# DESIGN AND SIMULATION OF SINGLE AXIS SOLAR TRACKER FOR IMPROVING THE EFCIENCY OF PARABOLIC CONCNTRATOR

A Thesis Submitted to EIT-M, School of Mechanical and Industrial Engineering in Partial Fulfillment of The Requirements for The Award of The Degree of Master of Science

in

**Mechatronics Engineering**

by

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**December, 2024**

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I hereby declare that this thesis is the result of my own investigations, except where otherwise stated. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea/data/fact/source in my submission. I understand that any violation of the above will be cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from who, proper permission has not been taken when needed.

Name of Candidate: Awet Welay

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## ADVISOR'S DECLARATION

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge and the thesis is adequate for the award of the degree of Master of Science in Mechatronics Engineering.

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This is to certify that Awet Welay has incorporated all comments forwarded by the external and internal examiners as well as by chairperson during the thesis defense held on...............2024.

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Thank you,

Awet Welay

# ABSTRACT

This research explores the design, simulation, and analysis of an active single-axis solar tracking system aimed at addressing the challenges associated with optimizing the performance of parabolic solar concentrators. Solar concentrators, particularly parabolic designs, offer significant advantages in harnessing solar energy for thermal applications, yet their efficiency is highly dependent on precise solar tracking. The current study develops a robust system designed to improve tracking accuracy, withstand challenging environmental conditions, and enhance overall system performance. Finite Element Analysis (FEA) was employed to validate the system's structural reliability under extreme wind speeds of up to 55 m/s, a critical factor for ensuring operational stability in windy regions like Ethiopia. Additionally, dynamic modeling and control system design were carried out using MATLAB/Simulink, where a PID controller was tuned for optimal tracking performance. Results from simulations showed that the system achieved a tracking accuracy of over 96%, with minimal errors even under disturbances. These findings underscore the importance of integrating advanced tracking mechanisms in renewable energy systems to maximize energy capture and utilization. By addressing key challenges identified in existing parabolic concentrators, this study contributes significantly to the body of knowledge on solar energy systems and presents a practical solution for enhancing their efficiency, particularly in resource-constrained settings like Ethiopia.



**Key words:** Solar tracking, parabolic concentrator, finite element analysis, PID controller

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# LIST OF SYMBOLS

| | |
|---|---|
| $IEA$ | International Energy Agency |
| $PCM$ | Phase Change Materials |
| $MSS$ | Maximum shear stress theory |
| MNS | Maximum Normal stress theory |
| FEA | Finite Element Analysis |
| $CSP$ | Concentrated Solar Power |
| $\rho$ | Air Density |
| $C_p$ | Drag Coefficient |
| MBD | Multibody Dynamics |
| $SPA$ | Solar Position Algorithm |
| LDR | light-dependent resistors |
| PID | Proportional Integral Derivative |
| MPC | Model Predictive Control |
| FLC | fuzzy logic controller |
| $e$ | error, exponential function |
| $k_d$ | Derivative Gain |
| $k_i$ | Integral Gain |
| $k_P$ | Proportional Gain |
| u$(t)$ | Control signal |
| $e(t)$ | Error signal |

# CHAPTER 1
# INTRODUCTION

## 1.1. Background and Justification

The human odyssey is intricately intertwined with energy consumption. As our global population relentlessly surges, so too does the demand for ever-increasing energy consumption. Fossil fuels, comprising coal, oil, and natural gas, have been the primary energy sources for centuries, powering industries, transportation, and households worldwide. However, their abundant use comes with a lot of disadvantages and have unveiled a harsh truth; their finitude and their effect on global warming. Their continued use casts a long shadow, one that stretches towards an environmentally precarious future marred by greenhouse gas emissions and a destabilized climate[1], [2], [3], [4]. Globally, energy consumption profile is largely dominated by fossil fuels with non-renewable energy sources accounting for as high as 83% of the total energy mix in 2023[5].

Despite being a rapidly developing nation in Africa with a population exceeding 129 million in 2024, Ethiopia faces a significant challenge in modern energy access. Biomass, including waste, remains the dominant source of energy, accounting for a staggering 88.1% of the country's energy supply. Oil contributes a modest 8.5%, while hydropower, with just 2.8% [6].

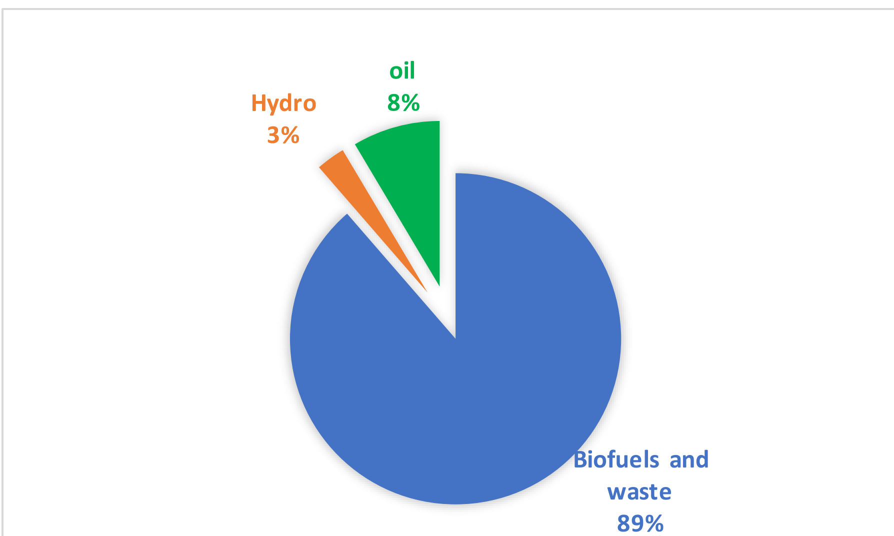


Figure 1.1: Ethiopia’s share of total energy supply in 2021 (International Energy Agency) [6]

In recent decades, the world has witnessed a profound shift in energy production, moving away from fossil fuels towards renewable sources like solar energy. This transition has been spurred by growing concerns over the environmental impact of non-renewable resources, particularly their contribution to climate change. Solar energy, with its abundant availability and minimal environmental footprint, it has become a symbol of hope in the pursuit of a sustainable future. [7], [8].

As the world intensifies its efforts to transition towards sustainable energy sources, the adoption of parabolic solar concentrators has emerged as a prominent solution in the realm of solar power generation. A Solar parabolic dish is an advanced solar collector that harnesses the power of sunlight through a precisely engineered parabolic reflector. This reflector concentrates sunlight onto a central receiver, intensifying its energy at a focal point. At this focal point, the solar energy is efficiently absorbed and converted into heat. This innovative design maximizes the capture of solar radiation, making Solar Parabolic Dishes highly efficient in converting sunlight into usable thermal energy [9], [10], [11], [12].

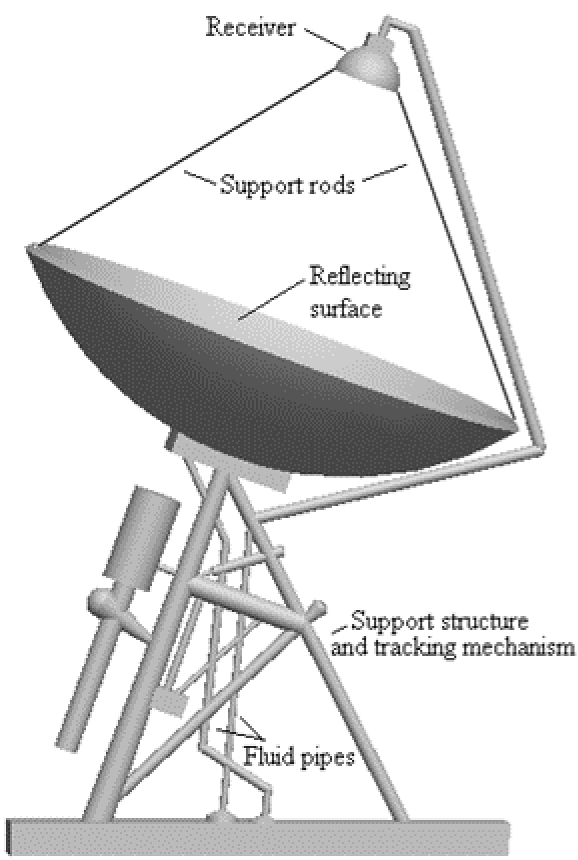


Figure 1.2: parabolic solar concentrators

Parabolic solar concentrators can achieve higher levels of solar energy concentration compared to flat photovoltaic (PV) panels.

Figure 1.3: parabolic dish solar concentrators [14]

However, this efficiency comes at a cost. Unlike their flat-plate counterparts, parabolic concentrators are highly dependent on the sun's position [14]. To maintain optimal focus and capture the maximum amount of sunlight throughout the day, they often require a solar tracker Figure 1.3.

## 1.2. Motivation of The Study

The increasing global demand for clean and efficient energy solutions, particularly in developing nations like Ethiopia, has underscored the need to enhance renewable energy systems. Solar concentrators, especially parabolic designs, have emerged as a promising technology for harnessing solar energy for high-temperature applications. However, their performance is often limited by inefficient tracking mechanisms, leading to reduced energy capture and system reliability. This study is motivated by the urgent need to address these challenges and develop an advanced active solar tracking system to maximize the efficiency of parabolic solar concentrators under real-world conditions.

Figure 1.5: Showcase and demonstration of the parabolic solar concentrator developed at Mekelle University [14]

This work draws significant inspiration from the pioneering efforts of Mekelle University in advancing solar energy technologies [13], [14]. The university's development of a solar concentrator system for Injera baking has demonstrated the feasibility of clean energy alternatives. By integrating phase change materials (PCM) for thermal energy storage, Mekelle University's project addressed the critical need for energy access while reducing reliance on biomass, indoor air pollution, and environmental degradation. However, the researchers highlighted areas for improvement, such as enhancing the robustness of the tracking mechanism and minimizing heat losses at the receiver. This study aims to build upon these recommendations, advancing the concentrator's design and efficiency by designing an active single-axis solar tracking system.

### 1.3. Statement of The Problem

While parabolic solar concentrators offer significant advantages in harnessing solar energy for thermal applications, their performance relies on precise alignment with the sun’s position throughout the day. Conventional fixed-mount systems cannot dynamically adjust to changing solar angles, leading to suboptimal energy capture and reduced efficiency. This not only limits the concentrator's potential but also challenges its wider adoption as an alternative to conventional heating methods. Thus, there is a need for a robust tracking system that ensures optimal orientation, maximizing energy capture and enhancing overall system performance.

## 1.4. Objectives

### 1.4.1. General Objective

The general objective of this thesis research is to design, model, and simulate an active single axis solar tracking system with a specific emphasis on enhancing the efficiency of parabolic solar concentrator developed by Mekelle University.

### 1.4.2. Specific objective

The specific Objectives of this research are:

- To design and analyze energy efficient solar tracking mechanism.
- To develop the dynamic model of the developed solar tracking system and design effective controller
- To design and analyze the performance of the controller for different environmental and working conditions.

## 1.5. Methodology: An Overview

In order to accomplish each specific objective of this research, a comprehensive array of scientific procedures, methods, and software tools were employed. The following sections delve into the methods and materials utilized to fulfill each specific objective.

### 1.5.1. Design and Analysis Energy Efficient Solar Tracking Mechanism.

To synthesis an efficient mechanical mechanism for the active solar tracking system, a morphological analysis was employed, considering different working conditions and functional requirements of the parabolic dish solar. To design the components of the active solar tracker for the parabolic solar concentrator a maximum sheer stress and maximum normal stress theories were used depending on the nature of the material and loading conditions of the component following appropriate mechanical design procedure, Figure 1.6.

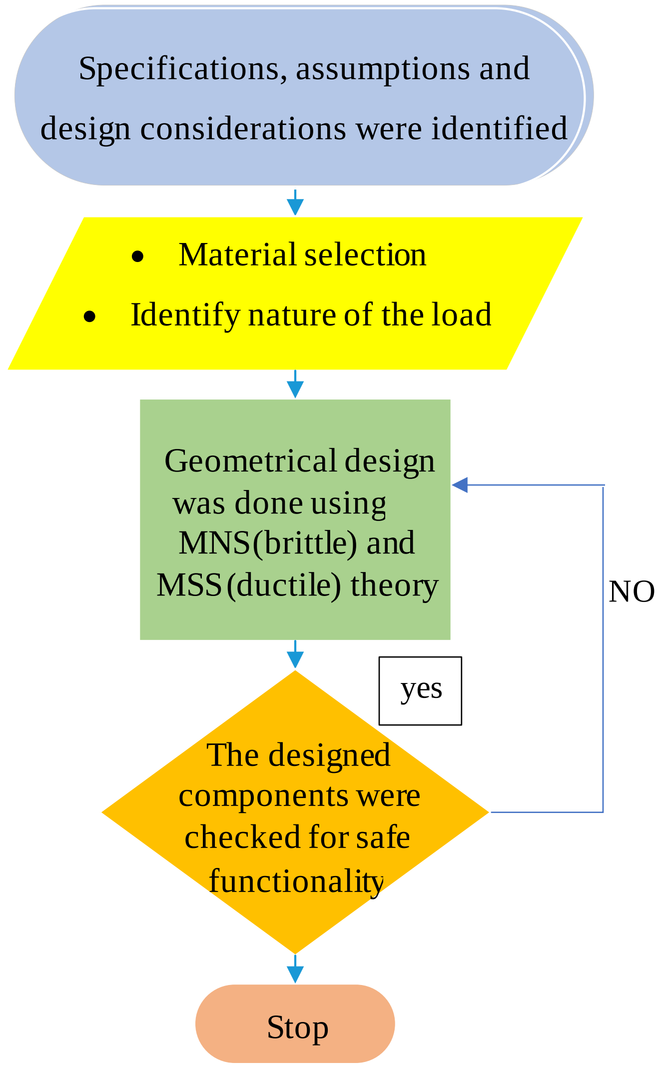


Figure 1.6: Mechanical design Procedures used for designing the active

After completing the mechanical design of the individual components of the solar tracking system, the 3D model of the system was created utilizing SolidWorks. Subsequently, Finite Element Analysis (FEA) was conducted on using ANSYS software.

#### 1.5.2. System Modeling and Controller Design for The Active Solar Tracking System

System modeling of the active single axis entails the comprehensive characterization of various system components, including parabolic concentrator, tracking mechanisms, sensors, actuators, and environmental factors. In order to design and simulate the controller a system model which resembles the actual system is necessary hence, a virtual representation of the parabolic concentrator was developed using a 3D CAD Modeling Software, SolidWorks, and then a Simulink model was developed using Simscape multibody modeling tool box, Figure 1.7.

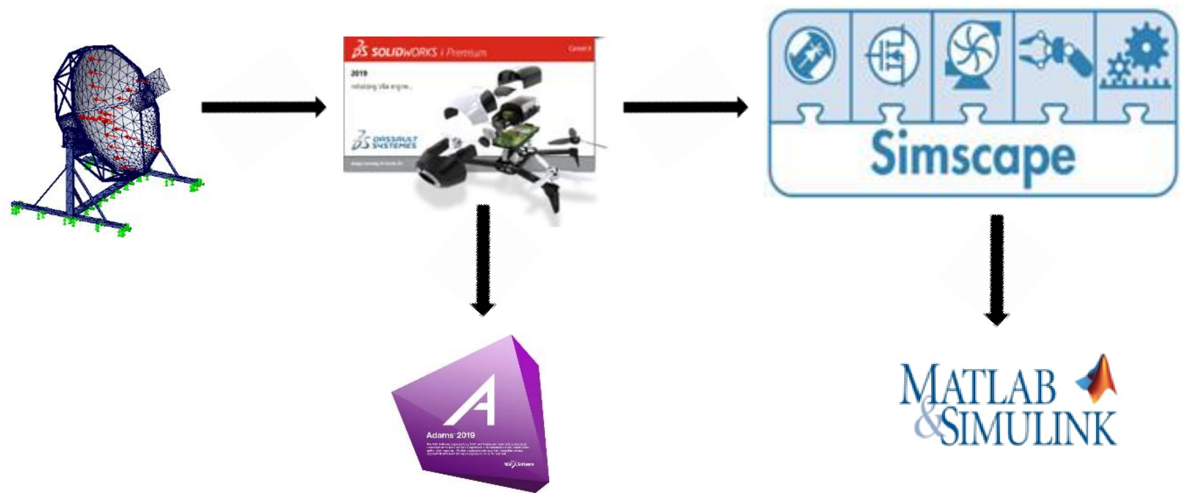


Figure 1.7: Software configuration used for the design, modeling and simulation of system

The Simscape Multibody toolbox, developed by MathWorks as an extension to MATLAB and Simulink, is a comprehensive toolbox designed for multidomain physical modeling and simulation of electro-mechanical systems. This facilitates the representation of mechanical systems using a combination of geometric, kinematic, and dynamic models, enabling to accurately capture system behavior, interactions, and constraints. Through its extensive library of prebuilt components, Simscape Multibody allows for the rapid prototyping and analysis of various mechanical systems, aiding in the design and optimization of a controller for the active single axis solar tracker. Following the development of the system model using Simscape Multibody, a controller was developed and its performance was analyzed using MATLAB/Simulink. This controller was tested using Simulink.

