hinder the laser's performance. The situation worsens in June, which sees 14 rain days and 157 mm of precipitation. This significant increase in rain frequency and volume makes June a challenging month for the laser method due to the high humidity and wet conditions that are less conducive to drying. July and August are the most challenging months for laser

operations. July has 16 rain days and 158 mm of precipitation, while August peaks with 17 rain days and 170 mm of rainfall. These months are marked by frequent and heavy rain, posing substantial difficulties for the laser's effectiveness in drying weed leaves. September, with 14 rain days and 142 mm of precipitation, remains unfavorable for the laser method, though slightly less so than August. The frequent rains during these months would likely disrupt the drying process, making them the worst periods for using the laser technique. The conditions improve in October, which sees a reduction to 8 rain days and 69 mm of precipitation, marking the transition back to drier weather. This change makes October a more suitable month for laser operations compared to the preceding summer months. November and December, with only 4 rain days each and the lowest precipitation levels of 36 mm and 51 mm respectively, present the best conditions for operating the laser-based weed drying robot. The reduced rainfall and fewer rain days during these months would enhance the effectiveness of the laser in drying the weed leaves efficiently [].

4.1.2 Economic Constraints

Building an autonomous laser weeding robot for agricultural use involves several economic constraints such as research and development costs, materials and manufacturing costs, maintenance and repairs over the robot's lifespan, economic viability for farmers, and market and competition economics. For this project, we will go into detail on how BEAM would impact market and competition, and how it would reduce costs for farmers using manual labor and pesticides.

4.1.2.1 Market and Competition

There are not many consumer-level laser-weeding robots available on the market now. The laser-weeding robots that are on the market are specifically available for large-scale farmers that have several hundred acres of land to cultivate, such as Carbon Robotics Laser-weeder [9]. The Carbon Robotics laser weeders are available for over \$1,000,000 and are said to return a profit after 1-3 years. They also require a trailer and hitch to operate the machinery because it needs to be towed through the fields to laser weeds. These large machines are often too expensive and hefty to prove useful for small scale farmers. There are also some large-scale machines, like the LettuceBot by Blue River Technology, [11] that use pesticides to remove weeds, but these are still quite expensive and are designed to be towed by a tractor through large fields. Many of the smaller farm and garden machines available are used for strictly mowing lawns or are too small to sufficiently cover fields of 10-50 acres. An example of the smallest robot we found designed specifically for removing weeds was the Tertill weeding robot [14]. This small solar powered robot is available at full price for \$350 and kills weeds with string trimmers and specially designed wheels. There were no small-scale laser weeding robots available on the market for less than the \$12,331 RBTX by ingus autonomous agriculture laser weeding robot [78]. The total cost of the BEAM robot will be less than \$1,000, and it is built to be most useful for smaller farms or large gardens. The BEAM robot could be very competitive for this portion of the

market and would be advertised as a lower cost environmentally friendly way for small farmers to control weeds. With proper maintenance, the lifespan of the BEAM robot could be at least 10 years and would provide farmers higher return on investment.

4.1.2.2 Reducing Costs in Labor and Pesticides

The economic impact of laser-handled weeding agricultural robots is multifaceted. It requires a major initial investment, has the capacity to create a major shift in the agricultural technology market, and helps to move weeding methodology away from using a much higher degree of manual labor and chemical compounds. Replacing it with a much cleaner, energy-efficient, and cost-efficient alternative would save farms of all sizes a lot of unnecessary costs on labor and pesticides. Laser weeding robots, such as those made by Paul Mikesell, the CEO of Carbon Robotics, have a high initial cost, compared to a midsize tractor that would run farmers numbers in the 5-figure range. [79] This upfront initial cost can be a serious barrier to entry, especially for smaller farms. Larger farming may find it easier to budget financially for new equipment, mostly due to the long-term savings in labor and chemical costs of pesticides. These new robots introduce a competition to the agricultural technology that the market hasn't been seen before. This much cleaner and safer alternative is going to challenge the dominance of chemical herbicide corporations over industrial weeding. Carbon Robots is one of the leading players in this space; however, other startups are continuing to enter the market. This may potentially continue to drive innovation and reduce costs over time. Leading to a new cycle of increased competition in this space, and ultimately to even more accessible technology being used by a much broader range of farmers.

