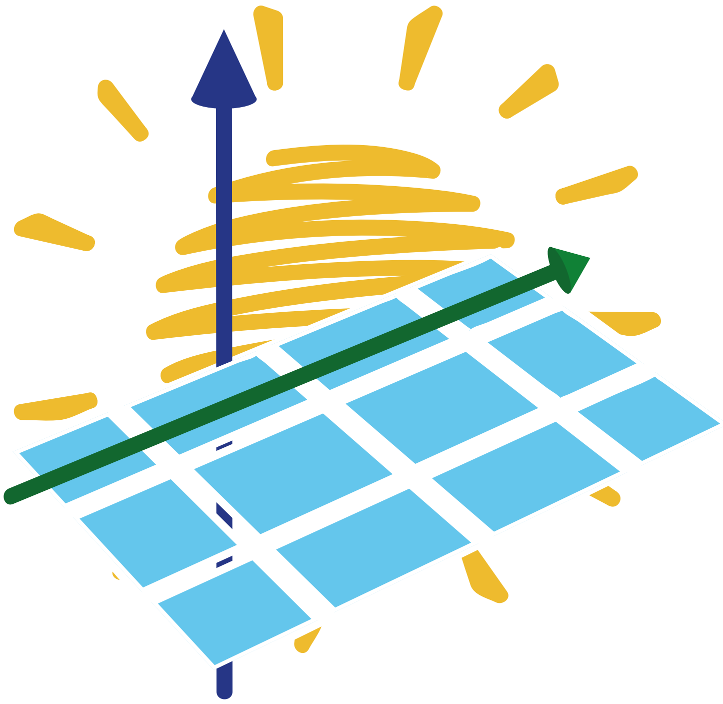
Sun Tracking



Project Report

AIE-B324a

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Abstract:

Photovoltaic solar power has in recent years been a rapidly growing industry, which means research into improvements is necessary. The aim of this study is to gain insight into the engineering, economics and viability of solar tracking technology for solar panels. This is studied by designing and building a solar tracking system, a MPPT system and a frame. The frame is built with a 35° degree tilt to help mimic the Sun's path in the sky and minimize motor movement. The solar tracker was tested and can track a moving light source, though no tests could be run on the efficiency gain, but from other studies and theoretical calculations the expected gain is around 20%-40% from the studies and around 58% from the calculations. The MPPT system was not tested, but is expected to get close to the optimal load since it has very fine control over the load resistance values. Though not enough tests were run, it can be stated, with a fair amount of certainty, that solar tracking does help provide more power.

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Preface

Aalborg University, December 22, 2021

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Chapter 1

Introduction

For some decades, well marked by the first Intergovernmental Panel on Climate Change in 1989, the concern regarding environmental challenges has increased, with much focus on energy production. This has caused a gradual shift away from non-renewable sources such as coal, oil and gas to renewable technologies like hydro energy, wind energy and solar power. According to data gathered by the organization Our World in Data [22], renewable energy generation has increased from under 1000TWh in 1965 to over 7000TWh in 2020. This growth has been particularly high within the solar power industry in recent years; a report by the International Energy Agency shows that photovoltaic solar energy for the period of 2018-2020 had the highest growth rate among renewable energy sources[1].

Photovoltaic solar technology can be found in different variations both in the industrial energy sector and small scale energy generation for private households. With variety in settings comes variation in technology. Solar cells come in different forms such as monocrystalline, polycrystalline and thin-film. In addition the panels can be installed stationary or with tracking technology to track the sun, adding to their efficiency. This can be done using single-axis, dual-axis and passive tracking systems. Tracking technology, despite its theoretical increase in efficiency, is used in many settings but is not ubiquitous.

The purpose of this study is to analyze the solar panel market with focus on the use of tracking technology, its pros and cons, and to specify why this technology is not universally used for solar panels. The initiating problem for this study was thus narrowed down to:

Why is sun tracking not ubiquitous, when it is accessible and useable?

Chapter 2

Problem analysis

2.1 Types of solar cells and efficiency

There are many types of solar cells, but the three main types of solar cells are monocrystalline, polycrystalline and thin-film.
The different solar cell types vary greatly in efficiency, cost and appearance.

2.1.1 Monocrystalline

Monocrystalline solar cells have a higher efficiency, but are also the most expensive ones. Monocrystalline solar panels have cells made of silicon wafers. The wafers are assembled into rows and columns, forming a rectangle. The panels are covered with a glass sheet and framed together.[19] This glass sheet makes sure that rain, snow or anything else won't get into the solar cells. Monocrystalline solar panels visually appear as panels with black cells. Monocrystalline solar cells can reach efficiencies higher than 20% [19]. Monocrystalline solar cells are also the most costly because of the manufacturing process. According to Energysage the high cost is a result of the Czochralski process, which is a process for making single silicon crystals[16], which results in wasted silicon. This wasted silicon can later be used to manufacture polycrystalline solar panels, since they don't require a single crystal [19].

2.1.2 Polycrystalline

Polycrystalline solar cells are cheaper than monocrystalline solar cells, but also have a lower efficiency. Polycrystalline solar cells are manufactured similarly to monocrystalline, but polycrystalline solar cells are composed of fragments of silicon crystals that are melted together in a mold before being cut into wafers[19]. Visually polycrystalline solar panels are more blue. While monocrystalline solar cells have an efficiency of ~20%, polycrystalline cells typically have efficiencies between 15 and 17%. Polycrystalline cells usually have a lower power output per m^2 [19].

2.1.3 Thin-film

Thin-film solar cells can be made from a lot of different materials. The most common are made from cadmium telluride(CdTe)[19]. When manufacturing these, a layer of CdTe is placed between transparent conducting layers. This will entirely capture the sunlight. There is a glass layer added on top for protection.
Another type of thin-film solar cell is Copper Indium Gallium Selenide. This type of cell has all four elements placed between two conductive layers such as glass, aluminium or steel. At last, electrodes are placed on the front and the back of the material - this helps to capture electrical current. Thin-film solar panels are often slimmer and thinner than the other types of solar panels. This is because of the thickness of the cells. The cells are about 350 times thinner than the crystalline wafers used in monocrystalline and polycrystalline solar panels. Both monocrystalline and polycrystalline panels can visually appear as blue or black, depending on what they are made from. Thin film solar panels tend to have an efficiency at ~11%. Thin-film solar cells do not come in uniform sizes like monocrystalline and polycrystalline do.[19].

The differences in solar cells make them more suitable for different situations. An example is that thin-film solar cells are easier to set up, than their crystalline counterparts, therefore they are useful in applications such as traffic lights or for powering a camper, where as the larger crystalline solar cells with their higher power output are more suited to provide power to an entire house or in solar farms. Table 2.1 summarizes a few important traits of these types of solar cells.

Type	Cost[USD/W]	Efficiency[%]	Portability
Monocrystalline	1-1.5 [10]	~20	Not portable
Polycrystalline	0.9-1 [10]	~17	Not portable
Thin-film	0.5-1 [27]	~11	Flexible and thin

Table 2.1: Cost, efficiency, and portability of different types of solar cells.

2.1.4 Power output

Different types of solar cells have different power output and efficiency. Monocrystalline solar cells have a higher efficiency at 20% where as polycrystalline solar cells have an efficiency of 17%, so to get the same amount of power from both types of

solar panels, polycrystalline have to be slightly bigger than monocrystalline. Several factors influence solar panel power output such as the weather, orientation and sun hours. Disregarding these negative influences on the performance of a solar panel, the power output is between 250 and 400 watts, depending on the kind of solar panel and its quality. (see table 2.2).
The calculations for power output will be presented in subsection 2.2.4

Name	Type	Min [W]	Max [W]	Efficiency [%]	Reference
AS-6M		360	400	20.29	[2]
BiHiKu	Mono	430	460	19.5	[24]
PM060MW2		290	310	18.4	[11]
AS-6P		325	355	18.3	[3]
BiHiKu	Poly	390	415	17.5	[25]
BVM6612P		320	340	17.5	[5]

Table 2.2: Minimum and maximum power output, and efficiency of monocrystalline and polycrystalline solar cells.

2.2 Current tracking technologies

Inconsistency is one of the key undesirable characteristics of solar panels. Power output approaches zero in the night time, peaks for a short period of time every day at noon, and has comparatively low values in the earlier and later hours of daylight time.

There are a number of factors that limit the instantaneous performance of solar panels, including atmospheric effects such as the scattering of photons as they travel through the air, obstructions in the path of the irradiation such as clouds, and the incidence angle of the Sun. This last factor could be optimized using electronics and engineering principles, resulting in a significant improvement compared to fixed panels, further discussed in subsection 2.2.4

The concentration of photons reaching the surface is at its highest when the incidence angle of the Sun's rays is zero, or in other words, when the Sun is directly above the observer. This however happens only at noon at a specific geographical latitude, lying between the Tropic of Cancer and the Tropic of Capricorn depending on the time of year. Aside from these locations, the Sun is at an angle, and the photons that reach the ground are spread over a larger surface area compared to when they have an incidence angle of zero. Conversely, this means that the effective surface area is smaller, since the same amount of photons could be collected in a smaller surface area if it was perpendicular to the Sun, see the Figure 4.5.

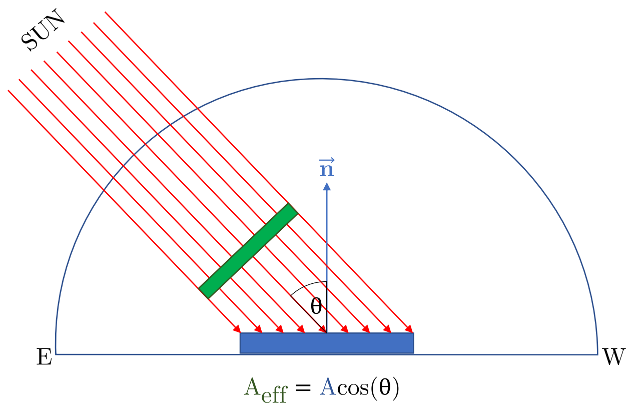

Figure 2.1: The effective area with respect to the incidence angle θ.