## 1.6. Scope and Limitation of The Research

The scope of this study was to design and model an active single axis solar tracker and test its performance under various conditions. The study mainly addresses

- Mechanical Design and Finite element analysis of the solar tracking system
- Developing a system model of the parabolic dish solar concentrator
- Controller design and simulation under various conditions

Regrettably, the validation of research findings through experimentation was impossible due to constraints stemming from insufficient financial resources and access to essential laboratory equipment.

## 1.7. Thesis Outline

This thesis is organized into five chapters. Chapter 1 introduces the background, motivation, problem statement, objectives, methodology, and scope of the research, setting the stage for the study. Chapter 2 reviews the literature on solar energy and parabolic solar concentrators, discussing existing technologies and identifying the gaps that this research aims to fill. Chapter 3 focuses on the design, analysis, and simulation of the active single-axis solar tracking system, highlighting the mechanical design through Finite Element Analysis (FEA) and dynamic modeling using MATLAB/Simulink. Chapter 4 presents the results, evaluating the system's performance under various conditions, including its time response and tracking accuracy. Chapter 5 concludes the thesis by summarizing the key findings and providing recommendations for future improvements and research to enhance solar tracking systems. These recommendations aim to further optimize system efficiency and increase its applicability in real-world settings.

# CHAPTER 2
# LITERATURE REVIEW

## 2.1. Solar Energy and Solar radiation concentrators

Solar energy has emerged as a promising renewable resource for addressing the world's ever-growing energy needs while simultaneously mitigating environmental concerns. With an abundant and virtually inexhaustible supply, solar energy stands out as a renewable resource with unparalleled potential to revolutionize the global energy landscape[4]. Despite the abundance and minimal environmental impact of renewable energy sources like solar power, the world remains heavily reliant on fossil fuels and other non-renewable resources. This dependence is due to several factors, including the established infrastructure for fossil fuels, their historically lower cost, and the ongoing development of efficient and cost-effective renewable energy technologies [15].

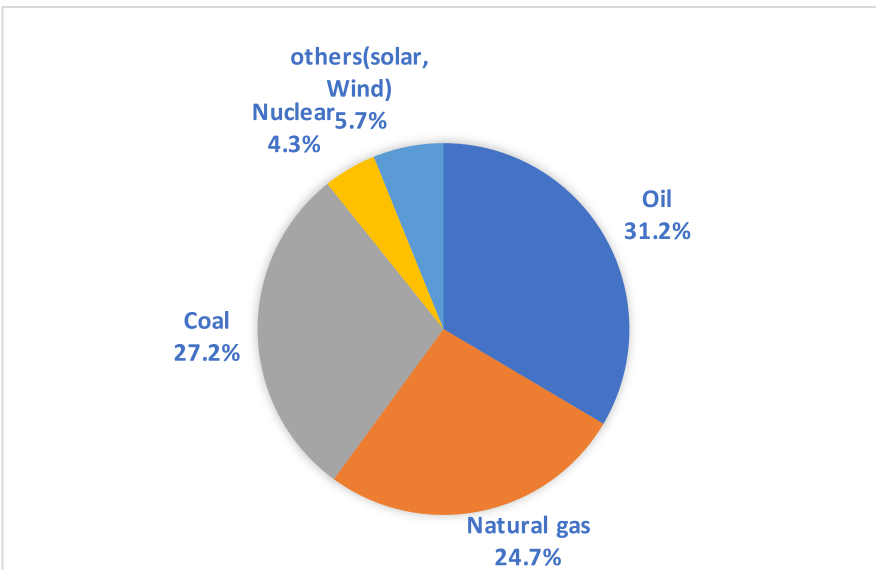


Figure 2.1: 2020's world energy consumption [15]

As the environmental consequences of fossil fuels become increasingly apparent and renewable energy technology continues to mature, the world is in a gradual shift towards a more renewable energy future [16]. Currently, solar energy is being harnessed at an unprecedented rate, employing a variety of methods to capture its abundant power [17], [18], [19]. The most common methods include photovoltaic (PV) systems, which convert sunlight directly into electricity, and concentrated solar power (CSP) systems, which utilize mirrors or lenses to concentrate sunlight onto a receiver for thermal energy generation [18].

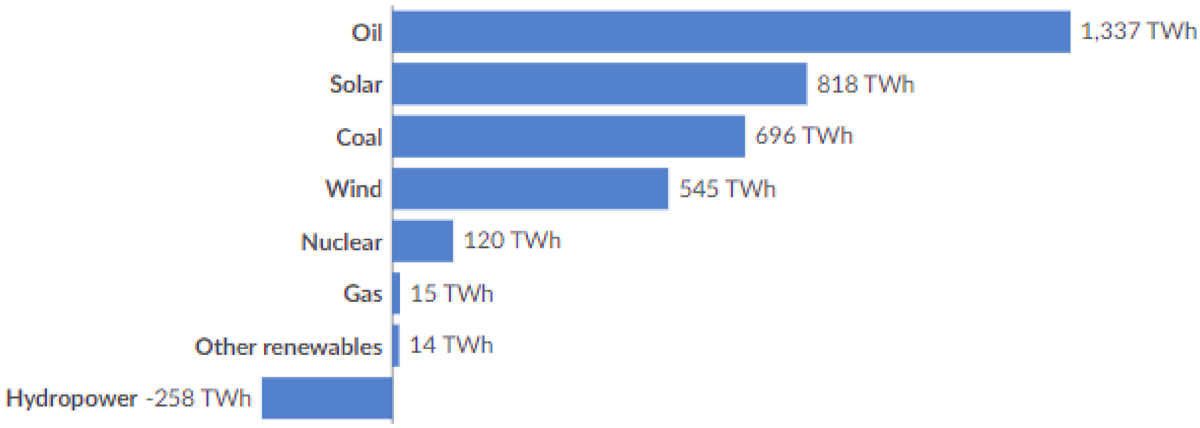


Figure 2.2: Year-Year change in primary energy consumption of the world in 2023 [19]

Solar concentrators are devices designed to collect and concentrate sunlight onto a smaller surface area, thereby increasing the intensity of solar radiation. This intensified sunlight can then be utilized for electricity generation, thermal heating, or other industrial processes [20].

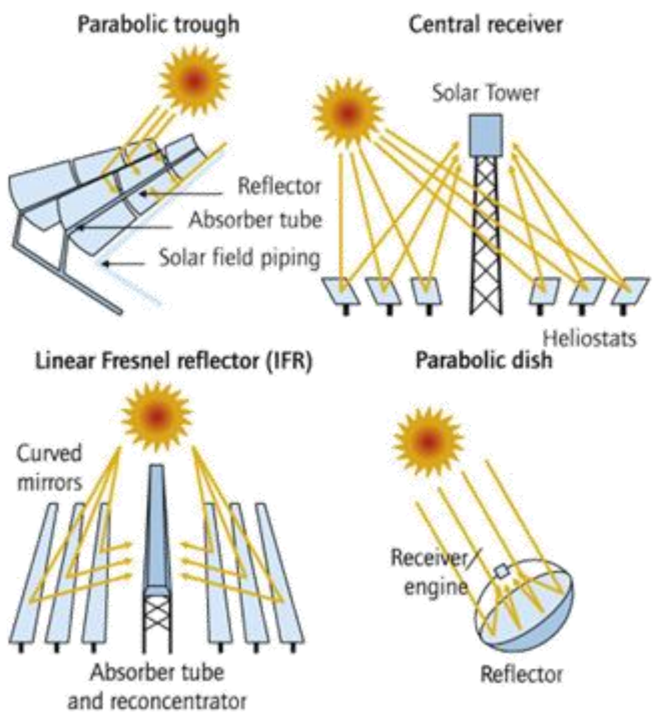


Figure 2.3: concentrated solar power (CSP) systems

## 2.2. Parabolic Solar Concentrators

Recently solar concentrators, particularly parabolic solar concentrators have gained special attention for their remarkable ability to efficiently capture and concentrate sunlight for thermal applications. But due to their limited manual solar tracking system which highly affects its efficiency their adoption has been very limited [21]. Parabolic dish solar concentrators reach their optimum energy peak when the sun is at its zenith, typically occurring for a duration of approximately two hours during the day. Beyond this period, their efficiency begins to degrade due to the changing angle of sunlight incidence [14].

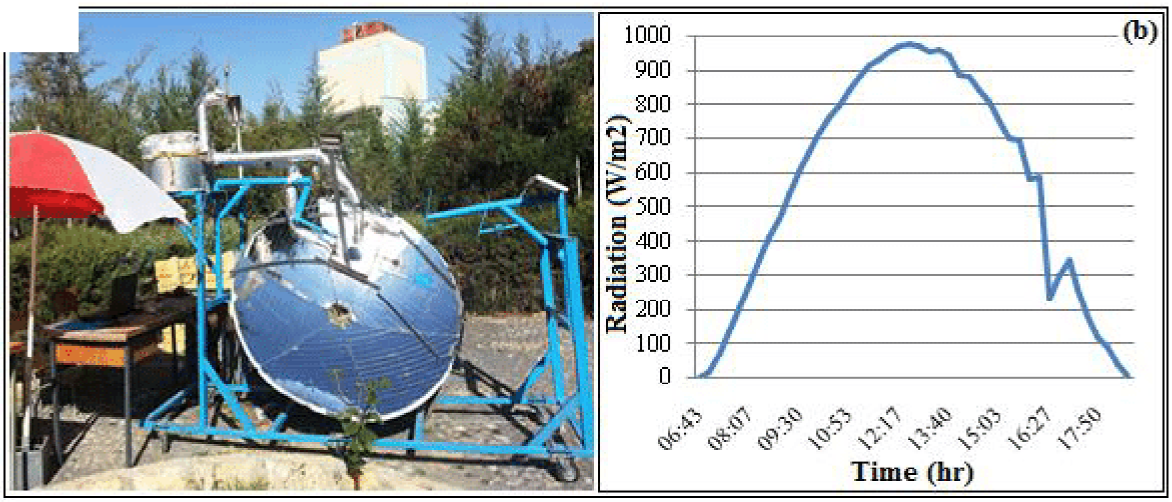


Figure 2.5: (a) Parabolic dish collector with PCM storage, (b) Global solar radiation of Mekelle on 27-02-2014 during the experiment. [A. H. Tesfay, M. B. Kahsay, and O. J. Nydal, figure 3.]

This phenomenon stems from the inherent design of parabolic dish concentrators, which are specifically configured to concentrate sunlight onto a focal point when the sun is directly overhead. Consequently, during other times of the day when the sun's angle deviates from its peak position, the concentrators are less effective in capturing and directing sunlight onto the receiver [22]. This limitation underscores the importance of precise solar tracking mechanisms to maintain optimal alignment with the sun's trajectory throughout the day, thereby maximizing the efficiency and energy output of parabolic dish solar concentrators in solar energy applications.

### 2.3. Comprehensive Study of The Existing Parabolic Dish Solar Concentrator

In an effort to enhance the livelihoods of rural communities in Ethiopia, Mekelle University has developed the development of a parabolic dish solar concentrator [13], [14], [23]. This existing parabolic dish solar concentrators under study were developed with limited tracking capabilities, relying primarily on manual adjustments or open-loop tracking mechanisms. thermal storage and heat transportation loop system suitable for high temperature applications. The system was designed to address Injera baking application. Injera, a fermented flat bread type, is the most common food type served three to four times a day in Ethiopia. Other countries like Eritrea, Somalia, Sudan and Yemen also use this food.

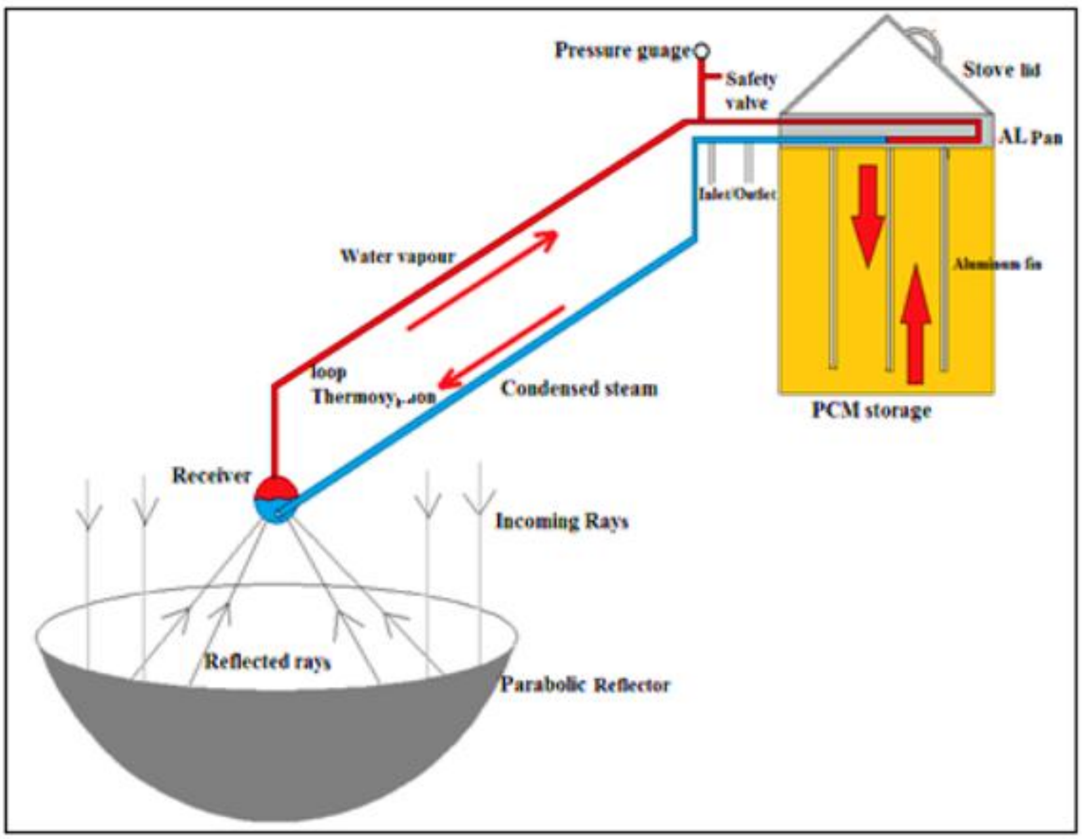


Figure 2.6: Representation of the parabolic solar concentrator [A. H. Tesfay, M. B. Kahsay, and O. J. Nydal, figure 1.]

This solar concentrator utilizes a frying pan with an embedded stainless steel steam pipe to act as the heating element, similar to an electric stovetop burner. A large, 1.8-meter parabolic dish collector captures sunlight and focuses it onto the pan. The collector is covered with a reflective film called Alando. The receiver, where the sunlight is concentrated, is made from two welded black steel cups. These cups are 10 cm in diameter, 0.5 cm thick, and 4 cm tall, designed to absorb the concentrated heat effectively. An east-west tracking system, powered by a small 10-watt solar panel, ensures the dish stays pointed towards the sun throughout the day. This open-loop system relies on pre-programmed values for the time and date. The tracking mechanism uses gears to convert the motor's speed (9 rotations per minute) for smooth movement, with a capacity to handle up to 50 kilograms.

## 2.4. Current state of the art solar trackers and their limitation

Solar trackers play a crucial role in optimizing the performance of parabolic dish solar concentrators by ensuring precise alignment with the sun's trajectory throughout the day. Solar trackers are devices used in solar energy systems to orient solar panels, mirrors, or other solar energy collection devices toward the sun's path throughout the day. Their primary function is to maximize the amount of sunlight that these devices receive, thereby optimizing energy output. Solar trackers typically use sensors, motors, and control systems to adjust the angle or orientation of solar panels or mirrors, ensuring that they remain perpendicular to the sun's rays for maximum efficiency. Dual axis tracker collects (35-50) % more energy than fixed axis tracker and single axis tracker collects (35-45) % more energy than the fixed axis tracker throughout the year [24].