Laser weeding offers many advantages over traditional manual labor and pesticide use. It provides environmentally friendly and much more precise weed control; this helps to reduce soil disruption and the elimination of negative environmental and health impacts associated with chemical herbicides. Along with precision weed removal, laser weeding allows for a much more accurate solution without affecting the surrounding plants, thus reducing overall crop damage [80]. For large-scale farms, this can lead to significant cost and operation efficiency over time. This is due to the reduction in labor costs and potential issues with groundwater contamination, and other issues caused by the rampant use of these chemical pesticides. Some pests have now become more resistant to certain pesticides the more they are being used, resulting in even higher use to compensate, propagating the situation until pesticides may become ineffective entirely, similar to the situation involving anti-biotics and our overuse causing a similar effect on how we treat bacterial infections. Smaller farms would also greatly benefit from the use of this technology; if they were able to get past the initial cost barrier, they would also see great long-term savings. [81] In the future, we hope that further initiatives and potential government subsidies would support this new technological adoption in agriculture. It could play a critical role in making these robots much more accessible to smaller farms and allow farms on any scale to benefit environmentally and financially.

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4.2 Industrial Design Standards

4.2.1 Standards for Lithium-Based Batteries

In the United States, many standards have been developed for installation, testing, and design of lithium batteries. There are internationally recognized created by the International Electrotechnical Commission (IEC), Underwriters Laboratories (UL), and Japanese Standards Association (JSA) [82]. The IEC has several standards for li-ion batteries including performance, safety, and testing. The Li-ion performance standard IEC 61960 discusses secondary cells and batteries containing alkaline or other non-acid electrolytes, and secondary lithium cells and batteries for portable applications. This standard is important to reference for the BEAM project and goes into detail about the performance of Li-ion batteries such as charge recovery, charge retention, final voltage, nominal voltage and many more features. It goes into detail about many electrical tests that can be performed to ensure that the capabilities of a Lithium-Ion battery fall within normal levels. The IEC safety standard IEC 62133-2:2017 is also very important to reference because it discusses general safety considerations surrounding battery wiring, ventilation, temperature/voltage/current control, and appropriate charging procedures [83].

4.2.2 Standards for Charge Controllers

The IEC has also produced a performance standard IEC 62509 that normalizes functionality and performance of a photovoltaic battery charge controller. The requirements for this standard are divided into 5 categories: battery lifetime protection,

efficiency, user interface, fail safe functions, and marking and documentation. This standard will help guarantee reliable operation and essential protection functions of charge controllers. This allows charge controllers to better protect batteries and increase user awareness of the charge controller's functions. In this standard, section 4.3.3.5 describes how charge controllers should be able to compensate charging set-points based on temperature. This is very useful in a component that will be exposed to high temperatures and needs to perform accurately. This standard greatly benefits overall charge controller design and usage, and the advantages increase the value of the charge controller for BEAM [84].

4.2.3 Standards for Solar Panels

Similarly to lithium-ion batteries, solar panels have many national and international standards created by the International Electrotechnical Commission (IEC), the Institute of Electrical and Electronics Engineers (IEEE), the Underwriters Laboratories (UL), and the American Society for Testing and Materials (ASTM) [85]. IEEE offers many guides for monitoring resources connected to electric power systems using PV, and practices for testing performance of stand-alone systems. The IEC has many standards on PV characteristics, commissioning tests and inspections, PV design for stand-alone systems, installation, monitoring, safety, and performance. IEEE Std 1526-2003 is a standard that discusses the best practices for testing and monitoring the performance of stand-alone PV systems. It discusses how many PV problems occur, and recommended practices to address them. This standard discusses several tests and inspections for the entire PV and battery system that could prove useful for arranging the power system for BEAM [86].

4.2.4 Standards for Motors

The IEEE Standards Association put together a guide (IEEE std 115-1983) where it lists and explains the testing procedures for DC Machines that includes the setup, analysis, and the reporting of test results, it can be divided in two main categories; the test of the machines designed for essentially ripple-free operation and the ones designed for use with rectifier power supplies [87]. It aids manufacturers, designers, and engineers to have a consistent and reliable method for testing these machines by providing forms and instructions on the different components that should be tested, environment conditions, how to perform different measurements, and how to determine its performance level.

The general tests consist of four categories, the first is the preliminary tests which include the conditions of the location of the tests, the ideal ambient air and altitude (3300ft [87]) where the tests should be performed, the terminal markings following the manufacturer's diagrams and ANSI/NEMA, the direction of the rotation when not specified. It also contains the winding resistance measurements at 25°C to calculate the copper losses in the

motor, the air gap measurements of each motor's pole should be to the nearest 0.100mm for integral-horsepower and to the nearest 0.050mm for fractional-horsepower [87] and the diameter of the wire should be "at least 70% of the difference between the diametric distance of the main pole faces and the outside diameter of the rotor" [87], how the polarity of each field winding should be independently determined and the impedance drop of field coils is an indication of a coil having shorted-turns, how vibration can be measured using a low ripple DC source and the mounting conditions change from small to large machines because of impracticality. In addition, it specifies the percentage a brush has to be in contact with the commutator in order to be a good fit and the different methods for test the brushes functionality, and the conditions that insulation resistance between the windings and the frame should be tested.