The panel's output could be at maximum (ignoring other factors) if it could be aligned so that the panel's normal vector points directly at the Sun. This is precisely what solar tracking aims to do, by using a control system that orient the panels so that they are facing the Sun directly, or minimize the angle of incidence in the case of simpler mechanisms.

Tracking the sun with solar panels is not without its drawbacks. While it increases efficiency considerably in theory, the energy consumption of the entire control system has to be taken into account. If the sensors and the motors and/or actuators consume more energy than what is gained by the system, making the transition to tracking solutions would not make sense from an energy standpoint. Also, since sophisticated electronics and moving parts are introduced to the panels, the initial cost of the installation of these solutions and the maintenance costs added by them increase the price of watts per square meters of the panel. For people to universally adopt Sun tracking technologies, the increased power generation would need to cover the costs of the higher initial investment in the long term. The economics of these solutions will be discussed in section 2.3.

There are a number of different approaches to Sun tracking, that can be grouped into categories depending on several criteria, including the degrees of freedom of the tracking system, the control system being used, tracking strategy, and the driving system[4]. For the purposes of this report, tracking strategy will be a part of the control system section.

2.2.1 Degrees of freedom

From the point of view of an observer on the ground, the path of the Sun along the sky is a complicated curve, due to the tilt of the Earth, and it depends on the geographical latitude as well as the time of year. Following the Sun accurately is thus not possible on a single rotational axis. Due to that, a trade-off has to be made; more precise tracking, higher power output but higher consumption, maintenance and installation costs of dual axis; or less precise tracking, lower output but lower consumption, maintenance and installation costs of single axis systems. Both of these types of motions can have different implementations, so they can be further classified into subcategories.

For single axis motion there are systems which rotate the panel throughout the day, following the Sun's path by rotating around the polar axis. In those cases, the panels have an optimized tilt angle, calculated using the geographical latitude. This ensures that the panel is following the Sun's path as closely as possible throughout the year(see Figure 2.2 (a)). There are also those that only change the tilt of the panel, meaning that they rotate around the East-West axis, so that they overall minimize the deviation from the optimal incidence angle, which is zero. While this solution has the lowest precision in tracking the Sun, the advantage of this type of motion is that it has by far the smallest energy consumption, since it does not move the panel throughout the day, but mostly just once on a daily, weekly or even monthly basis as seen in Figure 2.2 (b).

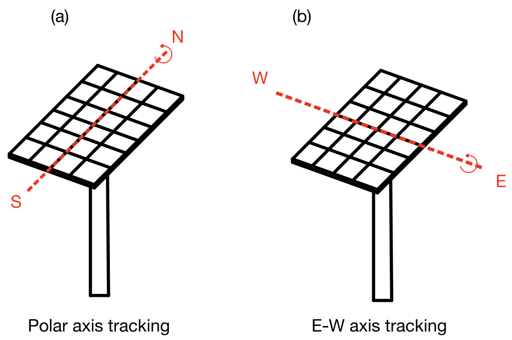

Figure 2.2: Two possible configurations for single axis tracking.

Dual axis tracking systems follow the Sun on both East-West and South-North axes, enabling them to orient themselves such that the panels are constantly pointed towards the Sun, leading to the highest efficiency and the highest power consumption. There can be implementation differences based on the planes on which the motors are installed, which lead to different amounts of consumption, but ignoring the errors in accuracy, all of them achieve maximum performance increase. For an example of actual configuration, see the Figure 2.3.

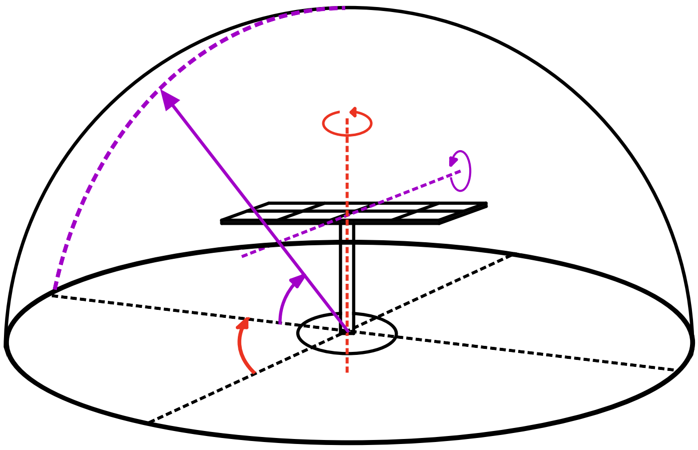

Figure 2.3: A configuration of dual axis tracking with azimuth(red) and altitude(purple) angle control.

With proposed low cost, consumption and maintenance solutions to these systems, efficiency gains lead to a net decrease of electricity cost of these panels, which could make them a competitive alternative to fixed setups under certain conditions.

2.2.2 Control systems

The control system used is another design choice which has an effect on the precision of the motion, and thus the overall efficiency of the panels. The two categories of solar trackers based on control systems are the closed and open loop systems. With closed loop tracking, the microprocessors use data received from sensors to adjust the position of the drivers accordingly. These are typically photodetector sensors placed in such a configuration that the data they produce can be used to deduce the direction in which the panels need to turn in order to capture the most light. Open loop systems on the other hand do not use sensors to track the Sun, but instead calculate the Sun's current location based on geographical location data, time and date.

2.2.3 Driving systems

Driving systems separate Sun tracking into two groups: active and passive ones. Active driving uses electrical/mechanical drives to produce motion, the result being a high precision motion, leading to higher efficiency in power generation. It also consumes energy to provide that motion, in addition to introducing higher maintenance and installation costs. Passive driving in turn provides a way to rotate the panels solely using low boiling point fluids, or so called shape memory alloys, which depending on the side that receives more heat, can go into shape or state changes, providing a different type of driving force on the panels, requiring no other energy input than solar radiation.

2.2.4 Efficacy

The amount of energy a fixed solar panel can generate is proportional to the angle between the Sun and the surface of the solar panel.
This can be expressed as:

$$I_{eff} = I_0 \cos(\theta), \tag{2.1}$$

where θ is the angle of incidence and goes through the interval $(\frac{-\pi}{2}, \frac{\pi}{2})$ during the day, I_0 is the radiation intensity of the Sun and I_{eff} is the effective radiation intensity after taking the incidence angle into account, see figure 4.5.
Assuming that a day is $t = 12\text{h} = 43200\text{s}$ and that the solar constant is $I_0 = 1366\frac{\text{W}}{\text{m}^2}$[29]. Finding the angular velocity of the Sun can now be done, knowing that the Sun moves one π radians in $t = 43200s$ then $\omega = \frac{\pi}{t} = 7.27 \cdot 10^{-5}\frac{\text{rad}}{\text{s}}$. So the power at any given point can be described as $I_{eff} = I_0 \cos(\omega t)$ now this can be integrated in the interval $(\frac{-t}{2}, \frac{t}{2})$:

$$W = \int_{-21600s}^{21600s} I \cos(\omega t) \mathrm{d}t = 3.76 \cdot 10^7 \frac{\text{Ws}}{\text{m}^2\text{day}} = 10.4 \frac{\text{kWh}}{\text{m}^2\text{day}}. \tag{2.2}$$

This can be compared to a tracking system having the optimal angle all day, given by:

$$W = It = 5.90 \cdot 10^7 \frac{\text{Ws}}{\text{m}^2\text{day}} = 16.4 \frac{\text{kWh}}{\text{m}^2\text{day}}. \tag{2.3}$$

This is an increase of $\frac{16.4-10.4}{10.4} \cdot 100 = 57.7\%$, disregarding all effects other than the effect of the incident angle. This provides an idea of the upper limit for increasing efficiency of a solar panel. Table 2.3 shows a few examples of what has been achieved experimentally, to contrast with the theoretical calculation.

Tracker type	Description	Gain[%]	Reference
Single axis	LDR based tracking	25	[20]
	Three positional solar tracker	24.5	[13]
	LDR based tracking	40	[23]
Dual axis	Tracking using calculations of the Sun's position	42.6	[26]
	Sensorless and sensor based tracking respectively	24.59-35.22	[9]
	Tracking with UV sensors	19.97	[15]

Table 2.3: Experimental values from practical applications of tracking technologies.

Note that the cause for the differences in gain include, but are not limited to, weather conditions, geographical location and time of year.

2.3 Economics

Although solar panels are sold and bought on the free market, plenty of the money for research into these technologies comes from tax money. A study from the University of London found that approximately 34.5% of financing into renewable technologies comes from tax-funded investors such as state banks, utilities, corporations and agencies[8]. A good example is the European Union's funding instrument "Connecting Europe Facility", which was awarded 8.7 billion euros for the period 2021-2027 to invest in energy infrastructure. Another of its projects "Horizon Europe", aims to invest 5.8 billion euros into clean energy technologies over 2021-2022[6].

These investments and those that came before them have aided in the spread and cost reduction of these technologies. Solar panels have become cheaper to manufacture, more efficient and more available to consumers. According to data collected by the International Energy Agency, the cost of producing solar panel modules has gone from just over 100USD/Watt in 1975 to around 0.2USD/Watt in 2020 [14]. This means that solar power has become more cost effective relative to non-renewable resources than it was in the past.
The installation of solar panels on private households in particular has changed the dynamic between producer and consumer in the electricity market. Previously consumers have only bought energy from their local provider, but now with household solar panels consumers are able to sell electricity to the grid when they overproduce. This phenomenon is for example incentivised in Denmark, where sales of electricity by household solar producers are not taxed up to 7000DKK

(1101USD)[7] on a yearly basis, any amount greater than 7000DKK will be taxed by 60%.

With more and more panels being installed, the question of efficiency arises. Panels installed on or by houses are almost exclusively mounted fixed, meaning that efficiency is lost due to the angle of the sun not staying normal to the surface. The lack of tracking technology being used may be for many reasons, but what would the theoretical monetary gains be if the panels did track the sun? According to table 2.3, we can expect efficiency gains between 24.5-40% for single-axis trackers and 20-45.5% for dual axis. An example cost of a ground installed home system of 11 units with 300W each cost in total 14625USD, circa 1300USD/panel, a single axis tracker per panel 500USD and dual axis 1000USD, according to an article by solarreviews.com[17]. The article assumes annual energy savings of around 1100USD for the entire system per year, which means one panel will save around 100USD in electricity costs per year.

