DESIGN OF A DUAL AXIS SOLAR TRACKER CONCEPT FOR PHOTOVOLTAIC APPLICATIONS

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MAY, 2020

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…… ……

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Date: ……. Date: ……

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ABSTRACT

Solar energy is an abundant and clean resource. However, solar energy applications face challenges of low efficiency and high capital investments. To mitigate low efficiencies, electro-mechanical trackers that follow the sun path to enhance reception of solar energy are used. Usually these devices are complex in design. In this study, a simpler and less energy consuming dual axis solar tracker concept is designed and evaluated. A design process model consisting of the three main phases; planning, functional analysis, and design evaluation, was used. The planning phase involved the generation of design requirements and constraints. During this phase, existing dual axis solar trackers were reviewed, an energy output efficiency map was generated, and the fundamental functional objectives embodied in the most efficient ones were collated. In addition, design requirements of an existing 1.3 MW photovoltaic solar power plant at Phakalane (Botswana) were established using a questionnaire and interview approach by the author.

From the collated functional objectives and the generated requirements from the Phakalane solar plant, key requirements and constraints were identified which were then used to generate design alternatives of a less energy consuming and a simpler dual axis solar tracking system, using a functional analysis technique. From the design alternatives, the best concept was selected using a weighted evaluation matrix based on a five point Likert scale. A three dimensional solid model of the selected concept was developed using a SolidWorks® platform. The concept was then, compared to existing dual axis trackers, on the basis of design complexity and energy consumption of the position mechanisms using Keating (2000) design complexity metric and a **What-If** analysis, respectively. The designed dual axis solar tracker concept was found to be ten per cent (10%) less complex when compared with existing trackers. Therefore, this study realised a simpler and less energy consuming dual axis solar tracking concept for implementation.

Keywords: Design Methods, design for complexity, functional analysis, meta-analysis review, solar tracking, photovoltaic, dual axis.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC: Alternating current

Act: Actuate

Alt.: Alternative

CBM: Counter balanced mounting

COTC: Converter Operator Transmitter Controller

CS: Cloud sensor

CU.: Control unit

EA: Electrical Anemometer

Elec: Electrical

Ener: Energy

ER: Energy Recycling

ERW: Energy recycling wheel

FPGA: Field programmable gate array

FS: Feedback sensor

GPS: Global positioning system

HSAT: Horizontal single axis tracker

LCD: Liquid crystal display

LDR: Light dependent resistor

LED: Light emitting diode

Mech: Mechanical

PC: Personal computer

PKM: Parallel Kinematics mounting

PLC: Programmable logic controller

Pos.: Position

Pow: Power

Prot.: Protect

PV: Photovoltaic

RP: Rotating platform

RS: Rain sensor

RTC: Real time clock

SCADA: Supervision control and data acquisition

SMA: Shape memory alloy

SS: Support system

Sys: System

Tor: Torque

TSAT: Tilted single axis tracker

UI.: User`s interface

VSAT: Vertical single axis tracker

WPG: Weighing precipitation gauge

CHAPTER 1: INTRODUCTION

1.0 BACKGROUND

The use of renewable energy resources has increased as they are environmentally friendly and abundant. These resources are alternative to fossil fuels whose supply is in constant decline. Among renewable resources, solar is the most vital resource as it is widely and easily accessible. Hence, the current significant research interest in solar energy technologies, especially photovoltaic (PV) systems. Photovoltaic systems convert solar energy into electrical energy with the use of semiconductors. The general use of PV technology is however not helped by low efficiencies and poor reliability arising from complexities in design. As a result, PV technologies contribute a small amount to the grid with only about 1.5% of global electricity generated using solar PV technology as at the end of the year 2016 (REN21 Secretariat, 2017).

Generally, research, innovation and development work on PV efficiency, has tended to focus on the following main areas, namely: improved solar cells, cooling of solar modules, cleaning of panels, design of hybrid systems, optimization of panel orientation, and solar concentration systems. These areas are briefly discussed next; to help locate the research problem reported in this thesis.

The goal of research on solar cells is to design solar cell materials with high conversion efficiency. Recent developments in this area have resulted in new materials with enhanced efficiency and application than the first generation of PV materials (e.g. the silicon crystalline structure). These materials include; polymer and organic PV cells, Perovskite, light-absorbing dyes, space cells etc. (Ja, 2014).

Since heat energy is a by-product of the photovoltaic process; often, overheating of panels occurs due to high ambient temperature and irradiance. Temperature increase, especially in open-circuit voltage, decreases efficiency. Therefore, cooling serves to lower the solar cell temperature to an optimum level and thus improve its efficiency.

Also cleaning off dust or dirt that builds up on solar panels is an important initiative for enhancing conversion efficiency and longevity thereof. This is because as dust accumulates on panel surfaces, it scatters the solar irradiance resulting in loss of power.

Also, dust creates hot spots on panel surfaces which lead to non-uniform power generation by panels, therefore damaging the solar cells (Fouad et al, 2017).

Hybrid photovoltaic systems combine PV and other forms of power generations (e.g. wind, solar thermal technology, biofuels, petroleum fuels etc.). These systems are often handy because solar energy is only available during the day; therefore, they reduce the cost of using power storage devices for night application. An example of a hybrid system is at Sekhutlane (Botswana). The plant uses biogas and solar PV system to power the community (Klintenberg et al, 2014).

Under optimized panel orientation is solar tracking, which is the focus area of this research. According to Mousazadeh et al, (2009) a solar tracker is defined as an electro-mechanical system which follow the sun path to enhance reception of solar energy. The first solar tracker was a mechanical system by C. Finster, invented in 1962. However, the Finster solar tracker realized insignificant energy gains. Years of testing and research have however, led to improvement in the conversion output of PV systems and consequently the emergence of different tracking technologies and applications such as concentrators and non-concentrators (Hafez et al, 2018).

1.1 PROBLEM STATEMENT

Tracking of the sun is in principle based on the relationship of the earth and the sun. This is described by the motion of the earth around the sun on its axis. The earth motion portrays a dual axis patterns, that is, it spins (i.e. on it poles) and rotates on its axis around the sun Therefore a more efficient and effective method of tracking the sun is one that is able to position the sun as per the earth's dual motion pattern. Such trackers are referred to as dual trackers. Besides dual axis tracking, there is single axis tracking that rotates only in one axis. Single axis tracking is more popular due to its simplicity. Dual axis tracking on the other hand uses more components, involve high capital investment to install and maintain, and also consumes a lot of energy.

1.2 AIMS AND OBJECTIVES

This research project therefore aims to design a simpler and less energy consuming dual axis solar tracking system for photovoltaic applications

The objectives of this study are to:

1) Develop requirements for a simpler and less energy consuming tracking system after the following;
    a) Conducting a meta-analysis review of dual axis solar tracking
    b) Establishing the energy output and efficiency trajectory map of dual axis solar trackers for the period 1997 to 2017
    c) Studying the complexity of dual axis solar trackers for the period 1997 to 2017
    d) Reviewing positioning mechanisms of dual axis solar trackers and their energy consumptions
2) Develop a concept of dual axis solar tracking as follows;
    a) Development of a functional model of a less energy consuming dual solar tracker
    b) Generation of design alternatives
    c) Evaluation of the alternatives and selection of the best design concept, and finally,
3) Evaluate the complexity and energy consumption of the developed concept against existing models.

1.3 SIGNIFICANCE OF STUDY

Development of a simpler and less energy consuming dual axis tracking system is important as it will improve the use of solar energy. The use of solar energy is beneficial as it is environmentally friendly and available in abundance. Therefore, maximising the use of this renewable energy resource could help to supply electricity to rural and remote areas hence, driving the development of such communities. Also, this research is vital for sharing knowledge with relevant stakeholders such as academic institutions, research bodies, policymakers, independent power producers, etc.

1.4 THESIS OUTLINE

The rest of this thesis is organised into four chapters as follows:

Chapter 2: Literature review: This chapter describes the literature architecture i.e. the current status of meta-analysis review of solar trackers. Moreover, it discusses the design complexity metrics, leading to selection of a suitable method of analysing complexity in this study. It also, identifies the gaps in the literature to justify the intervention offered in this thesis.

Chapter 3: Methodology: The meta-analysis and design processes engaged in this research project are discussed in this chapter. Under meta-analysis, a description of the search for and selection of references process is outlined. For the design process the activities performed, and design methods used to carry out those activities are also discussed.

Chapter 4: Result and discussions: This chapter presents and interprets the findings of the study conducted. The findings are in three parts, namely; review of dual axis solar tracking, development of the dual axis solar tracker concept and comparison of developed concept with existing solar tracker

Chapter 5: Conclusion and recommendation: A conclusion on the findings and future scope of this study is presented in this chapter.

CHAPTER 2: LITERATURE REVIEW

2.1 CHAPTER SUMMARY

What other researchers have done in the field of solar tracking is discussed in this chapter. This led to identification of gaps in the literature. After, the identified gaps, a plan for bridging them is defined; in terms of defining the design complexity and its metrics. Moreover, a selection process of the design complexity metric to be used for further analysis is outlined. Lastly the design process approach to be deployed is also stated.

2.3 CURRENT OF STATUS OF DUAL AXIS SOLAR TRACKING

The first solar tracking design was invented in 1962 and was a single axis tracker. Dual axis tracking was first developed in 1984 by Zobgi and Laplaze (Sumathi et al, 2018). Therefore, dual axis solar tracking mechanisms have been around for the past three decades. In this study the efficiency and complexity of dual tracking mechanism in the period between 1997 and 2017 is investigated. As established by Hafez (2018), research interest in solar tracking gained significant traction between 2009 and 2016 **(see figure 2-1)**. **Lee et al (2009)** made the first attempt to study efficiency of solar tracking mechanisms for the period 1984 to 2006. However, his research work was biased towards capturing the new control strategies achieved over the period. In this thesis the period from 1984 to 1996 is excluded after it was established that dual axis tracking mechanisms only became of field application between 1997 and 2017.

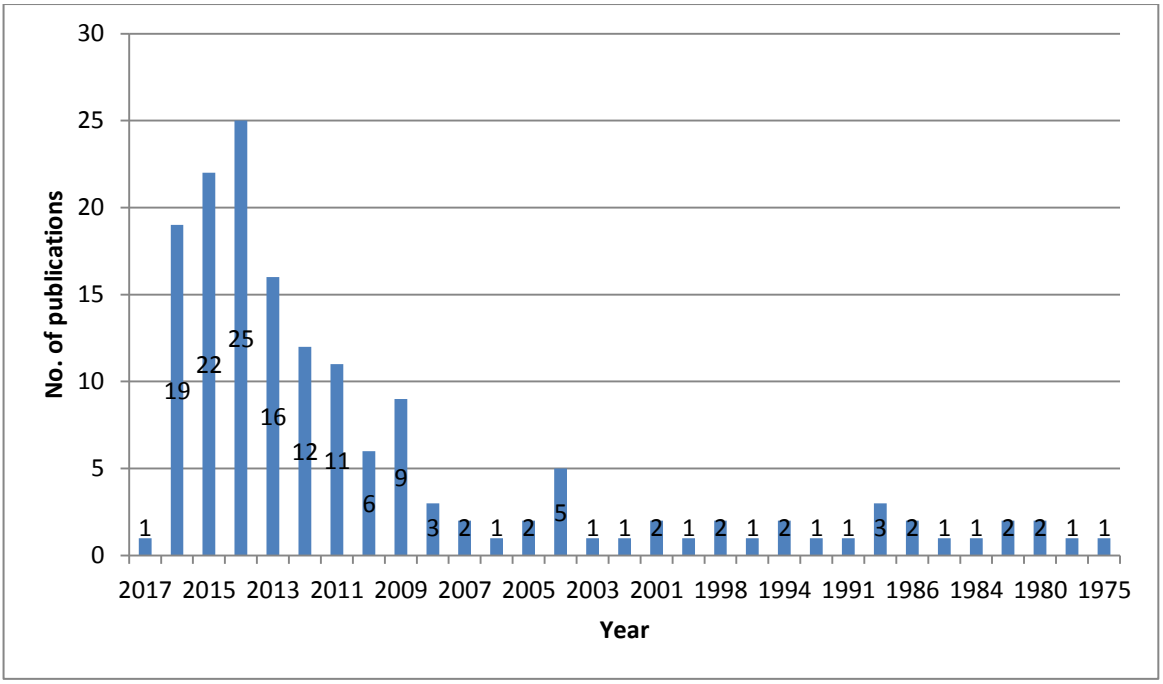


Figure 2-1: Solar tracking publication distribution source; (Hafez et al, 2018)

Although dual axis tracking mechanisms have been studied for the past three decades and general tracking technology has been studied for five and half decades (1962-2017), meta analysis reviews of solar tracking systems appears not to be popular. In this literature review, a summary of those few researches that have undertaken meta analytical studies (or general reviews) of solar tracking systems are preseted below;

Mousazadeh et al, (2009) carried a review study, which resulted in the general categorisation of solar tracking systems according to two main typologies, namely; Energy source (i.e. passive, active and manual), and Degree of freedom (dof) (i.e. single or dual-axis).

Hafez et al, (2018) conducted a review that discussed different solar tracking mechanisms (i.e. physical configurations and design parameters) and their applications. Furthermore; the authors, quantified the number of publications for both single and dual axis tracking mechanisms since the first tracker was invented. The authors concluded that; 42.57% of the published materials were about single axis tracking mechanism while 41.58% of the publications were about dual axis tracking mechanism.

Sumathi et al, (2017) evaluated different maximum power point tracking algorithms and control methods of solar tracking mechanisms. The authors concluded that active solar

tracking is more popular than passive tracking mechanisms. Furthermore, it was concluded that active trackers are easily monitored albeit at an additional cost.

Nsengiyumva et al, (2018) carried out a review study of solar tracking system for the period of fifty years. The review included; a description of historical landscape of solar tracking mechanisms (i.e. the physical configurations), economic feasibility and limitations affecting the use of solar tracking. The authors found that; solar tracking application is limited by several factors such as; climatic conditions, PV cell materials, grid connection losses, cost and availability of trackers in the market.

Singh et al, (2017) investigated the physical configuration of solar tracking mechanisms and assessed their economic feasibility. From the study it was concluded that, tracker that comprises of microcontrollers are more economic feasible than those comprising programmable logic controllers.

Kanyarusoke et al, (2015) reviewed solar tracking system`s physical configurations in the context of developing a mechanism suitable for tropical region of Africa, at a domestic application scale.

A review of solar tracking efficiency was last done by **Lee et al (2009)** for the period 1984 to 2006. In review tracking error and energy efficiency were investigated. The authors found that over the years tracking error has reduced, with an increasing efficiency of solar tracking. (See ***Table 2-1*** for the summary of the above review)

Table 2-1: A summary of literature review

Reference	Aims of Review	Type of tracking mechanism (dof)	Type of Solar Application	Period of study
Mousazadeh et al, (2009)	• Classification • Physical configuration	Both single and dual axis	• PV (plus concetrator system • Thermal system	Undefined
Hafez et al, (2018)	• History of solar tracking • Classification • Physical configuration • Quantified publication on solar tracking • Usage of solar trackers	Both single and dual axis	• PV (plus concetrator system • Thermal system	1962- 2017
Sumathi et al, (2017)	• Maximum power point tracking algorimths classification • Studied different controls of trackers	Both single and dual axis	• PV (plus concetrator system • Thermal system	Decade upto 2016
Nsengiyumva et al, (2018)	• History of trackers • Classification • Physical configuration • Factors limiting use of solar tracking (climatic conditions, PV materials, grid connection, cost and availabity of solar tracking)	Both single and dual axis	• PV (plus concetrator system • Thermal system	1962-2017
Singh et al, (2017)	• Classification • Physical configuration • Commercial availability • Economic assement	Both single and dual axis	• PV	Undefined
Kanyarusoke et al, (2015)	• Contextualised review for tropical climate based on physical configuration	Both single and dual axis	Domestic application (thermal and PV)	Undefined
Lee et al (2009)	• Compared tracking error of closed and open loop controlled tracker • A conducted a efficiency reviw of the tracker	Not specified	• PV (plus concetrator system • Thermal system	1984-2006

2.4 IDENTIFIED GAP IN LITERATURE

In summary, this research studies the efficiency and complexity of dual axis solar tracking mechanisms. It has been shown in the foregoing review that no publication to the knowledge of the author, has attempted to measure the complexity of dual axis solar tracking. Moreover, no previous work has done a meta-analysis study of the efficiency of dual axis tracking systems. In this study, these two attributes are investigated. Efficiency and complexity trajectory maps for dual axis solar tracking are generated in order to set a benchmark for the design of a simpler and less energy consuming mechanism. As noted before, the closest work to the investigation undertaken in this thesis is by Lee et al

(2009). However, Lee et al did not study dual axis tracking efficiencies and their design complexities.

2.5 DESIGN COMPLEXITY

Design complexity is a field in design engineering which focuses on analysing and managing uncertainties of designs (i.e. process and product) due to many interwoven elements and attributes which make an object difficult to understand. Managing complexity in design is important as it reduces effort and resources used when developing products. Design complexity metrics measure a number of design aspects such as; structural complexity: (i.e. physical arrangement and interactions of constituting components), functional complexity: (i.e. number, variety, and interactions of basic and support functions) behavioural complexity: (i.e. predictability and understand-ability of product`s behavioural in the field) (Ameri et al 2008).

Solar tracking literature, generally, acknowledges the importance of design complexity. However, no study has investigated complexity in solar tracking systems. Since this work investigated dual solar tracking systems from a functional analysis standpoint, only functional complexity was investigated. Three metric systems of measuring functional complexity have been developed. Bashir and Thompson (1999) developed a design complexity metric system that uses a functional decomposition approach. The devices are broken down from basic to advanced functions. This approach considers a linear relationship of functions at each level, but the number of assemblies and components in a device are neglected. Roy et al (2010) `s complexity metric method was formulated to address the demand of the device with regard to the commonality of components used to construct the device. In definition product commonality is number of parts being used for more than one product and is measured for all product family. Keating (2000) developed a complexity metric system which is based on the number of components and their interaction in a device. ***Table 2-2*** gives a summary of the metrics and reasons for disregarding some and choosing one.

Table 2-2: Design complexity metrics review

Reference	Description	Formula	Comments
Bashir and Thompson (1999)	Number of functions	$C = \sum_{j=1}^{l} F_j k_j$ Where; C =complexity L= number levels F_j = number of functions at level j K_j = weight of level j; 1,2,	Not selected because only a few of the publications reviewed in this study disclosed the functional decomposition of their designs.
Roy et al (2010)	Demand	$C = {}^{d_i}/_{d}$ Where; d_i=demand of part variant d = total demand of product	This approach is based on the availability of product components in the market. Therefore, this method is not relevant for use in this study.
Keating (2000)	Number of components and interaction	$C = M^2 + I^2$ Where; M= Module/components I= interactions	Since most publications describe their devices in terms of assemblies, components, and their interactions, this method was found to be the most suitable for this research.

2.6 JUSTIFICATION OF DESIGN PROCESS

In order to design a simple and less energy consuming concept, a functional analysis approach is used. This approach is not commonly applied in design of solar trackers as the majority of researchers discuss the structural design (physical configurations) of solar tracking system. Functional analysis is an early stage of product design in which customer`s requirements are transformed into functional means (physical components). In the approach, the designer surveys the prospective customer`s market to develop a product that is suitable for their need. Often, simpler and competitive products than existing ones are realised by this approach (Ahmed and Ahmed, 2016). The literature affirms that identification of functional requirements is crucial to the development of marketable and efficient solar tracking devices. Below is a discussion of researches that acknowledge importance of functional requirements use for design of solar trackers.

Nixon et al (2013) used an approach similar to functional analysis method namely; a multi-criteria decision-making, in the design of solar thermal collectors. When using the approach, the author translated the customer`s needs into technical requirements (i.e. specifications), This approach indirectly appreciates the development of functional requirements in order to formulate the technical requirements. This method is not sufficient for conducting a detailed functional analysis, because it focuses on transformation of customer`s needs into technical requirements.

Salem (2013) deployed a concurrent design approach in development of solar tracker for PV system. The author reports a physical configuration design of solar tracker, but also,

made an emphasis; on formulating functional requirements before a structural design of a solar tracker.

Lastly **Flores-Hernandez et al (2017)** proposed a mechatronic design approach (VDI 2206) for the design of solar tracking that uses a robotic sensor. The methodology also transforms customer`s needs into physical devices. The authors also noted that defining functional requirements is a crucial phase before the physical configurations design.

In conclusion the mentioned publications addressed the importance of functional requirements, but these researches did not demonstrate the process of establishing functional requirements. This shortcoming is addressed in this study through the use of a functional analysis approach.

CHAPTER 3: METHODOLOGY

3.1 CHAPTER SUMMARY

In this chapter, three methodologies used in this study are discussed, namely; a meta-analysis review process of dual axis solar tracking mechanisms, the methodology used to establish efficiency of components, and lastly, the methodology used to come up with the new design. The meta-analysis process describes how the selection of references used in the study was conducted. The second section discusses the complexity assessment of solar tracking design presented in the selected literature references. The third section of this chapter discusses the design process used in this research.

3.2. META-ANALYSIS PROCESS

Meta-analysis review is a process of aggregating information from different studies, with the aim of producing a more realistic estimate of a certain measure. This approach was used in the selection of references and information extraction of dual axis solar tracker, namely; efficiency (i.e. output and consumed energy) and complexity. The process is discussed below.

Several relevant keywords were deployed. These keywords include; "solar tracking", "dual axis" and "efficiency". Two search phrases were coined, for example; "*design of dual axis solar tracking and its efficiency*", and "*efficiency of dual axis solar tracking*". The search phrases were entered a browser such as the Google scholar platform. A total of about one hundred and eighty-nine (189) publications were identified at this stage. Duplicates and publications not conforming to the period of studies were removed.

Abstract screening process was then carried out to eliminate irrelevant references. In total, one hundred and fifty (150) materials were evaluated. Further to the above, the titles and the abstracts of the material were also screened against the goals and those that did not conform were rejected from the library of reviews created. That is references with irrelevant tittle were rejected. Also, the author rejected some irrelevant materials after evaluation, through read the abstract. And about ninety (90) materials were rejected at this stage. The remaining sixty (60) materials were then subjected to a full text review in which the author evaluated if the reference explicitly stated the information required i.e. efficiency and design of dual axis of solar tracking for PV applications. This stage resulted

in selection of twenty-one (21) references that were later used in extraction and synthesis of the relevant data. The data for efficiency obtained from the relevant pool of publications above was plotted in a graph (see **Chapter 4)** to describe trajectory and pattern of dual axis solar tracking for the period 1997-2017. The complexity assessment methodology is discussed in the next section of this chapter. However, the overall summary of these two methodologies is presented in ***Figure 3-1***.

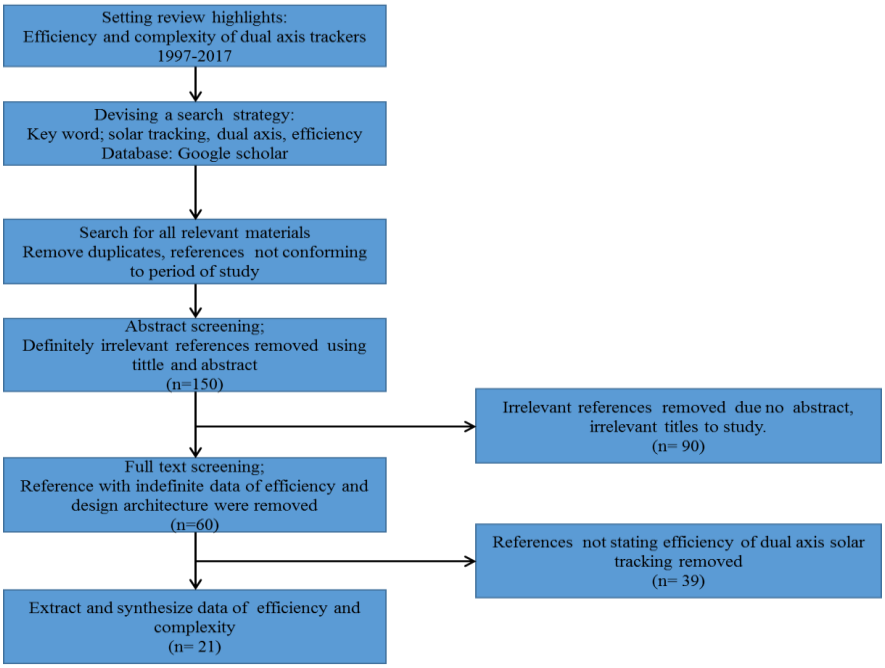


Figure 3-1: Meta-analysis process deployed in study

3.3 DESIGN COMPLEXITY ANALYSIS

The analysis was carried out by comparing the existing systems` design complexity with the developed concept. In the comparison, the approach used by Keating (2000) was adopted. This approach uses modules and interactions between the modules to compare design products. A typical Keating's model is given in ***Figure 3-2*** whereby the number of components/ modules (M), and number of interactions (I), in the design are counted and the inherent complexity computed using ***Equation (3.1)***. (A detailed presentation is given in **Appendix A**).

$$C = M^2 + I^2 \tag{3.1}$$

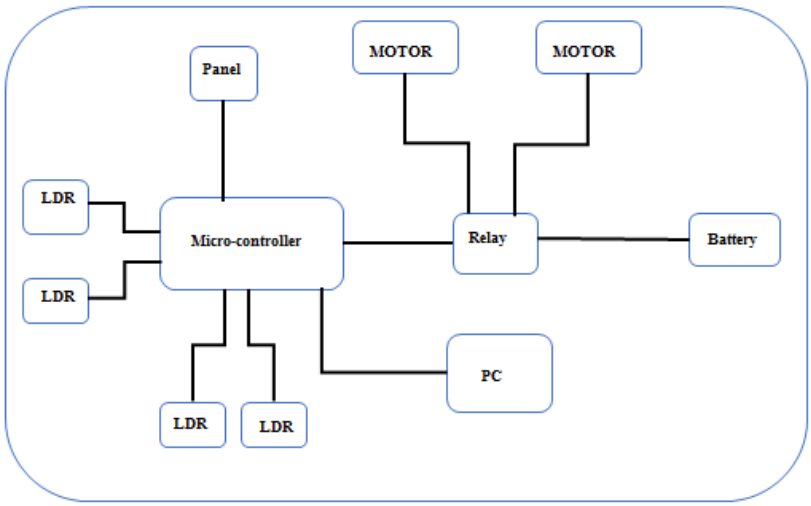


Figure 3-2: A block diagram showing module and interaction of system developed by Akbar et al, (2017)

3.4 THE DESIGN PROCESS

The design process model is also divided into three main stages, namely, planning, functional analysis, and design evaluation under which several prescriptive design stages were implemented as discussed below.