The second category are the performance determination tests that include the magnetic saturation curve requirements, how to achieve a successful commutation, how to calculate the regulation for motors and generators, how to calculate the efficiency for both motors and generators and different methods depending on the machine size for fractional and integral horsepower, the different I^2R losses for armature, windings, brush-contact, shunt-field, exciter, and stray-load. The third category are the temperature tests where it specifies the type of instruments that should be used, the several methods for the measurements, the test procedure with the amount of time they should last depending on whether they're a rated machine test or a load test, the armature shut-down temperature determination. The final category consists of miscellaneous tests that consist of audio-noise test, electromagnetic interference test, voltage wave shape, etc. Lastly, it states that these tests may not be all that should be performed since a particular standard may vary depending on the machine's type or size [87].

4.2.5 Standards for Motor Controllers

There are several standards to consider when choosing or designing a motor controller, which varies according to the current type. One of them is the IEC 61508 series called Functional Safety Standard by the International Electrotechnical Commission where it highlights the safety standards for electrical, electronic, or programmable systems [88]. These series categorize its integrity levels by their average probability of failure on demand and per hour whether it is on low mode or continuous mode, and provides risk reduction for different automated devices that may include sensors, actuators, micro-processors, etc. Another example to take into consideration is the IEC 60204-1 called the Safety of Machinery because it covers the programmable electronic equipment including different components working in a coordinated manner and it is specific for equipment not surpassing 1000V and 200Hz [89]. It also specifies the voltage range for both AC and DC supplies, the ambient temperature and altitude, and its storage, protection against electric shock and the protection of the equipment.

4.2.6 Standards for Laser Safety

When working with high-power lasers such as the 1W, 2W, and 5W red and blue laser diodes for the project, it is essential to adhere to stringent laser safety standards to ensure the safety of operators and the environment. Lasers of these power levels typically fall under Class 4, which means they can cause severe eye and skin damage and are a fire hazard.

In the context of a robot designed to use Class 4 lasers for drying weed leaves, adherence to laser safety standards is paramount to ensure both operational effectiveness and safety. These standards, such as IEC 60825-1, ANSI Z136.1, ISO 11553 series, and FDA Laser Product Safety Regulations, provide comprehensive guidelines that influence every aspect of the robot's laser usage [90].

Firstly, the robot's design incorporates engineering controls specified by these standards. It includes safety interlocks that automatically shut off the laser if protective enclosures are opened, preventing accidental exposure to high-power laser beams. This feature ensures that the robot can safely operate in environments where humans or animals may be present.

Administrative controls are equally crucial. The robot is programmed to undergo regular hazard assessments and operational checks to ensure that the laser emission remains within safe limits as defined by the standards. This involves monitoring the laser power output and ensuring that it does not exceed levels that could potentially cause eye or skin damage to operators or bystanders.

Furthermore, the robot's operation is guided by clear protocols derived from these standards. Operators are trained extensively in laser safety protocols, including how to handle emergencies involving laser exposure. This training ensures that operators understand the risks associated with Class 4 lasers and are prepared to respond appropriately in any situation.

Personal protective equipment (PPE) is another critical component. The robot provides operators with laser safety goggles specifically designed to protect against the wavelengths emitted by Class 4 lasers. This PPE is essential for safeguarding operators' eyesight during weed drying operations, where direct exposure to laser radiation is possible.

Overall, by adhering to these laser safety standards, the robot not only optimizes the efficiency and effectiveness of weed drying processes but also prioritizes the safety of operators and bystanders. It integrates robust engineering controls, meticulous administrative procedures, comprehensive operator training, and appropriate PPE to mitigate risks associated with Class 4 laser use in agricultural applications. This approach ensures that the technology contributes positively to agricultural practices while

maintaining the highest standards of safety and compliance with international laser safety regulations [90].

4.2.7 Standards for MCU

In the rapidly evolving field of robotics and MCUs, ensuring the reliable operation of these devices requires strict adherence to these engineering standards. The IEEE provides several standards and technical specifications:

IEEE 1801-2018 is a standard that provides a UPF format, specifying the power intent in the design of integrated circuits. Covering important aspects including power domain, power management strategies, and power modes, these are vital for creating low-power integrated circuits. [91]

Another useful standard to introduce would be IEEE 1620-2008, which is the standard for testability and diagnostic characteristics and metrics. Our robot will require rigorous testing and adjustment to make sure our design is working as we intend, so a set of standards and guidelines for testing and diagnosing these systems will be a boon for maintaining the overall reliability of the robot and its results. [92]

IEEE 1725-2011 is a standard focused on mobile computing devices, specifically for ensuring the safety and reliability of rechargeable battery systems. Our robot will have a rechargeable solar-powered battery, so these guidelines will serve us well when integrating these systems together. [93]

Finally, the IEEE 29119-1-2013 Standard provides a framework for testing the software of the MCU, which will be very helpful for our project as our coding knowledge could be supported by these standards. [94]

Chapter 5 – Comparison of Chat GPT and Similar Platforms

5.1 Chat GPT Pros

ChatGPT is highly effective for information consolidation and has a vast knowledge base on many subjects. ChatGPT's knowledge is derived from many diverse sources including books, websites, academic and scientific research papers, Wikipedia, and other publicly available databases and information repositories. This immense availability of information

allows the conversational AI to consolidate information on almost any topic and provide users with quick responses to any question. One of the best ways to use ChatGPT is for consolidating basic information about a subject.