The time it takes for the system to pay off its own initial investment can be calculated as follows:

$$\frac{P_c + T_c}{E \cdot A}, \tag{2.4}$$

where P_c is panel cost, T_c is cost of the tracking mount, E is the relative efficiency and A is the annual savings. Applying this formula to the data from Solarreviews.com, we get the following table:

Type	Cost/unit [USD]	Relative efficiency	Payback [years]
No axis	1300	1	13
Single axis	1300+500	1.25-1.4	14.4-12.9
Dual axis	1300+1000	1.20-1.45	19.2-15.9

Table 2.4: Payback time for tracking systems.

2.3.1 Life cycle cost analysis

The life cycle cost analysis is a key feature that concerns the economic part of using solar cells. The NREL carried out an experiment and reached the conclusion that solar cells degrade at a rate of 0.5% every year. This rate of degradation implies that a single solar cell will be functioning at the 95% of its full capacity in 10 years time. The rate of degradation can always vary having in mind different factors such as the changes in climate and positioning of the solar panels. The NREL stated that in hotter climates and for rooftop systems the rate of degradation is likely to increase due to higher ambient temperatures compared to the ground solar systems. This occurs due the lack of space underneath the solar system which restricts greater airflow.

A study held in Kazahstan gives more details about the life cycle of solar cells. The study was conducted with the already existing Bornoye 1 PV plant with the fiscal support of the European Bank for Reconstruction and Development and the Clean Technology Fund.

Table 2.5 gives information about the debt ratios for the two firms.

Bank	Debt Ratio	Debt [USD]	Debt Interest rate	Debt Term [years]
EBRD	62.02%	-77 300 000	11.5%	15
World Bank	12.3%	-15 000 000	1.25%	20

Table 2.5: Debt Details.

2.4 Legislation

Knowledge about building regulations is crucial when analysing the problems associated with solar panels. Knowing what restrictions and guidelines there are is necessary before it is possible to design and installed an array of solar panels.
There are a few essential laws concerning installing solar panels on a house, in Denmark these are put forth in a document by the Danish Ministry of Transport, Building and Housing[28]. The building code covers any building, whether new, an addition or alteration to a building, meaning the owner in principle must apply for a building permit to construct something on their property, though there are a few exceptions to this. According to the first chapter, fifth paragraph of the building code there are types of building works that must adhere to the regulations, but may be erected without the need for a permit. The implications of the rules are that solar panels can be mounted on a roof without a building permit, as long as the construction follows the regulations, but if the owner is looking to construct an array of solar panels on terrain, the construction must not exceed 50m^2 otherwise a permit is required, which may end up being a long process.
These are a few of the rules governing everybody in Denmark, but it is more complicated than this, if an owner is looking to install an array of solar panels they may be under more restrictive rules because of their municipality. Municipalities will release guidelines they want an owner to follow in addition to the building regulations. An example of this could be Esbjerg municipality, in Esbjerg solar panels may not cover more than 50% of the roof, at most 55m^2 per property, and

have to be in the shape of one or multiple connected rectangles, or it should fit the geometry of the roof, unless the solar panel is integrated into the roof, then it may cover the entire roof. [21]

Chapter 3

Problem definition

As solar panels are decreasing in cost, increasing in efficiency and receiving large investments from governments and companies advocating this technology, research in usage efficiency becomes increasingly important to make maximal use of the technology being invested in. Theoretical calculations and experimental data show that significant efficiency gains can be acheived by installing solar tracking devices, and that this can be economically feasible. The initiating problem was intitially narrowed to:

Why is sun tracking not ubiquitous, when it is accessible and useable?

To further the research in this field, a basic solar tracking module will be designed in order to run tests in different settings and conditions. This module will make use of both dual- and single axis tracking, and sensors. Sensors will be used to gather data, allowing comparison and analysis of efficiency between the tracking options to be measured and used to further optimize the tracking. The module will be controlled using a microcontroller. With the data gathered from the tracking module inferences may be made regarding technological shortcomings and advantages, scalability, and economics, shedding light on the the present and future of solar tracking.

Chapter 4

Problem solution

4.1 Delimitation

Efficiency is the main concern when it comes to solar cells, which occurs due to their positioning. Usually solar cells are fixed on rooftops or any kind of flat surface, which reduces their movement and rotation to zero, leading to losses in efficiency. Furthermore, this inefficiency results into a significant decrease of solar power generation.

This project focuses on modeling and building a working prototype of a solar tracking device, which is able to turn, accordingly, in the two axes. Thus, collecting data and making a comparison between a fixed solar cell, single axis tracker and a dual axis tracker, in order to see which one is more effective, when in comes to power generation.

Goals of the project:

- Carrying out tests to make sure the solar tracker works
- Measuring how much power is used to rotate the tracker
- Comparing fixed panel, single and dual axes trackers

4.2 Design of prototype

4.2.1 Overview

Figure 4.1 is a block diagram, creating an overview of the prototype solar tracker. It describes the interaction between each module. The main idea is that the LDRs (Light Dependant Resistors) inform the Arduino about the position of the Sun, enabling the Arduino to tell the motors to rotate towards that direction. Then when the panel is in position MPPT (Maximum Power Point Tracking) can be performed, using the information from the current and voltage sensor. The MPPT changes the current and voltage of the solar panel creating feedback that the Arduino can use to find the MPP (Maximum Power Point).

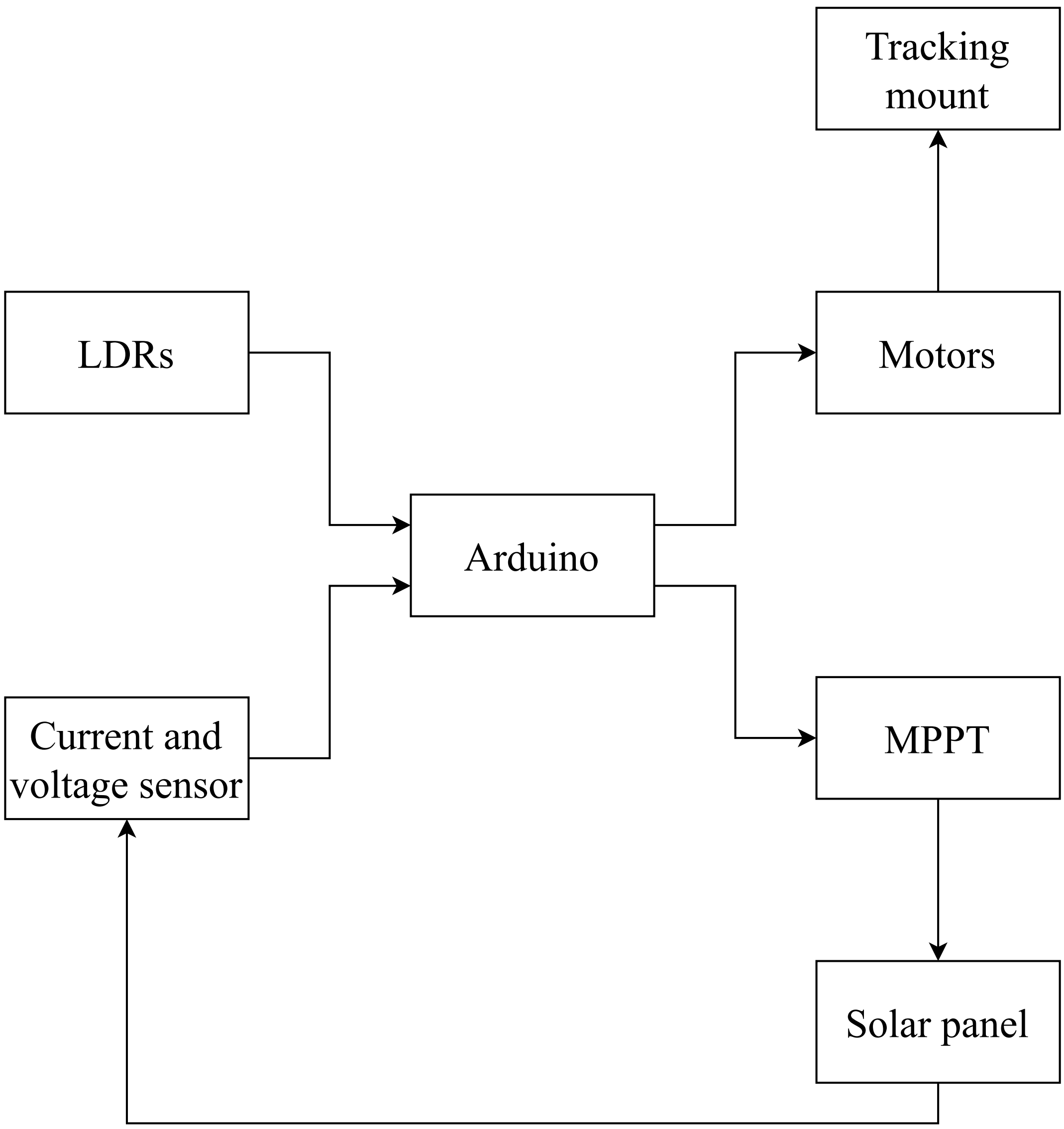

Figure 4.1: Block diagram of tracking system.

All these modules will be further explained in coming sections. Table 4.1 is a list of the components used for the prototype.

Component	Part number	Amount
Arduino Uno		1
Stepper drivers	TB6600	2
Geared stepper motors	23HS22-2804S-PG47	2
LDRs		2
100μF Capacitor		1
Current sensor	ACS712ELCTR-30A-T	1
90W Solar panel		1
470kΩ, 100kΩ, 10kΩ, 1kΩ resistances		1
220Ω resistance		2
N-channel MOSFET	STP16NF06L	1

Table 4.1: List of components used for the solar tracking prototype.

4.2.2 Frame

From the viewpoint of an observer on the ground in Esbjerg, Denmark, the Sun's path could be described as a circle that is tilted 35° with respect to the ground, but it is also shifted depending on the time of year. For example, on the equinoxes, when the daylight hours are equal to the night hours, one point of the circle is at the point the observer perceives as East, and another point is at West, with half the circumference of that circle being above the horizon, and the other half being under it. On other days, the points at which the Sun's path cross the ground are not directly to the East or the West, but shifted either to the North(on longer days) or the South(on shorter days), which means that the observer would see different amounts of the circle on different days.