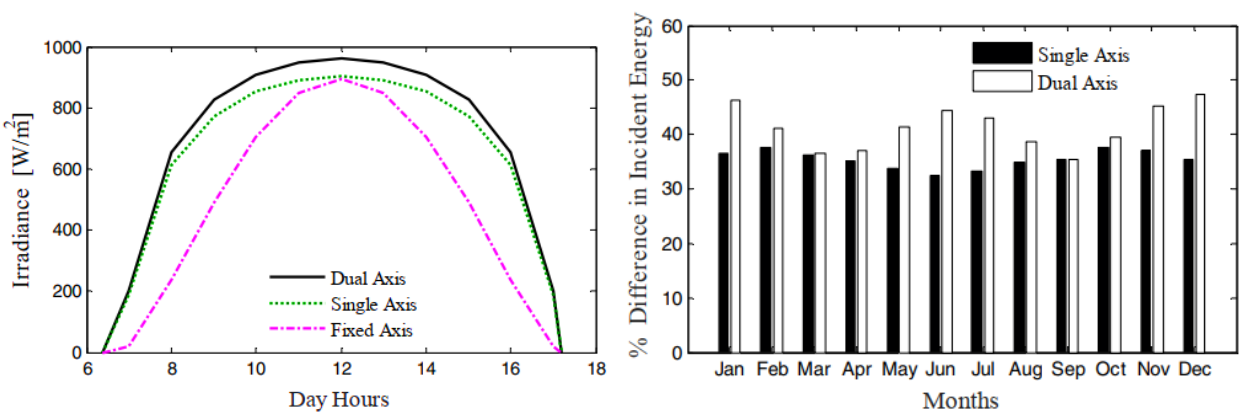


Figure 2.7: Percentage of difference in incident energy of single and double axis tracker with respect to fixed axis for different hours of the day and different days of the months [57].

While dual-axis tracking systems boast advanced capabilities in aligning parabolic dish solar concentrators with both azimuth and elevation angles, their efficiency gains over single-axis trackers are marginal. Single axis produces about 38.31% more energy in average compared to that of fixed ones and dual axis tracker produces about 43.79% more energy in average with respect to fixed ones [25]. Solar trackers, are categorized into three main types based on their method of operation [26]:

- ✓ Passive Tracking Devices,
- ✓ Active Tracking Devices, and
- ✓ Open Loop Trackers.

Passive solar trackers function autonomously, devoid of external power sources or intricate mechanisms, relying instead on natural occurrences or basic mechanical principles to align solar panels or mirrors [27]. While these trackers boast simplicity and minimal maintenance needs, they may exhibit reduced precision when contrasted with active systems. Active solar trackers employ motorized mechanisms, sensors, and control systems to actively regulate the alignment of solar panels or mirrors in real-time [28]. They maintain continuous monitoring of the sun's position to optimize alignment and maximize energy capture. Single-axis trackers adjust panels along a single axis (usually the north-south axis), whereas dual-axis trackers can fine-tune alignment along both the north-south and east-west axes for enhanced precision in solar tracking [29].

Open Loop Trackers uses controlled algorithms or time-based systems to adjust the orientation of solar panels or mirrors based on predetermined schedules or inputs [30]. These trackers operate without real-time feedback from sensors, relying instead on programmed algorithms to optimize energy capture. Open loop trackers adjust panel orientation at specific times of the day or under certain weather conditions, enhancing efficiency without continuous monitoring. While they are less complex and costly than active trackers, open loop systems may lack the precision of real-time feedback mechanisms.

# CHAPTER 3
# METHODOLOGY

## 3.1. Functional Requirements and Geometrical Specifications

The primary functional requirement of the active single-axis solar tracker for a parabolic dish solar concentrator is precision tracking. This entails accurately following the sun's apparent motion along the azimuth axis throughout the day. By maintaining precise alignment with the sun's position, the tracker is needed to ensures optimal sunlight capture and maximizes energy output from the parabolic dish concentrator [31]. Another critical functional requirement is reliability. The tracker must operate consistently and dependably under various weather conditions and environmental factors. Reliability ensures continuous solar tracking, minimizing downtime, and maximizing energy capture. Robust construction and reliable components contribute to the tracker's ability to withstand outdoor elements, ensuring long-term performance and system reliability [32]. Durability is crucial for the single-axis solar tracker, as its components must resist exposure to sunlight, wind, rain, and temperature fluctuations, ensuring longevity and reducing maintenance needs.

A robust design enhances the system's resilience in harsh environmental conditions, allowing uninterrupted operation and sustained energy production. Additionally, the tracker should optimize efficiency by minimizing energy consumption while maximizing solar energy capture through advanced control algorithms. Seamless integration with the existing parabolic dish solar concentrator is also essential, ensuring proper alignment for optimal sunlight capture and energy yield, ultimately boosting the overall system's performance. To develop an active single-axis tracking system for the parabolic dish concentrator that meets the required functional specifications, it is essential to first consider the geometric specifications of the current parabolic dish, which operates with manual tracking system. Understanding key factors such as the dish’s curvature, diameter, focal length, and reflective surface positioning is crucial for designing a tracker that aligns with the concentrator's structure and enables precise solar alignment. The new system must account for these geometric parameters to ensure continuous adjustment throughout the day, maximizing solar energy capture and system efficiency. Additionally, the mechanical constraints of the existing concentrator must be considered to ensure that the tracker’s range of motion, motor capacity, and control algorithms are capable of precise operation without compromising durability or stability. By tailoring the tracking system to fit the concentrator's design and operational needs, the overall energy output and effectiveness of solar energy generation can be significantly enhanced.

Figure 3.1: Existing parabolic solar concentrator [A. H. Tesfay, M. B. Kahsay, and O. J. Nydal, figure3]

enhance the tracking system of the parabolic solar concentrator currently in operation at Mekelle University, specifically the one developed for INJRA baking. The existing system, which is detailed in the attached published paper, serves as the foundation for this research. Following the recommendations outlined in the "Future Work" section of the paper, this work aims to address the suggested improvements with a focus on system efficiency [14]. Critical geometric criteria, operational conditions, and the location data were taken directly from this previous concentrator to ensure a comprehensive evaluation of its impact on the overall performance.

## 3.2. Mechanical Design and FEA analysis

To improve the tracking system of the parabolic solar concentrator, a new active tracking mechanism was developed, designed to increase the system's efficiency by precisely following the sun's path throughout the day. This mechanism uses sensors, located at the top and bottom of the solar panels, Figure 3.2, which continuously monitor the sun's position and provide feedback to the control system for real-time adjustments.

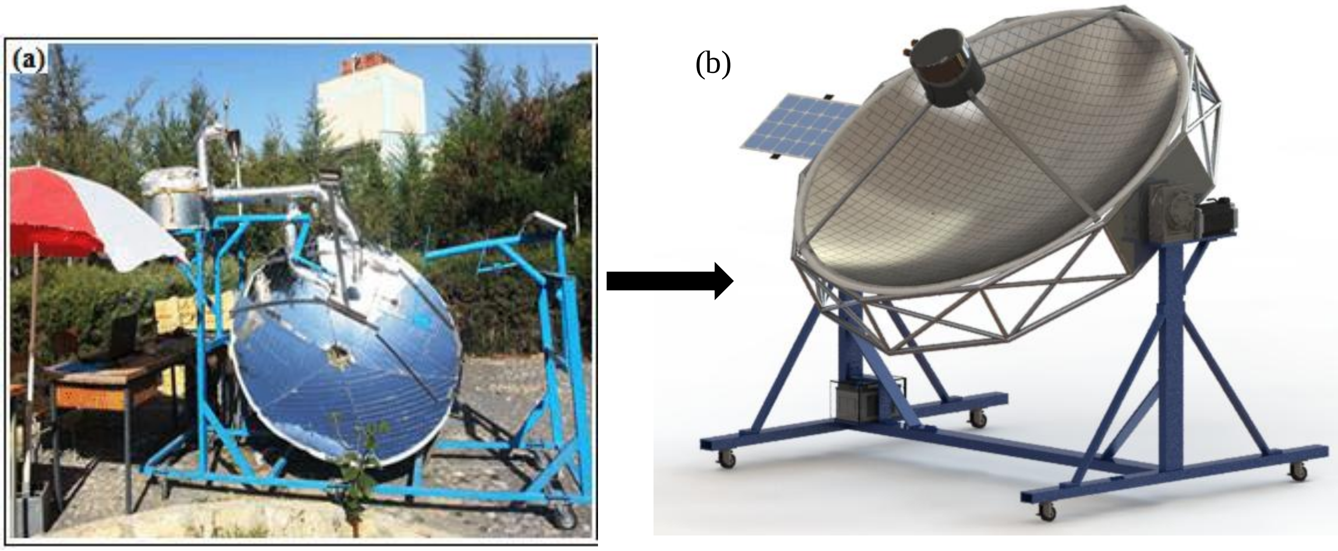


Figure 3.2:The olde parabolic concentrator (a) and the new one (b)

This newly developed active tracking mechanism for the parabolic solar concentrator consists of three main components: the concentrator, the worm gear drive, and the stand. Each of these components plays a crucial role in the overall functionality and efficiency of the system, ensuring that it can precisely track the sun’s movement and maximize energy capture.

The parabolic solar concentrator, *Figure 3.3*, is the central element of the system, responsible for focusing sunlight onto a specific point, typically where a receiver or heat-absorbing element is located. The design of the concentrator follows conventional parabolic dish principles, allowing for the reflection of sunlight to a focal point, optimizing thermal and electrical conversion efficiency. With a 2-meter diameter, the concentrator in this system is capable of capturing a substantial amount of solar energy, concentrating it onto a small, high-intensity area for energy conversion purposes. The geometric specifications of this parabolic concentrator were taken directly from the existing solar concentrators, as the objective of this research is not to redesign the concentrator but rather to develop a robust active solar tracking mechanism that integrates seamlessly with the current parabolic concentrator to enhance its operational efficiency.

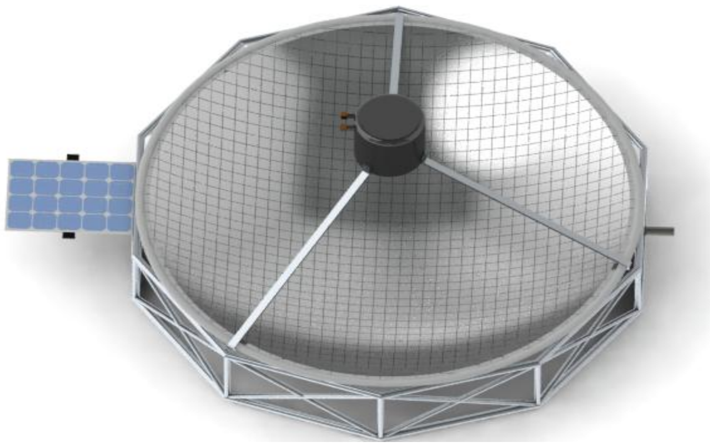

Figure 3.3: Parabolic concentrator

In this design, the concentrator is equipped with a side-mounted photovoltaic (PV) panel, which plays an essential role in powering the system. This PV panel is specifically used to charge the 12V battery that supplies power to the motor and controller. The integration of the PV panel ensures that the tracking system remains operational even in off-grid locations or during cloudy weather conditions. The sensors located at the top and bottom of the PV panel allow the system to adjust the concentrator's angle in real time, continuously aligning it with the sun for maximum energy collection.

The worm gear drive, *Figure 3.4*, is a critical mechanical component of the tracking system that ensures smooth, stable, and precise movement of the concentrator. This mechanism consists of a worm and a gear, where the worm (a threaded shaft) engages with the teeth of the gear. The worm gear drive offers several advantages:

- High Torque Transfer: The worm gear can handle the considerable weight of the concentrator while maintaining precise control over its movement. It allows the motor to easily adjust the dish's position without requiring excessive power [33], [34].
- Self-locking Mechanism: One of the key benefits of the worm gear system is its self-locking ability, which prevents the dish from moving backward when the motor is not engaged. This feature ensures that the concentrator stays securely in place between adjustments, even in windy conditions [33], [34], [35], [36].

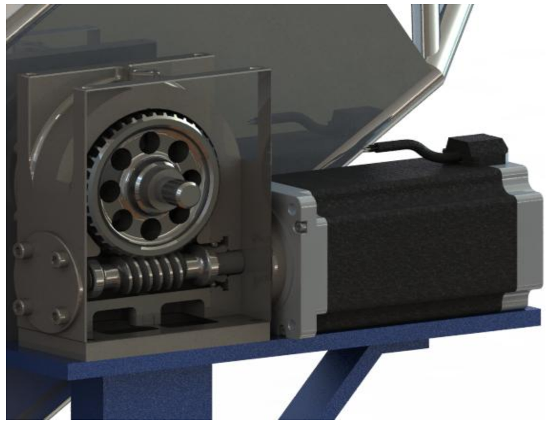

Figure 3.4: Worm gear drive of the tracking system

The worm gear system is driven by a 12V NEMA 34 stepper motor, holding torque of 15 Nm and a step angle of 1.8° which was chosen for its high precision and ability to make small, incremental movements. This motor ensures that the tracking system can make fine adjustments based on real-time feedback from the sensors, optimizing the concentrator's position for sun tracking throughout the day.

Figure 3.5: The stand of the parabolic concentrator

The stand, Figure 3.5, serves as the structural base for the entire tracking system. Constructed from robust materials, it supports the concentrator, worm gear drive, and all associated components. The stand is designed to ensure stability even in windy conditions, with its wide legs and cross-bracing to prevent any tipping or misalignment. The design of the stand takes into consideration both functionality and mobility. The stand includes casters or wheels, allowing for easy repositioning of the concentrator if necessary. This feature is particularly useful for adjusting the system's orientation based on seasonal variations or changes in the installation site. Additionally, the stand's frame is designed to hold the worm gear drive and motor in a secure position, ensuring that the concentrator's tracking movements remain smooth and precise throughout the day. The selection of the motor for the parabolic solar concentrator was conducted with careful consideration of the environmental and operational requirements specific to the project site in Mekelle, Ethiopia. Mekelle's climatic conditions include occasional high wind speeds, with a base wind speed of up to 55 m/s[37], necessitating a motor capable of handling significant torque to ensure the concentrator's stability and precise tracking.


Figure 3.6: Basic Wind Speed map of Ethiopia [ Details of the weather stations and their locations, G. Melesse et al.]

The required torque for the parabolic solar concentrator was determined using MSC Adams, which simulated the system under gravitational and aerodynamic forces, including the effects of Mekelle's environmental conditions with a basic wind speed. The force exerted by the wind on the surface of the concentrator leads to bending moments on the support shafts, which must be computed to ensure proper sizing and support. This drag force is given by;

$$F_d = \frac{1}{2} A \rho C_p v^2 \tag{3.1}$$

Where:

$\rho$ is the air density which is $1.225 kg/m^3$ ,

V is the base wind speed of Mekelle which is $55 m/s$,

$C_p$ is the drag coefficient which is 1.42 for concave surface,

$A$ is the projected area

By substituting the respective values, the maximum force excreted by the wind in the parabolic solar concentrator was found to be $2933.62N$. By using this wind load and applied it to the parabolic concentrator the maximum torque necessary to rotate the parabolic concentrator was determined using MSC Adams. This maximum torque was found to be 675 Nm, Figure 3.7.