Case Study 1: Question: “Tell me about linear motors.”

“Linear motors work by directly converting electrical energy into linear motion using electromagnetic principles. Here’s a brief description of how they function:

1. **Components:** A linear motor consists of two main parts:
 - **Forcer (Primary):** Contains windings that generate a magnetic field when electric current passes through them.
 - **Track (Secondary):** Contains permanent magnets or a magnetic material that interacts with the magnetic field from the forcer.
2. **Operation:**
 - **Electromagnetic Induction:** When current flows through the windings in the forcer, it creates a magnetic field.
 - **Magnetic Interaction:** This magnetic field interacts with the magnetic field of the track.
 - **Linear Force:** The interaction between the two magnetic fields produces a force that propels the forcer along the track, creating linear motion.

Key Points

- **Direct Drive:** The force generated is directly applied to move the load without the need for intermediate mechanical components like gears or belts.
- **Precision and Speed:** Linear motors offer high precision, rapid acceleration, and smooth motion, making them ideal for applications requiring exact positioning and high-speed operation.

Applications

Linear motors are used in a variety of fields, including:

- **Transportation:** Propelling maglev trains.
- **Manufacturing:** Moving components in CNC machines and robotic systems.
- **Medical Devices:** Precision movement in MRI machines and other diagnostic equipment.

Overall, linear motors provide an efficient and precise way to achieve linear motion in many advanced technological applications” [95].

In Case Study 1, the user asks ChatGPT to be informed about linear motors, and is then provided with components for this motor, how the motor operates, key points for the motor, and its applications. All the information was readily combined into an arranged list for the user to read. The 24/7 availability of an AI that can promptly search a large database to collect and coalesce information is an extremely beneficial tool to use when starting research or looking for answers to questions. The AI even searches across many databases to develop a well-rounded response with accurate information for the user.

Another benefit of ChatGPT is its ability to provide quick pros and cons for comparing simple components. If a user wants to compare the difference between a linear motor and a DC motor then ChatGPT will compare both on several specifications such as cost, design and control, variety of specific component types, and other motor specific parameters. The user can also use prompt customization to focus on specific areas of interest in the AI’s responses. This is very efficient for focusing, comparing, and understanding the difference between well-known components but may be less helpful for specific components because ChatGPT may provide the wrong data. ChatGPT is useful for providing well known qualitative information about components, and not necessarily quantitative information about a part. It is always important to fact check specific data when using ChatGPT as a resource.

Another Pro of using a tool like ChatGPT is generating creative ideas because it is trained to discover patterns, to handle and analyze massive amount of data in a matter of seconds, making it useful to pull information from multiple sources such as reports, scholarly articles, and websites the same time and compacting the said information. To achieve what we want, we first need to feed it a prompt or we can also feed it information in order to get a more detailed explanation of the ideas we want.

Case Study 2: Prompt: “I need ideas for a senior design project for the Electrical and Computer Engineer College”

“Certainly! Senior design projects in Electrical and Computer Engineering (ECE) can span various domains and technologies. Here are some ideas across different subfields of ECE:

Embedded Systems/Internet of Things (IoT)

1. **Smart Home System:** Design a centralized IoT-based system that controls various home appliances (lights, HVAC, security) through a mobile app or voice commands.
2. **Health Monitoring Device:** Create a wearable device that monitors vital signs (heart rate, temperature, etc.) and sends alerts to caregivers or doctors when anomalies are detected.

3. **Environmental Monitoring System:** Develop a sensor network to monitor air quality, temperature, and humidity in urban areas and display data on a web interface.

Robotics and Automation

1. **Autonomous Delivery Robot**
2. **Industrial Automation System**
3. **Robotics Arm Control**

Signal Processing and Communication

1. **Wireless Communication Network**
2. **Audio Signal Processing**
3. **Radar System**

Power Systems and Renewable Energy

1. **Solar Power Optimization**
2. **Energy Harvesting Device**
3. **Battery Management System**

Computer Vision and Image Processing

1. **Object Recognition System**
2. **Gesture Recognition Interface**
3. **Medical Imaging Analysis**

Other Ideas

1. **Blockchain-based Secure Voting System:**
2. **Augmented Reality (AR) Application**
3. **Wearable Technology for Sports**

These ideas can be tailored and expanded based on specific interests, available resources, and expertise within your team or academic institution. It's important to consider feasibility, scope, and potential impact when choosing a senior design project” [95].