Table 3-1: The design process used to develop dual axis solar tracker

Design stage	**Prescriptive design stage**	**Design method**	**Tasks**
Planning	Identifying customer`s requirements and constraints	Interview	Setting goals, evaluation measures and planning
Functional Analysis	Functional decomposition	Transparent box and function-means tree	Formulation of product function structure and behaviour.
	Generating alternatives	Morphological analysis	Ideation
Design evaluation	Development of concept	Concept selection	Evaluation of alternatives
		Technical Drawings	Drafting
	Concept evaluation	Complexity metric measures	Analysis and evaluation
		Energy consumption	

3.4.1 IDENTIFYING DESIGN REQUIREMENTS AND CONSTRAINTS

The requirements and constraints of a dual axis tracker were established from an interview conducted with a facility technician at the Phakalane solar plant (Botswana). This was to understand the requirements of a dual axis solar tracker from an expert. The following questions were asked in the direct interview, i.e. the author scribed the response on a notepad during this interaction with interviewee. The questions were divided into two categories, namely, functional and non-functional aspects.

Functional aspects: The following five (05) questions were asked under functional aspects

1. What defines the best performing solar tracking, in terms of its;

a. Level of efficiency
b. Power consumption
c. Tracking accuracy

2. How is the solar tracking going to be operated i.e. manually, semi-automatic or automatic?

3. Under which environmental conditions is the device going to operate?

4. Is the device profitable (i.e. what is it payback)?

5. What level of maintenance and repairing is required?

6. What type of technology is required to operate the device?

Non-functional aspects: the following four (04) questions were asked under this aspect

1. What method of waste disposal will be used after product life cycle?

2. Is the 3Rs (reuse, reduce and recycle) approach embedded in the product?

3. How will the operation of the device affect wildlife, birdlife and water sources?

4. What level of aesthetics is required for the system?

3.4.2 FUNCTIONAL ANALYSIS

3.4.2.1 FUNCTIONAL DECOMPOSITION

The form follows functions approach was used for this stage. This means that functions establishment should be independent of geometrical state to broaden the solution space (Ullman, 2010). A function is defined as a task that transforms input to output in the system (Tor, Britton, & Zhang). Therefore, functional modelling is a framework that relates functions in a flow, process, and operation applied to a certain system. This approach aided in the development of "*function chains*" for the solar tracking concept. Function chains are set of tasks commonly performed by a single physical component. This process was carried out as follows;

Firstly, existing solar tracking mechanisms were studied, to come up with functional objectives (i.e. basic functions of solar tracking system). The Universal Track Racks™ by ZomeWorks (in ***Figure 3-3***) was used in this regard.

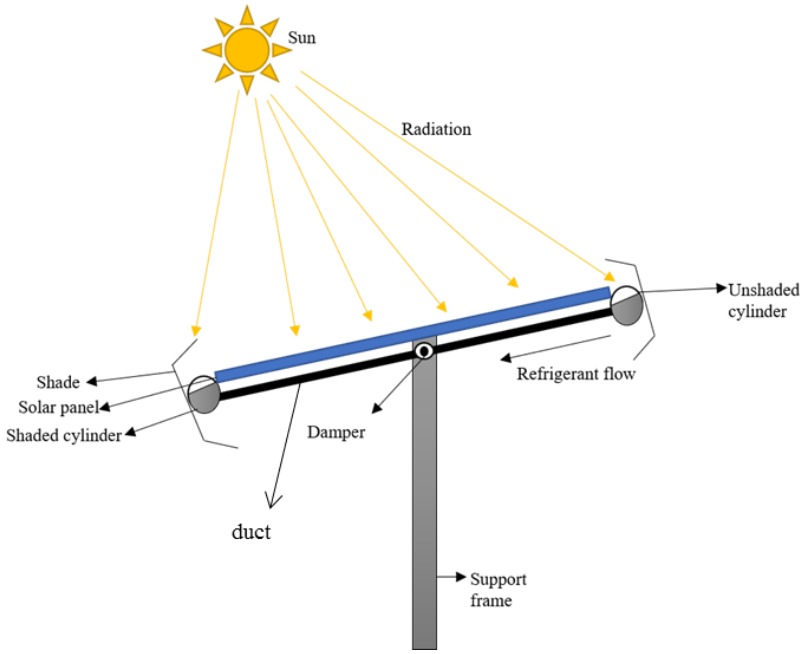


Figure 3-3: Passive solar tracking mechanism adopted from (ZomeWorks Corporation,2017)

This tracker was used to represent a model of existing tracking since it is a popular commercial solar tracking device. The tracking system uses two identical cylinders *if is single axis* and four *if is dual axis.* The cylinders are on a support frame as illustrated in ***Figure 3-3***. The cylinders contain a working thermo-fluid, normally a refrigerant. As the position of the sun changes with time, one cylinder receives more thermal power than the other. Due to this, the refrigerant in that cylinder expands and flows to the cylinder with less thermal power, through a duct, tilting the panel in that direction due to the weight differences. The tilting will progress gradually in that direction with the panel following the sun until sunset, after which the pressure between the cylinders becomes equal and the panel goes back to the normal start position. To avoid shock on the system, a damper is normally installed as indicated.

From the above process, the four sub-functions given in ***Table 3-2*** can be deduced;

Table 3-2: Summary of functional requirements identified through Zomeworks solar tracker

Process	**Function identified**
Unequal reception of solar energy by identical cylinder (the shaded and un-shaded)	To precisely determine the position of the sun
Pressure build up in un-shaded cylinder	To calibrate the positioning mechanism.
The liquid refrigerant escapes from the un-shaded cylinder into a shaded cylinder. A weight imbalance is then detected by the pivot point. Due to gravity the shaded then moves the panel.	To generate the tracking motion.
A dumper then regulates the motion of the solar panel to avoid shock in the system.	To monitor tracking effect.

These four main functions were mapped into the requirements by matching functions with the requirements. In this process the author used personal discretion and logic as a way of evaluating the process of converting the requirements into functions. Since the conversion process of requirements into functions is heuristic (meaning that it is done through, trial and error) therefore is important to check if the developed functions address the requirements. For example, the function "to precisely determine the position of the sun" fulfil requirements "Should have low tracking error". But this function to be achieved in a natural environment it is constrained by environmental disturbances like cloudiness, wind, and rain. Also, internal disturbances such as interfacing of components constrain the machine`s functionality.

In preparation for the next stage of the design process, being the generation and evaluation of design alternatives, the evaluation measures in ***Table 3-3*** were formulated. Using the same function "to precisely determine the position of the sun" as an example. The author established the evaluation measures using this thought aid process. "*What defines best sun positioning method or system?"* A best sun positioning method or system should work reliable under cloudy conditions, therefore this function match with the evaluation measure "*reliable in cloudy conditions".*

Table 3-3: Design requirements, constraints, and evaluation measures

QUESTIONS	REQUIREMENTS	CONSTRAINTS	FUNCTIONS	EVALUATION MEASURES
FUNCTIONAL ASPECT				
What defines the best performing solar tracking devices?	• Should have low tracking error. • Should consume as minimum energy as possible.	• Environmental disturbance (cloudiness, wind, rain etc.). • Internal disturbance (interfacing of components). • Power consumption.	• To accurately determine sun position • To precisely calibrate positioning mechanism • To rotate the panel towards the sun using a low amount of energy	• Reliable in Cloudy conditions. • Accuracy and precision of control • High response rate • Power consumption
How is the solar tracking going to be operated i.e. manually, semi-automatic automatic?	Should be fully automated.	Technical know-how of operator	• To monitor the tracking effects • To precisely calibrate positioning mechanism	Adaptability to different control techniques.
In which environmental conditions is the device going to operate?	Should be robust to extreme weather and instant changes.	Environmental conditions Cost	To monitor the tracking effects	Reliability
Is the device profitable (i.e. what is it payback)?	Should be at an optimum profit return	Financial budget for production	All functions	Cost
What level of maintenance and repairing is required?	• Should be made of components available within the locality of operation. • Should be easy for locals to repair or maintain.	Technical know-how of operator	All functions	Maintainability (cost and timeliness)
What type of technology is required to operate the device?	Should not be obsolete or too advanced for local uses.	Available technological aspect	All functions	Scalability Availability Assemble-ability
NON-FUNCTIONAL ASPECT				
What method of waste disposal will be used after product life cycle? How will the operation of the device after wildlife, birdlife and water sources?	• Should be environmentally friendly (reduced water, wild and birdlife pollutant) • Should be made of material easy to reuse and recycle	Environmental regulations	All functions	Sustainability
What size of land is available of the system?	Should cover minimal land as possible	Available land	All functions	Land coverage ratio
What level of aesthetics is required for the system?	Should be appealing to consumers	Budget Time	All functions	Versatility (different application of the device e.g. car parks, rooftop etc.)

Using *"to become the flow"* heuristic approach, the transparent box model was developed to identify the *"function chains"* (i.e. related tasks often performed by a single physical

component). "*Becoming the flow"* approach is based on the flow of energy, signal and material in a system. The first step engaged in this process was to identify the inputs, outputs and following their interactions in the solar tracking system. Inputs in this study are defined as fundamental *"causes"* that ensure that the overall function of the system is performed. Output is the *"effect"* produced in the system i.e. these include; desired and undesired effects. Some of the inputs remain unchanged, while others change (i.e. they are consumed) in a process carried out by a system. These inputs were traced until they exit the system as outputs. To identify inputs and outputs the following guideline were used, a consideration of the requirements (i.e. functional aspect of system), environmental conditions and designer`s understanding of the problem.

Figure 3-4 shows a function-means tree which match functions to the functional chains. It was used to check, if the realised function chains balance with functions. For example, a "sun position sensor" as a function chain was identified to perform the function; "To accurately determine the sun`s position", therefore proving that function chains match with their functions.

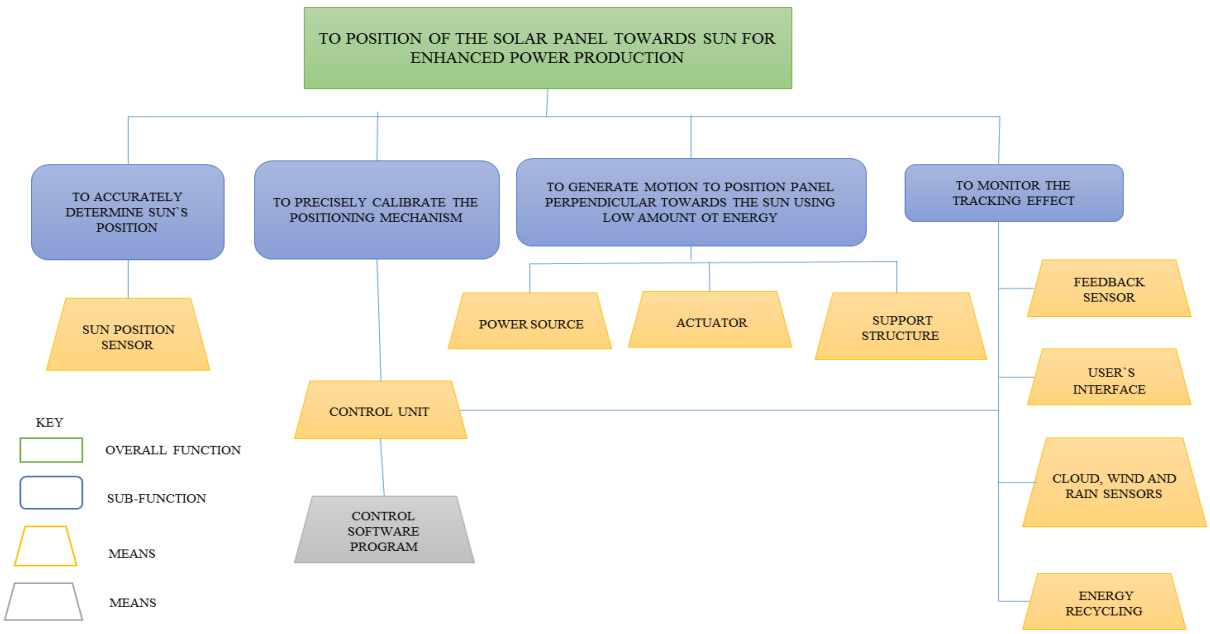


Figure 3-4: A function tree relating functions to function chains

3.4.2.2 GENERATION OF ALTERNATIVES

This stage, transition *"function chains"* realized from the transparent box model into physical components. A morphological Chart was deployed to perform this transitional process, i.e. to present design alternatives generated in this research. Firstly the function chains identified with the aid of transparent box model were listed in the column of morphological chart (grid). Then possible alternatives (i.e. these are physical components available in market) to perform the tasks of the function chains were identified. Through brainstorming, the grid of the morphological chart was filled by noting (with text) ideated alternatives alongside their relevant function chains (i.e. on the row of the function chain). For example, two alternatives; electronic anemometry (alt 1) and airflow sensor (alt 2) were brainstormed for the function chain; wind sensor.

3.4.3 DEVELOPMENT OF CONCEPT

The evaluation measures formulated at the planning stage (see **Table 3-2**) of the design process were then deployed to judge the alternatives. As a way of guiding selection of best alternatives, that will be used to develop a concept. Some of the evaluation measures, which are normally used for evaluation of concepts, are defined below:

- Serviceability/ maintainability: This attribute describes the timeliness, relative cost and availability of skilled personnel in the local areas to carry out replacement and/or repair of components.
- Reliability: the ability to maintain an expected functional behaviour at all times and under specific conditions
- Interfacing/ compatibility: the ability of the component to be useable with different configurations and strategies to achieve the desired function.
- Scalability: can a component be easily down or up sized for a specified application.
- Cost: the price value of a single component will affect the total cost of device hence its economic feasibility.
- Availability: ease of access of a component locally or less difficulties in sourcing it.

Evaluation of alternatives was then carried after a five-point Likert scale was established. Then each alternative was scored against the evaluation measure in a relevant manner (i.e. according to the knowledge and discretion of the designer). Points scored by each

alternative were aggregated, and the alternative scoring high points were ranked as first choice.

Lastly, a concept was developed from aggregating the best-selected alternatives. This resulted in the final design which was modelled using a SolidWorks® platform.

3.4.4CONCEPT EVALUATION

3.4.4.1 COMPARISON OF DESIGN COMPLEXITY BETWEEN DESIGNED CONCEPT AND EXISTING MECHANISMS

At this stage the developed concept`s design complexity was measured (i.e. using the same method deployed in **Section 3.3**). The results of design complexity of the designed concept were then compared to the existing mechanism, which was analysed as part of this research.

3.4.4.2 ESTIMATION OF ENERGY RATING USING WHAT-IF ANALYSIS

A What-If analysis is a black box approach in which the behaviour of the system is inspected based on relation of inputs to outputs, while subjected to specified hypotheses (also called scenarios). This technique is important as it helps in the pre-evaluation process of the systems before their implementation. It can be used for prediction and feasibility analyses of a system as a way of reducing risks in products design. In this study a what-if analysis was used to evaluate the energy consumption of developed solar tracking concept and existing mechanisms.

Using ***Equation (3.2)*** the yearly energy consumption (denoted;$E_{(kWh/year)}$) was estimated for various positioning mechanisms commonly used in existing solar trackers. These mechanisms include; electric motors and gearbox, servo/stepper motor and linear fluid power actuators. The systems were then compared with the developed solar tracking concept. (Note; ***Equation (3.3)*** was used to calculate Power (P) in ***Equation (3.2)***. While ***Equation (3.4)*** was used to calculate Force (F) which is a component in ***Equation (3.3)***)

From the listed equations;(t) denotes time, (η) is efficiency of system, (d) denotes centre of rotation, $V_{(a)}$is speed of operation (solar tracker), where (M) is the mass of moving components of the solar tracking, (g) is acceleration due to gravity, (ρ) represents density of air, $V_{(b)}$ denotes speed of wind, (A) denotes area of moving components in contact with wind and last (Cd) denotes coefficient of wind drag.

$$E_{(kWh/year)} = P_{(kW)} \times t_{(h/year)}$$

(3.2)

$$P_{(kW)} = \eta \times F_{(N)} \times d_{(m)} \times V_{(a)_{rpm)}} \times \frac{1}{9.5488}$$

(3.3)

$$F_{(N)} = \left(\left((M_{(kg)} \times g_{(m/s)})\right)_{internal\ load}\right) + \left(\left(\frac{1}{2} \times, (\rho)_{(kgm^{-3})} \times V^2_{(b)_{(m/s)}} \times A_{(m^2)} \times Cd\right)_{Wind\ load}\right)$$

(3.4)

To determine the time(t) and Speed of operation$(V_{(a)})$ the scenario of solar tracking operation was developed as follows. A chronological tracking strategy is deployed, that is the tracker operates at a speed equal to the earth`s rotation and tilt speed (Mousazadeh et al, 2009). The rotational speed of the earth is taken to be one-degree (1) per four (4) minutes (Wasfi, 2011). This will be applied on the primary axis, which tracks the daily motion of the sun (i.e. from sunrise to sunset). On this axis the tracker will operate for eight hours tracking window (i.e. 8am to 4pm). Tilt speed is taken to be twenty-seven hundredth (0.27) degree per day (Wasfi, 2011). This speed is then deployed on the secondary axis. The tracking motion is in between the winter and summer solstices, and also the tracking window is eight hours (per day).

Pailhes et al (2011) Converter, Operator, Transmitter and Controller (COTC) model was then used to understand how power is consumed in a solar tracking system**.** ***Figure 3-5*** show that in operation of solar tracking power from the input source is lost mainly through the actuator, transmission and joints of moving parts. Therefore, this led to establishment of systems` efficiencies(η) by aggregating the efficiency of stated components.

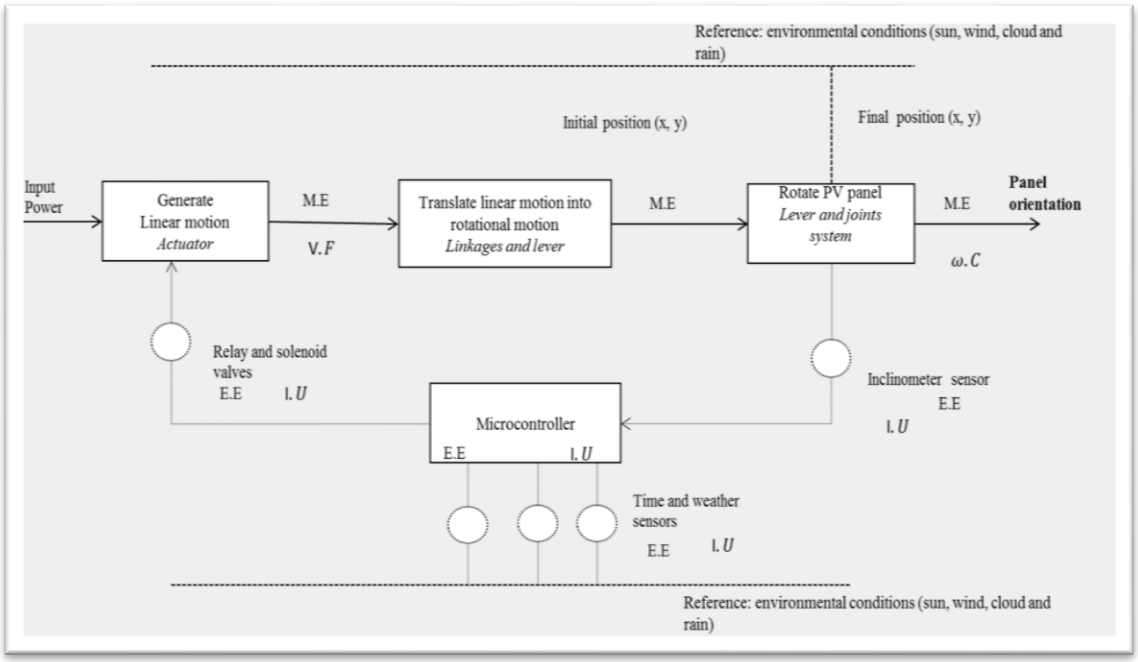


Figure 3-5: COTC model of a solar tracking mechanism

Then Hulscher (2019) energy conversions efficiency table of different systems was used to identify the efficiency of both the existing and developed mechanisms. For the efficiency of electric motor used in the calculations is 0.8 as taken from ***Table 3-5***

Table 3-4: Energy conversion efficiency for different devices, Source: (Hulscher, 2019)

CONVERTER	**FORM OF ENERGY INPUT**	**FORM OF ENERGY OUTPUT**	**EFFICIENCY (%)**
Petrol engine	Chemical	Mechanical	20-25
Diesel engine	Chemical	Mechanical	30-45
Electric motor	Electric motor	Mechanical	80-95
Boiler and turbine	Thermal	Mechanical	7-40
Fluid power system	Mechanical	Potential	40-80
Hydro turbine	Potential	Mechanical	70-99
Hydro turbine	Kinetic	Mechanical	30-70
Generator	Mechanical	Electrical	80-95
Battery	Chemical	Electrical	80-90
Solar cell	Radiation	Electrical	8-15
Solar collector	Radiation	Thermal	25-65
Electric lamp	Electrical	Light	Ca. 5
Water pump	Mechanical	Potential	Ca. 60
Water heater	Electrical	Thermal	90-92
Gas stove	Chemical	Thermal	24-30
Mechanical system (lever, gears, joint etc.)	Mechanical	Kinetic	80-90

From the studied existing solar tracker, the author established that variety of three (3) was used and these are namely; DC/AC motor coupled with gears, servo/stepper motors and pneumatic linear actuators. ***Table 3-6*** present the efficiencies of the system aggregated with the COTC model developed in order to fairly compare the existing systems and newly developed concept for energy consumption.

Table 3-5: Efficiencies of existing and developed solar tracking positioning mechanisms

Mechanism	**Efficiency of Actuator**	**Efficiency of lever and linkages**	**Efficiency of lever and joints**	**Aggregated efficiency**
DC /AC Motors and gears	0.64	0.8	0.8	0.41
Servo/stepper motors	0.8	0.8	0.8	0.51
Pneumatic linear actuator (electric)	0.32	0.8	0.8	0.2
Pneumatic cylinder	0.4	0.8	0.8	0.25

To determine the speed of wind($V_{(b)}$) that was used to calculate the load it exacted on the moving components of the solar tracking the following was considered. A light wind, clear and dry sky conditions are used for the analysis of the system. Based on the concept`s principle of operation; once wind speed reaches a thresh hold value the system then stops the sun tracking. From the National weather service (2019) the Beaufort scale a light wind speed is below 1.5 m/s.

3.5 METHODOLOGY MAP

Figure 3-5 summarizes the methodology used in this research study. In summary the author started by conducting meta-analysis review of dual axis solar tracking, this resulted in establishment of efficiency, complexity and general understand of existing dual axis solar tracking mechanisms. This influenced the formulation of questionnaire that was administrated through an interview, and functional decomposition of solar trackers. From functional decomposition, function chains were realised, and they were used to establish design alternative On the other hand the interview led to realization of customer`s need which was transformed into requirements and constraints these we used to formulate evaluation measures. These were then used to evaluate the design alternatives; this led to development of new design concept, which was then compared with existing mechanism for energy consumption and complexity.