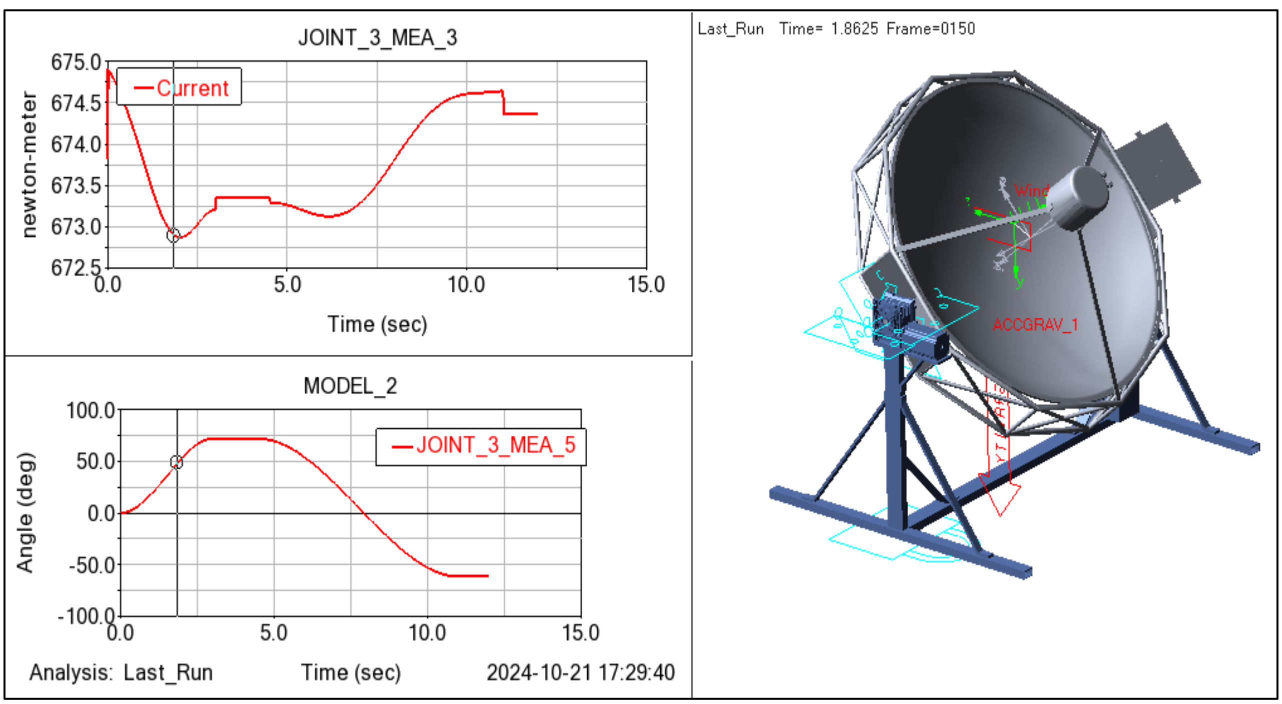


Figure 3.7: Required torque to drive the parabolic solar concentrator measure determined using MSC Adams

To meet this requirement, a NEMA 34 stepper motor was selected, featuring a holding torque of 15 Nm and a step angle of 1.8°, providing the necessary precision for solar tracking. A worm gear with a reduction ratio of 50:1 was incorporated to amplify the motor's torque, allowing it to achieve the required output while maintaining smooth and reliable operation. The structural support of the solar concentrator was design to withstand the basic wind speed and the necessary loads were considering while designing the main components of parabolic solar concentrator.

Finite element analysis (FEA) was conducted to test the structural integrity of the parabolic solar concentrator under heavy wind conditions, specifically at a wind speed of 55 m/s.

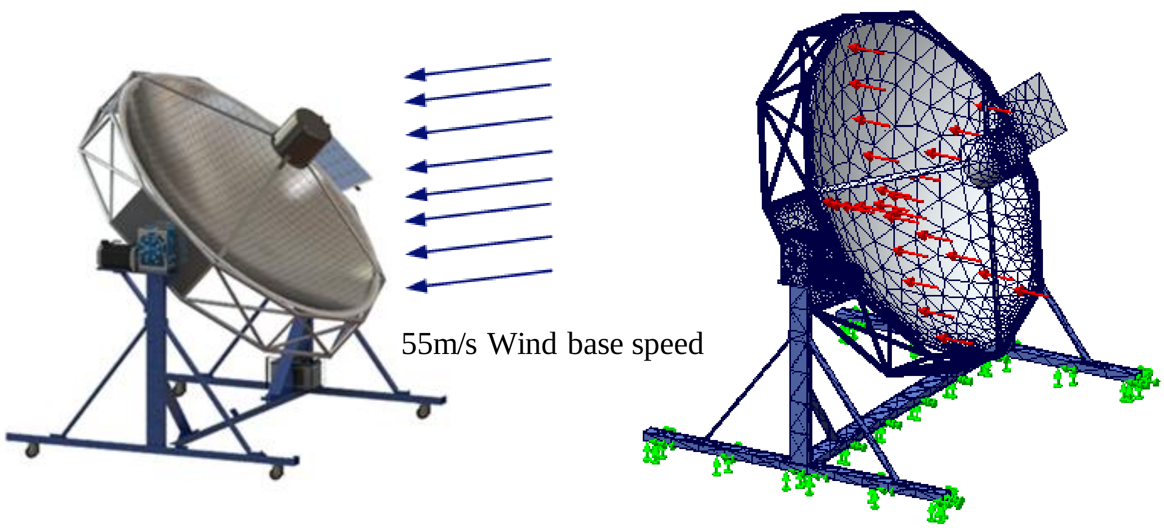


Figure 3.8: FEA simulation setup for the structural analysis

To perform this analysis, tetrahedral meshing[38] was employed, allowing for a detailed and accurate simulation of the concentrator's response to the wind load, Figure 3.8. The use of tetrahedral elements ensures that the model can capture the complex geometry and material behavior, providing insights into potential stress concentrations, deformation, and overall structural performance under extreme wind conditions.

### 3.3. Dynamic Modeling and Sample Trajectory Design

A plant model is a mathematical or computational representation of a physical system, designed to simulate the system's dynamic behavior. In control systems, it helps predict how the system will respond to various inputs and disturbances[39]. For a parabolic solar concentrator, the plant model encapsulates the relationship between actuator commands and system outputs, such as the reflector's position and orientation. Although analytical models based on Newton's second law can be used for modeling mechanical systems, they become impractical for complex systems like a parabolic solar concentrator due to their intricate geometry and the interactions between various components. MSC Adams, a specialized multibody dynamics (MBD) simulation software, is better suited for this task because of its ability to handle the complex geometry, nonlinear dynamics, and multibody interactions inherent in such systems.

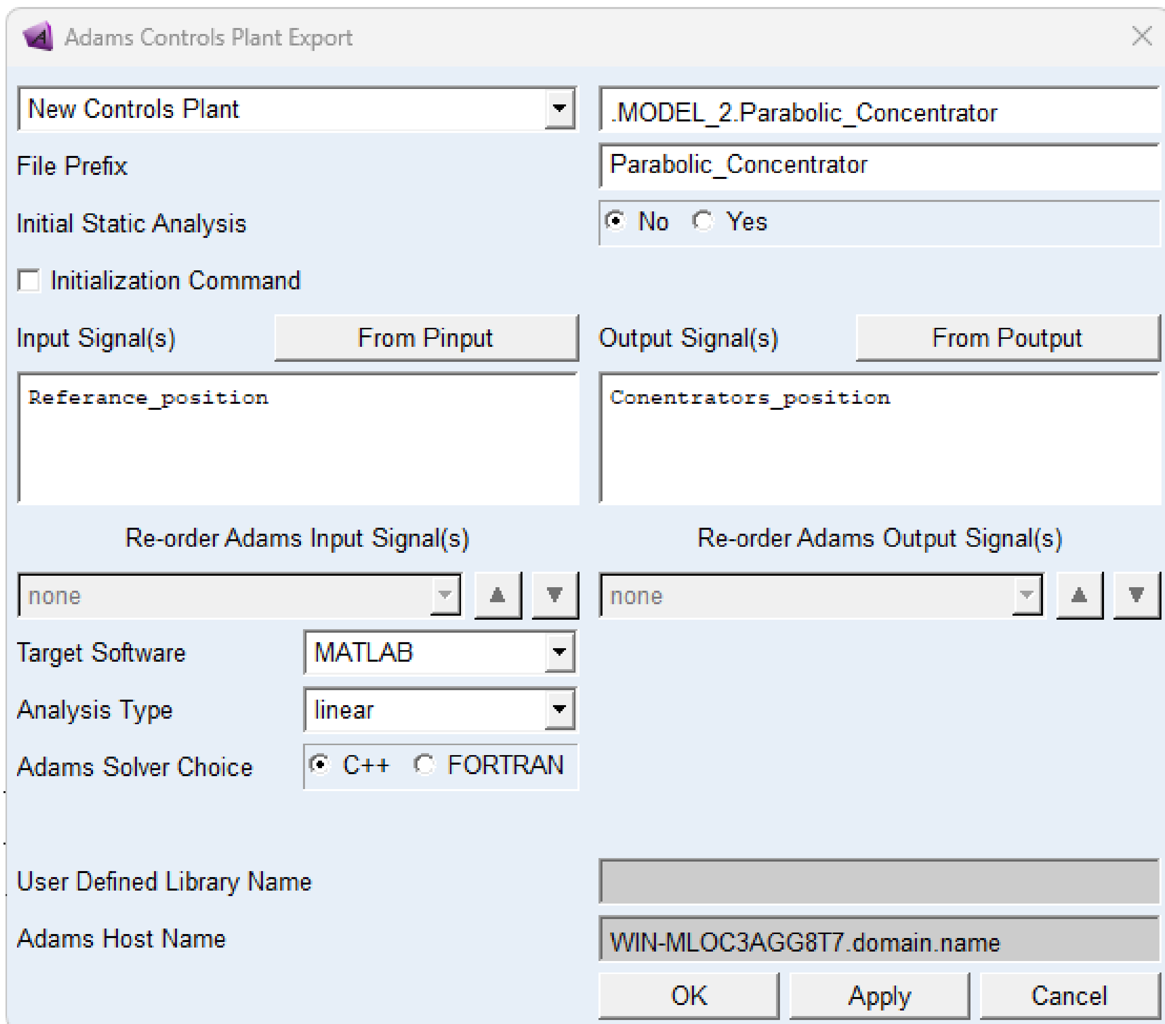


Figure 3.9: Plant model input/output parameters setup

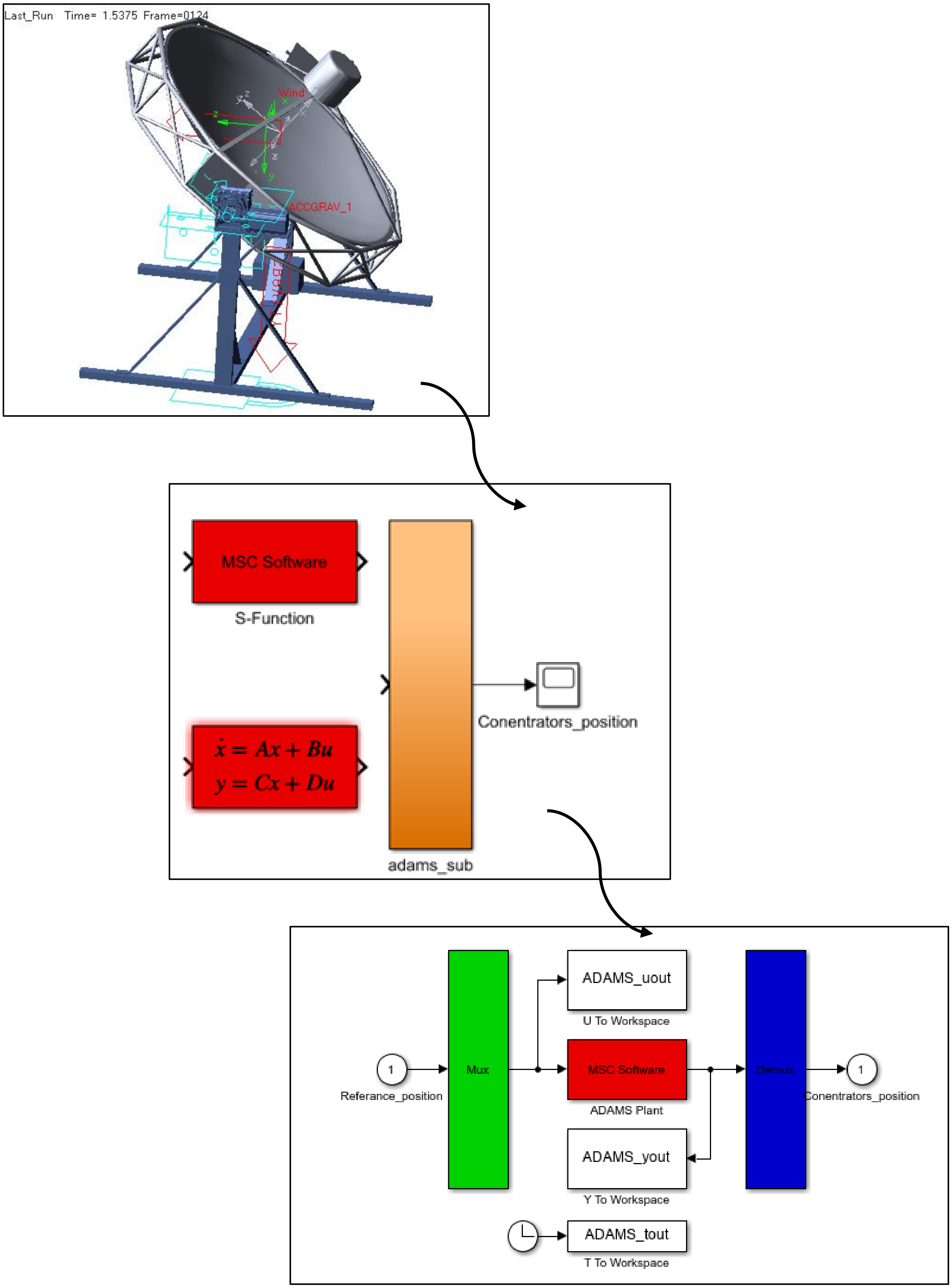


Figure 3.10: Dynamic (Plant) Model of the Parabolic Solar concentrator in Developed in MSC Adams

In addition to the plant model, the ADAMS exports an embedded Simulink block to facilitate seamless communication with MATLAB/Simulink during the co-simulation and controller design.

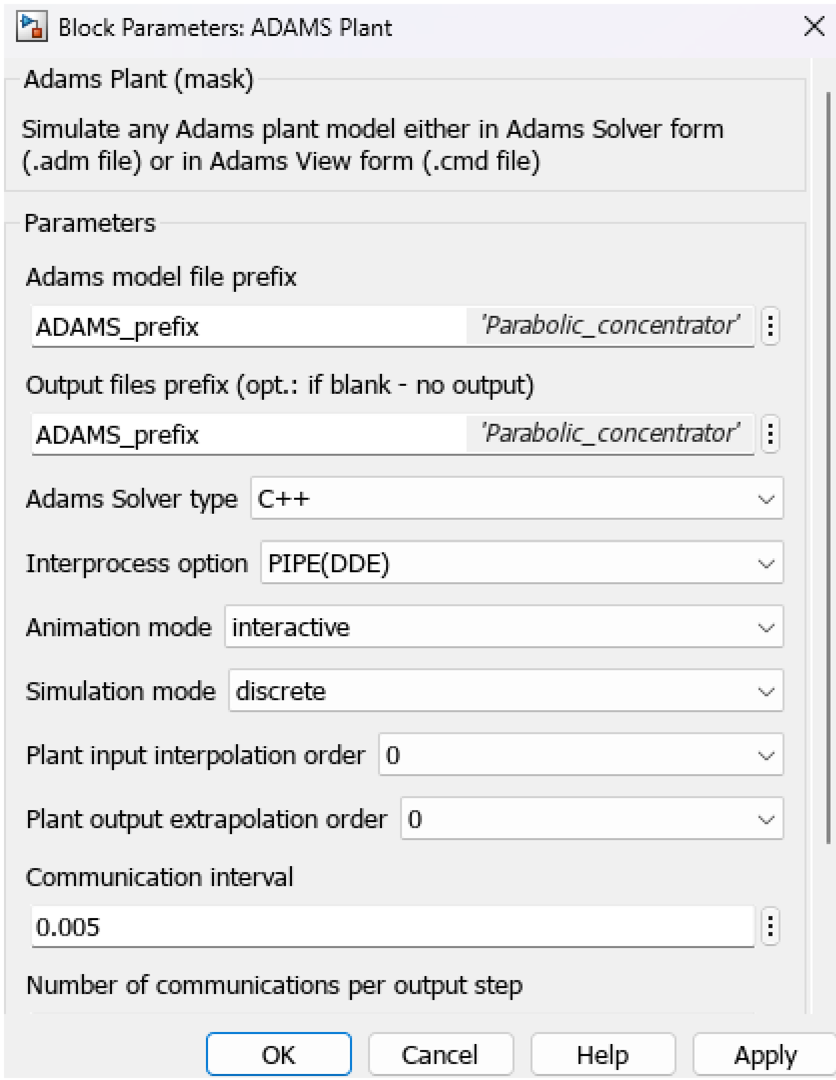


Figure 3.11: MSC Adams MATLAB/Simulink co-simulation setup

To assess and validate the performance of the control system for a parabolic solar tracker, a sample non-linear trajectory was meticulously designed to simulate the dynamic movements of the tracker over a duration of 15 seconds. This trajectory reflects the relative rotational motion of the sun during this period. Given the sun's continuous movement across the sky, the tracker must actively and consistently adjust its orientation to maintain optimal alignment.

$$\theta(t) = \begin{cases} 0 & for\ \ 0 \le t < 1 \\ -75\left(\frac{t-1}{5}\right)^2 & for\ \ 1 \le \text{t} < 6 \\ -75 & for\ \ 6 \le t < 7 \\ -75 - 150\left(1 - \left(1 - \frac{t-7}{5}\right)^2\right) & for\ \ 7 \le \text{t} < 12 \end{cases} \tag{3.2}$$

The primary objective of this sample trajectory is to mimic and track the sun's position, reflecting the natural movement of a parabolic solar concentrator throughout the day. By designing this non-linear trajectory, the goal is to simulate the dynamic adjustments the tracker must make as it follows the sun's path across the sky. Additionally, this trajectory serves as a test scenario for evaluating the performance and capability of the control system. The parabolic solar concentrator is designed to assume a horizontally flattened position, Figure 3.12, when not in use, typically during nighttime. This "home" position is strategically chosen to minimize exposure to wind forces, which helps protect the system from mechanical stress or damage caused by high winds. By reducing the surface area exposed to the wind, this orientation enhances the structural stability of the concentrator.