To have a mount that requires the least amount of motion to orient the solar panel perfectly towards the Sun using dual axis tracking, this solution proposes a frame that rotates around a tilted axis 35° tilted towards North, with a secondary axis of rotation that corrects for the shift in the Sun's path. The working principle can be seen on Figure 4.2, with the mount's initial design being on Figure 4.3.

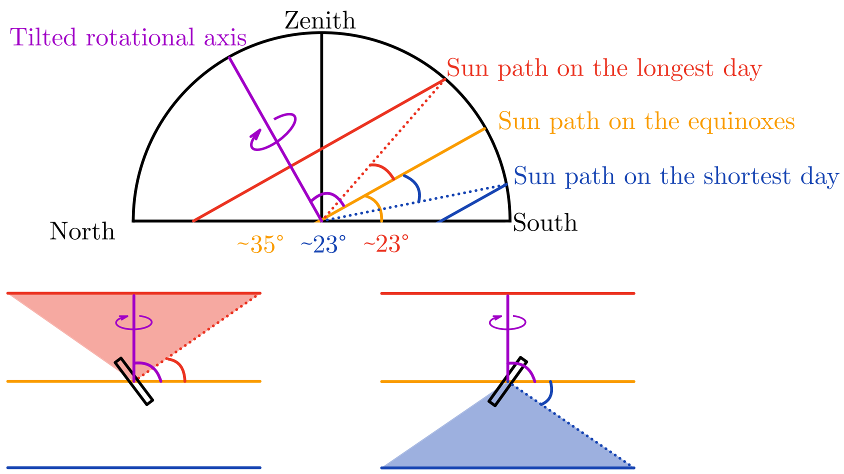

Figure 4.2: The Sun's paths illustrated with colored lines and the panel's adjustments for them.

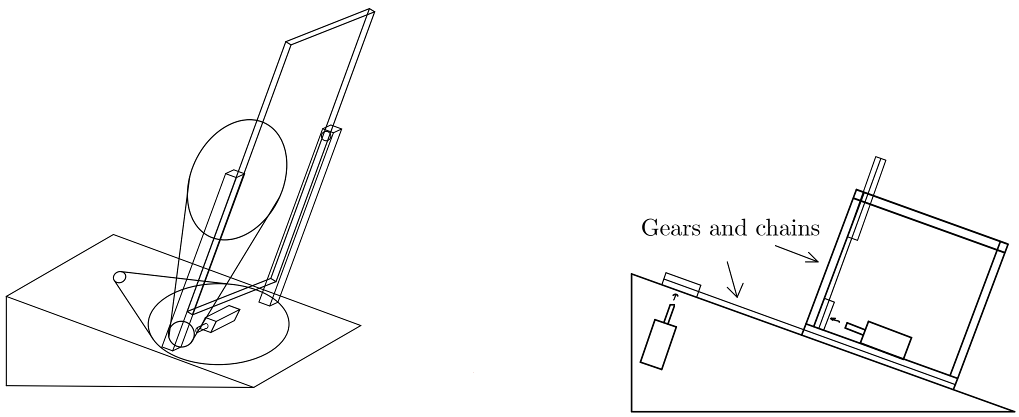

Figure 4.3: Sketch of the mount for the solar panel.

The movement of the panel is achieved by two stepper motors attached to the panel with gears and chains, placed at one end of the center lines on both the shorter and longer sides of the panel, to minimize the required torque. Since this use case requires a larger amount of torque than the usual applications where stepper motors are used, additional gears are needed within the stepper motors to reach the target torque.

4.2.3 Sensors and Control

The objective of automating the tracking system required sensors to gather light data that could be processed to make decisions of where to rotate the panel. This required sensors, a microcontroller to read and process the data, and motors to take instructions from the microcontroller.

Sensors

Input of information regarding light intensity was done through the use of two LDRs. Implemented with a voltage divider, these were used as sensors from which data could be read. With the use of two LDRs and a separating wall in between, the assumption was that the values read from both LDRs would be similar if both sensors normal vector pointed at the Sun. If the values were different, the platform which they were on would need to be turned until the values were again equal, the wall shading one sensor until the angle is corrected. To read data from the sensors and implement code to control the panel with motors an Arduino Uno was used. The LDRs were connected on a breadboard with voltage dividers connected to the digital pins on the Arduino in order to read values, as seen on 4.9. Initially some issues seemed to be present as the sensors seemed to have not only an inherent difference in values being read but the values being non-linear in different conditions.It was at this time unclear if the problem was the sensors or if the lighting in the room was the issue, as light was coming from several windows and several roof lights. In order to test the issue, a small experiment was performed. A lux meter was acquired, and measurements were taken outside with the lux meter and the LDRs, in order to see the difference in different light strengths. The results were the following:

Time	LDREast	LDRWest	Delta	Luminosity[kL]
09:17	311	431	120	20
10:15	270	380	110	30
11:12	300	420	120	42
12:40	435	550	115	76

Table 4.2: The table describes the time at which measurements were taken, the data collected from the two LDRs, the difference in value between these, and the data from the lux meter.

From the results in table 4.2, it was clear that the LDR differences were fairly static. This could then be accounted for with a constant offset implemented in the code.

The mount for the LDRs is designed specifically for this project. Its purpose is to keep the LDRs separated from each other. This means that the amount of sunlight on each side will not be the same, unless both LDRs point directly at the Sun. The solar panel can therefore turn in the direction with the highest amount of sunlight, until the values of the sensors are similar. It would be a problem for the system to find where to turn if the LDRs were not separated. Then they would receive equal amount of sunlight all the time, which would be ineffective. The mount is therefore an essential part of the tracking system.

The mount is 3D printed using PLA. This allows the mount to be constructed exactly as needed for the project. It is printed with 20% filament to reduce costs. The mount has two platforms specifically designed for the LDRs to rest on with holes for their legs to keep them in place all the time no matter what.

It was necessary to place the mount a few centimeters from the solar panel itself. Otherwise the shadow of the solar panel would affect the measurements from the LDRs.

Control

The processing of the data from the sensors into instructions to turn the panel was done with an Arduino Uno microcontroller. This was separated into single axis and dual axis, as one axis was turned via sensors and the other via calculation. The basic idea behind the single axis tracking code was the following:

- Assign a positive and negative direction
- Read the difference in value from the two sensors.
- If the value is positive, turn the positive direction, if negative, do the opposite
- Keep turning until the sensors are reading the same values.
- Stop turning

To minimize risk due to issues such as the panel jittering back and forth between small angles; not settling in one position, measures were designed in the code to minimize stability issues. This included inputting a sensitivity value, which is the minimum difference value at which the panel is allowed to move. In addition to this, several measurements over a set period of time are taken in order to reduce the effect of errors or noise.

For the secondary axis the tilt is calculated directly in the microcontroller, without any sensory input. The decision to perform calculations for this axis was because of the very limited motion it does throughout the year, only needing to tilt between the summer and winter solstices and back once a year. For the location in which this project has been developed, these angles are according to a model by Andrew Marsh between 11.6°-58°[18]

The implementation of the software was done in the Arduino language, which is based on C/C++. The single axis tracking part of the code runs on a continuous basis in a loop as it throughout the day needs to adjust. This is the main loop:

```
void SolarTracker::trackAndAdjust(){
  double sensorDifferences[3];
  double averageArray[3];

  for(int j = 0 ; j < 3 ; j++){
    for(int i = 0 ; i < 3 ; i++){
      sensorDifferences[i] = analogRead(_ldrEast) -
                             analogRead(_ldrWest);
      delay(50);
    }
    averageArray[j] = getAverage(sensorDifferences);
    delay(500);
  }

  int decision = decideDirection(averageArray);
  turnMotor(decision);
}
```

Input from the sensors is read at some interval set by the delay, which is then averaged and sent to a function which reads the averages to decide if and which direction to turn, and finally the decision is passed to a function which can instruct the motors to turn. Figure 4.4 is a flow diagram describing the single axis tracking.

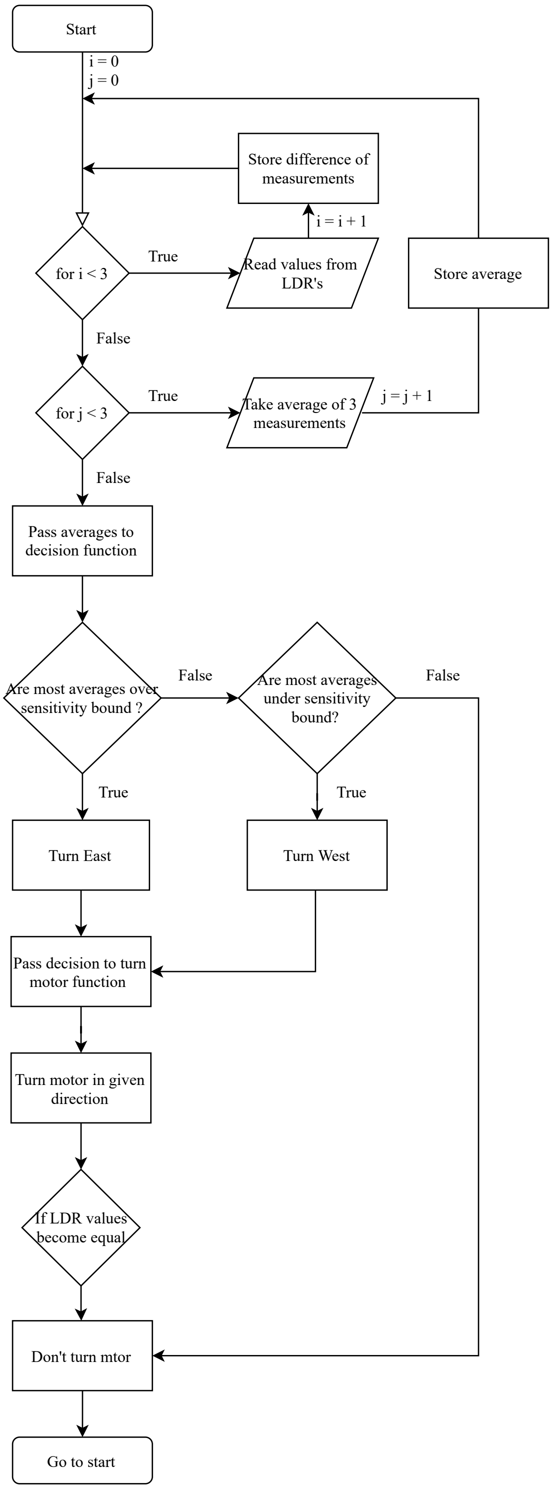

Figure 4.4: Flow chart for single axis tracking.