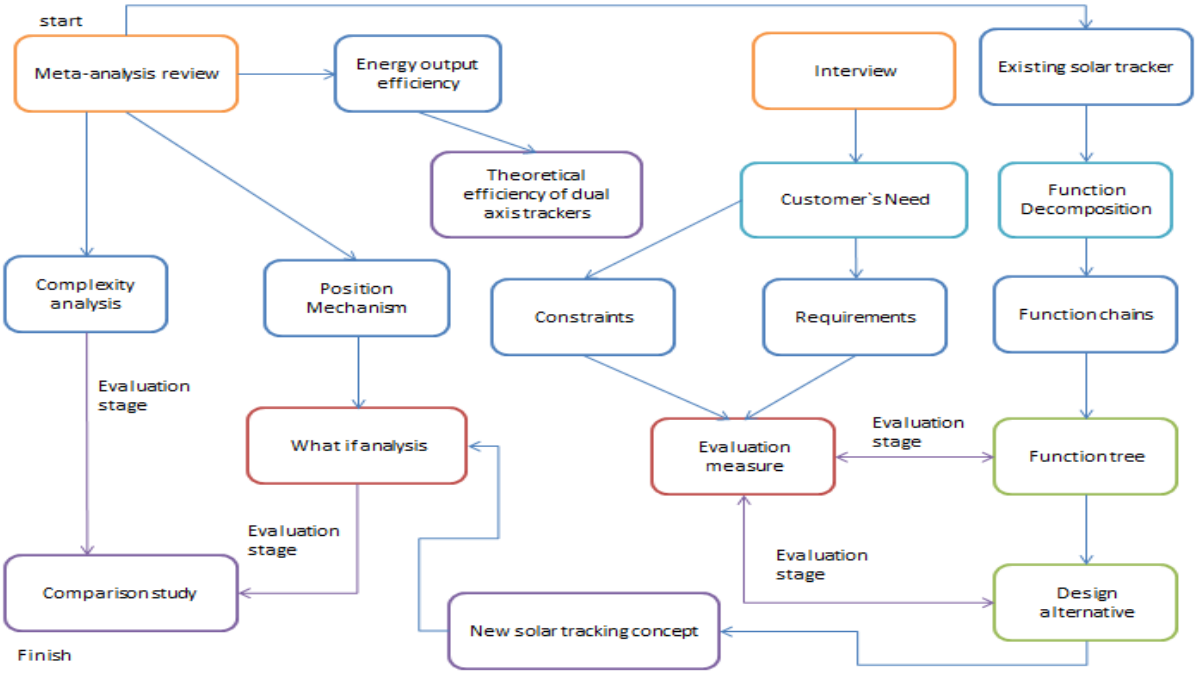


Figure 3-6: A summary of methodology used in this thesis

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 CHAPTER SUMMARY

This chapter presents and discusses the findings of this research study. The chapter is organised into three sections namely; efficiency of tracking systems, design of dual axis concept and comparison of the developed concept with existing mechanisms

4.2 DUAL-AXIS SOLAR TRACKER EFFICIENCY TRAJECTORY (1997-2017)

Table 4 1 gives dual axis solar tracking efficiencies and Figure 4 1 shows the efficiency trajectory map. As can be seen, solar tracking efficiencies are found to be between 20-60% whereby*:* the error bars in the graph indicate a 7.5% deviation, half of 15%, which was the highest difference presented in the literature. From the study, a slightly constant trend was noticed with an average efficiency of about 38% (as shown by the trend line in ***Figure 4-1)***

Table 4-1: Summary of dual axis solar tracker efficiency map

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007
Efficiency	30%	30-50%	50%	30%	40%	40%	19-24%	41.34%	21%	40%	40%

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	
Efficiency	49.2%	42.6%	40%	64%	30.79%	40%	35-42%	40%	40%	27.5%	

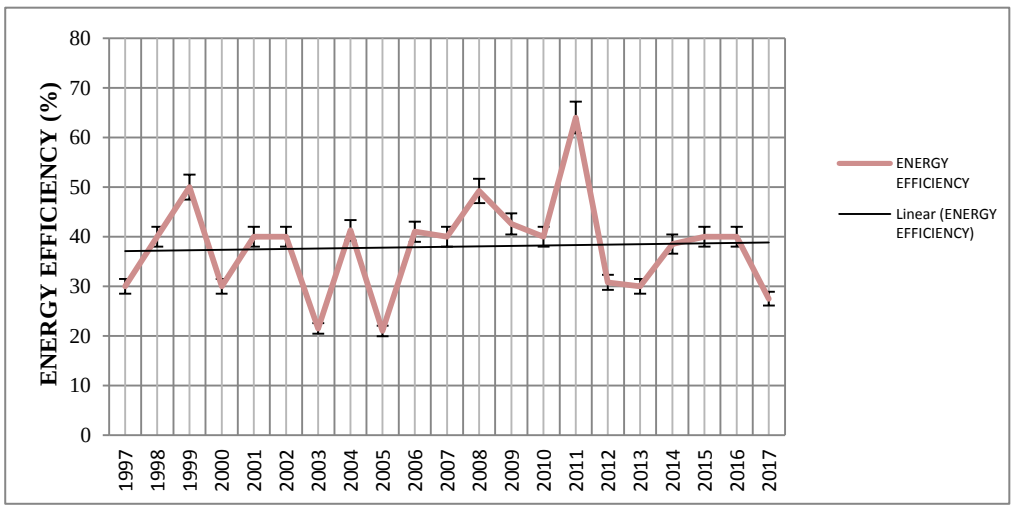


Figure 4-1: Dual axis solar tracking efficiency trajectory map for period 1997-2017

4.3 DESIGN OF DUAL AXIS SOLAR TRACKING CONCEPT

A designed concept is discussed under this section. The concept design entails the planning and development of the concept of the dual axis solar tracker. This process is divided into seven segments which are; design requirements and constraints, functional decomposition, transparent box model, morphological chart, evaluation of alternatives, and technical drawing of the concept developed.

4.3.1 DESIGN REQUIREMENTS AND CONSTRAINTS

The design requirements and constraints identified in this research are defined in the segment (see ***Table 4-3*** and ***Table 4-4***).

Table 4-2: Design requirements of a dual axis solar tracker concept

Design requirements	**Description**
Low tracking error	A highly efficient tracking is the one that can position towards the sun with relatively high accuracy, for an improved energy output.
Low energy consumption	For an economically feasible product, the tracking device should consume as little energy as possible or use a mechanism which saves energy.
Fully automated	A machine with little human interface of daily operation, but with ease of use by an operator.
Operational in Array setup (On-Grid)	The tracker should be used on national electrical grid-connected PV system.
Optimum Power output	The solar tracking device should generate enough power either equal or slightly lower than the theoretical expectation, for economical and functional viability.
Optimum Payback period	For an economically viable system there is a need that it has a lower payback period as the profit will be realised in the early period lifetime of the machine.
Environmentally Friendly	Solar energy aids in reducing pollution emission. Therefore, the device should not harm its surroundings e.g. ecological system, water sources, wildlife and birds through generation of toxic waste materials
Aesthetically appealing	Growth in the use of renewable energy technology has led to an increasing interest in many people to comprehend the technology. Therefore the solar tracking should be aesthetically attractive to attract tourists (i.e. technological tourism)

Table 4-3: Design constraints of a dual axis solar tracker concept

Design Constraints	**Description**
Environmental Conditions; consideration of environmental conditions on which the device would operate under is important. Major environmental conditions to consider are as follows	
Solar irradiance	In testing and evaluating a solar tracking device it is vital to determine the available amount of solar power to set the best performing conditions
Temperature	Extreme temperature can cause behavioural change in mechanical systems therefore designs should be done with consideration of this factor.
Wind	Might cause disturbance to the system, therefore, it has to be considered to mitigate its effect on the system during the design process.
Dust	Dust particles cause moving components of system to malfunction hence the design must consider a way of reducing its effects
Moisture	As the device will operate in an outdoor environment it will be subjected to moisture, and it might reduce the operational capacity and lifespan if not considered
Cloud cover	In a cloudy sky the solar tracker`s accuracy to turn reduces. Some of solar tracker designs continue to follow sun path without any energy realisation whereas other design loss their calibration due shade on sensors.
Financial budget	A financial constraint is considered because it is one of the major factors that lead to sourcing of relevant materials and knowledge required for developing a customer satisfying product
Power Consumption	A power-limited solar tracker is a constraint to the design as it will guide the designer in developing a device with certain power consumption rating to deliver a feasible system economically.
User`s operational skills	General technological and technical level of the operator should also be considered as it determines how the system and the operator will relate after production.
Land availability	A relatively conservative land system would be preferred. It should use minimal land available; therefore land is an important factor to consider as it's not always readily available at the required size.

4.3.2 FUNCTIONAL DECOMPOSITION OF SOLAR TRACKING SYSTEM

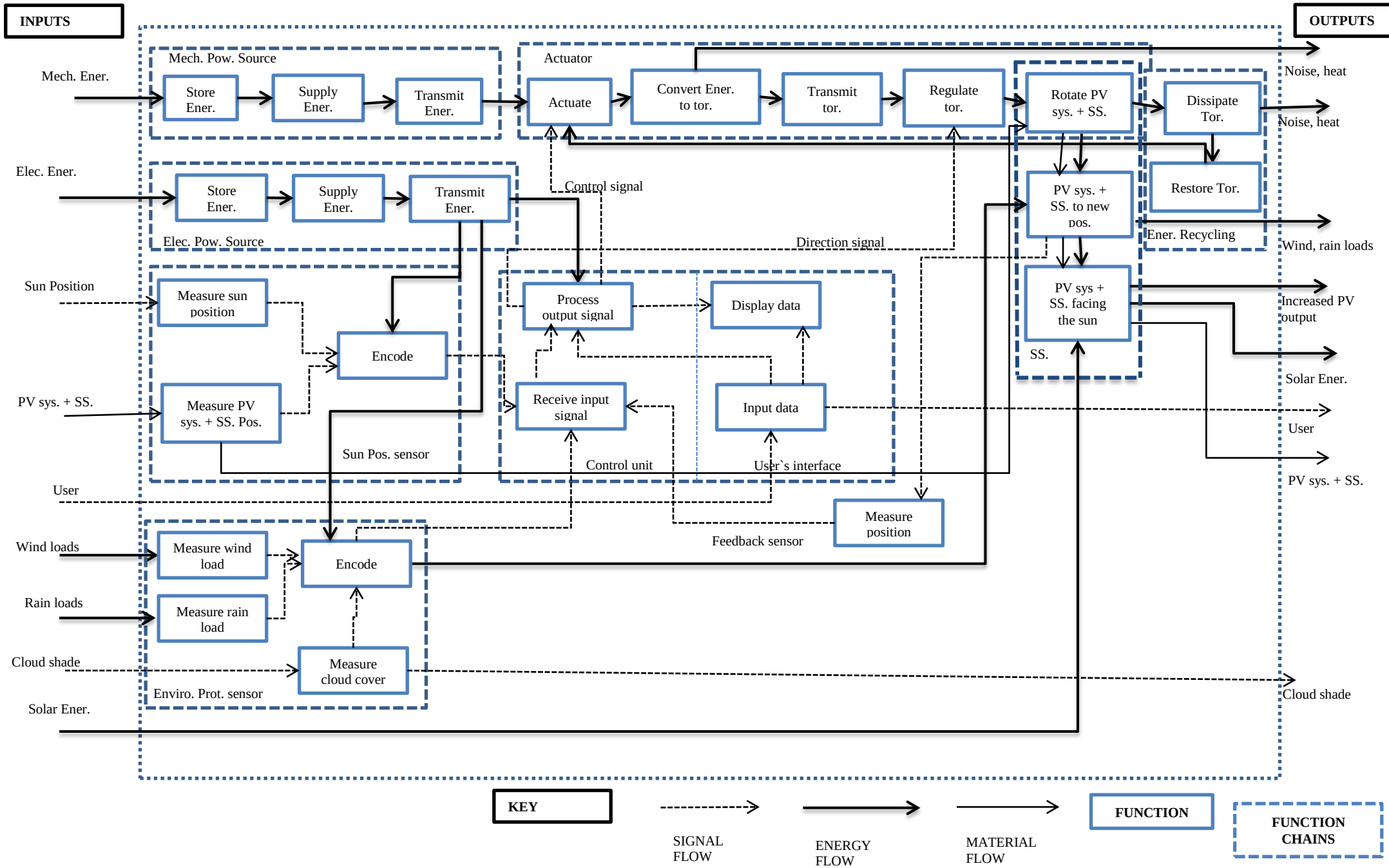
The overall problem a solar tracker should solve is how; **to track the path of the sun to expose the photovoltaic system to the maximum amount of solar energy**. From this overall requirement, four sub-functions were derived (***Table: 4-4*** furthers the process);

Table 4-4: Functional decomposition of solar tracking

Overall functional objective	**Level 1 Sub-functions**	**Level 2 Sub-functions**	**Level 3 sub-functions**
To track the path of the sun to expose the photovoltaic system to the maximum amount of solar energy.	1. To precisely determine the position of the sun.	1. To measure the precise sun position vector	1. To measure the solar azimuth angle of the sun
			2. To measure the altitude angle of the sun
		2. To encode all measured angles	1. To correct error reading
			2. To amplify measured angles
			3. To Convert measured angle into compatible signals
		3. To decode the measured angles	1. To accept the signals of measured angles
			2. To compare the signal with the reference points of sun position for each time interval.
			3. To send signal to control for generating motion for tracking
	2. To precisely calibrate the positioning mechanism	1. To receive signal of calculated sun position.	
		2. To compare the current orientation with calculated position of the sun.	
		3. To send a signal to activate the release of power to generate the tracking motion	
	3. To generate the tracking motion	1. To release power from the source	
		2. To transmit power to the actuator.	
		3. To convert the input power transmitted into motion.	
		To orientate the solar photovoltaic system by aligning PV perpendicular to the sun	1. To provide two degree of freedom for rotation
			2. To provide mechanical suspense to maintain the orientation
	4. To monitor the tracking effect	1.To monitor the feedback	1. To measure the orientation of the position
			2. To correct error reading
			3. To amplify measured angles
			4. To convert measured angle into signal
			5. To compare the signal with the reference points of sun position for each time interval.
			6. To re-orientation to reduce the tracking errors.
		2. To reduce energy consumption	1. To use potential energy during non-energy production cycles (i.e. at night/ after tracking)
			2. To recycle and regenerate waste energy back into the system.
		3.To provide user`s interface	1. To acquire data
			2. To store data about the performance.
			3. To display data for easy retrieval by the user.
			4. To warn about system malfunction.
		3. To minimise environmental disturbances	1. To measure the potential weather conditions thread (wind speed, direction, rain, cloud cover)
			1. To provide safety measures when the weather is unfavourable for tracking.

4.3.3 TRANSPARENT BOX MODEL

Transparent box model of a solar tracking device is shown in ***the next page***. In this model energy, material and signal are traced from input to their relative output state. The model was used to identify function chains to achieve relevant tasks. In the stated figure the (SS.) stands for support structure, (tor.) is torque, (sys.) is system, (Ener.) is energy, (mech.) is mechanical, (elec.) is electrical, (Pow.) is power, (Enviro.) is environmental, (Pos.) is position and (Prot.) is protection.


INPUTS
OUTPUTS
Mech. Ener.
Mech. Pow. Source
Store Ener.
Supply Ener.
Transmit Ener.
Actuator
Actuate
Convert Ener. to tor.
Transmit tor.
Regulate tor.
Rotate PV sys. + SS.
Dissipate Tor.
Noise, heat
Noise, heat
Elec. Ener.
Store Ener.
Supply Ener.
Transmit Ener.
Control signal
Elec. Pow. Source
Direction signal
PV sys. + SS. to new pos.
Restore Tor.
Ener. Recycling
Wind, rain loads
Sun Position
Measure sun position
Encode
Process output signal
Display data
PV sys + SS. facing the sun
SS.
Increased PV output
Solar Ener.
PV sys. + SS.
Measure PV sys. + SS. Pos.
Receive input signal
Input data
User
Sun Pos. sensor
Control unit
User`s interface
User
Measure position
Feedback sensor
PV sys. + SS.
Wind loads
Measure wind load
Encode
Rain loads
Measure rain load
Cloud shade
Measure cloud cover
Enviro. Prot. sensor
Cloud shade
Solar Ener.
KEY
SIGNAL FLOW
ENERGY FLOW
MATERIAL FLOW
FUNCTION
FUNCTION CHAINS

4.3.4 MORPHOLOGICAL CHART

Table 4-5 presents possible, practical design alternatives (marked: ALT 1, 2…) for each function chain. In engineering design, the number of possible solutions (permutations) is normally computed using the simple arithmetic ***Equation (4.1)*** to give 4,147,200 (where ***n*** is the last row).

(#entries row 1) x (#entries row 2) x (#entries row 3) …. x (#entries row ***n***)

(**4.1**)

$$=5\times2\times3\times4\times4\times2\times5\times4\times4\times2\times3\times2 = 4,\ 147,\ 200$$

Table 4-5: Morphological chart of solar tracker

FUNCTION CHAIN (FUNC.)	**ALTERNATIVES (ALT.)**				
	ALT 1	***ALT 2***	***ALT 3***	***ALT 4***	***ALT 5***
Sun position sensor (Sun Pos.)	Photo sensors	Real-time clock (RTC)	Camera	Global positioning system device (GPS)	RTC+ photo sensor (Hybrid)
Power source (elec.)	Mini PV panel	Grid electricity			
Power source (mech.)	Solar engines	Spring system	Gravity engines		
Control unit (CU.)	Micro controller	Personal computer (PC)	Programmable Logic controller (PLC)	Field Programmable Gate Array (FPGA)	
Actuator (Act.)	Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	Stepper motor	
User`s interface (UI.)	Keypad and LCD screen	Safety switch and LED flashlight			
Support structure (SS.)	Cable mount	Parallel kinematics device (PKD)	Rotating platform (RP)	Polar mount	Counterbalance mount (CBM)
Energy recycling system (ER.)	Spring system	Piezoelectric system	Spring return fluid power actuators	Energy recovery wheel (ERW)	
Feedback sensor (FS.)	Inclinometer	Accelerometer	Magnetometer	Gyroscope	
Wind sensor (WS.)	Electronic Anemometry (EA)	Airflow sensors			
Rain sensor (RS.)	Weighing precipitation gauge (WPG)	Optical rain gauge	Water Sensors		
Cloud sensor (CS.)	Optical sensor	Ceilometer			

4.3.5 EVALUATION OF ALTERNATIVES

Table 4-6 presents a process of alternatives evaluation; whereby a five-point Likert scale was used. Scale is from 1 (worst) to 5 (best). The points scored by each alternative for each evaluation measure are then aggregated, and then the alternative that scores the highest points is ranked as first (1), and the second is ranked (2) and so forth.

Table 4-6: Evaluation of generated design alternatives

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Sun Pos.		Photo sensor	RTC	Camera	GPS	Hybrid
	Serviceability	4	5	1	3	4
	Availability	5	4	1	3	4
	Interfacing	4	5	1	3	5
	Reliable in cloudy weather	3	2	4	1	4
	Point scored	**16**	**16**	**7**	**10**	**17**
	Rank	**2**	**2**	**4**	**3**	**1**
		Mini PV panel	Grid			
Electric.	Serviceability	5	4			
	Availability	5	5			
	Reliability	4	3			
	Points scored	**14**	**12**			
	Rank	**1**	**2**			
Mech.		Solar engines	spring system	gravity engines		
	Serviceability	5	5	4		
	Availability	4	5	2		
	Reliability	5	2	2		
	Points scored	**14**	**12**	**8**		
	Rank	**1**	**2**	**3**		
Act.		Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	stepper motor	
	High response	3	4	2	5	
	Controllability	4	4	2	4	
	Interfacing	4	5	2	3	
	Minimal energy consumption	3	4	3	5	
	Compatible to support structure	5	5	3	4	
	Points scored	**19**	**22**	**12**	**21**	
	Rank	**2**	**1**	**3**	**2**	
CU.		Microcontroller	PLC	FPGA	PC	
	Interfacing	5	3	2	3	
	Accuracy and Precision	3	5	4	4	
	Availability	5	4	3	5	
	Serviceability	5	4	2	2	
	Adaptability to control	4	5	5	5	
	Point scored	**22**	**21**	**16**	**19**	
	Rank	**1**	**2**	**4**	**3**	

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
UI.		Keypad and LCD screen	LED and switch			
	Accessibility of information	5	3			
	High alarm rate	4	4			
	compatibility	5	4			
	Points scored	**14**	**11**			
	Rank	**1**	**2**			
SS.		Cable mount	Polar	Parallel mech.	CBM	RP
	optimal land coverage	4	3	2	5	1
	Versatile utility	3	4	2	5	1
	Assemble-ability	5	3	1	5	3
	Optimal material consumption	5	3	1	4	2
	Robust mechanical	1	4	5	3	5
	Points scored	18	17	11	22	12
	Rank	2	3	4	1	5
ER.		Springs	Piezoelectric	Spring return fluid power actuators	ERW	
	compatibility to control	5	3	5	1	
	ease of use	4	1	5	2	
	Maintainability	5	2	4	1	
	Availability	4	2	5	1	
	Points scored	**18**	**8**	**19**	**5**	
	Rank	**2**	**3**	**1**	**4**	
FS.		Accelerometer	Inclinometer	Magnetometer	Gyroscope	
	Interfacing	4	5	1	2	
	Cost	5	5	1	1	
	Availability	5	5	2	2	
	Points scored	**14**	**15**	**4**	**5**	
	Rank	**2**	**1**	**4**	**3**	
WS.		Electronic anemometry	Airflow sensor			
	Interfacing	4	4			
	Availability	3	5			
	Scalability	3	4			
	Cost	4	5			
	Points scored	**14**	**18**			
	Rank	**2**	**1**			
RS.		Weighing gauge	optical gauge	water sensor		
	Interfacing	1	1	5		
	Availability	2	3	5		
	Scalability	2	4	5		
	Cost	2	1	5		
	Point scored	**7**	**9**	**20**		
	Rank	**3**	**2**	**1**		
CS.		Optical sensor	Ceilometer			
	Interfacing	5	2			
	Scalability	4	3			
	Availability	5	1			
	Cost	5	1			
	Points scored	**19**	**7**			
	Rank	**1**	**2**			

4.3.6 CONCEPT EMBODIMENT

Based on the evaluation, a simpler and less energy consuming design concept is the one consisting of all the high-ranking components. These components are: a real-time clock, a mini-PV cell (photo-sensor), solar engine, micro-controller, pneumatic cylinder, counterbalance mount, inclinometer sensor, water sensor, airflow sensor, optical sensor, keypad and liquid crystal display (LCD screen). PV cells are used to supply power to a

sensor that marks the change in sun position (real time clock), and also to detect shade due to cloud cover. The power supplied is stored in a battery to also supply other subsystems.

The output of the sun positioning process is used to control the direction and speed of the pneumatic cylinder which is powered by a solar engine. The solar engine runs the air compressor which has a storage tank which drives the pneumatic cylinder; this is to smooth operations as the power source generates varying power at times. As the orientation, of PV attached to the support structure reaches the maximum azimuthal position (at sunset) or maximum tilt (during winter season) a spring system within the pneumatic cylinder is engaged to return from sunset position or the minimum tilt orientation during the summer season. In case of unfavorable weather conditions, the wind and rain sensors will send signals to the controller to switch the operating mode into safe mode, i.e. the tracking will stop. ***Table 4-7*** shows the overall embodiment design of the new dual axis solar tracking concept.

Table 4-7: Embodiment of dual axis solar tracking design concept

FUNC.	Sun Pos.	elec.	mech.	CU.	Act.	UI.	SS.	ER.	FS.	WS.	RS	CS.
ALT.	RTC+ photo sensor	Mini PV panel	Solar engines	Micro controller	Pneumatic cylinder	Keypad and LCD screen	Counterbalance Mount	Spring return fluid power actuators	Inclinometer	Air flow sensors	Water Sensors	Optical sensor

4.3.7 TECHNICAL DRAWING OF DUAL AXIS SOLAR TRACKER

The working drawings for the embodiment design above were generated leading to the general assembly drawing presented in ***See next page***. The drawing shows how the entire sub-systems of the tracker are to be connected. Also, materials to be used for each component are stated in the drawings. The geometries of the components are also communicated in the drawings. The entire working drawings and back-of-envelope calculations for the solar tracker developed in this study are attached at **APPENDIX B** of in this document.



DETAIL 1
SCALE 1 : 2



DETAIL 3
SCALE 1 : 4

TRIMETRIC VIEW OF
SOLAR TRACKER



DETAIL 2
SCALE 1 : 4

Item No.	Part name	Description	Qty.
13	Pneumatic tubing	PVC tube	3
12	Support structure sub-assembly	.Arcylic square tubes (25*25)	2
11	Linkage	Arcylic	1
10	Pneumatic cylinder 1	STD	1
09	Rain & cloud sensors	STD.	1
08	Wind sensor	STD.	1
07	Pneumatic cylinder 2	STD.	2
06	PV panel	STD.	4
05	Control box	Arcylic (vacuun formed)	1
04	Solar engine sub-assembly	STD.	1
03	V-belt	STD.	1
02	Platform	Pinewod (1000*750*25)	1
01	Air pump sub-assembly	STD.	1

Notes :

1. All dimensions are in mm unless stated.
2. For all permanent joints an adhesive is used unless stated.
3. Finish is as machined unless stated.

GENERAL ASSEMBLY

DUAL AXIS SOLAR TRACKER

BIUST	Drawn: E. K. MPODI	Checked: Z. Tjiparuro	
Date 06/2019	Scale 1:8	DWG No: 300-01	Sheet 1/6

4.4 COMPLEXITY STUDY OF THE DESIGNED CONCEPT AND EXISTING SYSTEMS

A complexity analysis of designed concept and existing systems are compared in this segment of the chapter. Lastly energy consumption of different mechanisms deployed in literature and design concept are also presented.

4.4.1 COMPLEXITY STUDY

Table 4-8 shows a complexity metrics of systems developed in the period, 1997-2017. The average complexity of these systems was found to be 221.43 in this study.