In Case study 2 we fed it a straightforward, yet a slightly more specific prompt. In the example above we condensed the information given by the AI tool because of space reasons, it generated five precise subfields of ECE accompanied by a broader category for scenarios not encompassed by the initial subfields, each one presented three ideas and it even suggested execution approaches, in some of the example it detailed the project’s functionality in a real world application and the desired setting for testing. Case Study 2 demonstrated the impact that AI tools can be for generating creative ideas through the use machine learning algorithms because it reduced what would typically require hours of research across different source materials (like university websites detailing past projects) into seconds by providing concise yet detailed-enough ideas and in an organized manner. It also proves helpful for brainstorming ideas when given prompts such as “give me more examples for this” or asking it to ignore a certain part of the prompt after it is no longer useful so it stops searching across multiple sources for obsolete information.

ChatGPT can also be used to cross language barriers and gain understanding of complex word translations in specific fields. This is especially useful for students who understand multiple languages and use this to expand their resource base. Language barriers are problematic in general because they impede effective communication and understanding in various aspects of life. In social interactions, language barriers can create misunderstandings, foster feelings of isolation, and prevent meaningful connections between individuals from different linguistic backgrounds. Especially, language barriers pose a considerable problem in healthcare because they hinder effective communication between patients and healthcare providers, leading to misunderstandings and misdiagnoses. Patients who cannot communicate their symptoms accurately may not receive the appropriate treatment, which can result in adverse health outcomes and complications. However, using ChatGPT offers patients a simple method to overcome these communication challenges as study conducted at Stanford University School of Medicine showed ChatGPT (GPT-4) can accurately and understandably translate common patient-focused otolaryngology questions into multiple languages [96].

In Case Study 3, a native Korean speaker asked ChatGPT to translate a hard medical paragraph that was generated by ChatGPT and terminologies for each medical word.

Case Study 3: Prompt: “Please translate this paragraph in Korean and provide definitions for each word: The pathophysiology of myocardial infarction involves the abrupt rupture of an atherosclerotic plaque within a coronary artery, resulting in the formation of a thrombus that obstructs blood flow. This occlusion leads to ischemia and necrosis of the myocardial tissue distal to the blockage. The resultant myocardial cell death triggers an inflammatory response, with the release of cytokines and infiltration of neutrophils and macrophages, which further exacerbates tissue damage.”

심근 경색의 병리생리학은 관상동맥 내의 아테로스클러틱 돌기의 급작스러운 파열로 시작되어 혈액 흐름을 막는 혈전 형성을 초래합니다. 이 폐쇄는 막힘 지점 이후의 심근 조직에서 허혈과 괴사를 초래합니다. 이로 인해 발생하는 심근 세포의 사망은 염증 반응을 일으키며, 사이토카인의 방출과 중성 세포 및 마크로파지의 침윤을 포함하여 조직 손상을 더욱 악화시킵니다.

Definitions:

- 심근 경색 (simgeun gyeongsak): Myocardial infarction
- 병리생리학 (byeongri saengrihak): Pathophysiology
- 관상동맥 (gwansang dongmak): Coronary artery
- 아테로스클러틱 (ateroseukeulleotik): Atherosclerotic
- 돌기 (donggi): Plaque
- 혈전 (hyeoljeon): Thrombus
- 혈액 흐름 (hyeoraek heuleum): Blood flow

- 폐쇄 (pyesoe): Occlusion
- 허혈 (heohyeol): Ischemia
- 괴사 (goesa): Necrosis
- 심근 조직 (simgeun jojik): Myocardial tissue
- 사망 (samang): Death
- 염증 반응 (yeomjeung baneung): Inflammatory response
- 사이토카인 (saitokain): Cytokines
- 중성 세포 (jungseong sepo): Neutrophils
- 매크로파지 (makeuropa ji): Macrophages
- 조직 손상 (jojik sonsang): Tissue damage

Surprisingly, ChatGPT offered a Korean translation of a complex medical paragraph in Case Study 3, providing not only definitions for each term but also phonetic transcriptions. However, there was a minor mistake in the phonetic transcription for "plaque," which should be "dolggi," not "donggi." Nonetheless, the translated paragraph flowed naturally, employing appropriate translations of conjunctions, prepositions, and without any grammatical errors discernible from a native speaker's perspective.