The dual axis tracking is not run in a constant loop during the day, but instead run once when the system is started, as it only needs to be set once per day. It is built on two functions. One function which takes the Suns zenith angle for the specific day and outputs how many steps the motor needs to turn from the standard zero position to face this angle. The output of this function is then passed to a function which instructs the motor to turn that amount of steps. The first function is as follows:

```
int SolarTracker::getSecondaryMotorPosition() {
  float degreesToPosition = HIGHEST_SUN_POSITION_TODAY-
                                    ZERO_POSITION_ANGLE;
  float bigStepsToPosition = degreesToPosition/1.8;
  float smallStepsToPosition = bigStepsToPosition*GEAR_RATIO;
  return -smallStepsToPosition;
}
```

In this function the daily highest sun position in degrees needs to be input manually, which then converts it with regard to the gear ratio for the motors and gears to the amount of steps for the stepper motor, and passes it to the turnSecondaryAxis() function.

4.2.4 Panel Load

To quantify the effectiveness of tracking the Sun with a solar panel, measuring the power outputs in both fixed and tracking positions is necessary. After gathering data throughout a certain time period, assertions could be made of the performance increase. However, solar panels as power sources are inherently different than both a simple voltage or current supply. The difference is that compared to a voltage or current supply, neither voltage nor current is constant when connected in a circuit, while the other can be calculated from Ohm's Law, but both of those units are changing depending on the load or total resistance in the circuit.

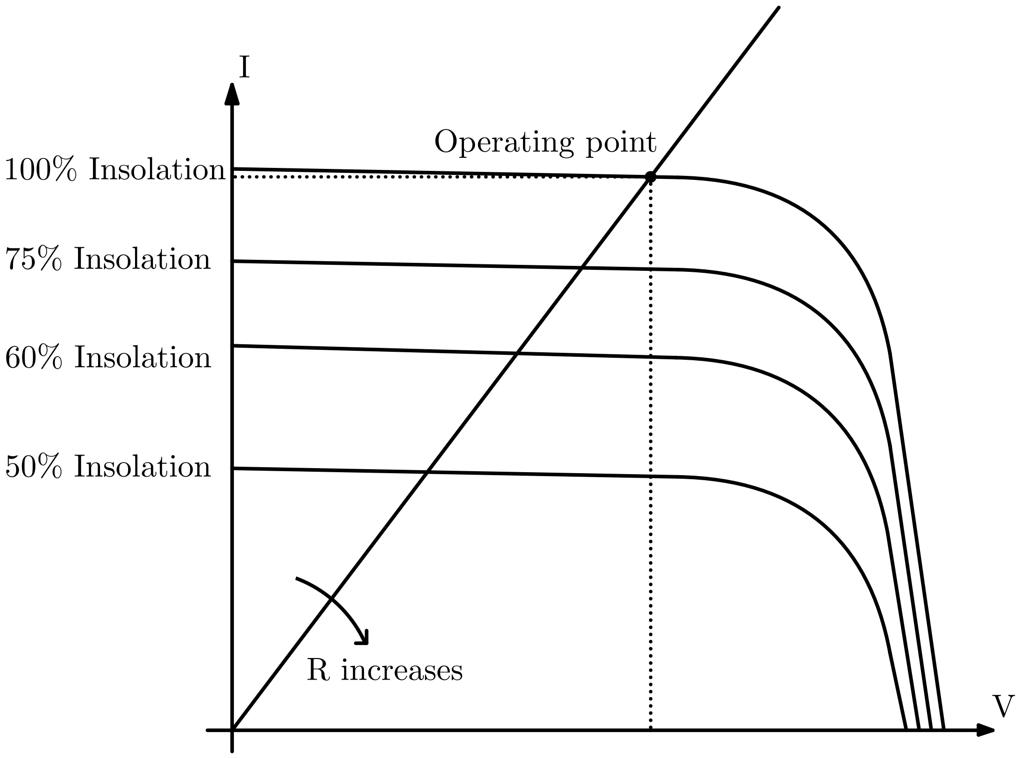

Figure 4.5: I-V curves of a solar panel with multiple insolation levels. Insolation is a term for the amount of incident solar radiation

In order to effectively compare the power output values in different settings, the operating point of maximum power should be found. Otherwise, the comparison of power values would be at arbitrary points of the solar panel's power curves. Finding the maximum power of a solar panel is called Maximum Power Point Tracking, or MPPT. To find the optimal operating point or Maximum Power Point, a variable load must be connected to the circuit as shown in Figure 4.5.

In real world applications, this is done by DC-DC converters, where by controlling the impedance seen by the source circuit(where the panel is connected), the Maximum Power Point can be found, thus maximizing the power output on the load circuit(where, for example, a battery would be connected). Using a DC-DC converter is beyond the scope of this project, so a simpler electronic solution is needed.

As a solution, a MOSFET is used, by taking advantage of the fact that a transistor can not go from practically infinite to practically zero resistance instantly when varying it's gate voltage. This means that by incrementally changing the gate voltage, the MOSFET can assume any kind of resistance value between several mega ohms to almost zero ohms. Another advantage of using a MOSFET is that it can withstand high amounts of both voltage and current, capable of conducting well above a hundred watts of power.

To control the MOSFET resistance arbitrarily, its gate is connected to an analog output pin on the microcontroller, which uses PWM (Pulse Width Modulation) to output a certain voltage. This allows for a finely tuned control over the resistances seen between the MOSFET's drain and source ends.

After maximizing power output to be able to compare performance in a fair way, reading those power values from the microprocessor is necessary. To obtain these values, both voltage and current measurements are needed. Since the maximum voltage can be a higher value than the maximum permitted voltage on the microprocessor's pins, it has to be fit into a 0-5V range by a voltage divider. To measure current, a current sensor is connected into the circuit which is also connected to an analog pin on the microprocessor to evaluate its measurements.

Between setting the MOSFET gate voltage to some value from the microprocessor, and measuring the panel's voltage and current from the voltage divider and the current sensor, some time has to pass so that more precise values can be measured. Since there are by default 1024 values that can be set to the analog pins of an Arduino Uno, trying out all of them would take up a considerable amount of time. During that time, obstructions could have a negative impact on measurements, for example clouds passing by and thus changing the entire power curve, the MOSFET heating up and changing its resistance even though the PWM signal is the same, etc. To minimize the risks of these happening, the time frame needs to be shortened by more optimal algorithms than simple linear search through the range of PWM signals and corresponding power outputs. Since the general shape of a power curve is known, and the relationship of the MOSFET's drain-to-source resistance and the microprocessor's PWM signal is also known, a linear and a binary search approach can be combined to reduce the time it takes to measure and the number of measurements needed.

From precise multimeter measurements, it can be observed that the MOSFET is in an OFF/open state until passing around 30% of the PWM signals, and fully ON/closed state after passing 45% of the PWM signals. This already cuts out around 85% of all signals, and gives 15% of the values where the Maximum Power Point could actually be. This can be restricted to a range of values given by iterating through the range of PWM values from lowest to highest and see when the current sensor starts measuring any meaningful increase in current, and iterating from highest to lowest PWM values and seeing when the voltage divider shows any kind of meaningful voltage drop from the open circuit (highest possible) voltage. These measurements do not need to be very precise, since this is the initial phase of the algorithm. The waiting times that normally are there to make sure the power value has settled can be skipped. After finding the range of useful values, phase two of MPPT can now be performed. Here is when a binary search approach is needed, and where the actual shape of the power curve comes into play. The power curve, as seen in 4.6, increases until the MPP and decreases after, this can be used when looking for the MPP.

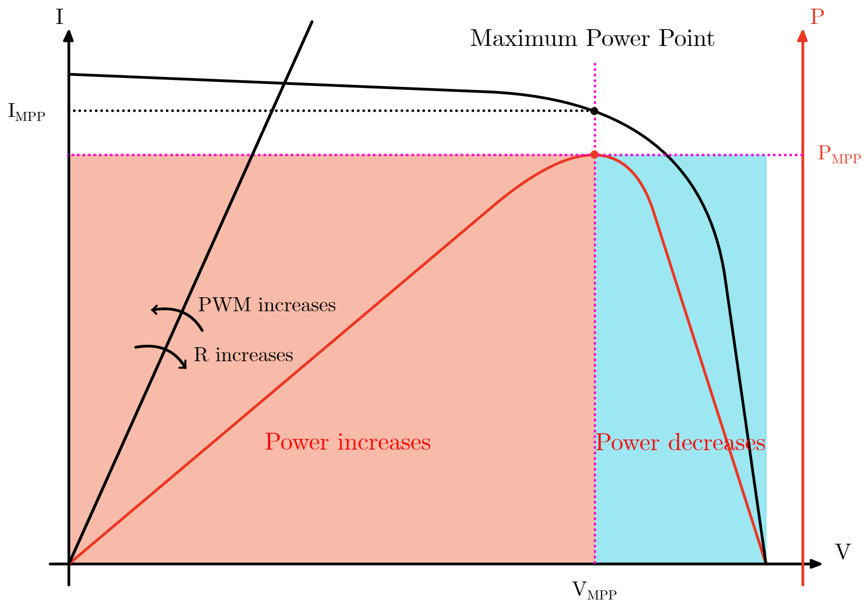

Figure 4.6: I-V and power curve of a solar panel. Relationship between PWM and resistance to I-V curve shown.