Table 4-8: Design complexity study of existing solar trackers

Reference	M	I	C	Efficiency
Hoffmann et al, (1997)	4	6	52	30%
Chiang & Jacob, (1998)	7	8	113	30-50%
Yousef, (1999)	5	4	41	50%
Helwa et al, (2000)	10	11	221	30%
Fanney &Dougherty, (2001)	15	18	549	40%
Yousif, (2002)	4	3	25	40%
Vilela et al (2003)	6	8	100	19-24%
Abdallah & Nijmeh, (2004)	10	10	200	41.34%
Piao et al, (2005)	14	16	452	21%
Mamlook et al, (2006)	13	11	290	40%
Rubio et al, (2007)	10	10	200	40%
Chun-Sheng et al, (2008)	10	9	181	49.2%
Sungur, (2009)	10	12	244	42.6%
Barsoum & Vasant, (2010)	12	11	265	40%
Kassem & Hamad, (2011)	9	10	181	64%
Eke & Senturk, (2012)	10	11	221	30.79%
Anusha & Chandra, (2013)	11	13	290	40%
Singh & Gupta, (2014)	14	15	421	35-42%
Ceyda and Cenk, (2015)	9	10	181	40%
Shashwati & Tripathi, (2016)	9	11	202	40%
Akbar et al. 2017	11	10	221	27.5%
Average			221.43	38%

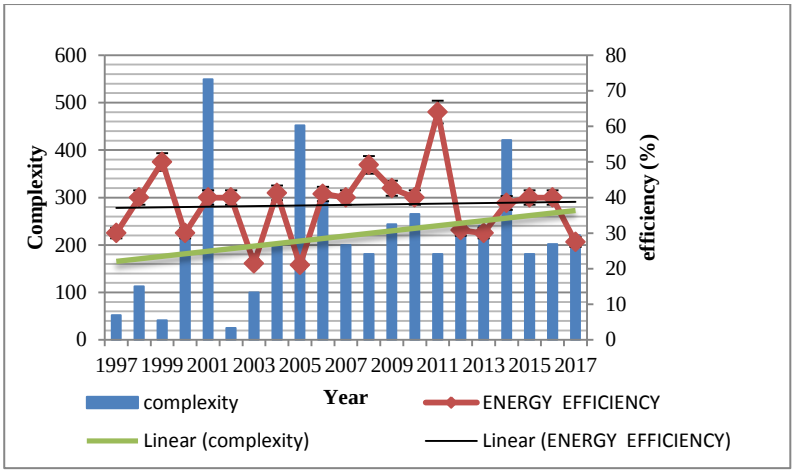


Figure 4-2 Design complexity map of dual axis solar tracker for period 1997-2017

A plot of the complexities and efficiencies of existing dual trackers show increases of both parameters between the year 1997 and 2017 (see ***Figure:* 4-2)**. The system developed in this research work, has complexity metric of 200 as calculated from the embodiment design in ***Figure 4-3***.

Plotting the complexity index against the complexity values of the existing systems give ***Figure 4-4***. Trend depicted by the graph shows a relatively constant increasing pattern at the beginning of the study period up to the year 2005-2007Generally the system designed is more complex when compared with developed between 1997 and 2004. While from 2005 to 2011 the existing systems are more complex the concept developed in this research study. For period between 2012 and 2017 the system developed, and existing system are generally equal in complexity (see ***Figure4-4)***. The pattern was realised because of the advancement which were made to the dual axis tracking such as including weather intelligent features (wind and rain shield systems). In summary the developed system, firstly, falls within the average complexity of existing systems, and secondly, it is 10% less complex than the existing systems

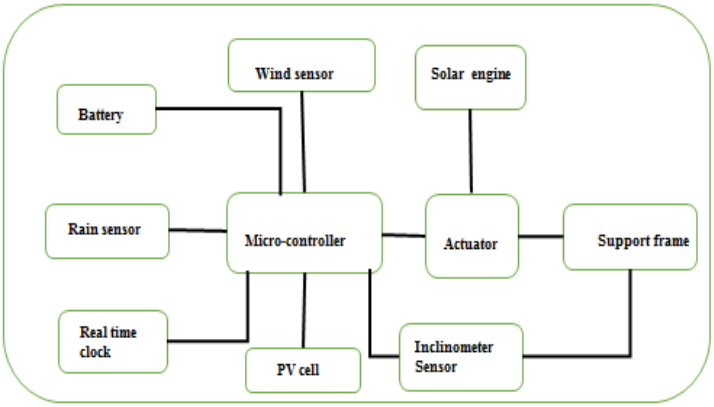


Figure 4-3: The embodiment of designed concept

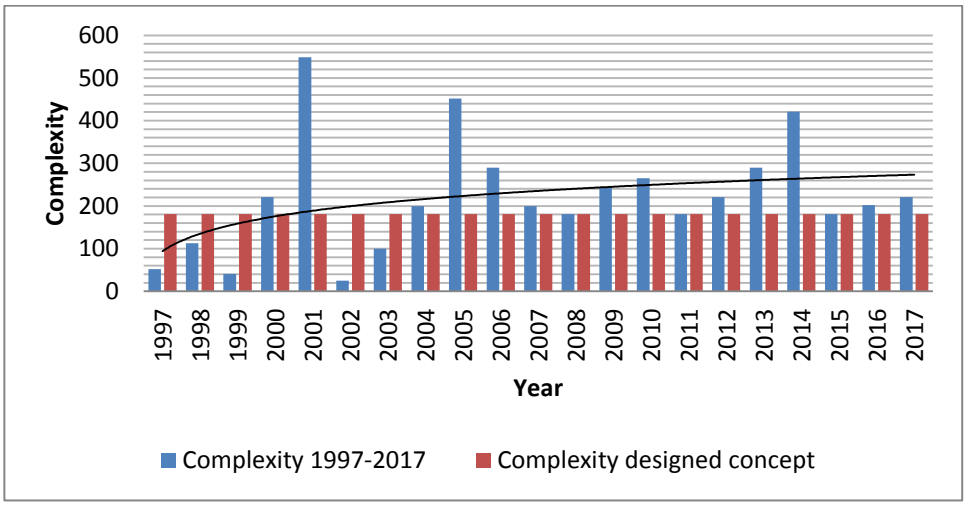


Figure 4-4: A comparison of design complexity for the developed concept and existing mechanisms

4.4.2 ENERGY CONSUMPTION OF DIFFERENT POSITIONING MECHANISMS

Table 4-9 gives the components of the positioning mechanisms of the concept designed in this thesis and those of the existing mechanisms, and their energy consumptions. It shows that the mechanism consumes less energy than existing mechanisms. Moreover, it does not consume the output energy from the PV system as it has an external power source. This is because the designed tracker concept uses potential energy stored in a spring to return PV panels to the sunrise position after the daily tracking. This approach is also used for the secondary axis, which is to return the Panel to a low angle after reaching the higher angle at low altitude angles of the sun. As for other positioning mechanisms; pneumatic actuators consume relatively higher than electric motors (i.e. servo, stepper and dc/ac motor with gearbox see ***Table 4-9***). The developed system reduces energy consumption by approximately thirty-three per cent (33%) for systems uses stepper motors, servo motors

and DC motor with gears and approximately fifty-seven per cent (57%) for designs that uses pneumatic linear actuators.

Table 4-9: Comparison of energy consumption of different positioning mechanisms

	Pneumatic Linear Actuator		Motor and gears		Servo/ stepper motor		Developed concept	
	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2	Axis 1	Axis 2
Power (kW)	7.86E-09	2.88E-08	4.91E-09	1.80E-08	4.91E-09	1.80E-08	4.91E-09	1.98E-08
Energy consumption (without return)	6.29E-08	2.30E-07	3.93E-08	1.44E-07	3.93E-08	1.44E-07	4.05E-08	1.63E-07
Energy consumption (daily)	7.86E-08	2.88E-07	4.91E-08	1.80E-07	4.91E-08	1.80E-07	4.05E-08	1.63E-07
Energy consumption (yearly)	2.30E-05	8.40E-05	1.43E-05	5.25E-05	1.43E-05	5.25E-05	1.48E-05	2.99E-05
Total energy consumption (kWh)	$\mathbf{1.07 \times 10^{-4}}$		$\mathbf{6.68 \times 10^{-5}}$		$\mathbf{6.68 \times 10^{-5}}$		$\mathbf{4.47 \times 10^{-5}}$	

4.5 PHYSICAL SPECIFICATIONS OF DESIGNED SOLAR TRACKER CONCEPT

Table 4-10 present the physical specifications for the dual axis solar tracking concept developed in this study. These specifications include aspect such as; size, weight, mounting type, number of panels, power output, etc.

Table 4-10: Physical specifications for the designed dual axis solar tracker concept

PRODUCT ASPECT	**SPECIFICATION**
Size	Length: 1200mm Width:750 mm Height: 500 mm
Weight	20 kg
Mounting type	Counterbalance mounting
Number of Photovoltaic panels	4
Connection of Panel	Series
System power output	12 Watts
Voltage output	12 volts
Battery size	8Anp-Hour
Current output	300 mil Amp
Type of Photovoltaic panel	Mono-crystalline
Photovoltaic panel power	3 Watts
Panel dimensions	Length: 215 mm Width: 135 mm Thickness: 18 mm Weight: 0.33 kg

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.0 CONCLUSIONS

In this research project, dual-axis solar tracking systems were investigated. An extensive survey of literature was undertaken. From the survey, an efficiency map was plotted over a period of two past decades (1997-2017). The functional flows of the most efficient systems were collated and integrated with those of the most popular passive; ZomeWorks tracker to develop a design objective model of how an efficient, effective, and simpler tracking concept should work. From the foregoing, the four (04) main functions identified as critical to an efficient, effective, and simpler dual tracker were the following; (a). Precisely determine the position of the sun, (b). Precisely calibrate the positioning mechanism, (c). Generate the tracking motion using minimum energy consumption, and lastly, (d). The system should operate in a way that it will monitor the tracking effect by reducing the impacts of environmental disturbances, on the mechanism and provide a platform for human interaction.

The functions were then, converted into a transparent box model which was presented as flow of energies (energy, material and signal) in the system. Twelve main function chains which perform the identified four functions were generated. A morphological analysis technique was used to generate design alternatives. This resulted in more than four million possible ideas. From there, one practical solution was selected and developed in SolidWorks® the, it was evaluated for complexity and energy consumption levels.

The complexity metric value for the new concept was calculated using Keating (2000) complexity method to yield a metric value of **200** which was found to be 10% less than an average solar tracker at **221.43**. Furthermore, a study comparing energy consumption of the concept designed to the existing mechanism has shown a less energy consuming system was realised in this study.

Energy consumption results established using the **What-If Analysis** for the developed system $\mathbf{4.47x10^{-5}}$ KWh. This value is thirty-three percent (33%) less than the values obtained for trackers that use motor and gears on the one hand, and those that use servo/stepper motor motors on the other hand, both of which are at $\mathbf{6.47x10^{-5}}$ KWh. Lastly, the designed system was found to be approximately fifty-seven per cent (57%) less

energy consuming than systems that use pneumatic actuators whose consumption stood at **$10.4x10^{-5}$** KWh.

5.1 RECOMMENDATIONS FOR FUTURE WORK

Though a prototype of the concept was built, the main limitation of this study was the non-availability of calibrated instrumentation to enable accurate practical determination of energy levels. This situation was not helped by the outbreak of the COVID-19 pandemic which made procurement very difficult. Therefore, it is recommended that future research directions should incorporate extensive simulations, laboratory and field testing, of the concept and the prototype. Also, an economic feasibility evaluation of the concept is recommended to determine opportunities for commercialisation.

5.2 PUBLICATIONS

This research work contributed the following four (04) research publications (for full texts refer to **APPENDIX E)**:

1 Mpodi, E. K., Tjiparuro, Z, & Matsebe, O. (2020). Improving product quality through a functional analysis approach: Case of a dual axis solar tracker, *in Pengzhong Li (ed)*; Quality Control in Intelligent Manufacturing, Intech Open London, UK [**BOOK CHAPTER]**

2 Mpodi, E. K., Tjiparuro, Z, & Matsebe, O. (2019). Development of dual axis solar tracking concept using morphological analysis**,** *in Rodrigo S. Jamisola, Jr. (ed.); BIUST Research & Innovation Symposium 2019 (RDAIS 2019)*; Volume 1(1), Palapye, Botswana, (pp. 46-53). ISSN: 2521-2292.

3 Mpodi, E. K., Tjiparuro, Z., & Matsebe O. (2019). Review of dual axis solar tracking and development of its functional model, *in T.-C. Jen, E. Akinlabi, P. Olubambi, & C. Augbavboa, (eds.) Procedia Manufacturing, 35,* (pp. 580-588). doi:10.1016/j.promfg.2019.05.082.

4 Mpodi, E. K., Tjiparuro, Z., Matsebe, O., & Namoshe M. (2017). Review of dual axis solar tracking, *in Rodrigo S. Jamisola, Jr. (ed.); BIUST Research & Innovation Symposium 2017 (RDAIS 2017);* Volume 1(1), Palapye, Botswana, (pp. 22-27). ISBN: 978-99968-0-608-7

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APPENDIX A: COMPLEXITY STRUCTURES OF DUAL AXIS SOLAR TRACKER REVIEWED

Below are the graphical representation of components and interactions of reviewed dual axis solar tracking system.

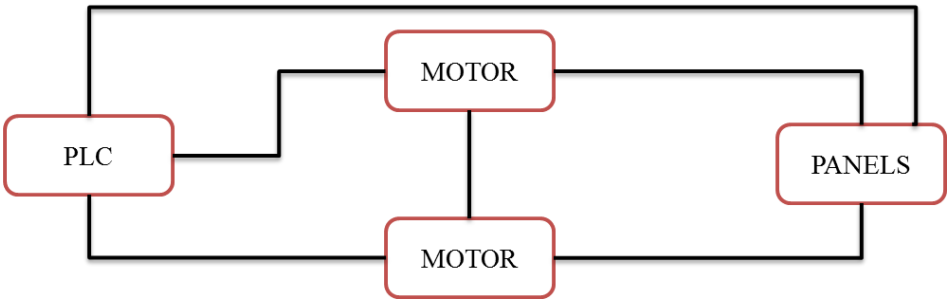


Figure A-1: A system developed by Hoffmann et al, (1997)

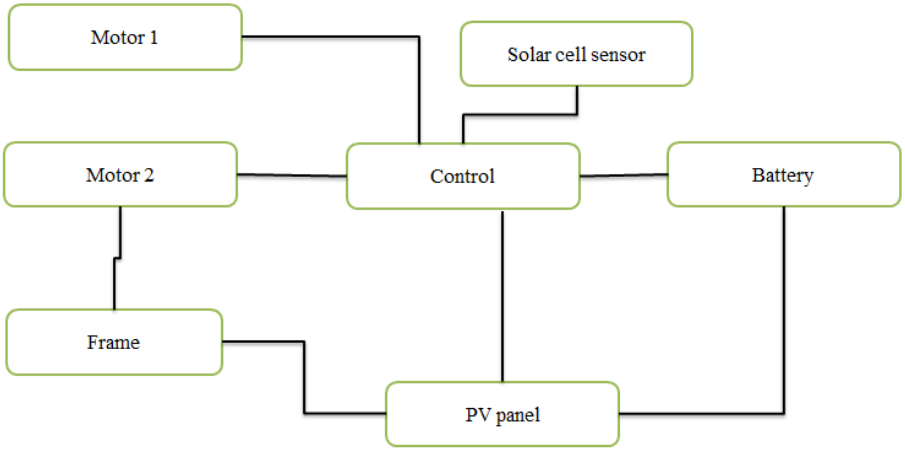


Figure A-2: A tracker designed by Chiang & Jacob, (1998)

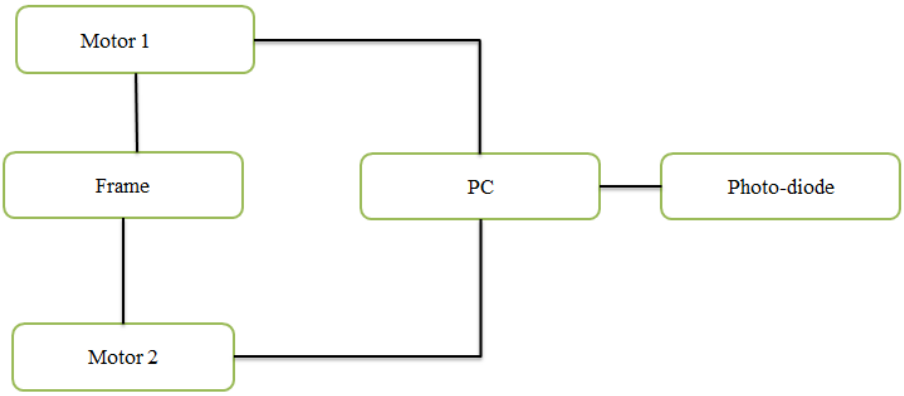
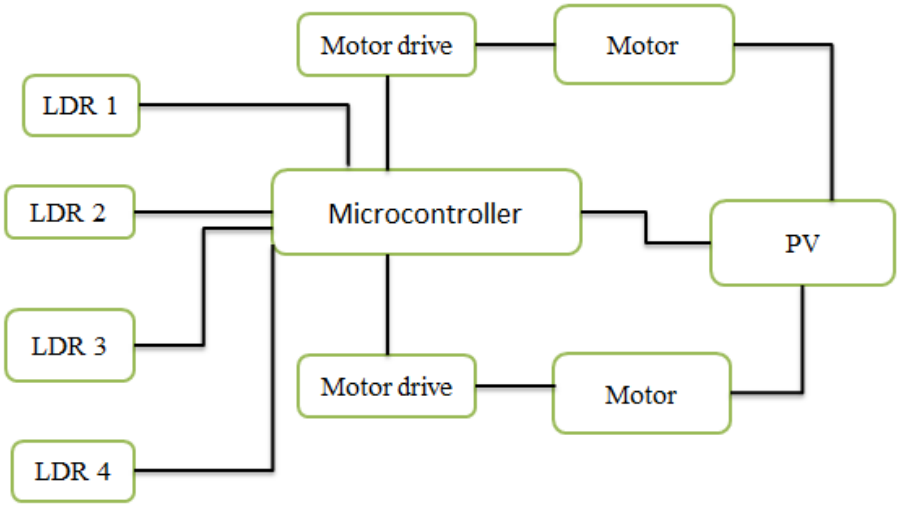


Figure A-3: Yousef, (1999) `s tracker



FigureA-4: System developed by Helwa et al (2000)

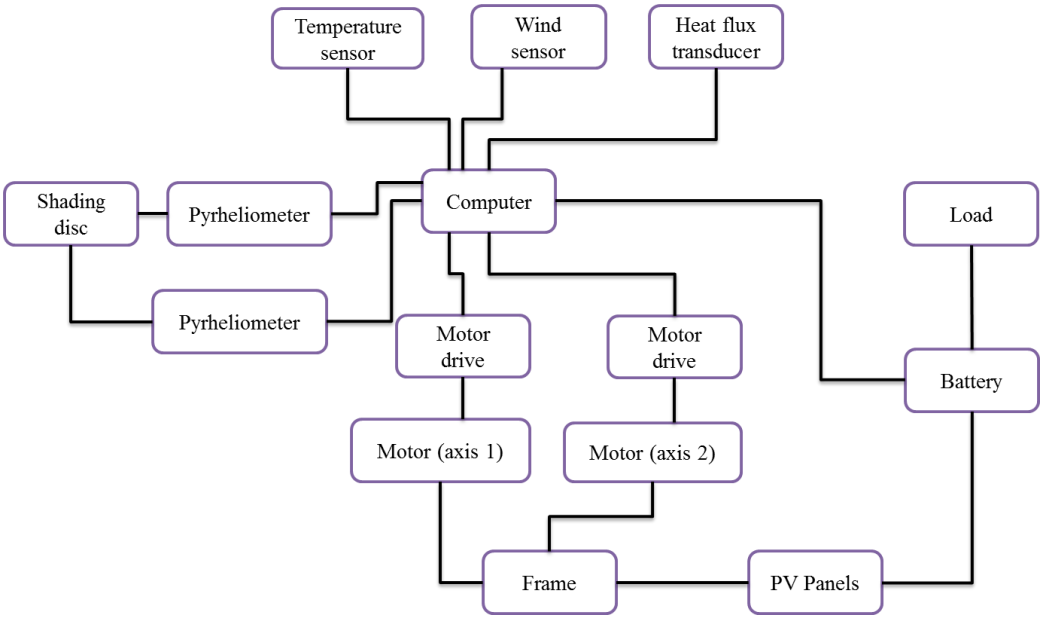


Figure A-5: Fanney &Dougherty, (2001) `s structure of dual axis solar tracker



Figure A-6: Interaction of component in Yousif, (2002) solar tracking

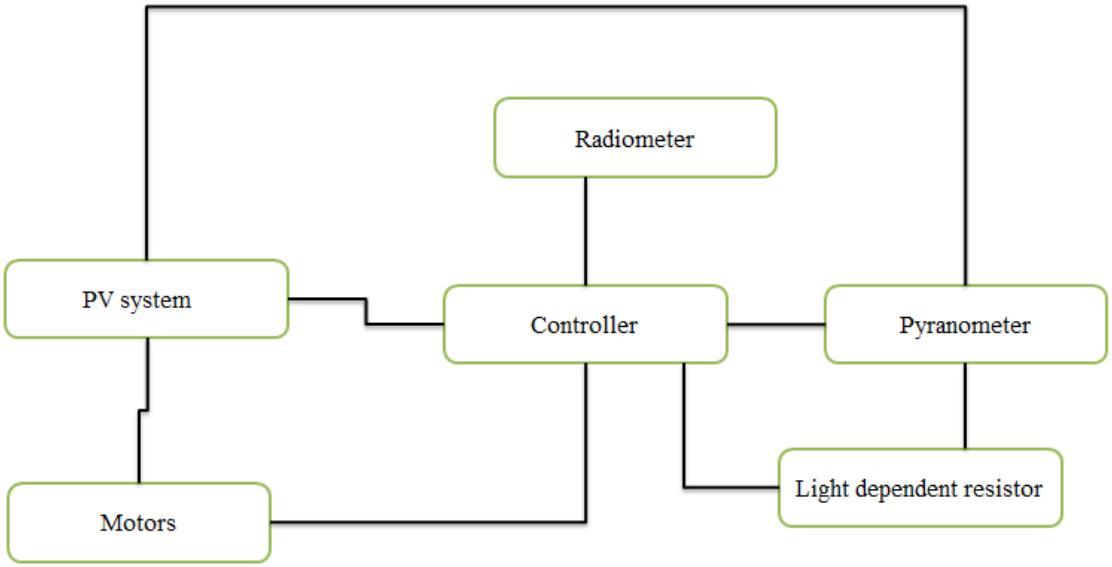


Figure A-7: Vilela et al, (2003) `s design of solar tracking system

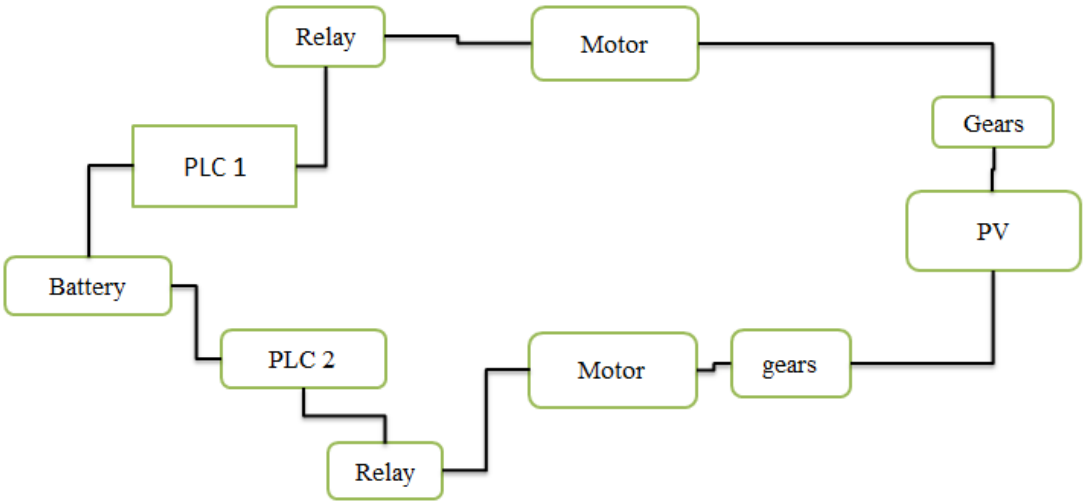


Figure A-8: A tracker developed by Abdallah & Nijmeh, (2004)