ChatGPT also facilitates easy learning of coding for students. Learning coding can be difficult for many students due to several reasons. Firstly, it involves grasping abstract concepts like algorithms and data structures, which can be challenging to understand initially. Additionally, mastering the syntax and grammar of programming languages is crucial, as syntax errors can lead to bugs and frustration. The Faculty of Art, Computing and Creative Industry at University Pendidikan Sultan Idris conducted a research subjected in Polytechnic students in the Electrical Engineering Department, who took the fundamental programming class. The results of the statistical analysis indicate that students have a moderate level of understanding of the topic. The most challenging aspect for them involves grasping abstract concepts related to the role of variable position in computer memory, such as multi-dimensional arrays, looping statements, and functions during program execution. Students also struggled with understanding the basic programming structure and designing programs to solve specific tasks. Additionally, the majority of students found practical situations, like laboratory activities, to be very helpful in learning programming. However, it was identified that insufficient provision of examples by lecturers significantly influences students' understanding of programming [97]. In this sense, ChatGPT offers students the opportunity to learn coding by providing relevant code for systems and explanations for each script.

In Case Study 4, the user asked ChatGPT for a MATLAB code to obtain a Fourier Transform of an image that the user uploaded.

Case Study 4: Prompt: “How do I get a Fourier transform of the image through MATLAB?”

To perform a Fourier transform of an image in MATLAB, you can follow these steps:

1. **Read the Image:** Load your image into MATLAB using the `imread` function.

```
img = imread('your_image.png'); % Replace 'your_image.png' with your image file path
```

2. **Convert to Grayscale (if necessary):** If your image is color and you want to perform Fourier transform on a grayscale version, convert it using `rgb2gray`.

```
img_gray = rgb2gray(img); % Convert to grayscale if needed
```

3. **Perform Fourier Transform:** Use the `fft2` function to compute the 2-dimensional Fast Fourier Transform (FFT) of the image.

```
fft_img = fft2(img_gray);
```

4. **Shift the FFT:** By default, MATLAB's `fft2` places the zero frequency component (DC component) in the top-left corner. To view the transform with the zero frequency in the center, use `fftshift`.

```
fft_img_shifted = fftshift(fft_img);
```

5. **Display the Fourier Spectrum (Optional):** To visualize the Fourier spectrum, you can plot it using `imshow` and `abs` to show the magnitude.

```
magnitude_spectrum = abs(fft_img_shifted);
```

```
imshow(log(1 + magnitude_spectrum), []); % Log-transform for better visualization
```

This process will compute and visualize the Fourier transform of your image in MATLAB. Adjustments can be made based on whether you want to work with the original or grayscale image and how you prefer to visualize the transform.

ChatGPT supplied the code for obtaining the Fourier-transformed image, we applied the codes to the following image in Figure 16 called 'a'



Figure 16 - Original Image 'a' inserted to MATLAB

Below in Figure 17 is the screenshot of MATLAB script window. We evaluated them in Command Window and checked the outcome image.

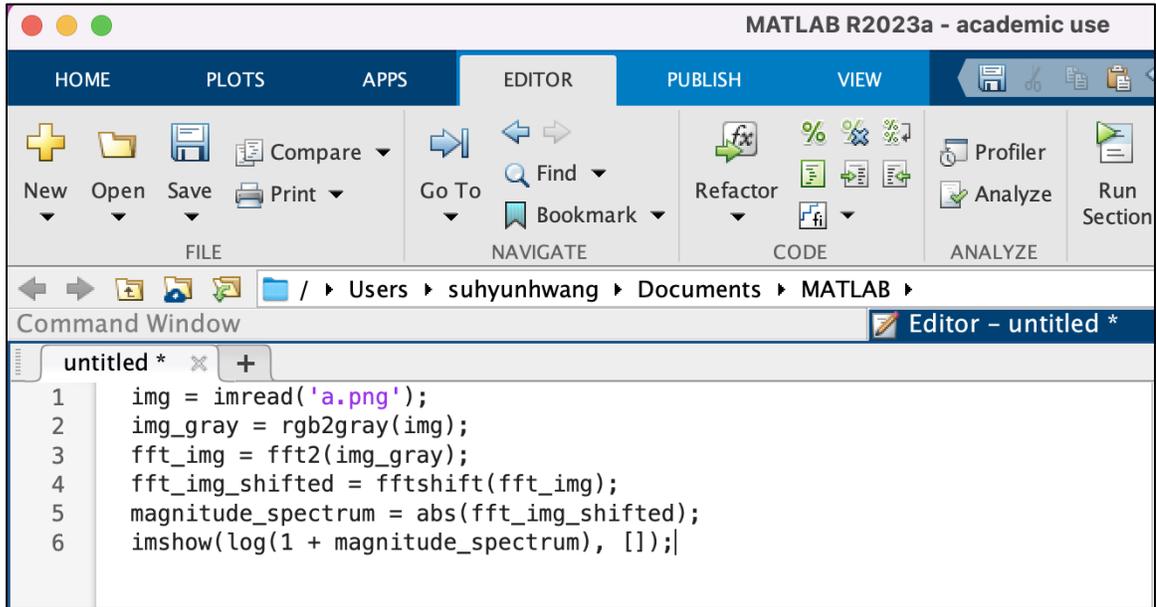


Figure 17 - Code applied to MATLAB

Figure 18 is the outcome image. We can see the image was Fourier transformed in a right way, and as such, ChatGPT indeed provides useful codes and explanations that students can apply and learn.