To find the Maximum Power Point, the PWM signal to pinpoint is the one that has a higher corresponding power output than both neighboring signals, each measurement having sufficient time to be performed so that the resulting mean from the measurements is statistically representing of the true mean value. By checking the power outputs due to a signal and it's neighboring signal, it can be decided if the signal is within the increasing or decreasing region of the power curve. In each iteration, the goal is to decrease the interval of possible values, by moving the left boundary to the midpoint if the midpoint is increasing, or moving the right boundary to the midpoint if the midpoint is decreasing. After performing enough iterations, the interval will be one value only, which will be arbitrarily close to the Maximum Power Point of the solar panel. A flowchart describing the algorithm can be seen on Figure 4.7.

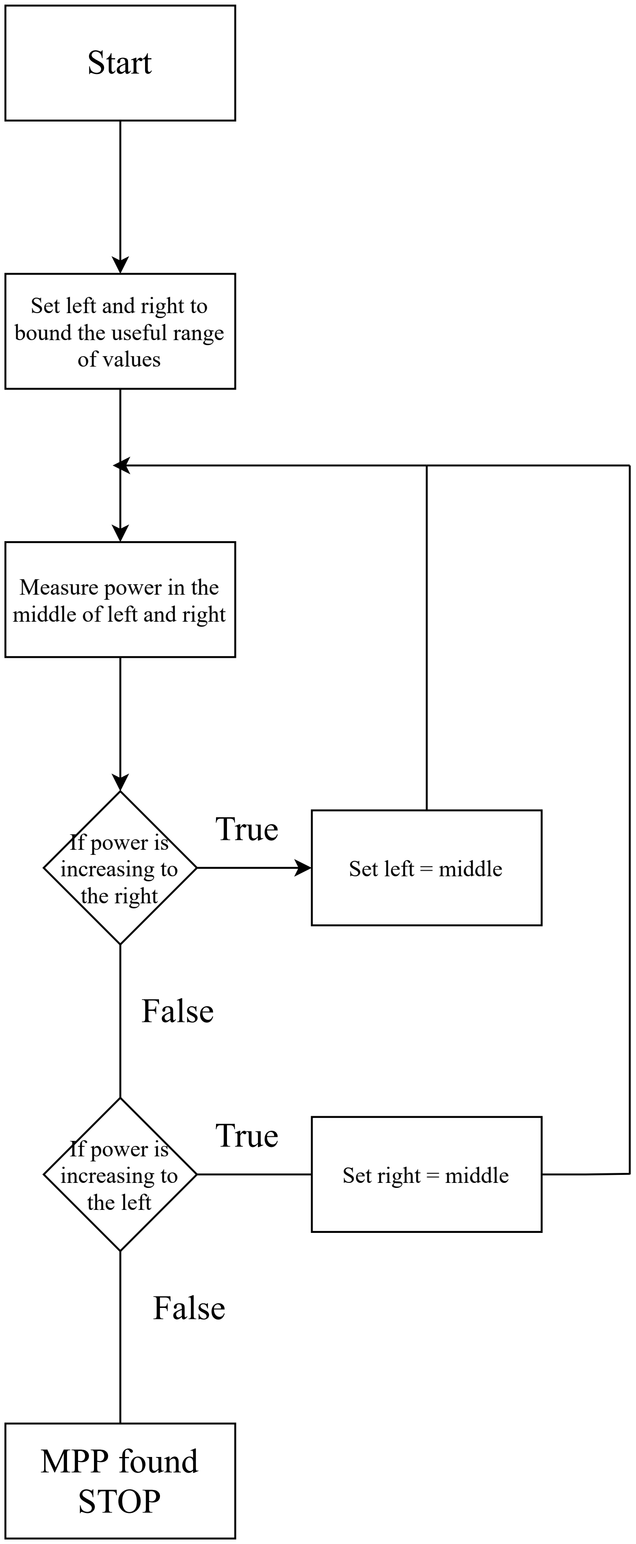

Figure 4.7: Flow chart for the MPPT algorithm. Left is the left pointer for the lowest currently viable PWM ratio, right is the highest currently viable PWM ratio and middle is the middle of these two values.

Circuit

The algorithm explained in figure 4.7 applies the PWM voltage to the following circuit.

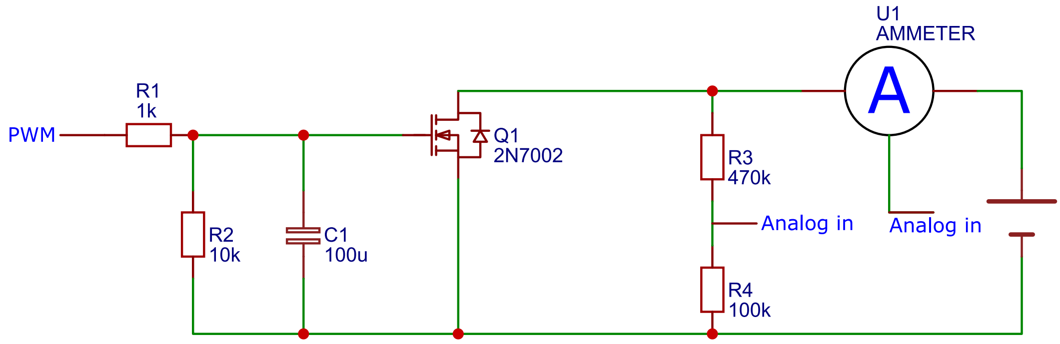

Figure 4.8: Load controller circuit.

The Arduino is reading the voltage and current from the voltage divider and the ammeter, respectively. Details of the circuit are explained in section 4.3.2

4.3 Technical specification

4.3.1 Frame specifications

The frame is a wooden pallet with wheels on the bottom, on top of the pallet is a steel scaffolding pipe where the solar panel is mounted on the right side of the panel is a geared stepper motor which is linked with a chain to a gear so it can move along the Y-axis to follow the sun across the sky, this is not the optimal placement since it is on the turning point on the panel it could make the balance on the mount uneven, so a more powerful stepper motor would be required for the base. In the middle of the pallet is where the second geared stepper motor is located that is connected with a chain and gears, attached to the solar panel mount in the middle, this is the ideal placement for the motor, minimizing the load on the motor and how much torque we would need in the motor.

The motors used are NEMA23 stepper motors with a built-in gear ratio of 1:47. The gears connecting the motors to the panel are both 16 teeth on the motor and 38 on the panel's side, giving a total of 1:111.625 as the gear ratio. This increases torque seen on the panel's axes by a factor of 111.625, but also decreases angular speed by the same factor of 111.625. This is a beneficial trade-off, since this use case does not require high speeds, but high torque.

4.3.2 Electronic connections

Circuit schematic

The schematic in figure 4.9 There are two LDRs to the left with connections to 5V and an analog pin each, through a voltage divider. The Arduino is in the middle, and to the right the battery, stepper motors and their drivers. Both the battery and stepper motor are connected with the driver, the battery in VCC with 9V and in ground, the stepper motor in the A and B outlets and the drivers are connected to two digital pins each.

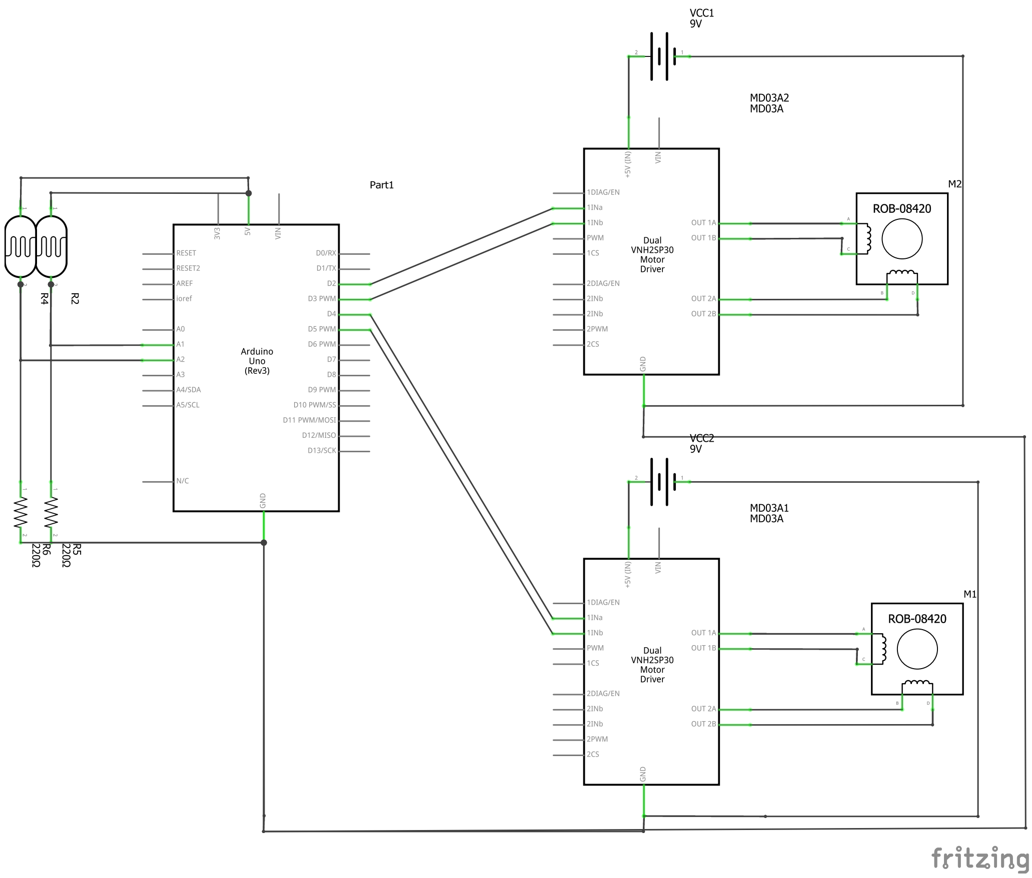

Figure 4.9: Schematic of stepper motors, drivers and LDRs.

LDR mount

The sensor mount is designed with a wall because its purpose is to start shading a sensor when they are at an angle to to sun. Without the LDR mount, the values of the two different LDRs would be similar all the time which results in the system not being able to decide which way to turn, because the decision is based on random noise and the decision will also be random. With the wall separating the LDRs, the outcome will be two different values when it is not pointed directly at the Sun, which is the goal. The panel can then turn until the two LDR sensors values are the same. Then the panel will be at its most optimal angle. Figure 4.10 shows the LDR mount from the top. Each LDR is mounted on one side of the wall, and the two holes in the top and bottom are for screws.