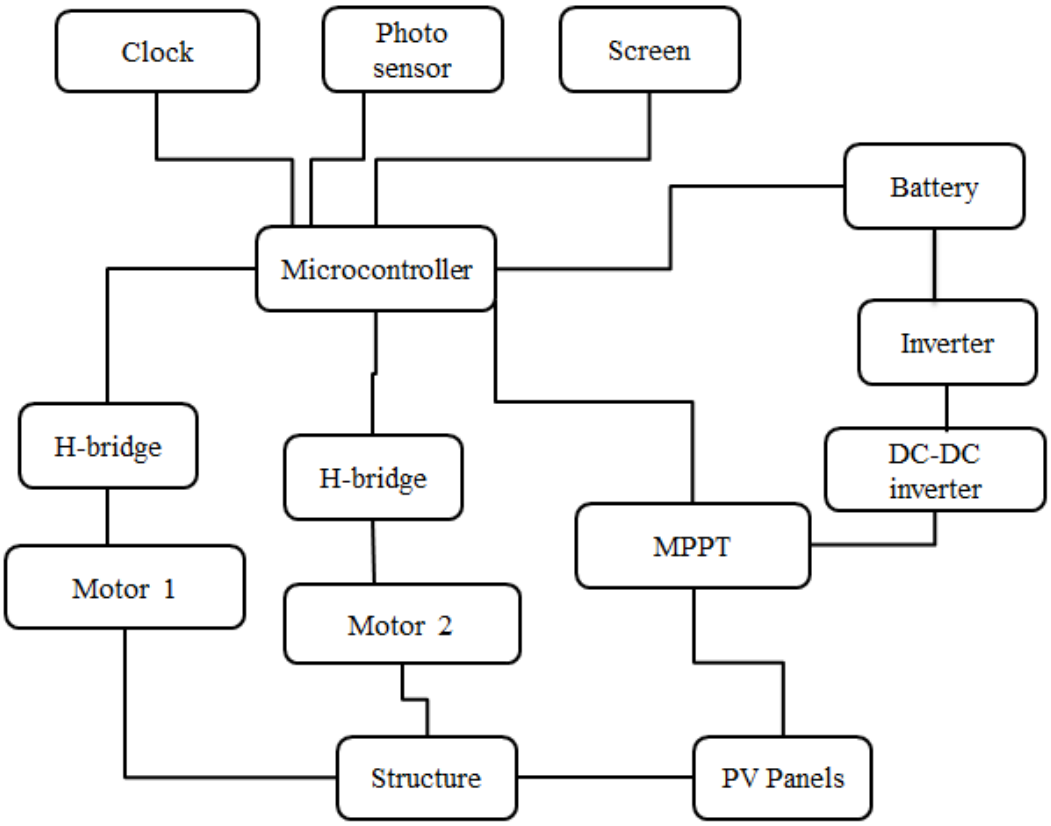


Figure A-9: system developed by Piao et al, (2005)

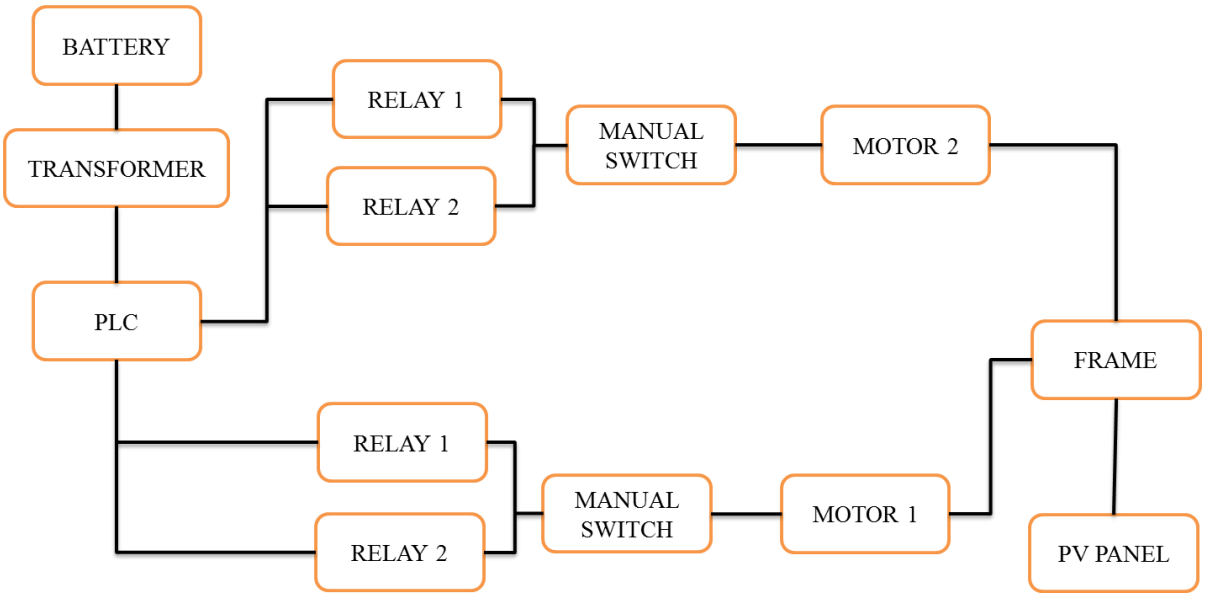


Figure A-10: Mamlook et al, (2006) dual axis solar tracking layout

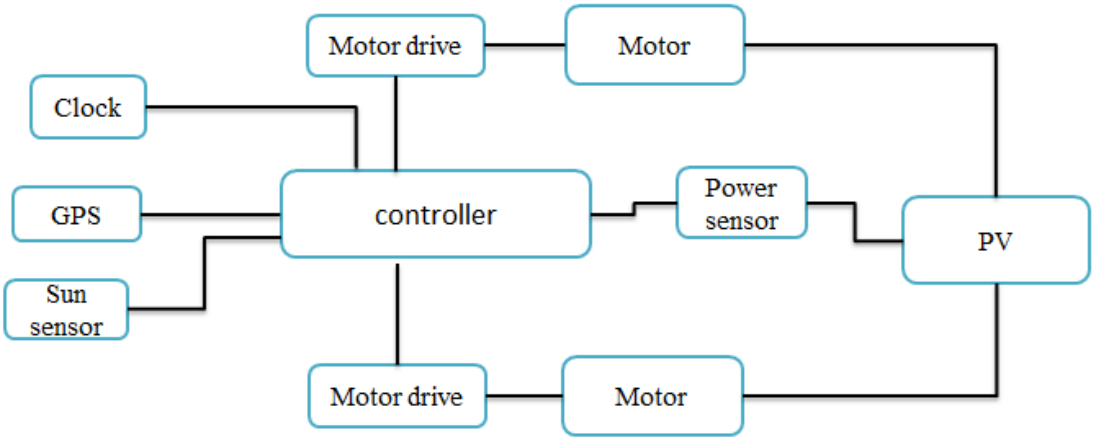


Figure A-11: Rubio et al, (2007) `s solar tracking system

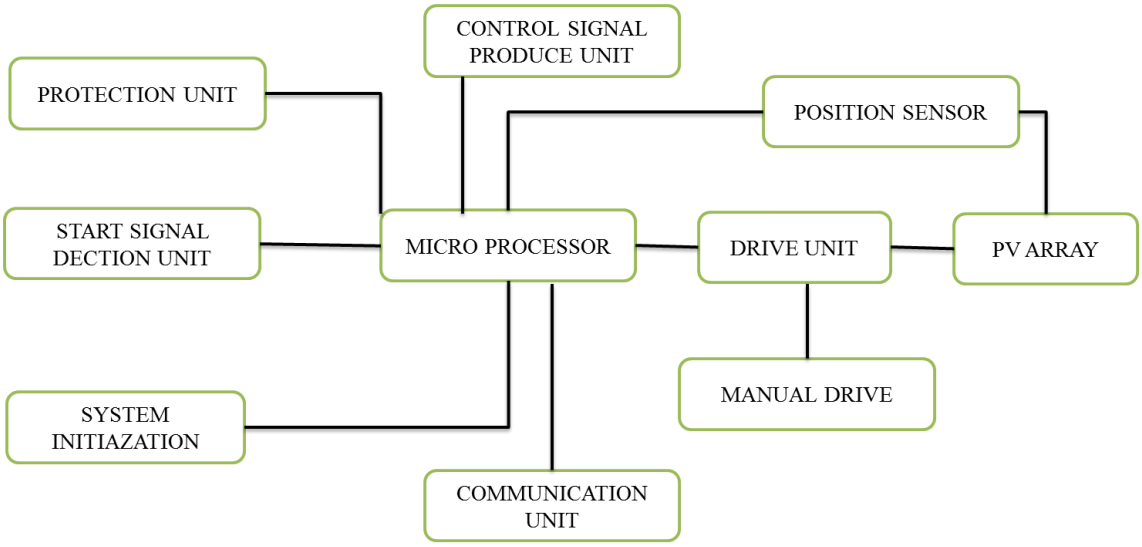


Figure A-12: A solar tracker constructed by Chun-Sheng et al, (2008)

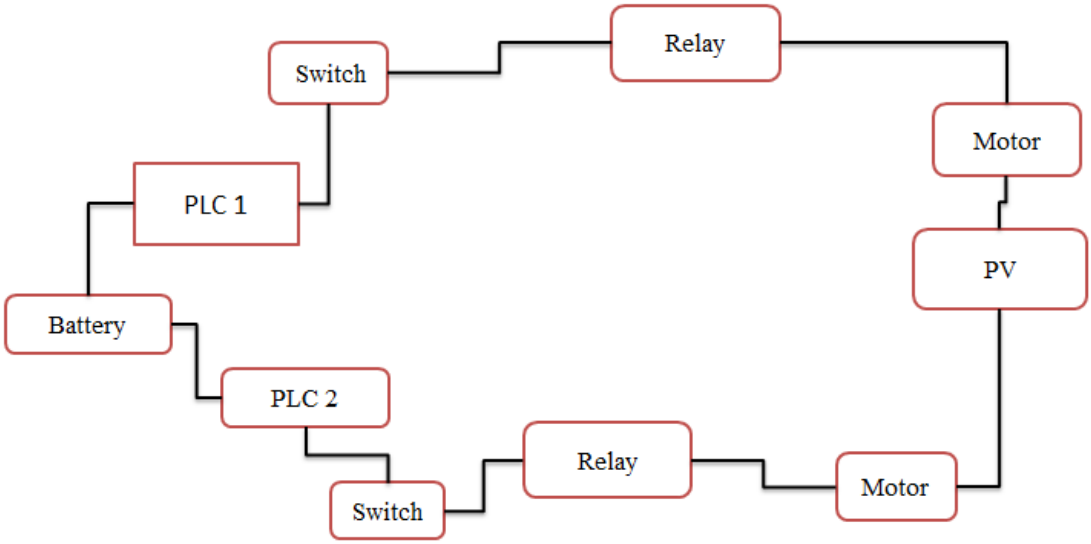
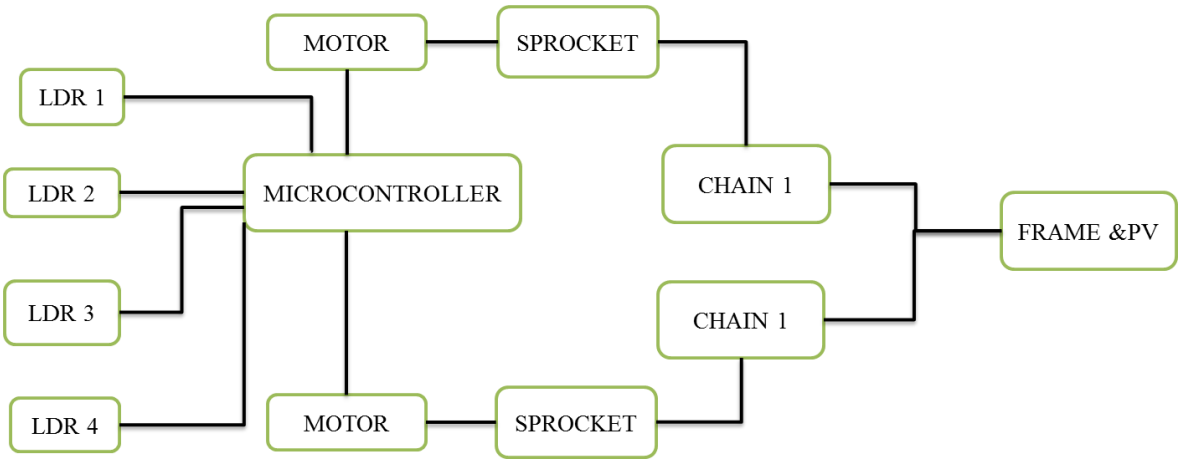


Figure A-13: A system developed by Sungur, (2009)



FigureA-14: Configuration of system developed by Barsoum & Vasant, (2010)

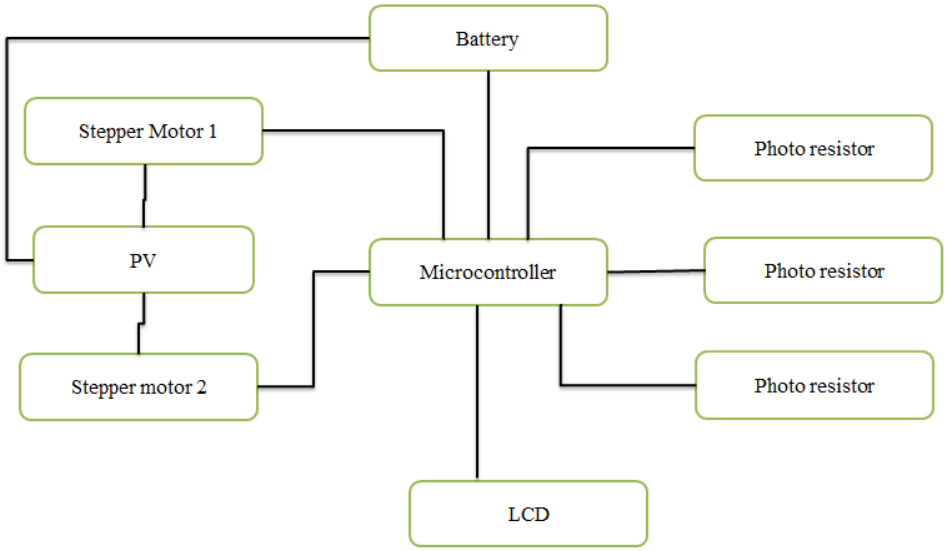


Figure A-15: Kassem & Hamad, (2011) `s solar tracking system

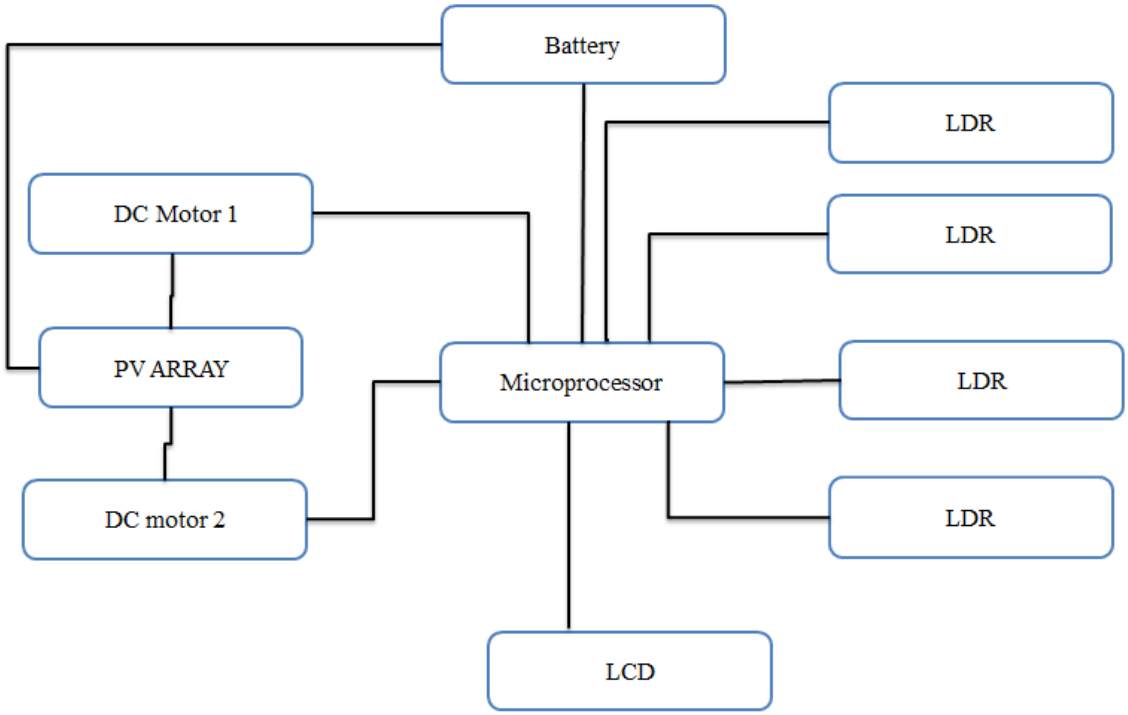


Figure A-16: Configuration of Eke & Senturk, (2012) `s solar tracking system

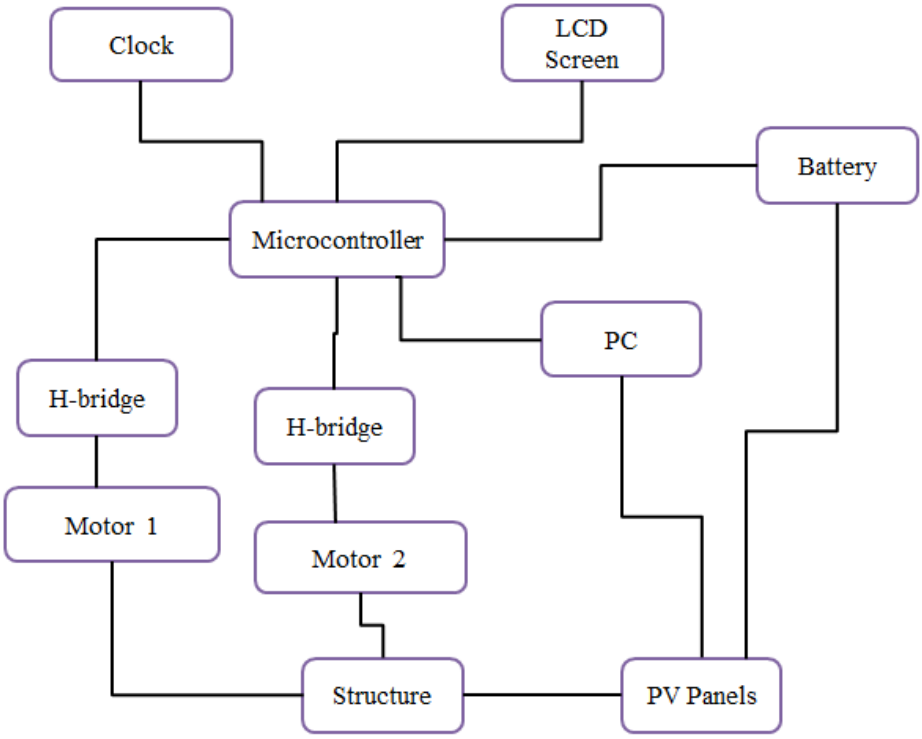


Figure A-17: Design of solar developed by Anusha & Chandra, (2013)

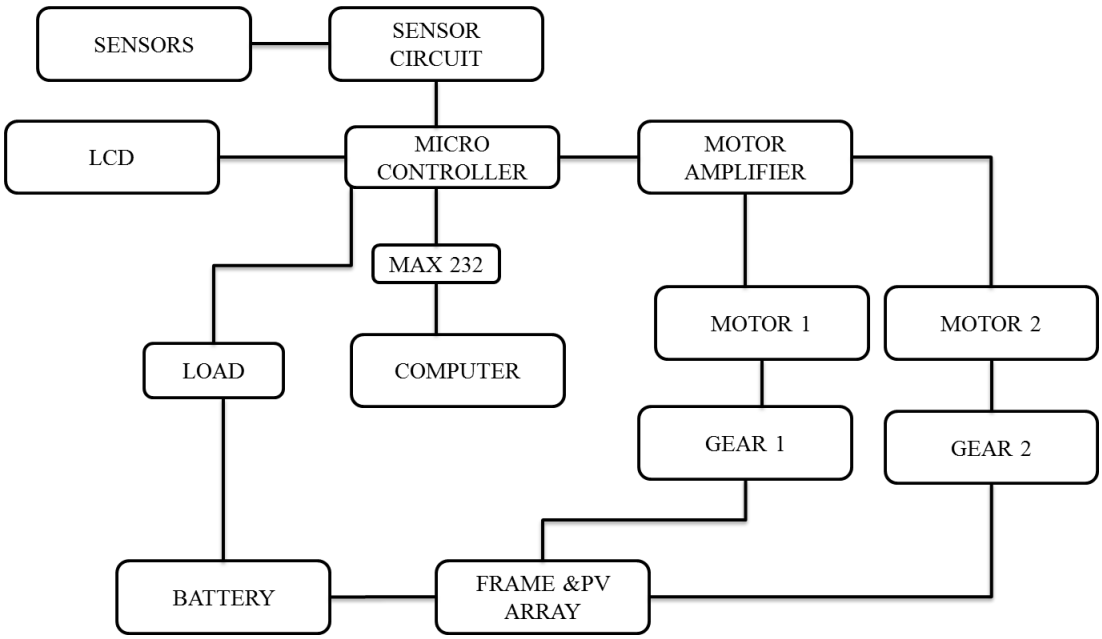


Figure A-18: A system developed by Singh & Gupta, (2014)

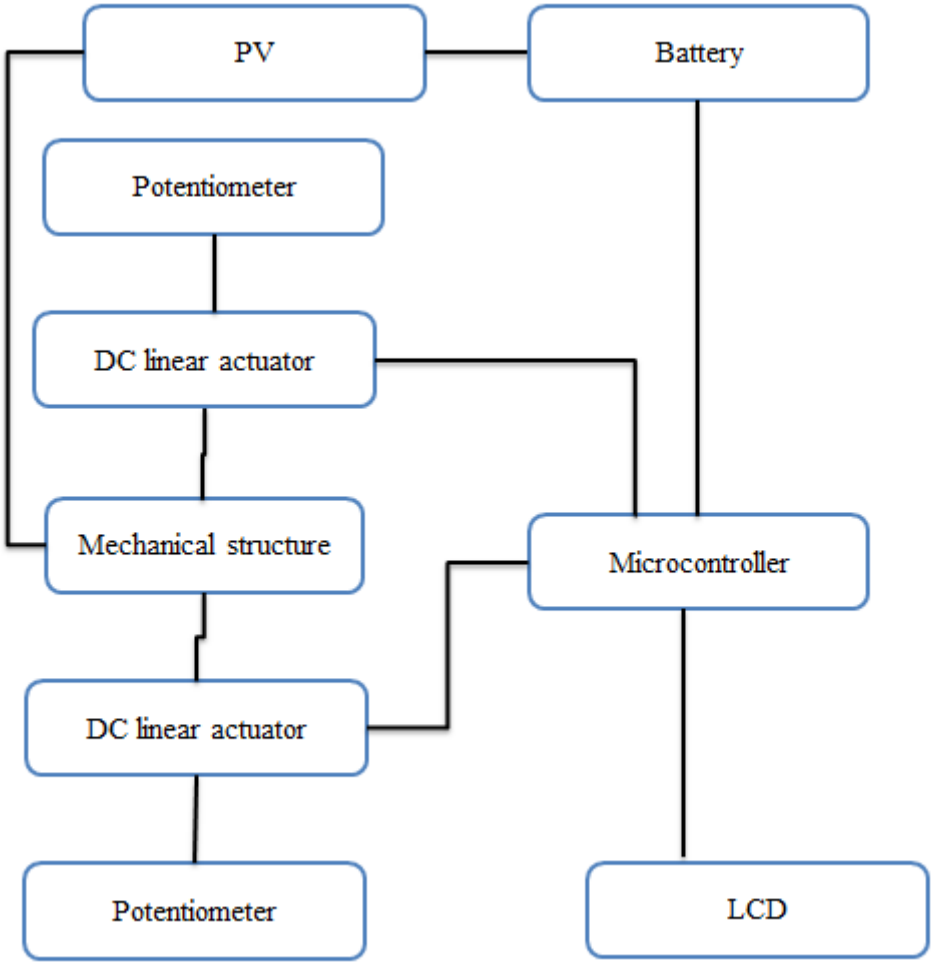


Figure A-19: Ceyda and Cenk, (2015) `s design of solar tracking system

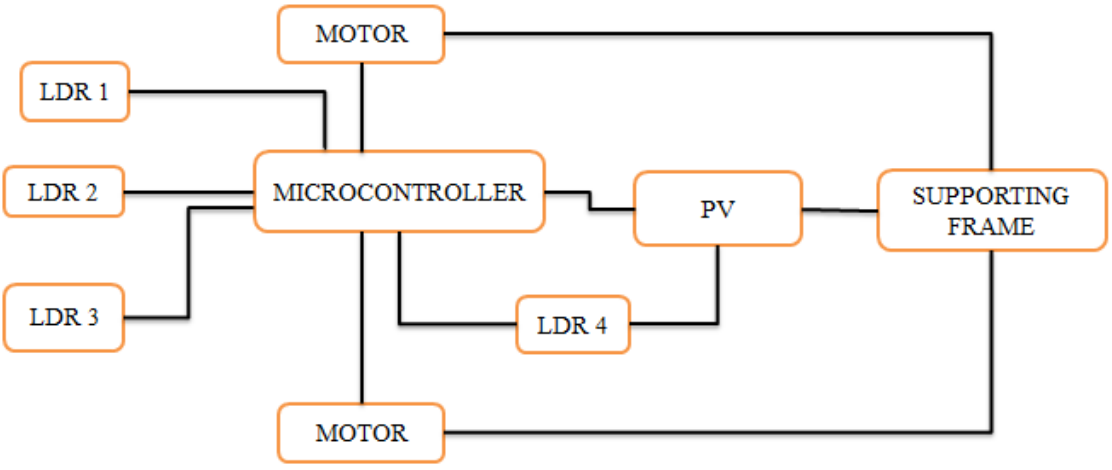


Figure A-20: Configuration of a solar tracking device developed by Shashwati & Tripathi, (2016)