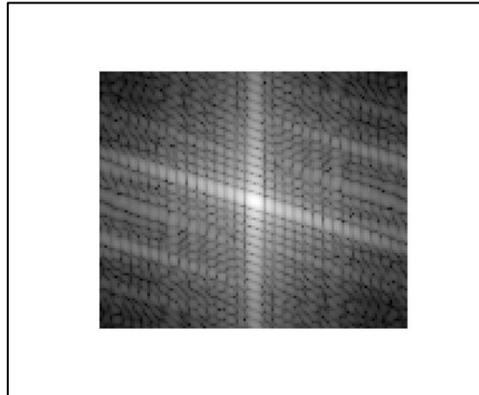


Figure 18 - Fourier Transformed Image

5.2 Chat GPT Cons

ChatGPT is a fantastic tool for generating solutions to given problems; however, it is nowhere near perfect. At times, the issue arises that chat GPT will give out either inaccuracies or just straight-up false information. This is likely due to the overall inherent limitations of the data that is given for training, as well as the specific AI models' inability to browse the web and check for verification the same way we do. This mostly comes down to one major issue with the technology that prove to be its tightest bottleneck. The first and more important issue of the two is the overall lack and nature of the training data. Chat GPT has been trained on a myriad of text data scrubbed from all reaches of the net. A very basic recap of how ChatGPT transforms text into useful information goes as follows: The AI scans and processes information from relevant sources, such as webpages. This data is then learned by the AI through a process called backpropagation, where the model adjusts its parameters to improve accuracy. Further details on backpropagation are beyond the scope of this paper and project. The point being that while the AI system can "learn" and "know" things, it is only able to draw from potentially flawed resources created by humans. The legality as well as morality of data farming and basically stealing most of the internet's text and images without proper compensation is still something that is widely debated within the AI industry as well as in all other industries that it affects. OPENAI and other AI organizations have tried to solve this issue by using AI-generated content to continue to train the AI models, but there is a very serious and glaring flaw with that solution. That being the overall increase and projection of errors. If the AI is fed bad information created by another mistaken AI, these inaccuracies can become propagated and applied in the training cycles. This can severely degrade the performance and accuracy of new models. Not to mention that there are some horrifying and sometimes comical examples of how these poorly trained AI algorithms can lose the sense of real work nuances in favor of making sure a user is given a result. Leading to potential consequences for the people who depend on these resources for accurate information. The greatest number of examples showing AI hallucinations ironically, comes from Google's own Gemini AI model. Ironically a website famous for its accuracy and prestige is now being flooded and oversaturated by its own AI results at times directly contradicting normal google search results, and overall misleading, and confusing its users. Most of the training data comes from web documents, math, and code attached to their own Google AI page. A reference has been provided to a page that has shown plenty of examples of incorrect or dangerous responses. Some of these include the response to "What are the health benefits of taking a bath with a toaster?" Google's AI responded that it would be a "fun way to unwind and wash away stress." The AI then thankfully immediately contradicted itself by correctly stating that it may be dangerous and lethal and to not attempt it. Another example was the suggestion to mix glue into a cheese sauce to make it stickier when responding to the prompt "cheese not sticking to pizza." Thankfully, the AI does seem to be able to correct itself mid-prompt; however, a user is less likely to read the corrected portion due to the

habit of internet users focusing on the first few highlighted lines, and thus having the chance to take this very dangerous and false information as the truth without proper verification [98].

As previously mentioned, AI tools operate on defined parameters and rely heavily on particular data, therefore, when presented with an ambiguous or vague prompt, they may struggle to accurately interpret the meaning, humans can often draw context of a sentence by facial expressions or tone of voice, however, AI systems solely source of context is that piece of text that when it's insufficient, it can lead to wrong or irrelevant outputs that don't address the user's needs. When given the prompt "Write a Report on Robots" it started by listing the types of robots, their applications and advancements, and impact on society, however I wanted a more detailed explanation of agriculture robots and their electronic components, meaning that AI needs a more detailed input for the desired output.