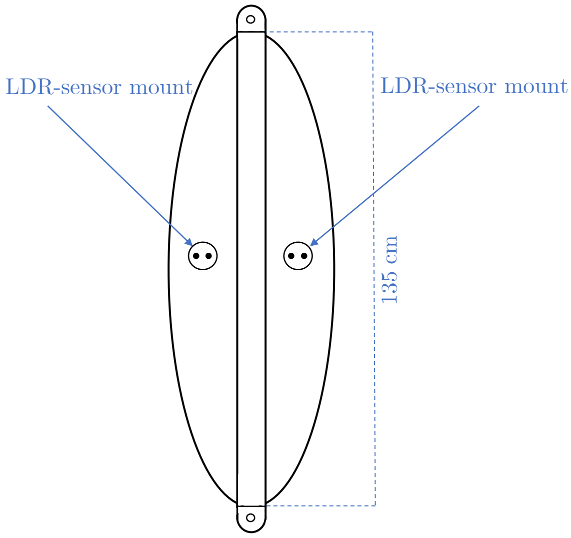

Figure 4.10: The LDR mount seen from the top.

Figure 4.11 shows the LDR mount seen from the side. The mount for the LDRs with an angle at 85 degrees relative the wall is seen here. This ensures that the values of the LDRs aren't similar in value, unless it is at its most optimal angle.

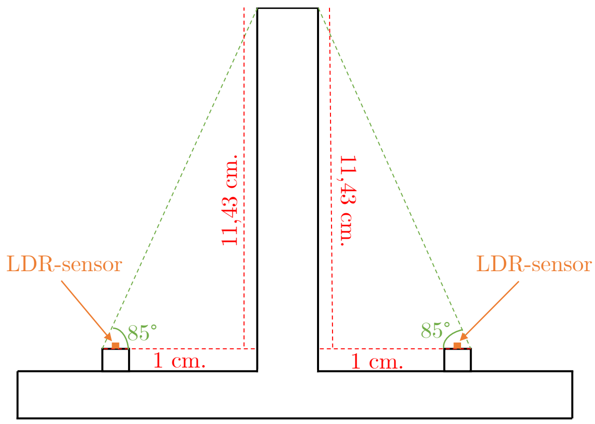

Figure 4.11: The LDR mount seen from the side.

In order to get the same angle relative to the sun, it is necessary to mount the mount to the solar tracker itself as shown in Figure 4.12. The mount is screwed onto a wood plate which is screwed directly into the side of the solar panel. This makes sure that whatever angle the solar panel is at, the LDRs would always be at the exact same angle. The wood plate is also necessary to get the LDRs a few centimeters away from the panel. Otherwise solar panel's shadow would affect the LDRs.

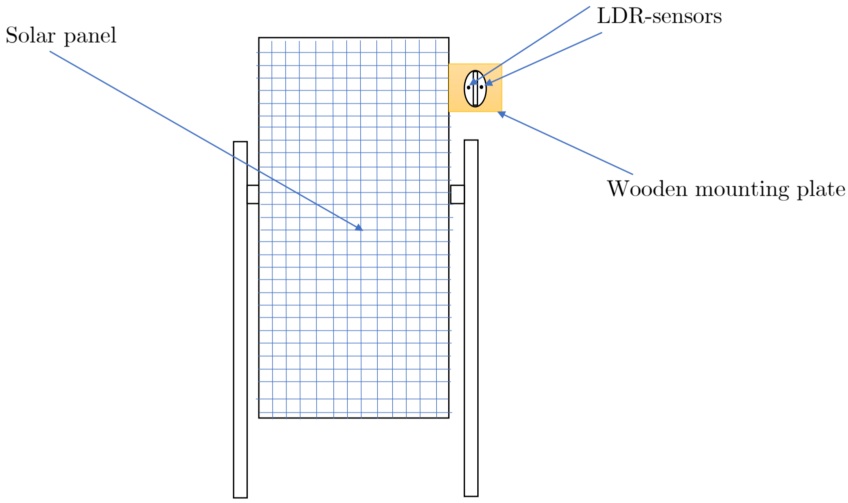

Figure 4.12: The LDR mount attached to the wooden plate next to the panel.

Load controller circuit

The schematic for the load controller circuit can be seen on Figure 4.8. On the right side, the solar panel as a power source can be seen. From there, a current sensor is connected, which is used to measure the current that the solar panel outputs. The analog pin from the sensor is connected to an analog pin on the Arduino Uno. Next is the voltage divider, where comparatively large resistors are connected, so that the whole circuit's resultant resistance is not affected by the two resistors of the voltage divider in a noticeable way. The maximum voltage on the panel is 21.5V, so the voltage divider has to divide that by at least 5 times. This circuit cuts it down by a factor of 5.7, making the maximum voltage as measured from the Arduino 3.77V. This is found using the formula for a voltage divider.

$$V_{out} = \frac{R_2}{R_2 + R_1} \cdot V_{in}, \tag{4.1}$$

substituting values into the formula it returns the factor of 5.7

$$V_{out} = \frac{100k\Omega}{470k\Omega + 100k\Omega} \cdot V_{in} = \frac{1}{5.7} \cdot V_{in}. \tag{4.2}$$

The MOSFET, which is the main load on the circuit is controlled by pin 9 of the Arduino. This is crucial, since the standard 8 bit resolution on the PWM signal is simply not sufficient for this application, so pin 9 and 10's ability to produce finer signal is taken advantage of, using instead a 13 bit number for analog output(8192 steps to go from 0-5V)[12]. A 1kΩ resistance is used to protect the microcontroller if the gate and drain short, while a 10kΩ resistance is connected to ground to give the gate a path to discharge the gate and a 100μF capacitor is connected to ground to flatten out the PWM signal, turning it into more of an analog value, this is sacrificing some speed in the circuit, but that is not much of a concern here since the MPPT doesn't have to be performed continuously.

4.4 Construction

The mount for the solar tracker consists of metal scaffolding pipes, forming a right angle triangle shape, which are screwed on a pallet that provides support and stability for the whole construction. Furthermore, there are metal wheels on the bottom side of the pallet which aids with transportation of the sun tracker, due to its weight.

On the metal pipes there is a wooden board which is screwed into the fours corners to the scaffolding's pipes. The wooden board is used as a base for the gear motor which rotates the solar tracker. A wooden block is screwed on the board for support of one of the motors and for welding the small gear wheel on a metal sheet that is screwed for the wooden block.

For holding the tracker onto the stand a custom frame has been designed. The frame is made of three steel profiles that are welded in the corners. At the ends of two steel profiles a steel pipe is welded, running halfway through the panel, allowing it to move in the Y-axis. The other gear motor has been welded to the right steel profile alongside with a big gear wheel. For fixing the tracker on the made stand a cylindrical pipe has been cut and fitted with one of the bike gear wheels. Afterwards it has been welded to both the steel frame and to a metal sheet that is screwed into the wooden board.

For the movement of the solar tracker four bike gear wheels and two chains have been used that drive the tracker in the two axis. In order for the tracker to rotate light has to be detected using the two light sensors mounted on the left side of the panel. The two light sensors are held on a 3D printed model, being separated by a wall.

4.5 Experiments

4.5.1 Description of the experiment

As the stated issue in the problem definition concentrated on the advantages, scalability, and economics of solar tracking, the experiments that were intended for the protoype were designed to test the function of the design and the efficiency of the design. Testing was to be focused on both the function of individual parts and on the larger goals. This was to be done in the following way:

- Test of sensor tracking system.
- Test of MPPT system.
- Comparison of efficiency gains from solar tracking.
- Energy losses due to tracking.

4.5.2 Test of the sensor tracking system

Method

The tracking system was moved to a dark room and a flashlight was used to provide a movable light source to see if the tracking system could adjust to changes in the light level. The following tests were run:

- Check if the tracker can track the light in both directions.
- Check if the tracker could stop in the middle of moving and turn the other direction.

After these tests it would have been optimal to test the tracker with sunlight, but due to weather conditions these tests could not be run.

Results

The tracker passed both indoor tests, indicating that it can track a moving light source. It is expected that the tracker can do the same with real sunlight since the wall between the two LDRs didn't let light through when using a flashlight.

Sources of error

The primary concern during testing outdoors is diffuse radiation or light being reflected directly into one of the LDRs, this could make the tracker rotate the wrong direction.

4.5.3 Test of MPPT system

Method

The tracker is to be brought outside and placed in sunlight. An ammeter is placed in series with the panel and a voltmeter is placed in parallel to the panel, then the panel is connected to the MPPT circuit. After connecting the panel to the circuit the MPPT algorithm is run and the power output is logged. Then the panel is unplugged from the MPPT circuit and placed through a variable resistance, the MPP is manually found by turning the dial on the resistance and the power output is logged. These values can now be compared to figure out how effective the MPPT is.

Results

The test could not be run because of weather conditions. The expected result is that the MPPT algorithm picks a PWM ratio fairly close to the optimal PWM ratio since the resolution is fairly large on the PWM ratio.

Sources of error

A discrepancy between the two power outputs measured could be explained by, the Sun moving, the solar panel being moved and shading

4.5.4 Comparison of efficiency gains from solar tracking

Method

There are three modes of tracking to test: Fixed solar panel, single axis tracking and dual axis tracking. These three modes should be tested concurrently, this makes comparing the different modes easier since they are experiencing close to the same amount of irradiance. The panel is set to the standard position, pointing directly south, MPPT is performed and the power logged. Then the single axis tracking is done, keeping the tilt the same, MPPT is performed and the power logged. Then dual axis tracking is done, keeping the rotation from single axis and changing the tilt, MPPT is performed and the power logged. Doing this every 30 minutes, should give good grounds for comparison. This should also be done over multiple days.

Results

The test could not be run due to weather conditions. The expected result is that single axis provides more power during the day than fixed, somewhere around

20%. Dual axis is expected to be slightly better than single axis tracking, but as seen in table 2.3 there isn't much difference between single and dual axis tracking.