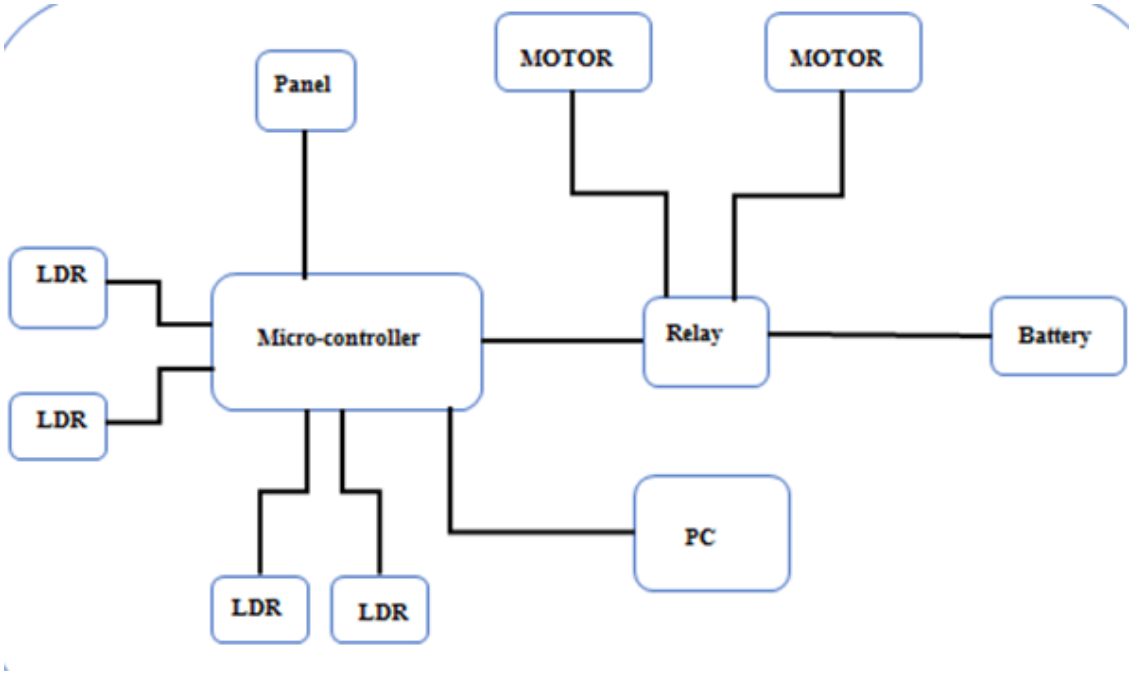


Figure A-21: A block diagram showing module and interaction of system developed by Akbar et al, (2017)

Table A-1: Summary of dual axis solar tracker efficiency map

Year	System description	Efficiency achieved
1997	Hoffmann et al, (1997) reported efficiency of more thanv30%. The evaluation was done on an open-loop active tracker on PV concentrators.	30%
1998	Chiang & Jacob, (1998) conducted an experimental testing on a closed-loop active tracker and efficiency of 30-50% was registered.	30-50%
1999	Yousef, (1999) built a PC based fuzzy logic controlled system, which increased conversion efficiency of PV system by 50%.	50%
2000	Helwa et al, (2000)'s study conducted a comparison studies on different trackers and realised an efficiency of 30% through the dual axis active tracker.	30%
2001	Fanney &Dougherty, (2001) described a mobile solar tracker which was part of building integrated PV testing facility and they recorded 40% efficiency.	40%
2002	Yousif, (2002) tested an auxiliary PV cell-based tracker under field conditions and efficiency of 40% was recorded.	40%
2003	Vilela et al (2003) developed and evaluated a tracker in a water pumping system, its efficiency was found to be 19-24%	19-24%
2004	Abdallah & Nijmeh, (2004) designed and constructed a PLC based tracker and efficiency of 41.34% was achieved.	41.34%
2005	Piao et al, (2005) recorded an efficiency of 21% this was due to a micro-controller based active tracker.	21%
2006	Mamlook et al, (2006) conducted an experimental evaluation of mathematical formulae PLC based tracker and an efficiency of 40% was recorded.	40%
2007	Rubio et al, (2007) constructed and experimentally tested a PC controlled system, and realised an efficiency of 40%.	40%
2008	Chun-Sheng et al, (2008) reports a 49.2% increase in efficiency due to a microprocessor controlled solar tracking system.	49.2%
2009	Sungur, (2009) realised an efficiency of 42.6% from an experimental testing of PLC and DC motor based solar tracker.	42.6%
2010	Barsoum & Vasant, (2010) achieved 40% efficiency through a system made-up of micro-controller (PIC16F84A), LDRs and DC motors	40%
2011	Kassem & Hamad, (2011) designed a micro-controller based tracker and recorded 64% efficiency improvement.	64%
2012	Eke & Senturk, (2012) evaluated a commercial Pesos SF-40SD and found an efficiency of 30.79%.	30.79%
2013	Anusha & Chandra, (2013) realised 40% efficiency from a micro-controller (LPC2148) and stepper motor.	40%
2014	Singh & Gupta, (2014) performed an experimental testing on a tracker constructed of micro-controller (PIC16F877A), stepper motor, worm and spur gear, the authors recorded 35-42%	35-42%
2015	Ceyda and Cenk, (2015) designed and evaluated a micro-controller (PIC16F877A), linear actuators and potentiometers based system, and efficiency of 40% was achieved.	40%
2016	Shashwati & Tripathi, (2016) constructed and experimentally tested a micro-controller (ATmega 8), DC motors geared and L293D motor drivers based tracker, the studied recorded 40% efficiency.	40%
2017	Akbar et al, 2017 developed a micro-controller (ATmega 3328), LDRs, DC motors and relays based system and the authors reported an efficiency of 30-55%	27.5%

APPENDIX B: WORKING DRAWINGS

BACK OF ENVELOPE CALCULATIONS/GUESSTIMATIONS

In order to develop a three dimensional model these following guesstimations calculations were made;

1. Panel spacing calculation; an online sun path generator (University of Oregon online resources) was used to determine the possible lowest angle of the sun during a year. Then panel spacing formulae was used for sizing the system for modelling.

Assumptions:

i. Height of the model was assumed to be 500 mm since the fabrication of the design is for laboratory applications. Therefore it will be spacing efficient for storage, application purposes.

ii. Panel of the following dimensions (215x135x18mm). A portrait orientation was used for the calculation.

iii. Using the below sun path graph the lowest sun vector during winter solstice is approximately; solar elevation 20˚ at 8 AM and 4 PM, solar azimuth 60˚ at 8 AM and -60˚ PM respectively.

iv. Location of the site is assumed to be -22.55˚ latitude and 27.11˚ longitude at +2 hour time zone.

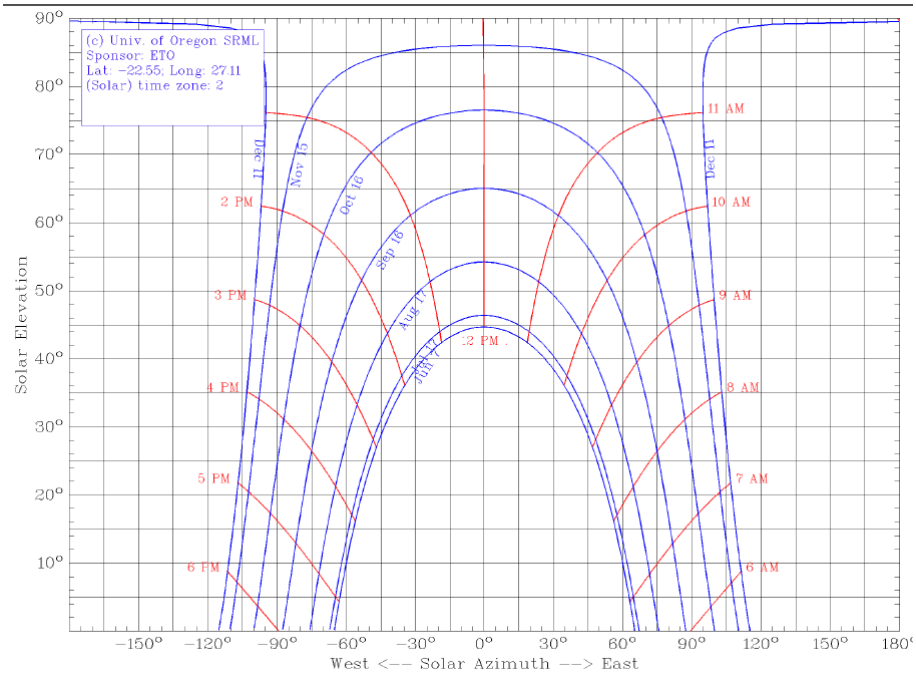


Figure B-1: Solar window graph for Palapye

a) Panel spacing in east-west direction

$$I_{EW} = \left\{H * \sec(\gamma_s) + \left(\frac{L_{EW}}{2}\right)\right\} \operatorname{cosec}(\gamma_s) * \cos(\propto_s)$$

(**B.1**)

b) Row spacing in north-south direction

$$I_{NS} = \left\{H * \sec(\gamma_s) + \left(\frac{L_{NS}}{2}\right)\right\} \operatorname{cosec}(\gamma_s)$$

(**B.2**)

2. Sizing and selection of cylinders

Assumptions:

i. The formula below was used to calculate the diameter of the required cylinders i.e. east-west direction cylinders (two identical) and north and south-direction. The mass of the panel was assumed to be 0.35 kg for a standard 3 watts mono-crystalline PV panel. For a single row the system was design to carry to panels.

ii. A frame which support and provide the degree of freedom is assumed to weigh double as much as the panels. Therefore a factor safety factor of 2 was used to cater for this weight in calculations.

iii. Gravitation acceleration used in this calculation was assumed to $9.81ms^{-1}$

$$d = \sqrt{\left(\frac{4F}{P\pi}\right)}$$

(**B.3**)

iv. To select a cylinder that relatively performs a designed the online catalogues (e.g. Festo) for pneumatic equipment was used to aid the process.

3. Compressor sizing estimation

Assumptions:

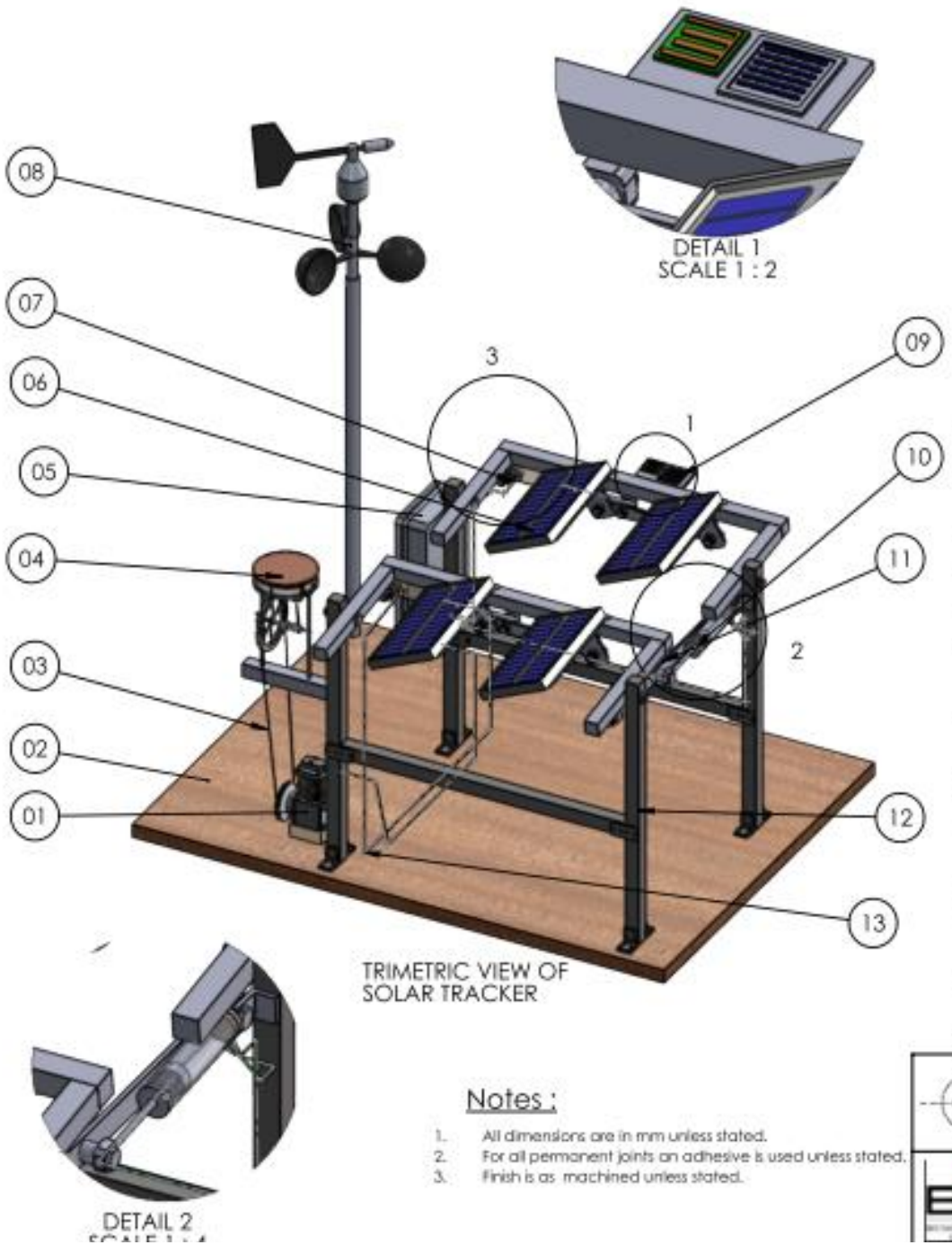
i. To calculate the air flow consumption rate of the system designed i.e. two cylinders of 6mm and one 8mm bore respectively. For both the standard stroke available in the market is 50mm. It is assumed that a full stroke of the east-west direction cylinders is reached in 8 hour (if operation between 0800-1600hours).

$$power\ (w) = flow\ rate\left(m^3/_{sec}\right) \times pressure\ (Pa)$$

(**B.4**)

4. Stirling engine sizing and selection

The Stirling was selection was based on the assumption that it should provide enough power required by the air compressor. Therefore an engine that could supply one and half or double power required was selected.



Item No.	Part name	Description	Qty.
13	Pneumatic tubing	PVC tube	3
12	Support structure sub-assembly	.Arcylic square tubes (25*25)	2
11	Linkage	Arcylic	1
10	Pneumatic cylinder 1	STD	1
09	Rain & cloud sensors	STD.	1
08	Wind sensor	STD.	1
07	Pneumatic cylinder 2	STD.	2
06	PV panel	STD.	4
05	Control box	Arcylic (vacuun formed)	1
04	Solar engine sub-assembly	STD.	1
03	V-belt	STD.	1
02	Platform	Pinewod (1000*750*25)	1
01	Air pump sub-assembly	STD.	1

Notes :

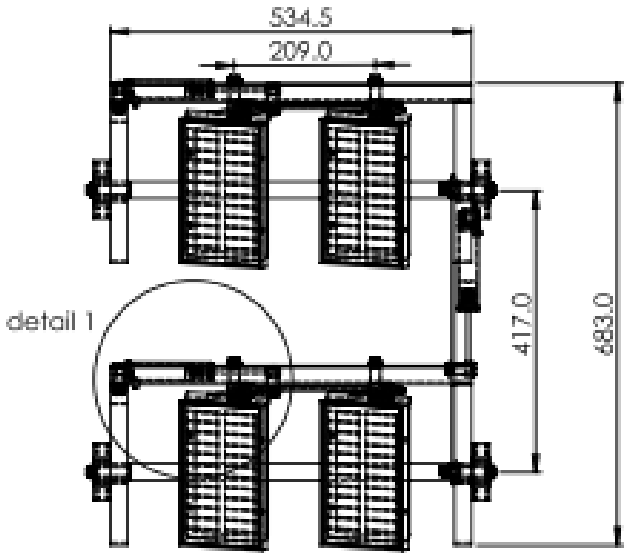
1. All dimensions are in mm unless stated.
2. For all permanent joints an adhesive is used unless stated.
3. Finish is as machined unless stated.

GENERAL ASSEMBLY

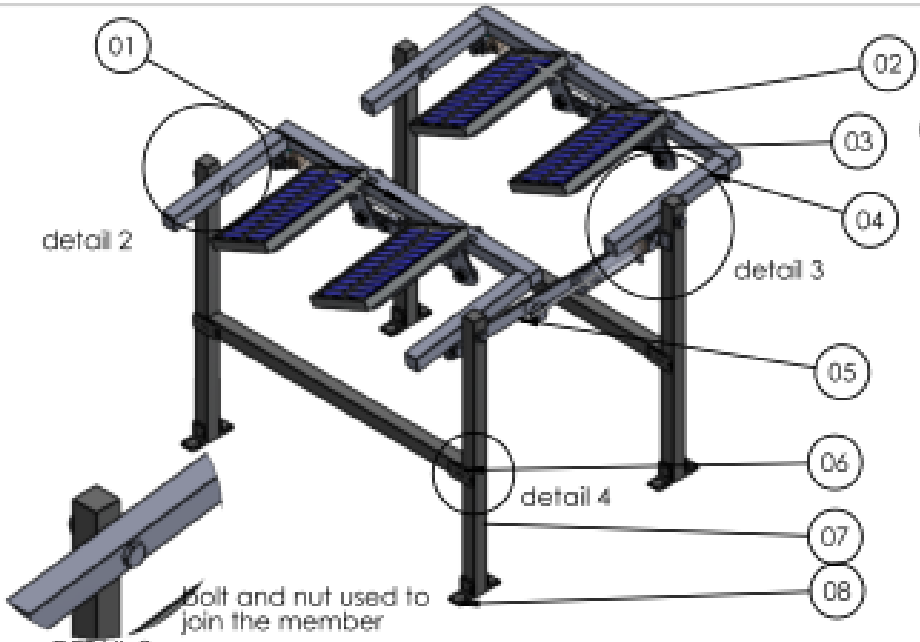
DUAL AXIS SOLAR TRACKER

Drawn: E. K. MPODI | Checked: Z. Tjiparuro

Figure B-0-2: Transparent box model of solar tracking concept

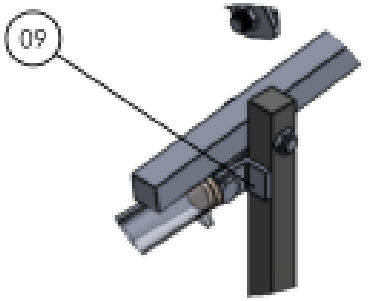


TOP VIEW

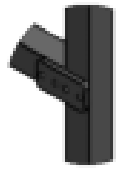


TRIMETIC VIEW

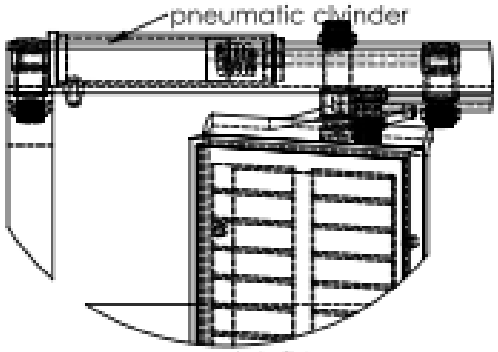
DETAIL 2
SCALE 1 : 4



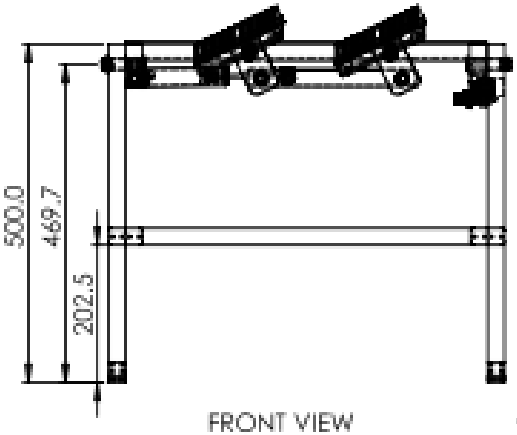
DETAIL 3
SCALE 1 : 4



DETAIL 4
SCALE 1 : 4



detail 1
SCALE 1 : 3



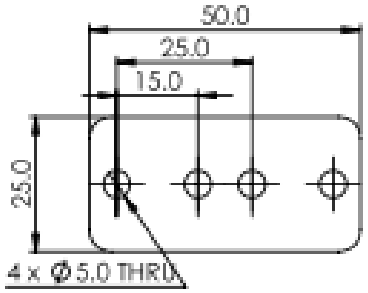
FRONT VIEW

Item No.	Part name	Description	Qty.
09	Cylinder holder	50*25*5 Arcylic sheet	3
08	Base-frame attachment	50*25*5 Arcylic sheet	8
07	Vertical supporter	500*25*25 Arcylic square tube	4
06	Butt plate	50*25*5 Arcylic sheet	4
05	Tilt linkage	220*25*5 Arcylic sheet	1
04	Tilt supporter	239*25*25 Arccylic square tube	2
03	Panel holder	305*135*5 Arcylic sheet	4
02	Azimuth linkage	457*25*5 Arcylic sheet	2
01	Azimuth supporter	535*25*25 Arcylic square tube	28

Notes :

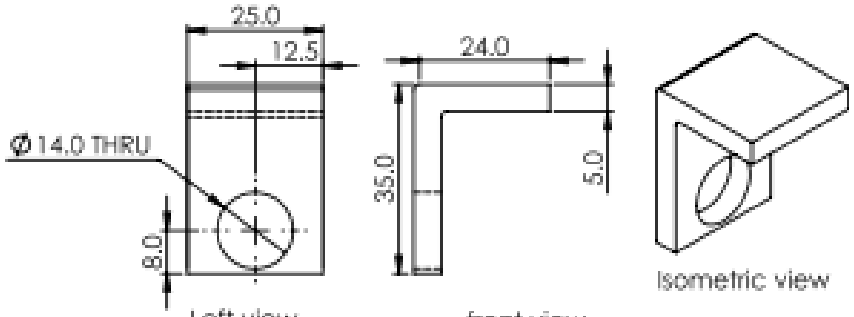
1. All dimensions in mm unles stated
2. For all permanent joints an adhesive is used unless stated.
3. Finish is as machined unless stated

BIUST	support structure sub-assembly		
	DUAL AXIS SOLAR TRACKER		
	Drawn: E. K. MPODI	Checked: Z. Tjiparuro	
	Date 06/2019	scale 1:8	DWG No: 300-01	Sheet 2/6



front view
Butt plate

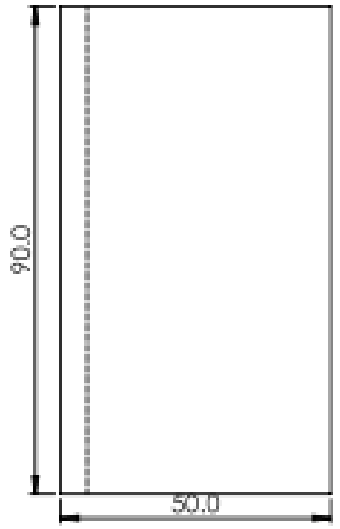
Scale 1:1



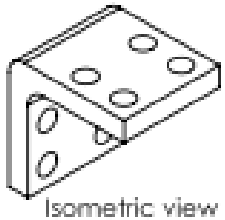
Cylinder holder

Scale 1:1

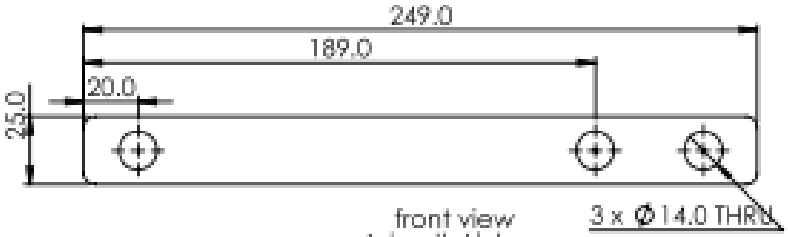
Isometric view



Top View



Isometric view



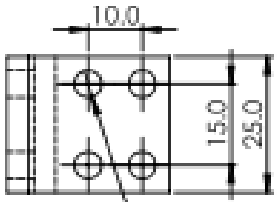
front view
Azimuth Linkage



front view

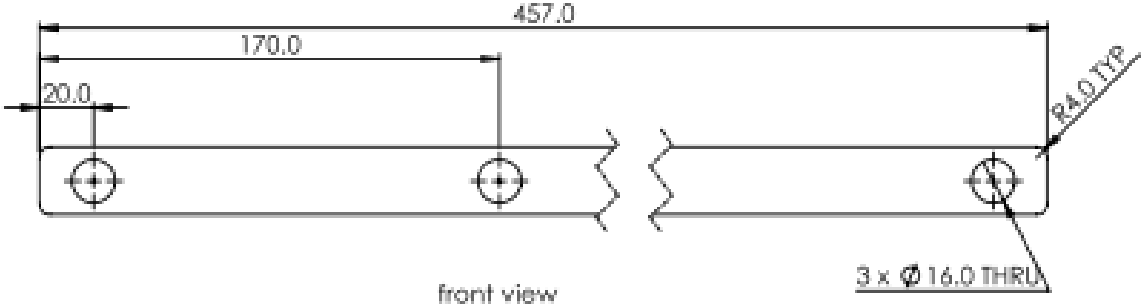
Sensor holder

Scale 1:1

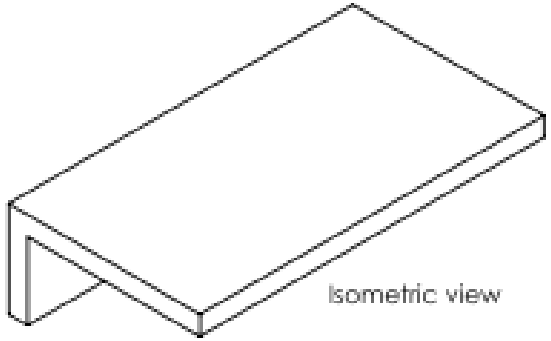


Top View

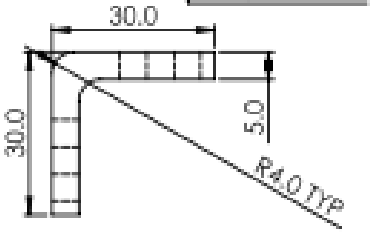




front view
Tilt Linkage



Isometric view



front view

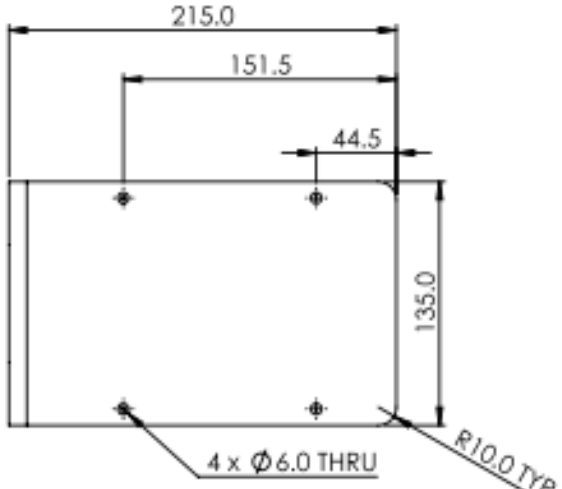
Frame-base attachment

Scale 1:1

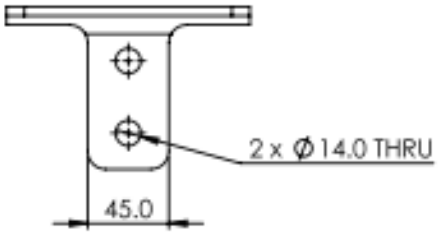
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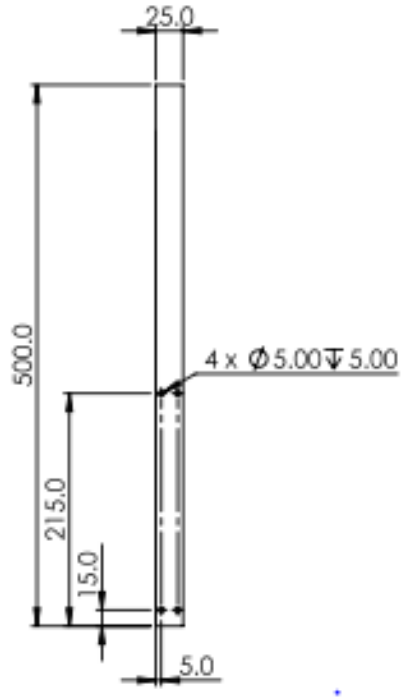
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BIUST	DUAL AXIS SOLAR TRACKER		
	Drawn: E. K. MPODI	Checked: Z. Tjiparuro	
Date: 06/2019	Scale 1:2	DWG No: 300-01	Sheet 3/6