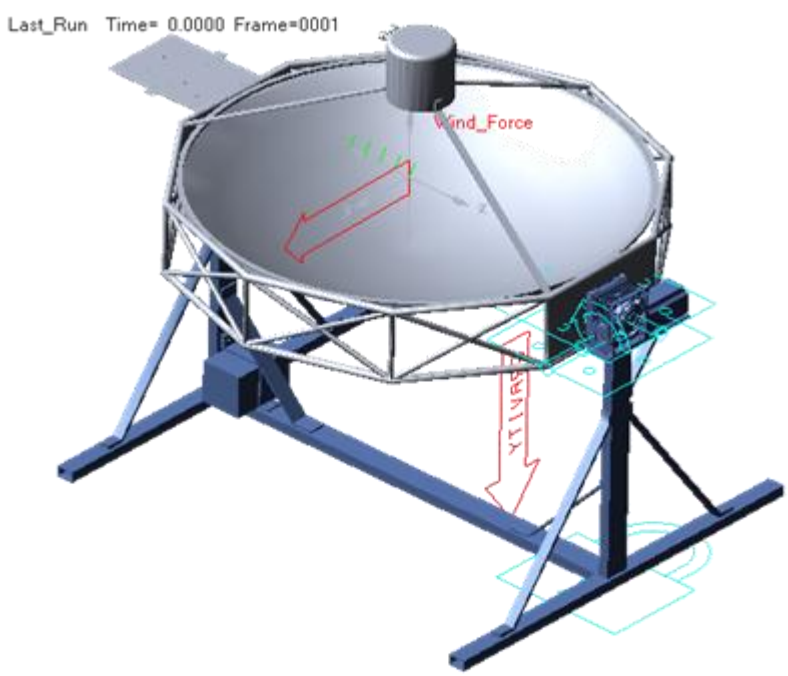


Figure 3.12:Home position of the concentrator

This trajectory, Figure 3.13, is defined by a series of smooth, gradual transitions that mimic the sun's apparent motion due to the Earth's rotation. Over the 15-second duration, the trajectory begins at an initial angle of 0 degrees, positioned horizontally to minimize wind effects during the night, progresses to a minimum angle of -75 degrees, and subsequently transitions to a final angle of 75 degrees. The non-linear approach allows for a continuous, fluid motion rather than abrupt changes, which is crucial for maintaining optimal alignment with the sun. This design not only enhances the realism of the simulation but also ensures that the control system can effectively respond to varying solar angles, ultimately maximizing solar energy capture. The initial transition from 0° to -75° is represented by a quadratic function to emulate the non-linear motion of the solar concentrator. The starting position was chosen arbitrarily to simulate the movement of the concentrator as it adjusts from its home position to align with the sun's rising position. The second segment of the trajectory, ranging from -75° to 75°, is modeled utilizing a quadratic function to evaluate and assess the tracking capability of the solar concentrator as it follows the sun's movement.

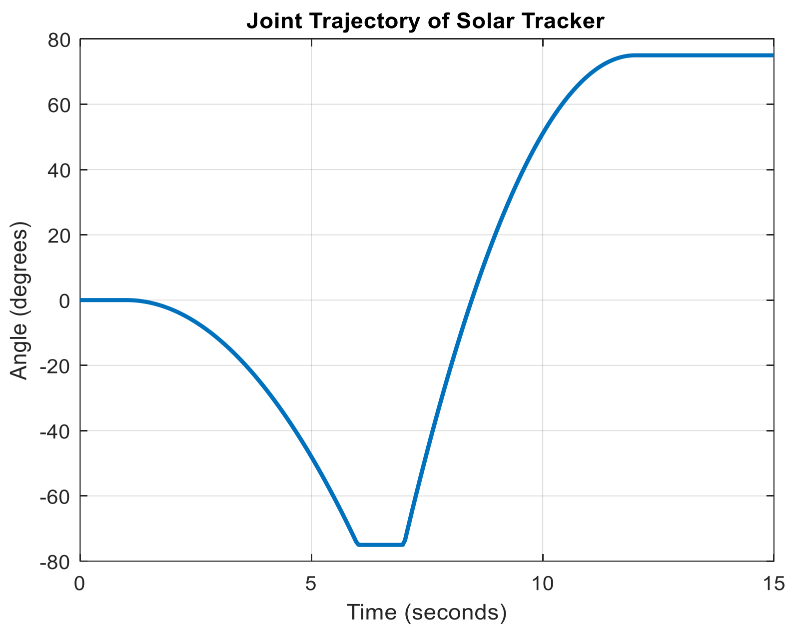


Figure 3.13: Concentrator trajectory

Following the development of the trajectory function, a custom MATLAB Simulink function block was created to test the capability of the tracker in following the specified reference trajectory. This function block integrates the trajectory parameters, allowing for the assessment of the controller's performance in accurately tracking the designated path. By simulating the system's response, the function block facilitates a comprehensive evaluation of the tracking accuracy and overall effectiveness of the solar concentrator.

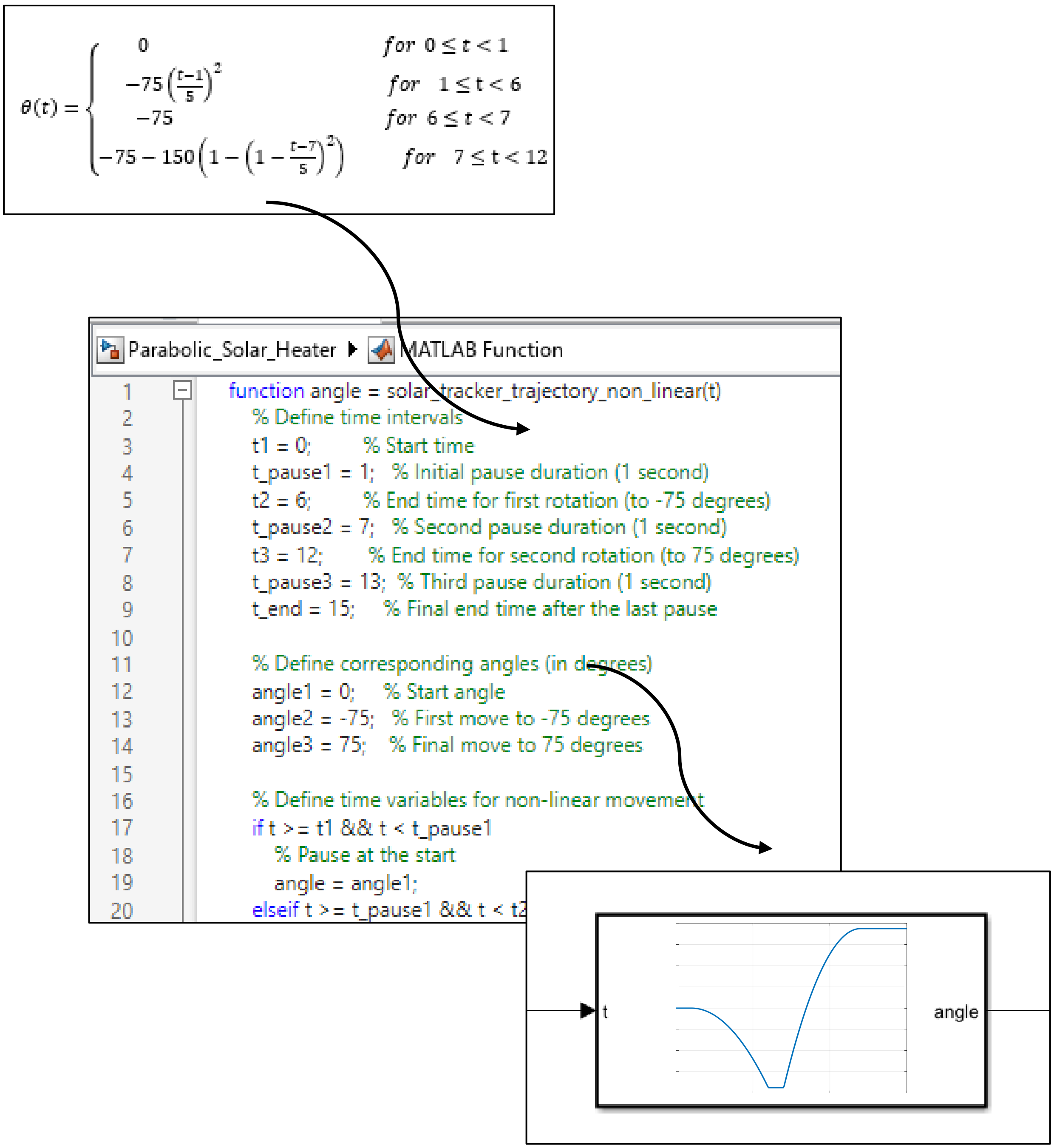


Figure 3.14: Custom function block of the sample solar tracking trajectory

### 3.4. Controller Design

The control of solar concentrators is crucial for maximizing their efficiency by ensuring accurate solar tracking and optimal energy capture. Before delving into the controller design, it is essential to understand the functional requirements of a parabolic solar concentrator controller and the closed-loop control architecture necessary to achieve efficient solar tracking. The functional requirements include:

- Tracking accuracy
- Stability
- Adaptability to environmental disturbances
- Simplicity
- Reliability
- Robustness

There are two primary modes of control employed in solar concentrators: open-loop and closed-loop systems. Open-loop time-based control systems operate without feedback, relying solely on pre-programmed inputs or deterministic models. In the case of solar concentrators, this approach uses astronomical data to calculate the sun's position such as azimuth and elevation angles through predictive algorithms like the Solar Position Algorithm (SPA) [40]. While computationally simple and cost-effective, open-loop systems cannot account for real-world disturbances such as mechanical inaccuracies, environmental factors, or unexpected shading. As a result, tracking errors may accumulate over time, reducing the system's overall effectiveness[41], [42].

In contrast, closed-loop feedback control systems continuously monitor the concentrator's alignment with the sun and make real-time adjustments based on feedback from sensors such as photodiodes or light-dependent resistors (LDRs)[43]. This dynamic response allows closed-loop systems to mitigate errors caused by environmental disturbances or mechanical imperfections, ensuring precise solar tracking[44]. Closed-loop controllers can be classified into classical, modern, and intelligent types, each offering unique advantages and complexities. Classical controllers, such as the Proportional-Integral-Derivative (PID) controller, are widely used for their simplicity and reliability, while modern and intelligent controllers, including model predictive control (MPC) and fuzzy logic controller (FLC), provide advanced features at the cost of increased computational requirements[45], [46]. Considering the specific requirements of parabolic solar concentrators, which primarily involve tracking and following the sun with high accuracy, simplicity, and minimal computational demand are essential factors in controller selection. While modern and intelligent controllers may deliver superior performance in complex scenarios, the PID controller is more suitable for this application due to its balance of performance, ease of implementation, and computational efficiency[47] hence, PID was used.

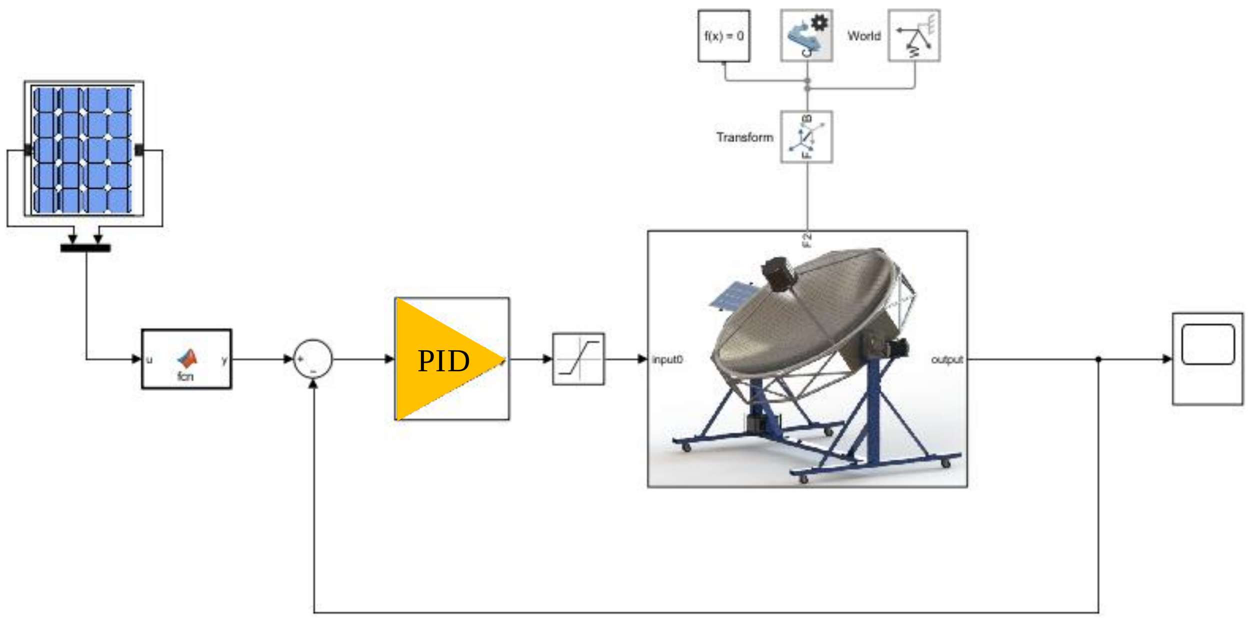


Figure 3.15: Closed loop controller

PID controller is one of the most widely used control algorithms in engineering due to its simplicity, effectiveness, and reliability. It is particularly suited for applications requiring stability and ease of implementation over extreme precision, making it ideal for solar tracking systems in parabolic concentrators[48], [49]. The PID controller operates by calculating the error between a desired setpoint and the system's actual output and applying corrective actions based on three components: proportional, integral, and derivative terms[50], [51]. These terms adjust the system's response to minimize error, ensure steady-state accuracy, and improve overall system stability. For solar concentrators, where the primary goal is accurate yet straightforward solar tracking, the PID controller strikes an effective balance between performance, computational efficiency, and implementation simplicity, which is particularly beneficial for systems where processing power and complexity need to be minimized [52], [53].

The mathematical representation of a PID controller is given as:

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau) d\tau + k_i \frac{de(t)}{dt} \quad (3.3)$$

Where:

$u(t)$: Control signal

$e(t)$: Error signal

$k_p$: Proportional gain

$k_i$: Integral gain

$k_d$: Derivative gain

Tuning a PID controller involves selecting appropriate values for $k_p$, $k_i$, and $k_d$ to achieve the desired system performance. Proper tuning ensures the system responds quickly and accurately while minimizing overshoot, settling time, and steady-state error[54]. Several methods are commonly used to tune PID controllers, each with its own strengths and applications:

- Manual Tuning
- Ziegler-Nichols Method
- Cohen-Coon Method
- Optimization Algorithms

One way to tune a PID controller is by using the optimization method available in the Simulink environment. The PID Tuner tool in Simulink uses optimization techniques to automatically determine the best values for the PID parameters. This approach adjusts the gains by evaluating the system's dynamic response and optimizing performance criteria such as minimizing tracking error, achieving a fast response, and maintaining stability under varying conditions[55]. Simulink's optimization-based tuning method is iterative, adjusting the controller parameters and evaluating the system's performance until the desired specifications are met. This method is particularly useful for solar concentrator systems where simplicity and stability are prioritized over extreme precision. The use of Simulink for PID tuning allows for efficient and practical controller parameter selection while providing an intuitive interface for monitoring the system's behavior [56].