Sources of error

Doing the measurements concurrently reduces the sources of error, but weather could still get in the way, a cloud could pass by while doing the measurements. The same tracking concerns as in 4.5.2 are relevant here.

4.5.5 Energy losses due to tracking

Method

A normal day of tracking is performed, while the tracking is running current and voltage on the motors are measured. Then the power consumption from an entire day can be subtracted from the power gain of tracking, if this number is positive then the tracker is generating more power than it is using. This should be done on multiple days with differing amounts of sunlight. This should be repeated for both single and dual axis tracking.

Results

A normal day of tracking could not be performed due to weather conditions. The expected result is that in general the power consumption of the motors is negligible since they are only running for a few minutes out of the entire day. An interesting result from this would be using the consumption data from the secondary motor to determine if it is worth it to adjust the tilt every day or every few days. Or, to find the optimal minimum amount of rotation.

Sources of error

Faulty measuring equipment.

Chapter 5

Discussion

5.1 Prototype

5.1.1 Sensors

The Sun produces UV, IR and visible light. When picking a sensor it makes sense to think about availability, what kind of light it senses and how easy they are to test. UV and IR sensors have some issues first of all, humans are not able to see those wavelengths making it hard to test since you won't be able to rely on your senses for troubleshooting. Furthermore UV and IR aren't the primary source of energy for solar panels. While IR sensors are fairly available, UV sensors are not as available. LDRs are very available and they measure visible light, making it easier to troubleshoot problems, and they are easy to work with.

5.1.2 Software

Changing the code during testing was frequently necessary in order to experiment with different ways to make the system stable and less error prone. With many changes being made over time, it would have been easier to work on in an online environment which saves previous versions and allows access to all group members at all times.

Keeping better track of the position of the motors would be helpful for calibration purposes if the tracker were to be left out for an extended period of time, this could be done using limit switches and programmatically defining the zero position from there. The issue with keeping track of position in the systems current state without switches is that the stepper motors risk skipping steps, meaning errors would build up over time.

5.2 Testing

The main issue hindering testing with the prototype was weather. Lack of visible sun meant that neither the sensor tracking nor the MPPT could be tested. This meant that further testing to research efficiency or economics was made unfeasible. These tests would have been easier to perform during summer months when sun is more available. Although the goals of testing for efficiency and economics were not reached, it has potentially been shown that both sensor tracking and MPPT systems can be built with very low cost devices. Even though the weather conditions meant that testing was not a possibility, a hypothesis can still be made. This means that it can be described how the testing should take place and what results are expected.

5.3 Future work

Making the measurements more automatic by sending the data to a server, this would allow testing to be easier and allowing for more measurements during the day. This would also necessitate making sure everything can handle poor weather conditions. Improvements to the mount are crucial to ensure that it works properly during testing, needing minimal amounts of maintenance, this would mean using better gears and making sure nothing could get stuck in the chain by adding a screen, this would also serve as a security measure. Adding a display that shows information about the performance of the tracker would make it easier to do maintenance and have real time information about the tracker.

Chapter 6

Conclusion

The goal of the project was to develop a solar tracking system, with the aim of showing the efficacy of such a tracking system. It was decided that this would involve using a tilted rotational axis tracking system, since that reduces the amount of movement needed for the motors, while still mimicking the path the Sun moves in the sky. A solar tracker was designed and tests were run to ensure it could follow a moving light source, this was done with good results, the tracker could track a flashlight moving from one side of the panel to the other. A MPPT system was designed and constructed to ensure the panel is providing the maximum amount of power possible by controlling the load on the panel, no conclusive tests could be run on this system, but theoretically the MPPT system should work, based on the fact it has access to $2^{13} = 8192$ values for the PWM ratio. A simple theoretical calculation has been made and results from other studies have been researched in section 2.2.4. From the studies an increase between ~20%-40% has been seen and the very simple calculation proposed here provides ~58%. Though not enough tests were run, it can be stated, with a fair amount of certainty, that solar tracking does help provide more power.

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Chapter 7

Appendix

Code

The code can be found on GitHub: `https://github.com/NorbertPap/SolarTracking`.

Midway Process Analysis

Introduction

At the time of this text being written, our group has been working on a project within the subject of *Basic Electronic Systems* for almost three months. This endeavor is a part of a first semester curriculum for the *BSc Applied Industrial Electronics* program at AAU Esbjerg. The project's specific topic is Sun Tracking, where the aim is to build a system which allows a solar panel to rotate in order to track the sun, with the goal of increasing the efficiency of the panel. During this process a course in *Problem Based Learning* has worked alongside the project equipping us with tools to work more efficiently within the group and with the project itself. The aim of this text is to analyse how the project has evolved through time with the acquisition of differing tools from the courses, and how it has affected our work, what problems have been encountered, and what can be improved for future project work; both for finishing the current one and for future ones.

Project Management

The initial structure of the project work was set by the university. The group members were picked by the university administrator(s), and initial work was guided by tutors and a supervisor, also pre-chosen. The first weeks were used to work on the P0, an introduction meant to research the topic we had chosen, Sun Tracking, and formulating a specific problem which we were to solve. We started out with an initiating problem:

Why is sun tracking not ubiquitous, when it is accessible and usable?

From this initial guideline we conducted research to answer this question, and further narrowed down our problem definition. This was mainly done individually, as we split up our research into a few key topics we wanted to cover and delegated the topics to group members so that we could work independently and simultaneously. After this process we concluded that we were going to build our own Sun Tracking module, in order to first hand research the advantages, scalability and economics of this technology. Parallel to this, we created a backcasting timeplan, helping us structure key deadlines we wanted to achieve during this phase. This part of the project culminated in a P0 presentation, where we presented our initial findings for two supervisors and an opponent group. This presentation was a positive experience for several reasons; it mimicked the structure that our final project exam will have later, and it gave valuable feedback from several angles, not just ones that our initial supervisor had given us earlier.

From this point onwards the responsibility on the group itself to structure our work was higher. It became quickly apparent that more group meetings were necessary in order to discuss where to go next. Although we had decided to build something; how it was to look, what components it should contain, size and so forth were still entirely unknown. By this point we had written group and supervisor contracts, but quickly realized that they were far too short and unspecific. This period in the project was very unstructured, as we had almost infinite options, and were largely left to our own devices. Important feedback we had gotten in the P0 presentation was to always keep in mind the curriculum requirements for the project course. Since the main focus within the course is to solve a problem using sensors, we started with this part. We worked on using light dependent resistors and programming in order to get inputs which we can use to decide when to move the panel. From this base we found it easier to then start with acquiring additional parts such as the panel, motors, and utilizing the student mech lab to get help with building a frame. During this process we continually had to discuss where we were headed, narrowing down specifics with the design and parts. This process has correlated well with the curriculum necessities of defining, analyzing and setting up solutions to our problem. Looking back upon this part of the project a few things could be improved for future projects. For one, discussing perception and ambition for the project would have made design progress quicker. Group members' individual goals with the project were brought up to some extent but not in a particularly formal manner, thus discussions surrounding size and complexity of the design were hard to pin down.

Cooperation

The curriculum states under its competences section that it is necessary to:

Be able to contribute to team work, cooperate, handle conflicts and ensure motivation in the project work

These topics were covered during lectures in the PBL course, and assignments were given in order to work with these topics in the project groups. Cooperation and teamwork was to be structured under a group contract which we were to write. Although our group did complete the task and sign the contract, we realized soon that the contract was lacking in areas. The contract was for example far too broad. A section guiding our conduct if rules were broken was written, but it turned out to be far too broad and lacked details. Running into issues during the project was thus unnecessarily time consuming since we could not easily refer to the contract for exact guidelines. Although we did have opportunities to rewrite our contracts, by the time that this was made apparent, we were far too focused on the technical part of the project and thus pushed it aside. This is something that for future work will have to be revisited properly. Pushing such administrative tasks to the side in favor of the technical parts is a problem that was pointed out as common by the lecturer, yet it is something we knowingly did anyway.

- **Roles in group**

Roles within the group have not been dictated formally. Over the course of the project roles have however formed to an extent. These roles were for example contacting and booking meetings with the supervisor, planning administrative tasks and meetings, steering group liaison and so forth.

- **Task management**

Tasks throughout the project have been handled somewhat sporadically. Initiative has come from individual members splitting up the project into smaller tasks, and then tasks have been chosen by the remaining members at a first come, first serve principle. For example during the final design phase of the project time was running short and the workload was split into three parts:

- Panel
- Mount
- Sensors

We then chose ourselves what we would prefer to work with, ending up with 3 groups of 2 people. In doing so we could all work in parallel, making simultaneous progress on several fronts. It may have been beneficial if we split up the workload earlier, in case any major issues would have arisen. Progress was rapid during this phase, and we agreed that updates from all subgroups should be presented at least once a week, so that we could steer additional resources to other parts if need be. These progress reports were however not executed exactly as planned, updates were done but very informally in conversation or in our messenger group instead of during official group meetings as initially planned. One could argue that this isn't necessarily an issue when group sizes are fairly restricted as now, but of course had this been a larger engineering project it would be all the more important to go through with more official administrative tasks and meetings.

Cooperation with the supervisor

The supervisor has for the duration of the project had different levels of involvement in the project. During the first half; through the P0 and the first part of P1, the supervisor was involved quite a bit, as the uncertainties throughout the first stages required more guidance. The guidance in the beginning was mainly around how a project is supposed to be done, what the goals were, structure and so forth. This however changed once the design stage had gotten further, and more questions around technical parts came about. The initial routine was weekly meetings, but once the design had started coming together the supervisor suggested we book meetings only when needed, unlike the once per week we had previously had. Holgaard et al.(2021 p.86) describes this as a process supervisor, which in general is more present at the beginning of a project making sure that the project gets going, but gives the students the responsibility of learning and finishing the task. This has worked very well for our group, as we have not encountered any issues with the supervising.

Summary

In summary, the group work effort has been functional but somewhat informal. This has worked but carries risks of work being missed or mismanaged, and is something to improve on for future work. The style of supervision has worked well, and no issues have arisen. Giving formal roles to individual members would be a good way to disambiguate who is responsible for which administrative tasks.

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