Top view



Right view

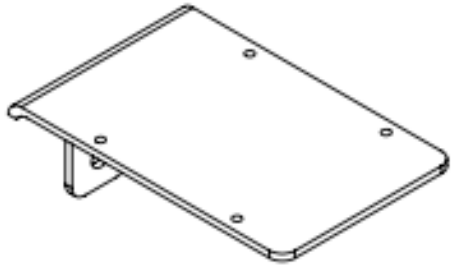


Front view
Vertical Supporter

scale 1:5



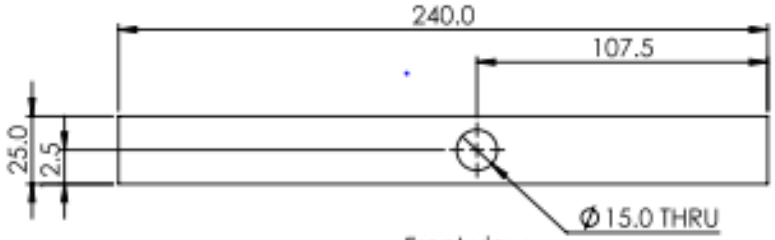
Right view



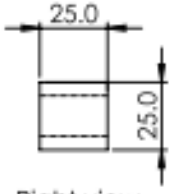
Isometric view

Panel Holder

scale 1:3



Front view
Tilt Supporter

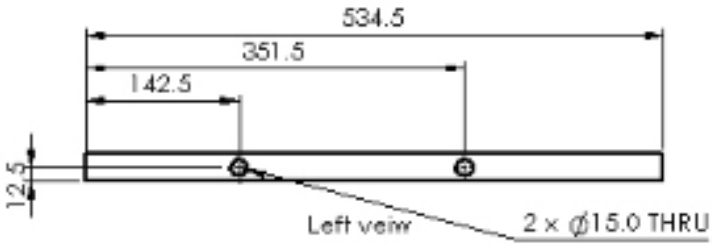


Right view

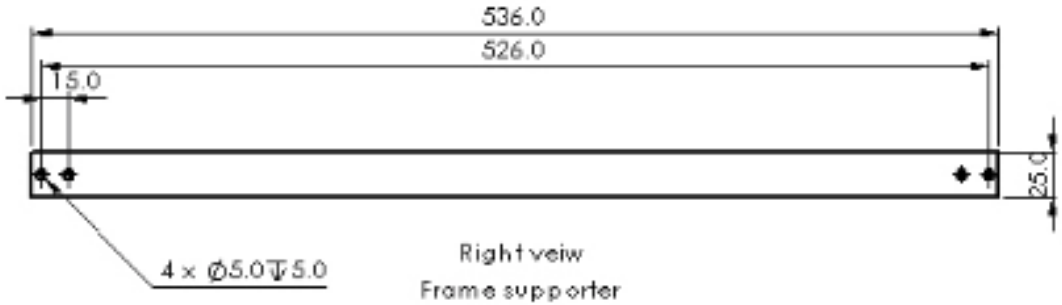
Notes :

1. All dimensions in mm unless stated.
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3. Finish is as machined unless stated.

BIUST	Support structure sub-assembly parts		
	DUAL AXIS SOLAR TRACKER		
	Drawn: E. K. MPODI	Checked: Z. Tjiparuro	
Date: 06/2019	Scale 1:2	DWG No: 300-01	Sheet 4/6

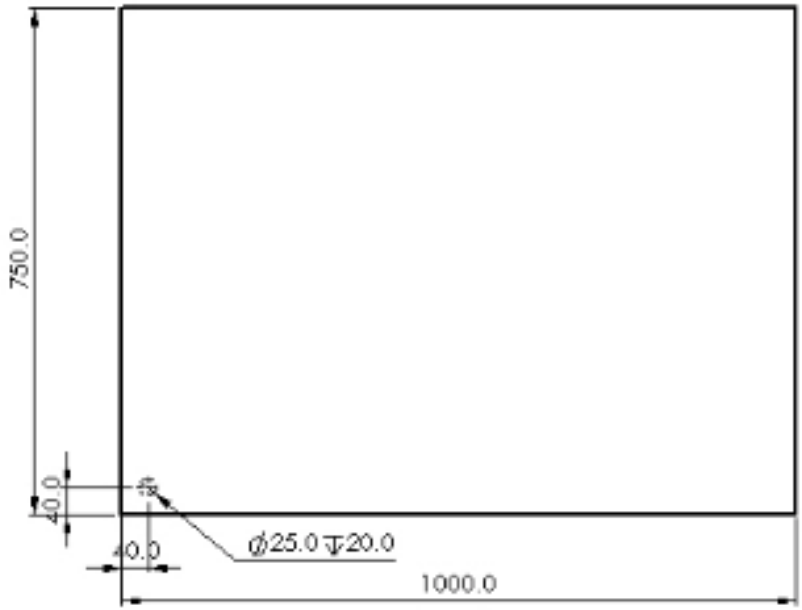


Azimuth supporter

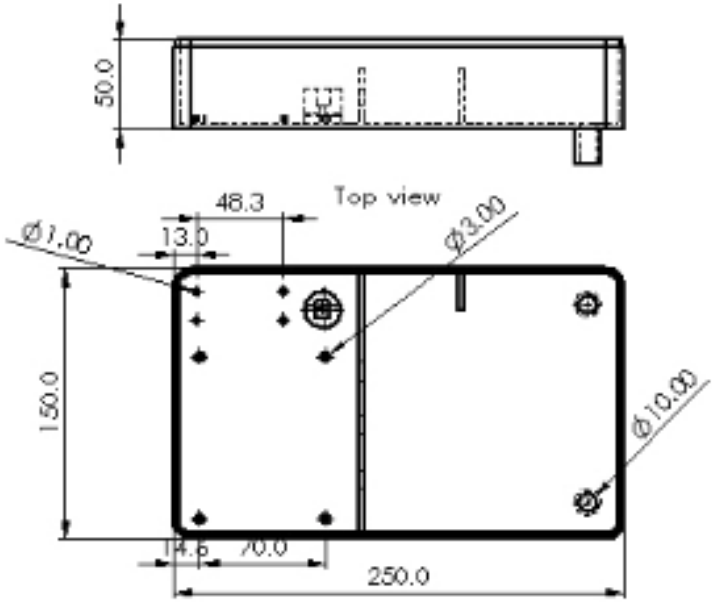


Frame supporter

Scale 1:3

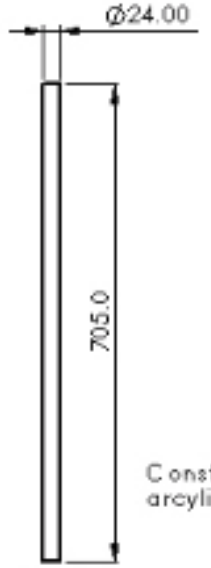


Top view
Platform
Scale 1:8



Front view
cotrol box container

Scale 1:8



Front view
Wind sensor stand
Scale 1:8

Notes :

1. All dimensions are in mm unless stated.
2. For all permanent joint use adhesive is used unless stated.
3. Finish is as machined unless stated.

	Control box sub-assembly parts	
BIOST	DUAL AXIS SOLAR TRACKER	
	Drawn: E. K. MPODI	Checked: Z. Tjiparuro
Date: 06/2019	Scale 1:5	DWG No: 300-01 / Sheet 6/6

BILL OF QUANTITY

Part	Description	QTY.
Wind sensor	Anemometer Output: 4-20mA three wire connection Working Voltage: 12-24V DC Range: 0.5- 50m/s Starting speed 0.5m/s Accuracy ±3% Conditions temperature -20◦c ~ 85◦c Maximum speed 70m/s Connection m12 weather proof Protection IP65	1
Photovoltaic panel	Mono-crystalline silicon solar cell 3 watt 18volts 24A 215x135x18mm 0.3kg flat glass	4
Rain sensor	Ambient operating temperature: -10◦c to 50◦c Dimension 95x55x40mm IP rating: IP65 Weight: 0.25 kg	1
Acrylic tube	25*25mm square tube	
Air pump/ compressor	Power consumption: 15W Rated pressure: 1bar Receiver tank capacity: 2 litres Rated Airflow 0.8 Litres per minute Outlet: 6mm O.D Power source: Mechanical Duty cycle: 30 minutes Mounting dimension: 48x63mm (receiver tank) Weight: 0.7kg (compressor)	1
Solar Stirling Engine	Rated Power output: 30W RPM: 1000 Dish size: 200 mm Fly wheel size: 70mm Material: Aluminium precision casting	1
Pneumatic Cylinders	Single acting spring return cylinder Operating medium: compressed air Connection: Female thread M5 Mounting type: clevis Bore diameter: 6mm Stroke length: 50mm Weight: 0.024kg Material: stainless steel (barrel)	2
	Bore diameter: 8mm Stroke length: 50mm Weight: 0.03kg	1
Solar battery	12 V DC Rated capacity; 4 Ah Lead acid Dimension 90x70x101 mm Weight: 1.23 kg	1

Charge controller	System Voltage: 12V/24A Charge type: PWM Dimensions: 168x92x34mm Weight: 0.32kg	1
Sensor box	Mono-crystalline silicon (50*33mm) Housing: powder coated aluminium Dimensions: 150x85x40mm Weight: 0.36kg Supply current: 80mA	1
Solenoid Pneumatic Valve	3 ports 2-ways valve Normally closed valve 12V DC Operating medium: Compressed air Flow rate: 180 litres per minute Nominal size 2.1mm Temperature: 0 to 50◦c Operating pressure: -0.9 to 8 bar Electric connection: Plug (2-pins) Dimension: 10mm width	2
Solenoid pneumatic valve	Flow control valve 12 V DC Operating medium: Compressed air Flow rate: 180 litres per minute Nominal size: 2.1mm Temperature: 0 to 50◦c Operating pressure: -0.9 to 8 bar Electric connection: Plug (2- pins) Dimension: 10mm width	3
Inclinometer sensor	Dual axis inclinometer sensors Power supply: 1W Power consumption: 0-36V DC Roll/ Pitch range: ±180◦ ±90◦ Dimension: 81x54x28.5mm Weight: 0.24kg	1
Tubes	Polyurethane tubing Outer diameter 4mm Operating medium: Compressed air 50m	1
Pneumatic Accessories	Push-in Fitting Connecting thread M5 for tubing 4mm O.D Polyurethane	1 set (10 pieces)
	Fitting and Connector (mini) Pushing-in fitting T,Y, connector Multi distributor Connecting for 4mm O.D Polyurethane	1 set (10 pieces)

APPENDIX C: CTOC MODEL

Identification of required function (the function show be a minimized) using Converter, Transmitter, Operator and Controller (CTOC) in terms of power in the system. Pailhes et al (2011) functional basis database tables were used to aid in analysis the flow of power and relation of modules in physical perspective

The model present in the ***figure b-1*** presents a solar tracking from a power flow basis. In the model the solar tracking process is describe in terms power flow. From the developed CTOC model efficiency (i.e. output to input ratio of system) of solar tracker depend on efficiency of; the motion generating module (cylinder denoted;η_{cyl}), transmitter (linkage and lever;η_{lin}) and positioning modules (lever and joints;η_{lev}).

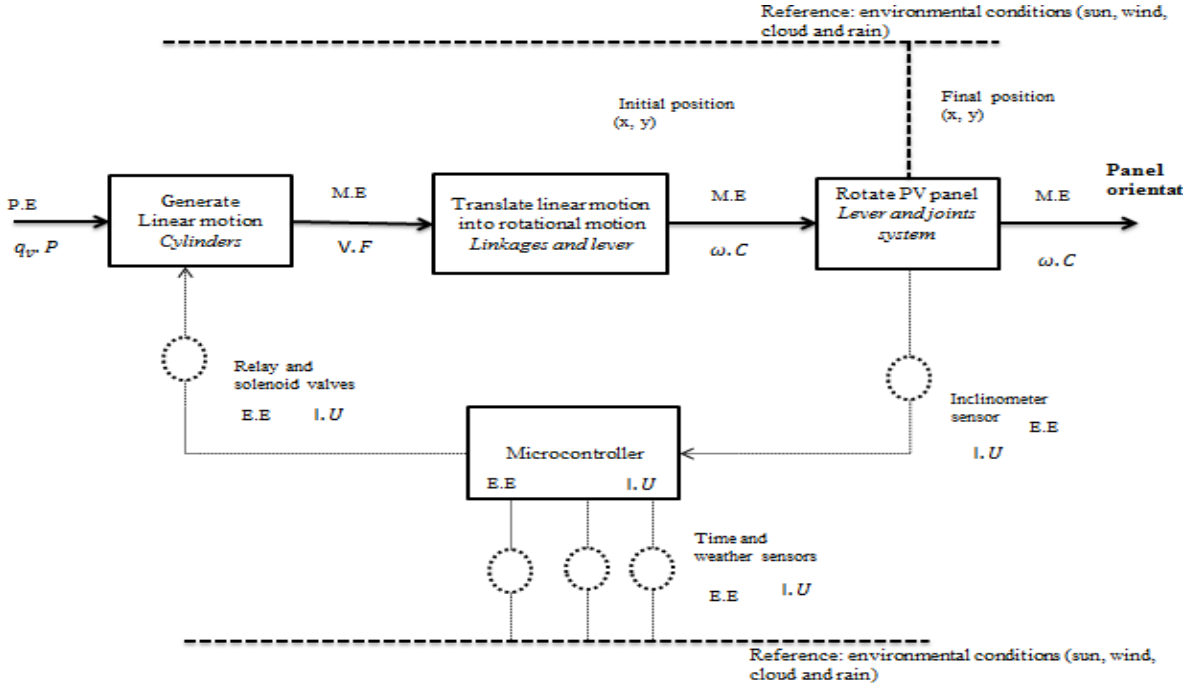


Figure B-1: CTOC model for solar tracking concept

$$\eta_{cyl} = \frac{V.F}{q_v.p} \tag{C.1}$$

$$\eta_{lin} = \frac{\omega.C}{V.F} \tag{C.2}$$

$$\eta_{lev} = \frac{\omega . C_{out}}{\omega . C_{in}}$$

(***C.3***)

Table C-1: conjugate variables used in energy flow functional

Type of energy	Relevant conjugate variables		Energy Flow (power)
	Temporal variables	State variables	
Mechanical (Translational)	Speed (V)	Force (F)	$V \cdot F$
Mechanical (Rotational)	Rotational speed (ω)	Couple (C)	$\omega \cdot C$
Hydraulic/ Pneumatic	Volume flow rate (q_v)	Pressure (p)	$q_v \cdot p$
Thermal (sensitive)	Capacity flow rate ($q \cdot C_p$)	Temperature (T)	$q \cdot C_p \cdot T$
Thermal (Storage)	Flow rate (q)	Internal Calorific Value (PCI)	$q \cdot PCI$
Electrical	Current (I)	Electrical Potential (U)	$I \cdot U$
State Mechanical (Translational)	Virtual speed (V^*)	Force (F)	0
Static Mechanical (Rotational)	Virtual rotational speed (ω^*)	Couple (C)	0

APPENDIX D: THE PROTOTYPE OF DUAL AXIS SOLAR TRACKER



APPENDIX E: PUBLICATIONS

REVIEW OF SOLAR TRACKING DEVICES FOR PHOTOVOLTAIC SYSTEMS

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Abstract: Solar tracking systems are devices used to optimize the harnessing of solar energy by the receiver. These systems use electro-mechanical devices which orientate the angle of solar receiver so that it is perpendicular to the sun. Therefore, developing tracking systems is vital as these systems could be used to track the bidirectional path of sun which constantly changes every day and seasonally. Dual axis tracking systems are often complex and consume a lot of energy when compare to single axis tracker but are usually more efficient. This paper provides a review of active solar tracking systems for PV modules. Future work will focus on the development of a dual axis.

Key words: Dual axis tracking devices, Electro-mechanical, Photo-voltaic (PV) Module.

Introduction

The use of renewable energy resource in power generation has increased as they are environment friendly and are found abundance. These resources also create an alternative source rather depending on the use of depleting fossil fuel. Among renewable resources solar is the most vital resource as it is widely and easily accessible. This led researches to be done in order to utilize this resource, of which a photovoltaic system was developed, thereby enhancing the use of solar energy. Photovoltaic system (PV) converts solar energy into electrical energy with the use of semiconductors. Though the use of PV is commonly associated with low conversion rates, years of testing and research have led to improvement of the conversion output of the PV system. Improved solar cells have been developed and the use of solar tracking system over the use of conventional fixed PV system has grown. In fixed photovoltaic system the solar receiver (PV module) is in a stationary position facing the true north.

Solar trackers are devices used to direct solar panels or modules toward the sun. These devices change their orientation from to time as they follow the sun's path to maximize energy capture resulting in minimized incidence angle between the incoming solar radiation and module surface. The system is made up of different components such as; receiver, solar irradiance sensors, automation/ control system and mechanical system.

CLASSIFICATION OF SOLAR TRACKING DEVICES

Tracking devices are either passive or active solar trackers. Passive trackers are simple device which uses thermal expansions properties of a material (i.e. thermo-sensitive fluid or shape memory alloys). These types of tracker are commonly single axis as they only orientate the module along the east-west (azimuthal) direction. Low boiling point liquids are used to sense solar irradiance making use of their temperature increase and the resulting compression. (1).

Passive trackers uses direct energy from the sun involuntarily to drive the whole tracking system without the use of generated electric energy. Though these trackers do not follow the sun precise they are used in the equatorial region which has an abundance of solar irradiance.

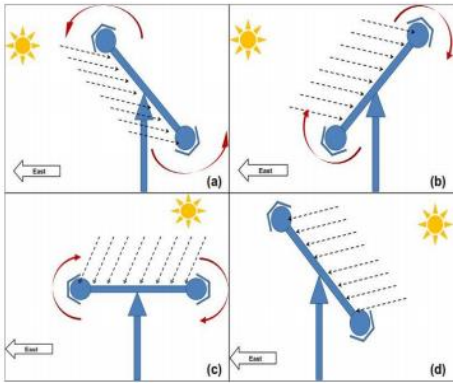


Figure 1: Fluid based passive solar tracker (1)

Active trackers

Electronic systems or mechanical systems are normally used to achieve more accurate sun tracking than that of the passive tracker. The active tracking can be further categorized into different classes according to the number of axial rotation, the type of actuator and the control system deployed on the tracking system. Solar trackers named according to the number of axial of rotation are the single axis and the dual axis.

SINGLE AXIS SOLAR TRACKING DEVICES

The single axis trackers have one degree of rotation which plays the role of the axis of rotation, which is aligned to the true north, therefore tracking the sun in only one direction of east-west, this tracking can either be open loop or closed loop controlled system for different types of actuator motorised or hydro/pneumatic system that drives the tracking devices. Varies types of single axis tracker include; horizontal single axis tracker (HSAT), vertical single axis tracker (VSAT) and tilted single axis tracker (TSAT) which are illustrated on *figure 2* below. Different studies shows that a single axis tracking system can yield an increase of about 20% above the conventional system of fixed system (2). Though common in application than the dual axis tracker for their simplicity but are limited since they only track the sun in single direction. A theoretical comparison of different solar tracking devices report, scored single tracking devices 67% over the fixed system whereas the dual axis tracking system realised a 84.11% increased output over the fixed system (3).

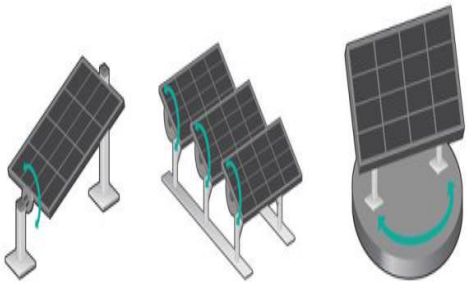


Figure 2: different types of single axis tracking device (from left to right; TSAT, HSAT and VSAT) (2)

DUAL SOLAR TRACKING DEVICES

Dual axis tracking system has two degree of freedom which is perpendicular to each other. These tracking devices are generally classified as tip-tilt and the azimuthal-altitude trackers.

MECHANICAL TRACKERS

These tracking devices entirely uses the mechanical systems to track the path of the sun with the help of predefined mathematical algorithms which are derived from sun path diagrams, the control of the devices is normally a real time mechanical clocks. Agarwal, Rohit (n.d) describe a tracking device that uses the mechanical potential energy to drive the whole system, and also train gears are deploy as control of the tracking speed as they reduce the speed of the system a per the hourly and seasonally pre-calculated mathematical algorithms in order predict the sun position. In the study it

was concluded that though the tracker could increase the output of the PV system tracks even when the weather condition are unfavourable such as when there is cloud cover.as it pre-set that is an open loop controlled system (4).

Kusekar et al., (2015) presents a hydraulic tracking system which uses high pressure fluid to convert the potential energy in the mechanical structure that hold up the PV panel into kinetic energy (5). This kinetic energy is then used to move panel toward the sun. In this system the use of levers is important to manipulate the weight of the entire body which is the main source of energy and for control, hydraulic valves are used to regulate the flow of the fluid (i.e. direction, flow rate) before it reaches the actuator (hydraulic cylinder) which transmit the motion from the fluid to the mechanical positioning mechanism. This tracking device is based on the real timer control principle.

AUTOMATED

CONTROL STRATEGY

The control strategy of solar tracking systems is categorized into two main types which are; the open loop (also referred to as passive control) and the closed loop control (active control). The open loop is a non-feedback system and commonly uses the solar algorithms to follow the path of the sun, whereas the closed loop is feedback systems that compensate the realised disturbance of the system. Combination these two methods; result in a hybrid control which in some instances can be used in tracking devices.

OPEN LOOP CONTROL

This type of control system uses an electronic logic device which uses mathematical formulae to manipulate the positioning mechanism. Though sensors are not importance in this system they can be used in calibration of the device. This mode of solar tracking ensures that the receiver is positioned at the calculated solar angle for a specific time and date, through the use of solar astronomical algorithms or formulae which are developed based on the sun path chart (maps) that predict the sun`s position according azithumal and altitude angle of the sun at specified geographical location and time.

Anusha, K, Chandra, S and Reddy, Mohan, (n.d.) reports a high performance rate for PV system with a tracking device. The study shows a 40% improvement of power generation due to the installation of tracking device rather the fixed panel. The research employed a real time clock tracking method, a DC motor is controlled by ARM processor which is programmed to a local solar time, with timer it compare the result and align the panels toward the sun (6).