One of the biggest problems with information collection using ChatGPT is its inability to understand complex user input. If a user uses ambiguous language or wants the chat to use complex problem solving, it might struggle to follow along and forget necessary details. When a user provides too many details to keep track of, the chat's response can be full of errors or become oversimplified. ChatGPT often struggles to maintain context over long conversations, which can lead to inconsistencies in responses. These responses will often turn up as contradictory information or incorrect data. Length inputs can also overwhelm the system and cause it to miss important details. To lessen complexity issues with the system, users can ask follow up questions to clarify vague responses, break down lengthy or detail-heavy problems into smaller questions, or verify ChatGPT's information across reputable sources. Using these skills will help users mitigate limitations around complex information with the AI and allow it to provide more useful responses.

Another concern is that ChatGPT does not cite its sources, which can present challenges regarding the accuracy and reliability of the information it provides. When prompted to cite sources, ChatGPT may generate responses that include inaccurate websites or links that lead to outdated or unmaintained sources. This lack of citation and reliance on internal data means that information generated by ChatGPT may not always reflect the most current or verified data available. This issue is particularly evident in fields where information rapidly evolves, such as current events or cutting-edge research. As a result, users should exercise caution and verify information obtained from ChatGPT through other reliable sources before relying on it for critical decisions or authoritative information. This aspect highlights the importance of using ChatGPT as a tool for generating ideas and insights rather than as a sole authoritative source of information.

Chapter 10 – Administrative Content

10.1 Budget and Financing

Basic Budget:

Item	Description	Quantity of item	Estimated Cost	Total Cost
LiDAR System [99]	LiDAR System	1	\$40	\$40
Blue Laser Diode [100]	Wavelength : 455 nm Optical Power: 5000 mW	1	\$42	\$42
Red Laser Diode [101]	Wavelength : 639 nm Optical Power: 2100 mW	1	\$90	\$90
Green Laser Diode [102]	Wavelength : 530 nm Optical Power: 1650 mW	1	\$150	\$150
Chassis and Motors: DIY and Pre-Assembled [103] [104]	DIY and Pre-Assembled Chassis and Motors	2 + 1	\$27 + \$24	\$78

Microcontroller and Sensors [105]	Raspberry Pi and Arduino with sensors	2	\$80	\$160
Battery and Power Management [106]	Battery and power management components	1	\$37	\$37
Miscellaneous Components [107]	Electronic components kit	1	\$30	\$30
Solar Panel [108]	Solar panel + charge controller	2	\$25	\$50

Total Overall Cost: \$677

10.2 Project Milestones

10.2.1 Senior Design I

Week	Date	Milestone Description
1	5/13/24 – 5/19/24	Form group project and storm ideas.
2	5/20/24 – 5/26/24	Choose a project idea and start the D&C Report.
3	5/27/24 – 6/2/24	Finish the first draft of D&C 10-page Report.
		Submit Bootcamp Assignment.
		Work on the group website.
4	6/3/24 – 6/9/24	Attend the D&C Group meeting.

		Start the updated version of D&C Report after meeting with professors.
5	6/10/24 – 6/16/24	Submit updated version of D&C Report to the website (20-page minimum).
6	6/17/24 – 6/23/24	Start the 60-page Report.
		Assignment on Standards
7	6/24/24 – 6/30/24	Finalize the 60-page Report
		Finish Quiz A to G.
8	7/1/24 – 7/7/24	Upload the 60-page Report. (Preferably more than 60 pages).
9	7/8/24 – 7/14/24	Attend the 60-page Report Group Meeting
		Start working on the updated version of the 60-page Report.
		Submit the updated 60-page Report onto group website
10	7/15/24 – 7/21/24	Order parts
		Work the Final draft of the Project Report.
11	7/22/24 – 7/23/24	Submit the SD I Final Report

10.2.2 Senior Design II

Week	Date	Project Milestone
1	8/19/24 – 8/25/24	Order remaining parts
2	8/26/24 – 9/1/24	Start testing individual components functionalities.
3	9/2/24 – 9/8/24	Start the design of the App.
4	9/9/24 – 9/15/24	Finish Power functionalities
5	9/16/24 – 9/22/24	Finish Motor control
6	9/23/24 – 9/29/24	Finish Sensor functionalities
7	9/30/24 – 10/6/24	Finish connecting all code in MCU
8	10/7/24 – 10/13/24	Assemble hardware
9	10/14/24 – 10/20/24	Meet with professors

10	10/21/24 – 10/27/24	Redesign if needed
11	10/28/24 – 11/3/24	Finish App
12	11/4/24 – 11/10/24	Test app functionality
13	11/11/24 – 11/17/24	Finish final prototype
14	11/18/24 – 11/24/24	Test final prototype
		Record Demo
15	11/25/24 – 12/1/24	Finalize and submit Final Report
16	12/2/24 – 12/7/24	Live Demo

Appendix A1 - References

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