In this study, the Simulink PID Tuner was employed to fine-tune the PID parameters of the solar concentrator system. By leveraging the automatic optimization capabilities of Simulink, the controller gains were adjusted to ensure optimal performance while minimizing computational requirements, making it ideal for applications like solar tracking where simplicity and reliability are crucial.

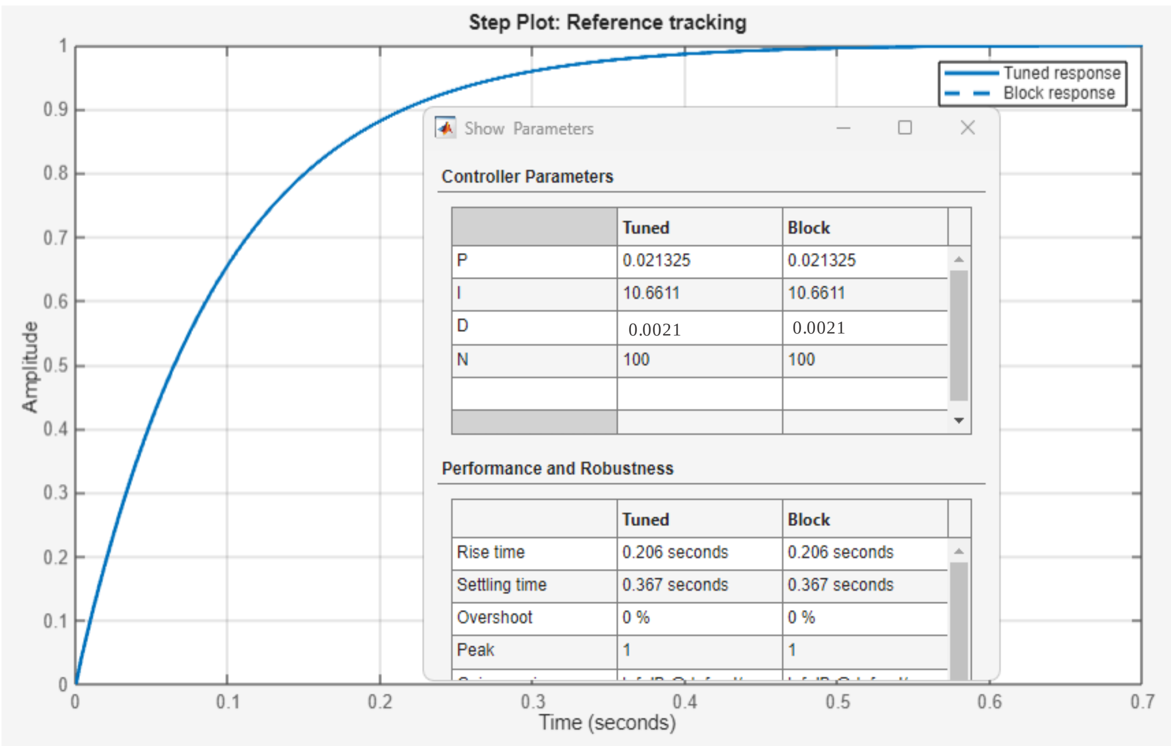


Figure 3.16: Tunned PID controller

## 3.5. Wind Disturbance Modeling

Disturbance modeling plays a critical role in evaluating the performance of solar concentrator systems, particularly in the context of maintaining optimal positioning despite various internal and external disruptions. To ensure the effectiveness of the tracking controller, it is imperative to develop a robust disturbance modeling framework that can accurately simulate these disruptions and assess the controller's effectiveness in rejecting them. The primary objective of disturbance modeling is to create a realistic simulation environment that mimics the operational conditions faced by solar concentrators. Wind disturbances, particularly in outdoor environments, introduce challenges by causing undesired angular deviations in the concentrator's joints. These disturbances are irregular, with varying magnitudes and frequencies, necessitating accurate modeling for effective controller design and testing. In this study, wind-induced disturbances are modeled as angular deviations and incorporated into the joint position control system. The controller's ability to maintain trajectory accuracy despite these external influences is evaluated, ensuring reliable performance in dynamic environmental conditions.

In Mekelle, wind speeds can vary significantly, with a base speed of approximately 55 m/s observed during peak conditions. Such high wind speeds exert considerable forces on the structure of parabolic solar concentrators, leading to angular deviations in their joints. Since the control system implemented in this study operates as a joint position controller, disturbances are modeled as angular deviations directly affecting the joint positions. These disturbances are represented as sinusoidal variations superimposed with random noise, simulating the irregular nature of wind patterns. The disturbances are limited to a maximum angular deviation of ±5 degrees to reflect the physical constraints of the concentrator's joints, ensuring a realistic evaluation of the controller's ability to mitigate these effects and maintain accurate positioning under varying wind conditions.

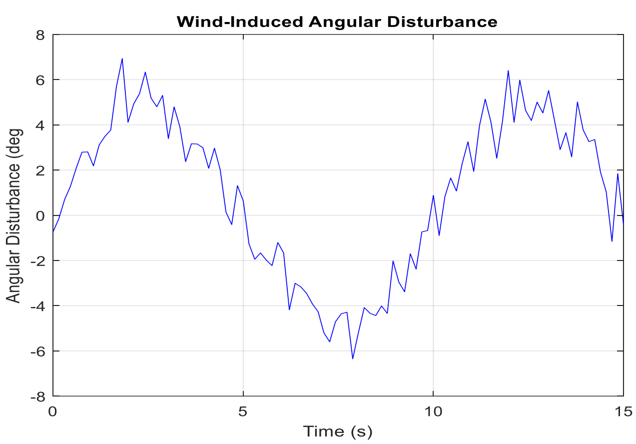

Figure 3.17: Wind disturbance model

Figure3.18. Design basic wind map of Ethiopia

from 25 to 55 m/s from those 32 stations are ranges from 25 to 30 which is under category (zone I), 36 stations are ranges from 30 to 35 which is under category (zone II), 43 stations are ranges from 35 to 40 which is under category (zone III), 17 stations are ranges from 40 to 45 which is under category (zone IV)), 12 stations are ranges from 45 to 50 which is under category (zone V), 18 stations are ranges from 30 to 55. According to the above map Mekelle is located at north Ethiopia. The north Ethiopia is colored by red color in this map so that, the wind speed for red colored 50 - 55m/s

The modeled wind disturbance for the joint position control system is implemented as a combination of a sinusoidal wave and white noise, accurately reflecting the dynamic behavior of wind. The sinusoidal component has a frequency of 0.1 Hz, capturing the periodic gusts commonly observed in wind patterns, while the white noise represents stochastic variations with a magnitude of 2 degree, Figure 3.17. Furthermore, in order to study the disturbance rejection of the controller a custom function block was added to the system control architecture, Figure.

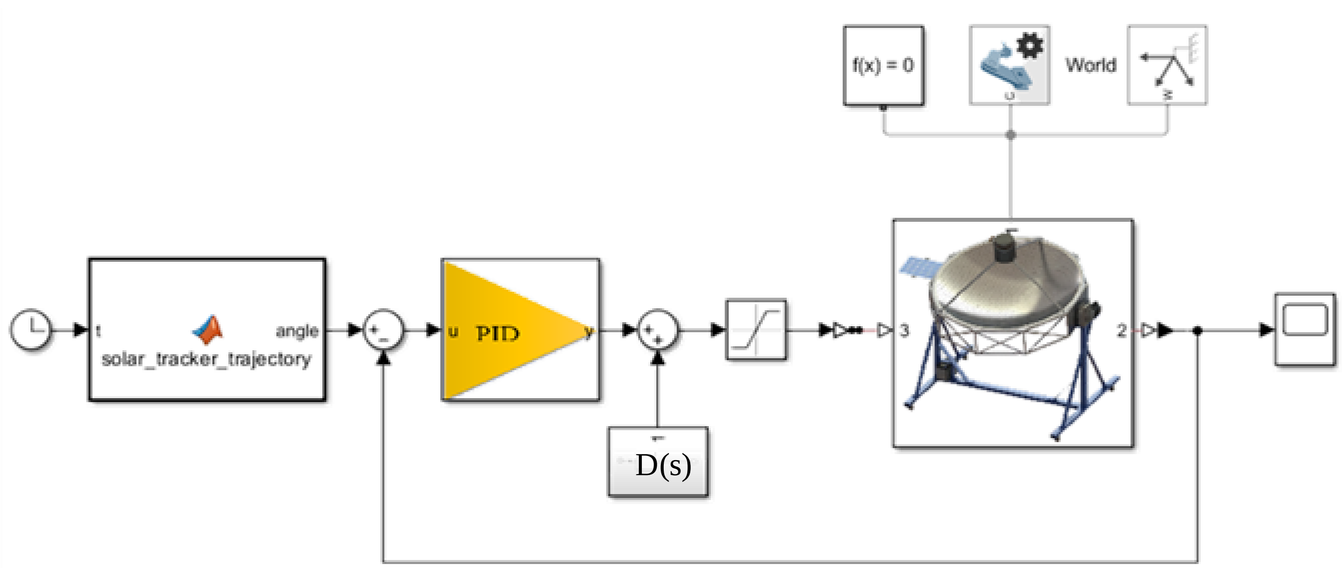


Figure 3.18: Block diagram of the system under a random disturbance

# CHAPTER 4
# RESULT AND DISCUSSION

## 4.1. Finite Element Analysis of the Parabolic Solar Concentrator

The finite element analysis (FEA) of the parabolic solar concentrator was conducted to ensure its structural reliability and durability under extreme environmental conditions. Wind forces, particularly at high speeds, pose significant challenges to solar concentrators by introducing stresses and deformations that can compromise their performance and longevity. Given the operational setting in Mekelle, Ethiopia, where wind speeds can reach up to 55 m/s, it was essential to evaluate the concentrator's response to such loads to validate its design and ensure safe and efficient operation. The wind load, calculated based on aerodynamic principles, was applied uniformly across the concentrator's surface, simulating a worst-case scenario.

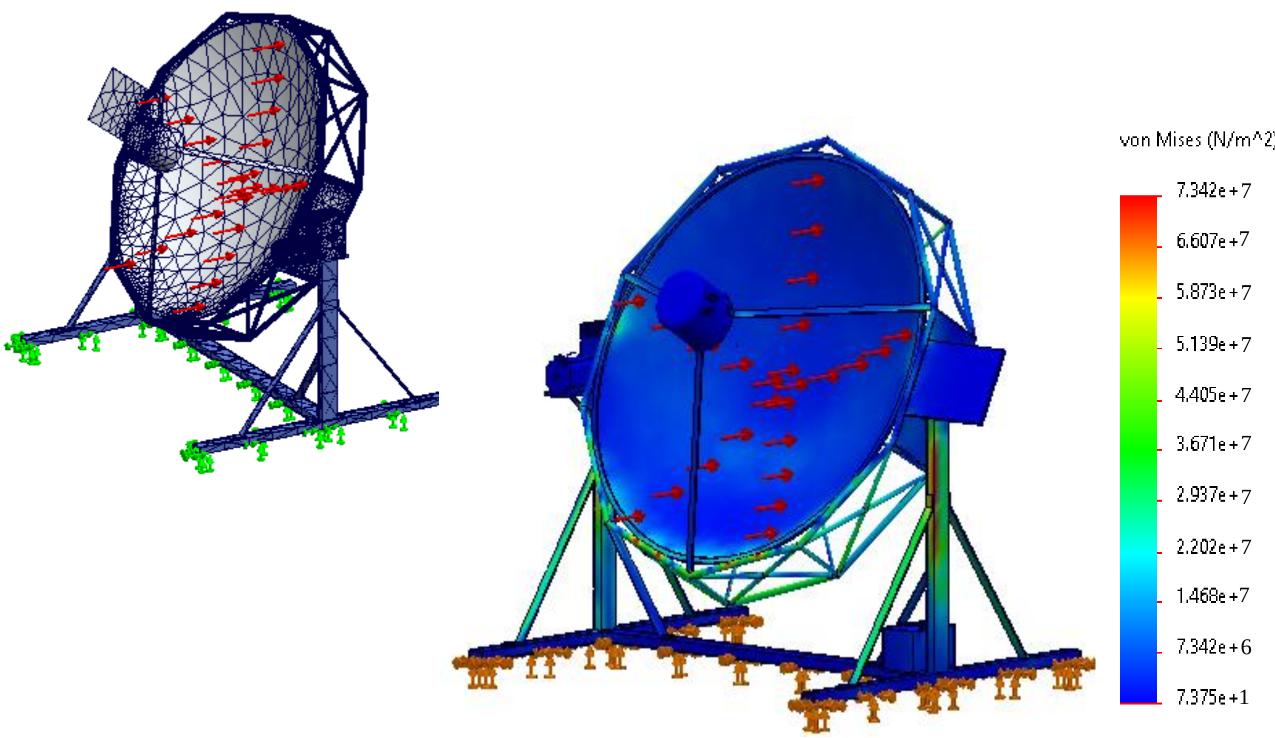


Figure 4.1: Equivalent(vone-mises) stress distortion analysis result

As it can be seen from the equivalent (vone-mises) stress distribution analysis of the parabolic solar concentrator the maximum stress induced is at the stand support which is 73.42MPa. since the yield stress of the selected material, which is the aluminum alloy, is 280Mpa the concentrator is safe.

### 4.2. Time response analysis results under no disturbance

The time response analysis evaluates the performance of the control system developed for the parabolic solar concentrator, focusing on its ability to accurately track the sun's trajectory without the influence of external disturbances. This analysis was conducted using PID controller designed and tuned within MATLAB/Simulink, as outlined in the methodology. The goal was to assess the controller's stability, accuracy, and responsiveness during solar tracking. The PID controller was tuned to minimize tracking error, ensuring smooth and precise adjustments to the concentrator's position.

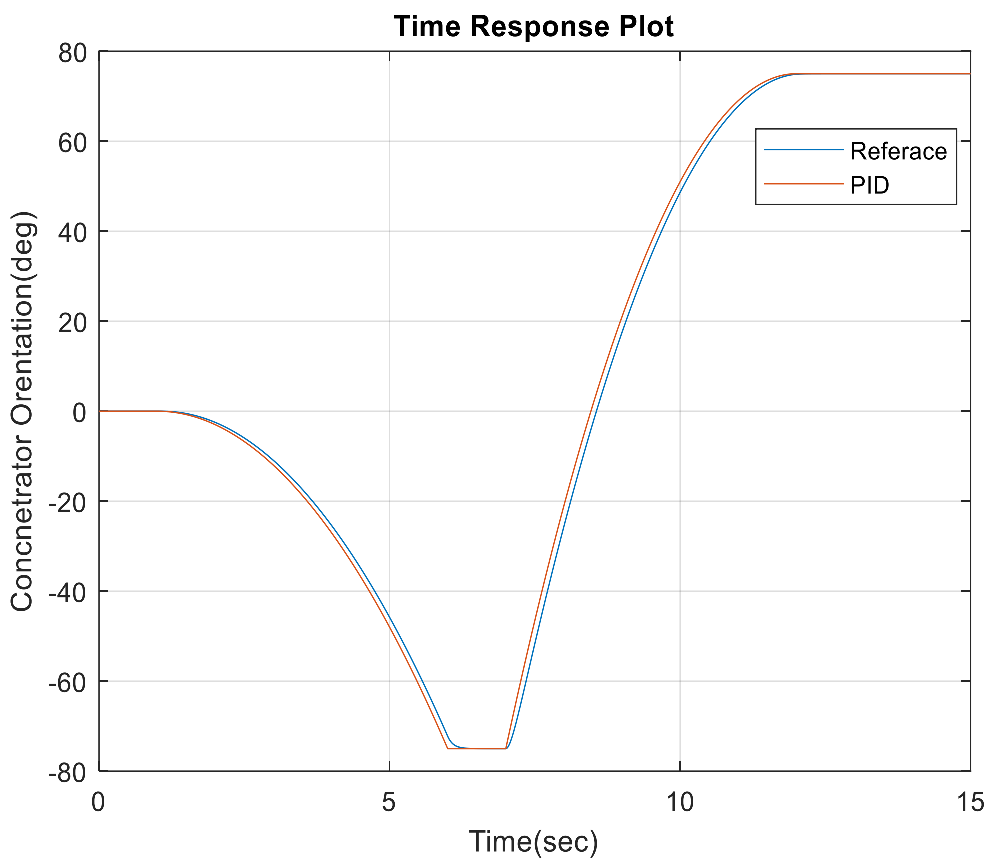


Figure 4.2: Time response of the concentrator for sample trajectory

From the time response the tracking efficiency of the PID controller of the parabolic solar concentrator, the minimum tracking accuracy of the developed controller was found to be 96.97% and the maximum tracking error was found to be $2.03^{o}$.

energy loss in the tracking system is directly proportional to the **tracking error**. We can approximate the energy loss based on the given efficiency.

Energy Loss = 1−Tracking Efficiency

Energy Loss =1−0.9697 = 0.0303or3.03%

So, the **energy loss** is approximately **3.03%** due to the tracking error and the imperfect alignment of the concentrator.

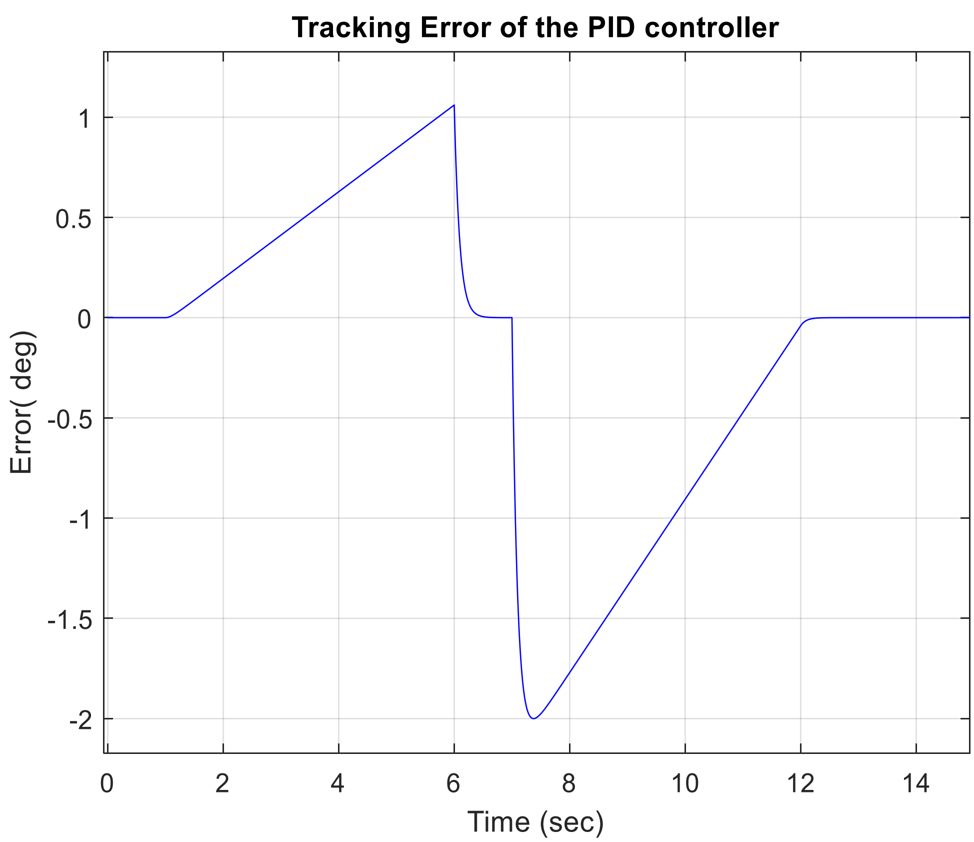


Figure 4.3: Trajectory tracking error of the PID controller

### 4.3. Time Response Analysis Results of the System under Disturbance

The time response analysis investigates the system's performance under the influence of wind-induced disturbances, which are modeled as angular deviations superimposed with random noise. This analysis evaluates the controller's ability to minimize tracking errors and maintain system stability when exposed to dynamic environmental conditions. The disturbances were introduced as sinusoidal variations with a frequency of 0.1 Hz, representing gusty winds, combined with white noise to simulate stochastic fluctuations. The simulation results illustrate the controller's effectiveness in rejecting disturbances and maintaining trajectory tracking accuracy.

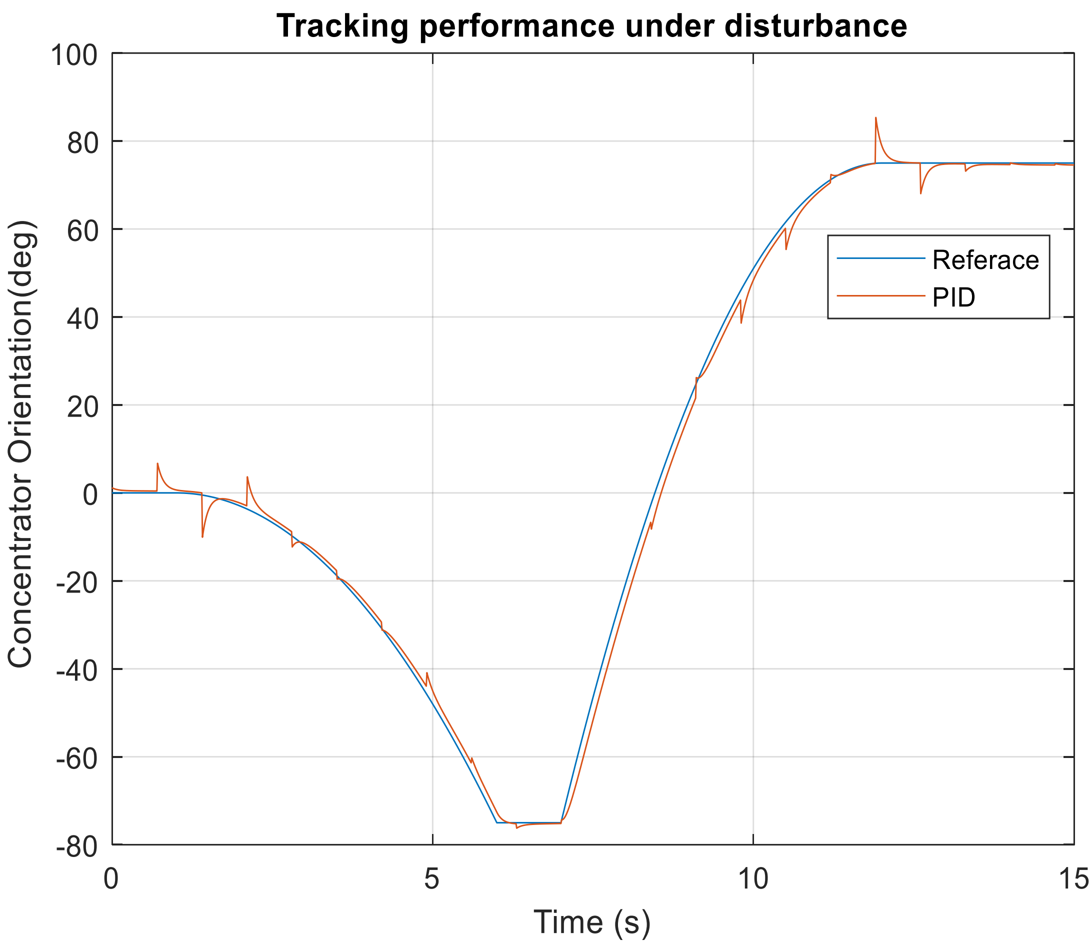


Figure 4.4: Response of the PID controller under aggressive wind disturbance

The response demonstrates rapid convergence of the joint angles to the desired trajectory, with minimal oscillations and acceptable levels of overshoot. Despite the disturbances, the system

- Tracking Error and Response Time

remains stable, and the tracking error is normalized with short period response time, showcasing the controller's robustness. The simulation confirms that the PID controller effectively compensates for the introduced disturbances, ensuring precise control of the solar concentrator's positioning.

The active solar tracking system was designed to improve the tracking accuracy of parabolic solar concentrators, even in harsh environmental conditions. The results from the simulation of the designed system show that it was able to achieve high tracking accuracy and fast response time.

- Extreme Condition Analysis

The system was simulated under extreme conditions, specifically high wind speeds of up to 55 m/s, to test its structural reliability. The results of the Finite Element Analysis (FEA) showed the system's ability to maintain structural integrity under these conditions.

- Comparison with Existing Methods

The designed active tracking mechanism is an improvement over existing methods, particularly the manual tracking systems used in the parabolic solar concentrator developed by Mekelle University. The active system uses sensors and a control system to adjust the concentrator's orientation in real-time, ensuring optimal alignment with the sun’s trajectory throughout the day. This is a significant improvement over manual or open-loop systems that cannot dynamically adjust to changing solar angles, leading to suboptimal energy capture and reduced efficiency.

# CHAPTER 5
# CONCLUSION AND RECOMMENDATION

## 5.1. Conclusion

This developed an active single-axis solar tracking system specifically designed to enhance the efficiency of parabolic solar concentrators. The motivation for this study stems from the critical need to address inefficiencies in solar tracking mechanisms, which significantly impact the energy capture and overall performance of solar concentrators. By employing advanced modeling and simulation techniques, this study provided a comprehensive solution that integrates structural robustness with precise tracking control. The Finite Element Analysis (FEA) conducted in ANSYS Workbench confirmed the system's capability to withstand wind loads of up to 55 m/s, demonstrating its structural integrity and suitability for operation in challenging environmental conditions such as those in Mekelle, Ethiopia.

Furthermore, the dynamic modeling and controller design carried out using MATLAB/Simulink showcased the system's ability to maintain high tracking accuracy. The PID controller developed for this system was meticulously tuned to optimize tracking performance, ensuring minimal errors and effective disturbance rejection. Results indicated a tracking accuracy exceeding 96%, with the system remaining stable even under simulated environmental disturbances such as wind-induced angular deviations. These findings highlight the importance of incorporating advanced control mechanisms to maximize solar energy capture and system reliability. The successful integration of structural and control design elements underscores the potential of active solar trackers to enhance the scalability and adoption of renewable energy systems, particularly in regions with limited energy access. Therefore, the objectives were met in both design and simulation.

## 5.2. Recommendation

In this thesis work, while designing and simulating the active single-axis solar tracker, several simplifications were made to manage complexity and computational limitations. The elasticity of the components in the tracking mechanism and friction between moving parts were not explicitly considered. As a result, the dynamic model developed using the MATLAB/Simulink environment may not fully capture the behavior of the actual system. Additionally, the actuator dynamics were not included in the modeling process to reduce the degree of complexity. For further improvements, it is recommended that future dynamic analyses consider both the elasticity and actuator dynamics to enhance the accuracy of the model and its representation of the real system. Moreover, the integration of advanced control techniques, such as ANFIS or fuzzy logic controllers, trained with sufficient iterations and enhanced computational capabilities, is also recommended.

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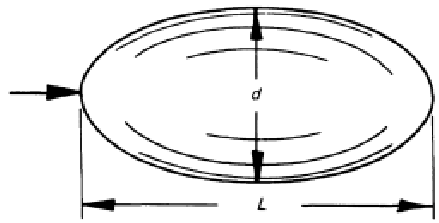
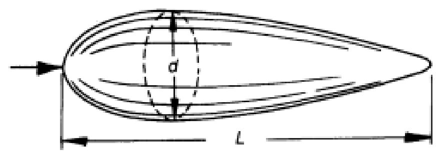
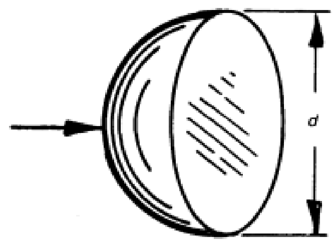
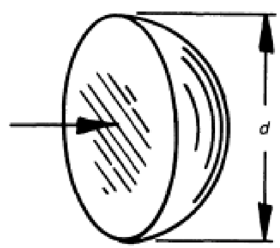
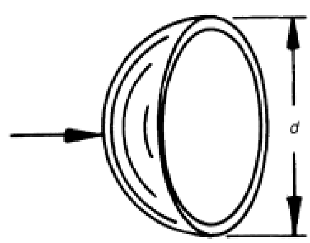
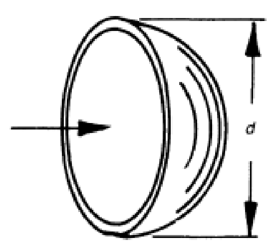
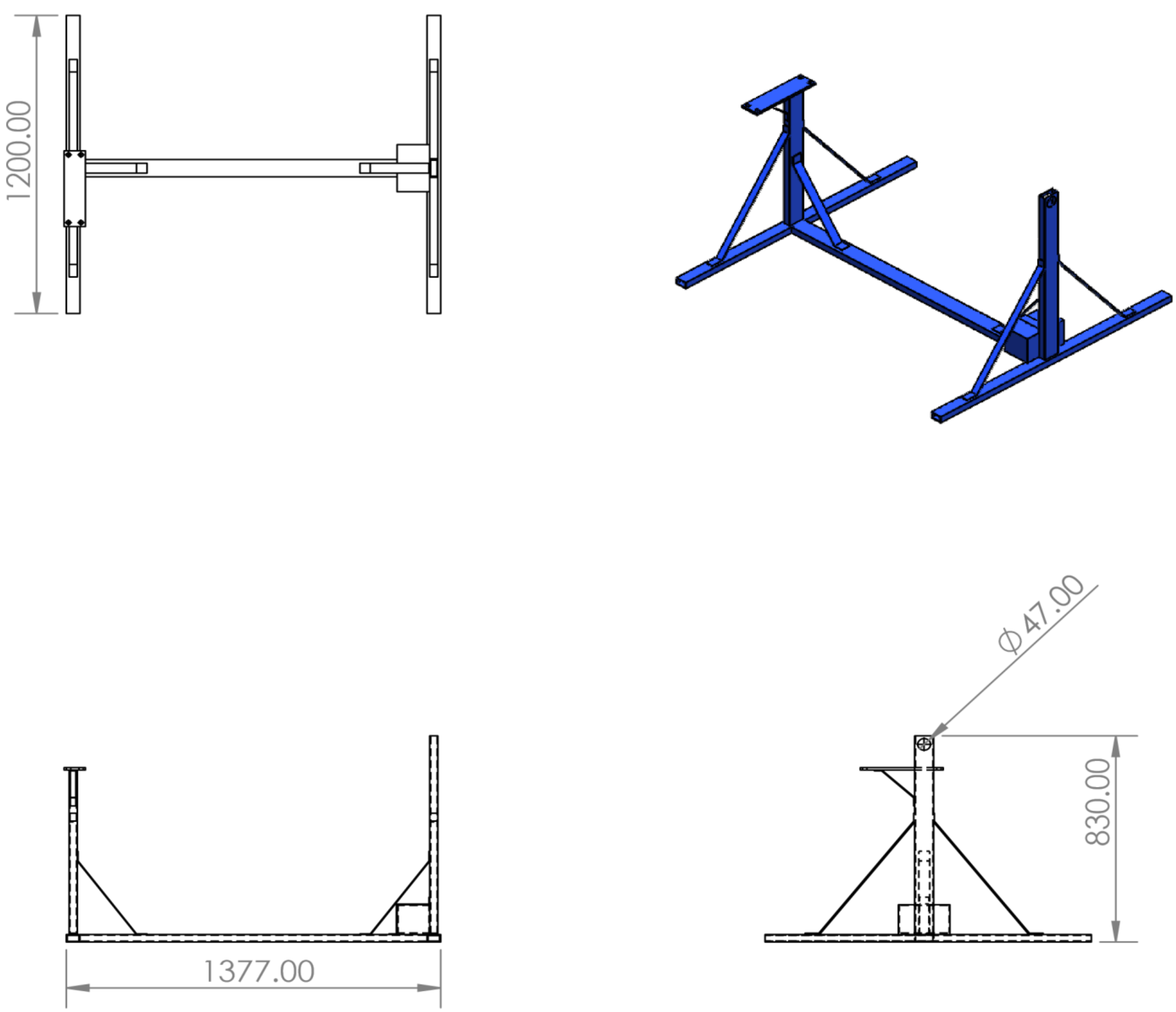
# APPENDIX

## Appendix-1: Drag Coefficients and The Projected Frontal Areas

| | | | | | |
|---|---|---|---|---|---|
| Ellipsoid | 5<br>2.5<br>1.25 | 0.06<br>0.07<br>0.13 | 100 | $\frac{\pi d^2}{4}$ |  |
| Streamlined body of circular cross-section | 3<br>4<br>5<br>6 | 0.049<br>0.051<br>0.060<br>0.072 | 500 | $\frac{\pi d^2}{4}$ |  |
| Solid hemisphere flow on convex face | | 0.38 | 0.1 | $\frac{\pi d^2}{4}$ |  |
| Solid hemisphere flow on on flat face | | 1.17 | 0.1 | $\frac{\pi d^2}{4}$ |  |
| Hollow hemisphere flow on convex face | | 0.80 | 0.1 | $\frac{\pi d^2}{4}$ |  |
| Hollow hemisphere flow on concave face | | 1.42 | 0.1 | $\frac{\pi d^2}{4}$ |  |

**Appendix-2: Part Drawing**

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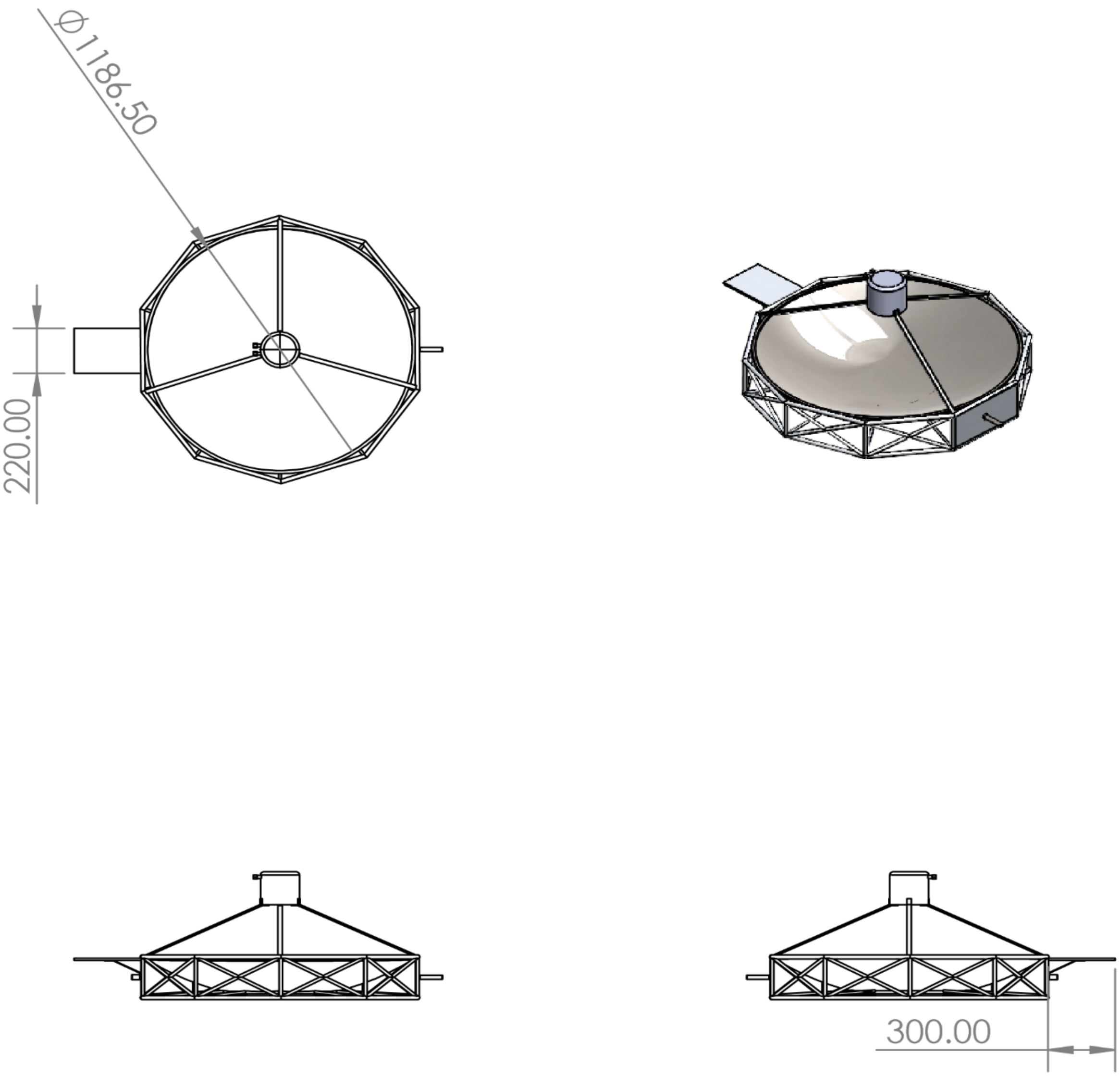
|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>DIMENSIONS ARE IN MILLIMETERS<br>SURFACE FINISH:<br>TOLERANCES:<br>LINEAR:<br>ANGULAR: | FINISH: | DEBURR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION |

| | NAME | SIGNATURE | DATE | |
|---|---|---|---|---|
| DRAWN | Awet Welay | | 12/9/2025 | TITLE: Stand |
| CHK'D | | | | |
| APPV'D | | | | |
| MFG | | | | |
| Q.A | | | | MATERIAL: AISI 1018 |
| | | | | WEIGHT: |

DWG NO. 1 — A4

SCALE:1:25 — SHEET 1 OF 1




UNLESS OTHERWISE SPECIFIED:
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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

| | NAME | SIGNATURE | DATE |
|---|---|---|---|
| DRAWN | Awet Welay | | 12/9/2024 |
| CHK'D | | | |
| APPV'D | | | |
| MFG | | | |
| Q.A | | | |

TITLE:

parabolic concentrator

MATERIAL:

50

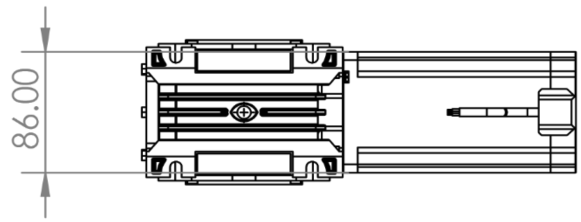
WEIGHT:

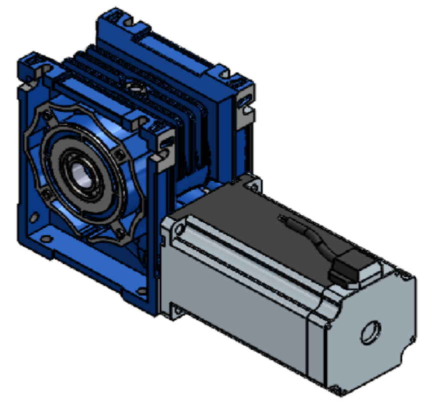
DWG NO. 2

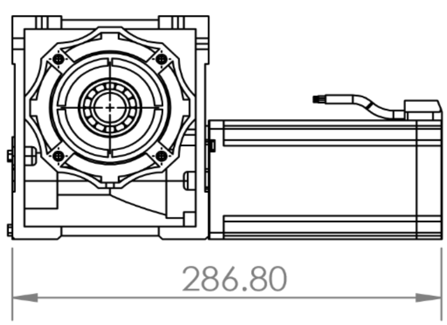
A4

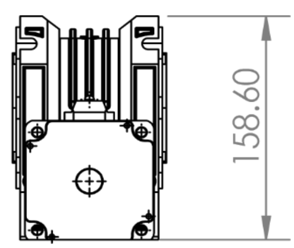
SCALE:1:33.3

SHEET 1 OF 1



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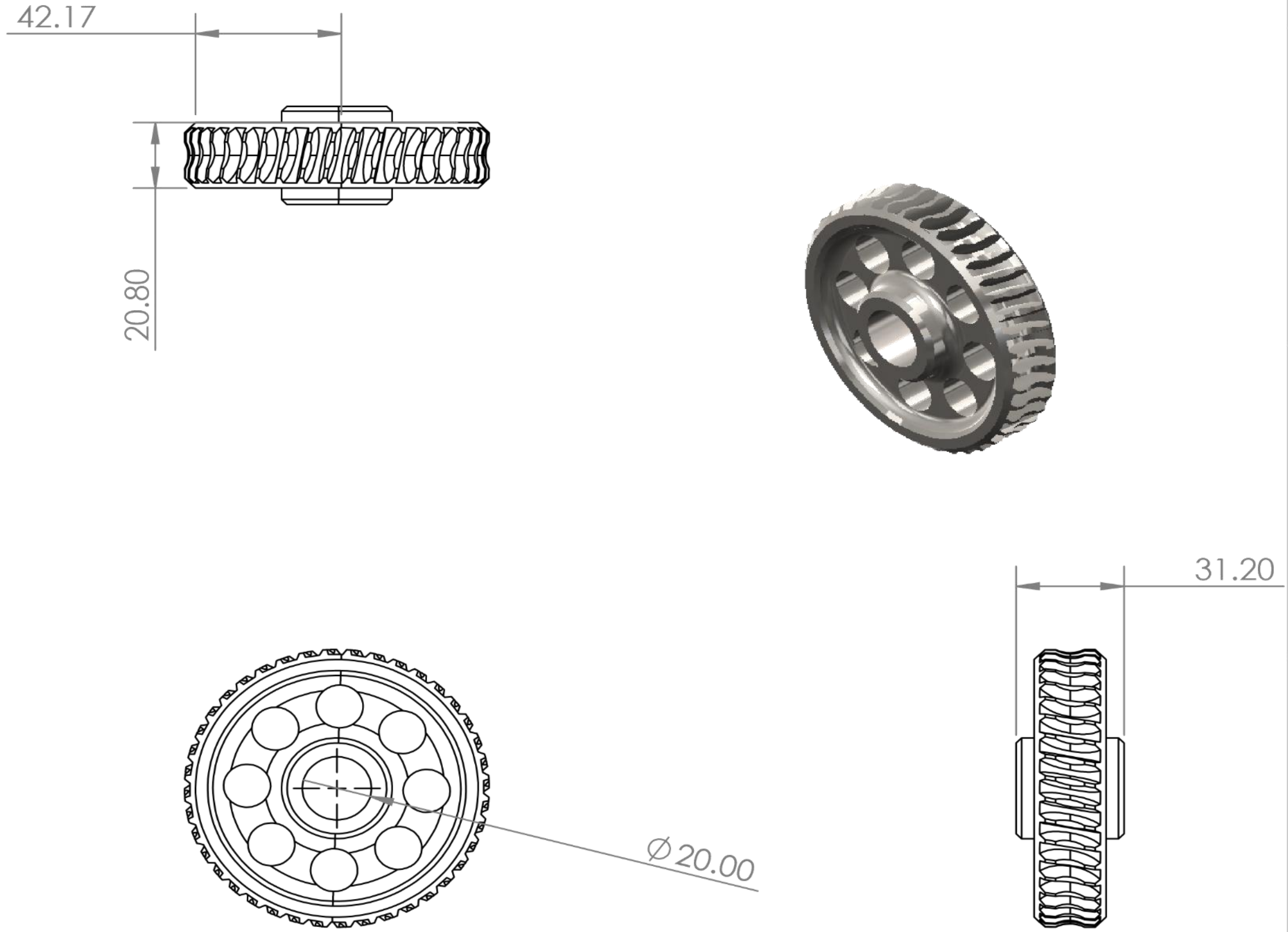
|---|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>DIMENSIONS ARE IN MILLIMETERS<br>SURFACE FINISH:<br>TOLERANCES:<br>LINEAR:<br>ANGULAR: | FINISH: | | DEBURR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION |
| | NAME | SIGNATURE | DATE | TITLE: | Motor Drive |
| DRAWN | Awet Welay | | 12/9/2024 | | |
| CHK'D | | | | | |
| APPV'D | | | | | |
| MFG | | | | | |
| Q.A | | | MATERIAL: | DWG NO. 3 | A4 |
| | | | WEIGHT: | SCALE:1:5 | SHEET 1 OF 1 |




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS SURFACE FINISH: TOLERANCES: LINEAR: ANGULAR: | | FINISH: | | | DEBURR AND BREAK SHARP EDGES | DO NOT SCALE DRAWING | REVISION |
| | NAME | SIGNATURE | DATE | | | TITLE: Worm wheel | |
| DRAWN | Awet Welay | | 12/9/2024 | | | | |
| CHK'D | | | | | | | |
| APPV'D | | | | | | | |
| MFG | | | | | | | |
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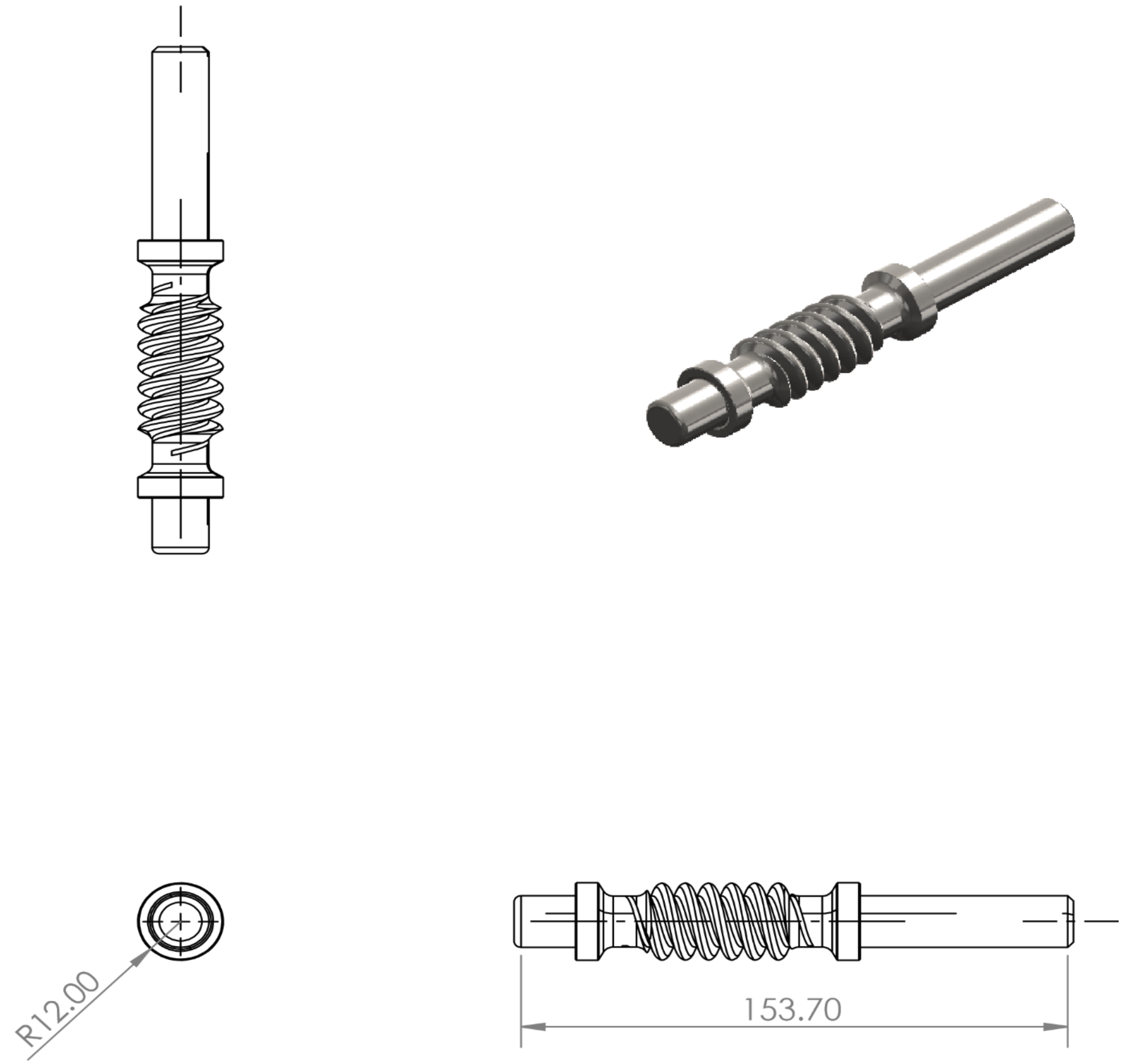
| | | | | WEIGHT: | | SCALE:1:2 | SHEET 1 OF 1 |




| | | | | | | | |
|---|---|---|---|---|---|---|---|
| UNLESS OTHERWISE SPECIFIED:<br>DIMENSIONS ARE IN MILLIMETERS<br>SURFACE FINISH:<br>TOLERANCES:<br>LINEAR:<br>ANGULAR: | | FINISH: | | DEBURR AND<br>BREAK SHARP<br>EDGES | | DO NOT SCALE DRAWING | REVISION |
| | NAME | SIGNATURE | DATE | | | TITLE: | |
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| CHK'D | | | | | | | |
| APPV'D | | | | | | | |
| MFG | | | | | | | |
| Q.A | | | | MATERIAL:<br>S45C 53 | | DWG NO.<br>4 | A4 |
| | | | | WEIGHT: | | SCALE:1:2 | SHEET 1 OF 1 |