CLOSED LOOP CONTROL

The main characteristic of the control system is the uses of electro-optic sensors and microprocessor as main controller for the plant. Light dependent resistor (LDRs), photo-transistor and PV cell are commonly used as sensor to detect the coordinate of the sun through light intensity. Singh et al (2013) designed a optical sensor based dual axis tracking devices, both of the studies used LDRs arranged in criss-cross manner whereby a single LDR receive a higher light intensity than another which is coupled to . This system uses 2 pairs of the LDRs; one for the east-west direction and another for south-north, as the light strikes the sensor the microcontroller compare the input signal therefore executing the command through an H-bridge drive circuit which determines the direction of the motors. In these studies a gain of were realized respectively (7; 8).

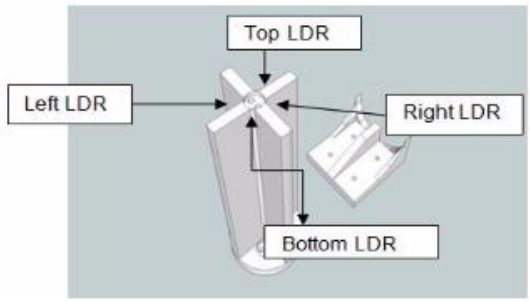


Figure 3: A crisis-cross arrangement of LDRs for dual tracking devices (8).

A PV cell based tracking is reported to have increased the energy gain by 16-20% which was attained by a system made up of four mini- solar module positioned on the North-south and east-west that detect the light intensity, this is system also use the Programmable Logic Controller (PLC) manipulate the two positioning mechanism through two DC motors (9).

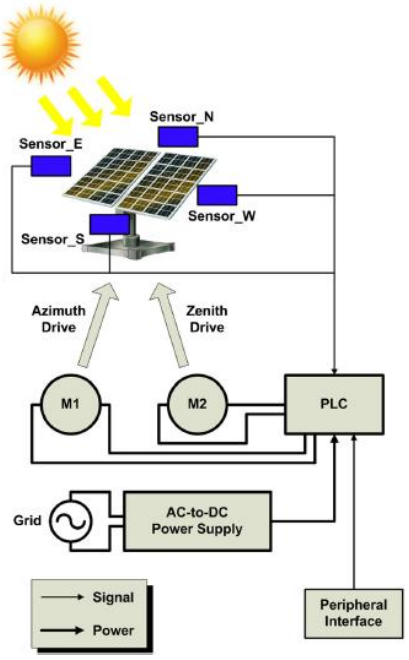


Figure 4: solar cell based dual tracking devices (9).

HYBRID LOOP CONTROL

Hybrid loop controllers combine the open and the closed loop systems. Ferdaus et al (2014) designed and implemented a hybrid control strategy, whereby a module tilt angle was varied by the means of a controller in real time based as the altitude position of the sun according to seasons. This tracking system followed the sun in a chorological manner. As the author shows, the azimuthal angle the photo-sensor based closed loop tracking follows the sun continuously. The authors conclude that the implemented tracking strategy was approximately equal with the continuous tracking in terms of energy gained when compared to the fixed conventional system, while it saved about 44.44% of power used for system operation (10).

TRACKING METHOD (MOTION OF TRACKING)

Solar tracking device are proven to be vital in improving the efficiency of PV array, but if the tracking performance is low due to factors such as installation and maintenance costs, reliability and high energy over the realised energy due to installation of the tracking device, these factor led to different development of tracking methods in-terms of the motion of tracking this is divide into two main; chronological and continuous tracking.

Chronological trackers track the sun`s position in a predefined time intervals or in steps. The method of tracking is commonly applied for change of the altitude (seasonal) angle of the sun as change is gradual in this case, but in some researches chronological tracking is implemented for azimuthal direction as position correcting device that is the actuator is only engaged to orientate the PV system toward the sun after a certain period of time.

As for continuous is a method of tracking whereby the PV is moved along with the change solar vector it can be in a single or dual manner but the literature shows that this tracking method is more practical for daily/ azimuthal direction rather than the altitude direction. This is due to increased energy consumption of the system while gain is

relatively equal with the chronological tracking method.

POSTIONING MECHANISM

A mechanical system of the solar tracking device is made up of the actuation devices, transmission system. The main function of this component is to convert any form of input energy into the require kinetic energy as it orientate the PV module towards the sun. Different actuator can be used in the solar tracking but the commonly used trackers are; hydraulic, pneumatic linear actuator and electric motor (that is either DC motor or servo-motor).

DISCUSSION

This study reviewed different solar tracking devices presented in various literature sources, and the various architectural designs of the solar tracking system. It was found that solar tracker can be classified according to if it is active or passive, the number of rotational axes, motion of tracking, control mechanism, and the type of positioning mechanism which can be referred to in the *appendix 1*. Also it was found that dual axis tracking mechanism can improved conversion rate of PV system by about 40% and an ideal system the conversion rate can reach approximately 85%.

CONCLUSION

It is therefore concluded that solar tracking devices are of great importance in photovoltaic system for improve efficiency of the system and reliability. However trackers still faces challenges such as loss of energy due to factors such as mechanical configuration, climatic condition, tracking efficiency, energy consumption of the tracking system and energy loss in the tracking system**.**

RECOMMENDATIONS

This study recommends:

- A design of electro-mechanical dual axis tracking with energy recycling and regeneration system to enhance the energy efficiency of tracking system.
- Improvement of tracking device to withstand unfavourable weather/ environmental conditions such as strong wind, dust etc.

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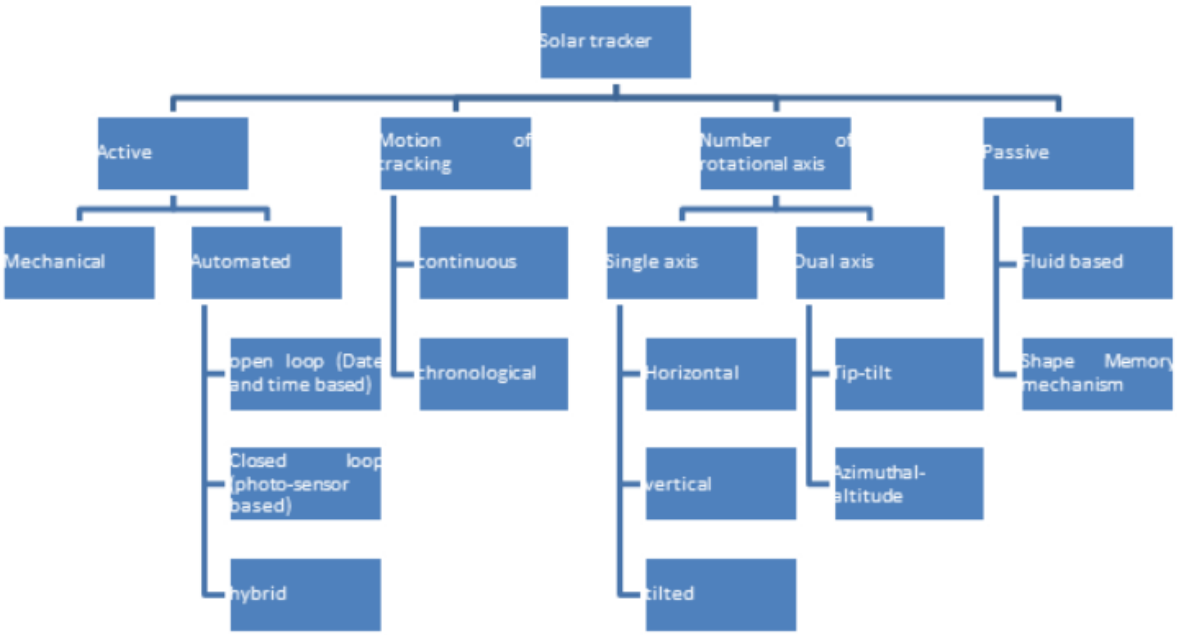
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APPENDIX

Appendix 1: SOLAR TRACKERS CLASSIFICATION TREE



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International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2019, Sun City Resort, South Africa, 08 – 10 March 2019

REVIEW OF DUAL AXIS SOLAR TRACKING AND DEVELOPMENT OF FUNCTIONAL MODEL

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Abstract

The use of solar energy is in the upswing due to its environmental friendliness and abundance. That notwithstanding, efficiency remains a major problem in many of the applications. Mitigation is normally in the form of tracking systems. This paper therefore investigates dual axis solar tracking systems from two dimensions. Firstly, a review of extant literature was conducted to draw up a trajectory of where we are in the efficiency map, Therefore it was found that the current efficiency of dual axis tracking configuration is about 35-43%. Secondly, from the above review, a generic functional model of how an efficient and effective tracking system should be is presented. The two components, coevolving, shall be used to inform the design and development of an efficient solar tracker.
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Keywords: Photovoltaic;solar tracking; efficiency; coevolving design; dual axis, design methods, functional analysis

Introduction

The use of renewable energy resources in power generation has increased as they are environment friendly and abundant. These resources are alternatives to fossil fuels whose supply is in constant decline. Among renewable resources solar is the most vital resource as it is widely and easily accessible. Hence, the current significant research interest in solar energy resources, especially photovoltaic (PV) systems. Photovoltaic systems convert solar energy into electrical energy with the use of semiconductors. Though the use of PV is commonly associated with low conversion rates, years of testing and research have led to improvement of the conversion output of the PV system. Improved solar cells have been developed. Moreover, solar tracking systems have developed and preferred over conventional fixed PV systems. Design methods is a series of technical procedures employed in the generation of new or refining existing engineered systems/products. The use of design methods has the desired effect of bringing rationality and order to the otherwise ill-defined and ill-structured [1] process of systems' generation. Very important to this process is the functionalized approach. In the approach, design problems are conceptualised as Functions and the designed products as Structures. Thus, all design activities are functions. For instance, design objectives are restricted to functional objectives, so are design requirements (or product design specifications), and the functional analysis diagram leading to the morphological chart. Results from the two situations indicate a more organized and focused approach to parameters that bear on the ultimate performance of the product to be designed.

Thus this paper has two dimensions. Firstly; extant literary materials in solar dual axis tracking is reviewed to draw up the efficiency trajectory map. Efficiency map is defined, in this paper, loosely as "answering the question of *where did we start in the efficiency of dual axis trackers and where are we now?*" *To that end,* a review solar trackers in the last two decades was undertaken and an efficiency-time graph plotted. In the second part, structural arrangement or the embodiment designs of the most highly efficient solar trackers were distilled and a functional model that represents efficient solar trackers built. The model is presented in the form of both an objective tree diagram and functional analysis diagram.

Literature review

The first solar tracker was a mechanical system by C. Finster, invented in 1962. Though the Finster solar tracker realized insignificant energy gains, years of testing and research have led to improvement of the conversion output of the PV system and consequently the emergency of different tracking technologies and applications (e.g. concentrator and non-concentrator). In short, improved solar cells have been developed and the use of solar tracking system over the use of conventional fixed PV system has grown. In fixed photovoltaic system the solar receiver (PV module) is in a stationary position facing the true north. However, with mechanical or electro-mechanical systems, the orientation of the collector change continually in reference to the azimuthal directions (east-west) and also in its elevation. This is dependent on the tracker's geometrical capacity.

Classification of solar tracking system

Mousazadeh et al, (2009) carried a review study, which resulted in the general categorisation of solar tracking systems [2] according to two main typologies, namely, Energy source (i.e. passive, active and manual), and Degree of freedom (i.e. single or dual axis). **Passive tracking systems-** designate all devices that position solar collectors for optimum capture of energy using mechanical potential and thermal energy principles. Passive systems do not use of electrical energy. Some of the typical mechanical working principles are Shape Memory Alloy (SMA), Thermo-fluids, Mechanical potential system (lever, weight and springs). In Shape Memory Alloy, cylindrical actuators to change the shape the SMA receivers through mirrors until an optimum orientation is achieved [3] Recent developments, among others by Kusekar et al (2015), have seen the use of high pressure fluids to convert the potential energy in the mechanical structure that hold up the PV panel into kinetic energy, which is then used to move the panel toward the sun. [4]

Active tracking systems- use electrical energy as their source. A number of categories exist such as; Electro-optical based tracker, Auxiliary bifacial solar cell and chronological (time and date based) tracker. At some instances, a combination of these different systems may be realised and the resulting system will be referred to as Hybrid. Of all active trackers, electro-optical based-trackers are is generally more popular. Mousazadeh et al (2009) report [2] the use of differential illumination of coupled electro-sensors to generate a differential signal to a controller which then sends a signal to drive the solar system. For improved photosensitivity, the sensor can be mounted on a pyramidal structure (in the *figure 2b outlines* the photo-diode mounted on pyramid) or use of collimator tube might be vital as it prevent diffuse irradiation from reach the sensors therefore ensuring precise measurement of the position of the sun. Fig.1c is a system made up of four mini- solar module positioned on the North- south and east-west that detect the light intensity, this is system also use the Programmable Logic Controller (PLC) manipulate the two positioning mechanism through two DC motors [5].

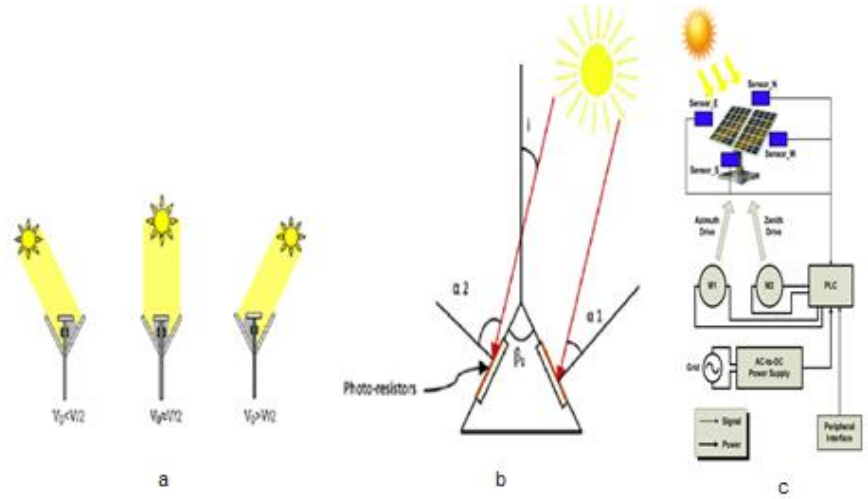


Fig. 1, Different configuration of Photo-sensor used for active tracking mechanism, a b, [6] c [7]

Auxiliary Bifacial Solar cell tracker- In this type of trackers an auxiliary PV cell is used to sense the position of sun and also provide the tracking energy, as it is connected to a permanent magnet DC motor. Both these are fixed to a driving axle of the tracker [8].

Chronological tracker- Uses the geographical and astronomical data to calculate the relative path of the sun for a specified period of time (day and month), with the aid of mathematical formulae and algorithms. To follow the predicted sun`s path the system will rotate at constant speed which the sun moves.

Manual tracking system- it is a tracker that is humanly operated and powered. In this method of tracking the operate physical manipulate the position of the collector through a uses of the form of mechanism provide. In some case this strategy is integrated to an active or passive for secondary axis of dual axis, as way of reducing complexity implicated by the uses dual axis.

Degree of freedom based typology

Single axis tracking system- These trackers are capacitated to rotate only in one axis in order to position the sun in desirable orientation for maximum solar energy harvesting. The following are single axis configurations which include; horizontal single axis tracker (HSAT), vertical single axis tracker (VSAT), tilted single axis tracker (TSAT) and polar single tracker (PSAT). The nomenclature of these tracker is derived from how tracker rotate in reference to the surface, that is HSAT`s motion is horizontal to ground. The motion in VSAT is vertical to the ground and is aligned to the east to west direction. The axis of TSAT is projected at angle from the horizontal or vertical. Lastly the PSAT also has a tilted axis which is aligned to the polar star.

Dual axis tracking systems- These system has two degree of freedom which are perpendicular to each other. These tracking devices are generally classified as tip-tilt and the azimuthal-altitude trackers. Dual axis can be deployed for both passive and active tracking strategies.

2. 2. *EFFICIENCY TRAJECTORY OF PV OUTPUT DUE TO DUAL AXIS TRACKERS OVER THE PAST TWO DECADE*

In 1997 Hoffmann, R., et al. reported an efficiency improve of more than 30% on an open loop active tracker which was evaluated on PV concentrators [9]. In 1998 an experimental review of closed loop active tracker, with solar cell used to sensor the position of the sun result in improvement of efficiency 30-50%. The tracking was tested in northern regions of Chile [10]. Yousef, H. (1999) [11] developed a tracker that deployed an artificial intelligence approach. A PC based fuzzy logic control, which acquired data through photo-diode to drive motors was engaged, the system increased conversion efficiency of PV system by 50%. A study on performance of different tracking configuration carried out in Germany outlined a 30% increase due to active tracker [12]. Dougherty, B. (2001) describes a mobile tracking device which was part of

Building Integrated PV testing facility and achieved 40% conversion efficiency over fixed [13]. A field tested (in Malta) auxiliary PV cell based, roof mounted tracking system recorded a 40% efficiency increase [14]. A tracker used in water pumping is reported to have increased efficiency about 19-24% [15]. Abdallah, S. and Nijmeh, S. (2004) Carried out experimental evaluation on a PLC; real time based tracking system in Jordan. The authors found a 41.34% increase of efficiency [16]. In 2005 Piao, Z.G., et al developed and conducted laboratory test for a time based active tracker, which used a micro-controller and engaged idle mode in gloomy sky conditions. Furthermore a 21% efficiency increase was reported (Piao, Park, Kim, Cho, & Baek, 2005) [17]. Experimentally tested tracking system in Jordan by Mamlook, et al., (2006) achieved efficiency improvement of 40%. This tracker was a solar mathematical formulae based with a PLC [18]. Rubio, F., et al., (2007) developed and experimentally tested a PC controlled through mathematical formulae with PV arrays used as feedback sensors. SCADA used for supervision and monitoring with an application developed in LABVIEW. The system attained a 40% efficiency over fixed PV collector [19].

Chen-Sheng, et al., (2008) repots a 49.2% increase in efficiency due to a system, developed and filed tested in Tibet. The tracker was developed to deploy a Microprocessor as a controller, (time based system with feedback from position sensors). Also it had a poor environment protection (Wind, Vibrations and cloud) and human-machine interface [20]. In 2009 Cemil Sungur recorded 42.6% efficiency improved after experimentally testing a real time based, PLC controlled and DC motor driven tracker in Turkey [21]. Barsoum, N. and Vasant, P., (2010) achieved 40% efficiency improvement over fixed through a microcontroller (PIC16F84A), LDRs and DC Motor based tracker [22]. A Micro-controller was used for multi-function approach tracking, by Kassem, A. and Hamad M. (2011) achieved a 64% [23]. In 2012 Eke, R. and Senturk, A., evaluated a commercial (in Turkey) Pesos SF-40SD dual axis tracking mounted on Mono Crystalline silicon PV and found a 30.79% increase in efficiency. [24]. Anusha, K. and Chandra Mohan Reddy,S. (2013) realised a 40% increase due to a real time based tracking system, which deployed Microcontroller (LPC2148) and Stepper Motor [25]. Singh, K.P., and Gupta, B., (2014) experimentally tested (in India) microcontroller (P1C16F877A programmed in DOTNET), Stepper Motor geared (Worm and spur) Infra-red sensor and realised efficiency increase of 35-42% [26]. In 2015 Ceyda, A.T., and Cenk, Y., (2015) evaluated a microcontroller (PIC16F877A programmed in MPLAB IDE) with linear actuators and potentiometer (feedback sensors) based tracking system at laboratory scale in Turkey. In this study efficiency of 40% was recorded [27]. A Microcontroller (Atmega 8), LDRs, DC motor geared and L293D motor driver was also constructed and tested at experimental scale by Shashwati, R. and Tripathi, A.K (2016) and 40% efficiency was established [28]. Akbar, H.S., et al., (2017) developed a microcontroller (Atmega 328), LDRs, DC motors and relays. Through the system efficiency of about 55-30% was recorded [29].

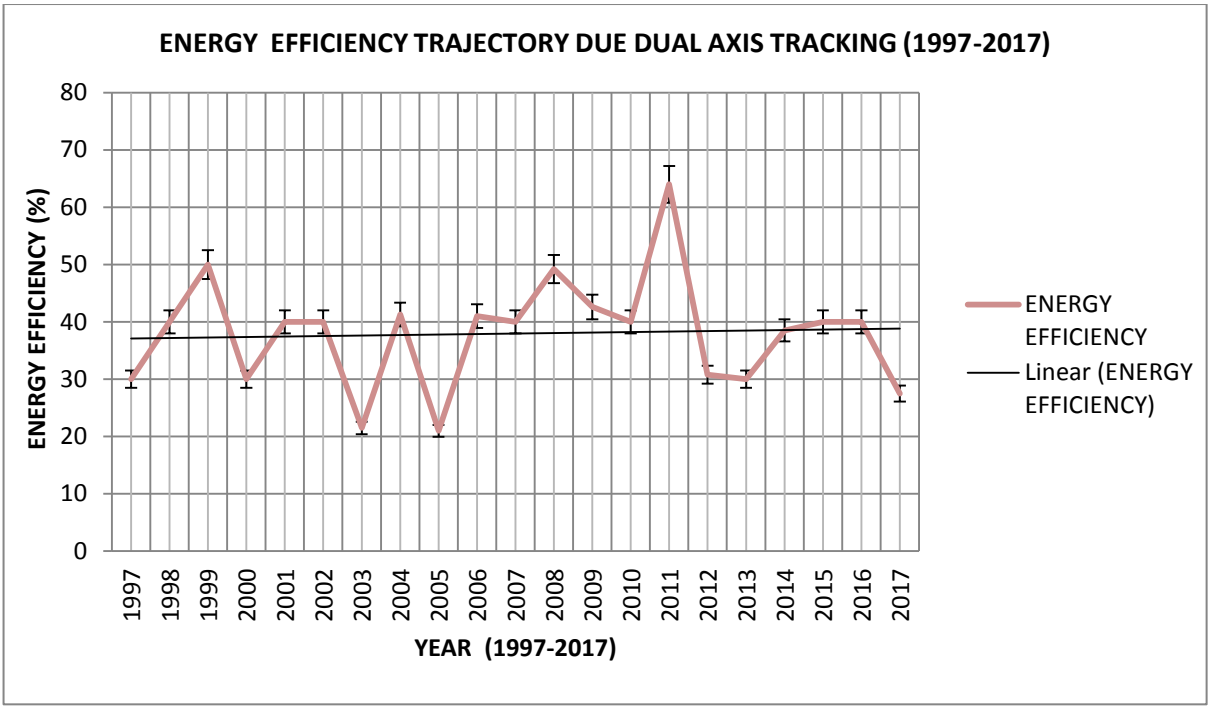


Fig. 2, Dual axis solar tracking system efficiency trajectory map for period of 20 years

The above fig.2 is a trajectory map of energy efficiency due to dual axis tracking systems. Generally the efficiency of PV technology is constant, as it is defined by a linear pattern in the graph. The average efficiency of dual tracking system is estimated to be 38±5%. Therefore a region of 33-43% defines a general point at which the efficiency of dual axis tracking system is that currently.

3.0. PROCEDURE FOR DEVELOPMENT OF FUNCTIONAL MODEL

An overall function of a tracker was identified then broken into it sub-functions, then presented in a solution independent manner. These functions were then translated to a black and transparent boxes to further determine the inputs and output to the process, in terms of energy, material and signal flow of the process. Finally the relation between input and output in a process was studied to aid in identification of functional modules.

4.0. RESULTS AND DISCUSSION

4.1. Objective tree diagram

Table 1: solar tracking objective tree diagram

Overall functional objective	**Level 1 Sub-functions**	**Level 2 Sub-functions**	**Level 3 sub-functions**
To tracking the path of the sun in order to expose photovoltaic system to maximum amount of solar energy hence increase the power output of photovoltaic system.	1. Determine the position of the sun.	1. Measure the precise sun position vector	1.Measure the solar hour angle of the sun 2.Measure the Altitude angle of the sun
		2.Encoding all measured angles	1. Correcting of error reading 2.Amplification of measured angles 3. Conversion of measured angle into compatible signals
		3.Decoding the measured angles	4. Accepting the signals of measured angles 5. Comparing the signal with the reference points of sun position for each time interval. 6. Signal sent to help generate motion for tracking

	2. Calibrate the positioning mechanism	1. Receiving signal of calculated sun position. 2. Comparing of current orientation with calculated position of the sun. 3. Sending signal to activate release of power to generate the tracking motion	
	3. Generating the tracking motion	1. Power generated form the storage/ generating device. Transmission of power to the actuator. 2. Actuator converts the input power transmitted into motion.	
		3.Orientation of the solar photovoltaic system changes to be aligned perpendicular to the sun	1.The support platform provide two degree of freedom 2.Provide a mechanical suspense to maintain the orientation
	4.Monitoring the tracking effect (Support functions)	1.Monitoring the feedback	1.Measure the orientation of the position 2.Correcting of error reading 3. Amplification of measured angles 4.Conversion of measured angle into readable signal 5. Comparing the signal with the reference points of sun position for each time interval. 6. Re-orientation to reduce the tracking errors.
		2. Energy consumption conservation	1. During non-energy production cycle (i.e. at night/ after tracking) switch to uses of other form of energy other than electrical. 2. When the tracking process reaches high tilt angles during the winter solstice, then turn to the uses of potential energy to return to the summer solstice position to conserve energy. 3. Recycling of waste energy back into the system.
		3.User`s interface	1.Data acquisition 2. Store data about the performance. 3. Display data for easy retrieval by the user. 4. Warning about system malfunction.
		4.Environmental interference/disturbance	1. Measure the potential weather conditions (wind speed, direction, rain, cloud cover) that could disturb the tracking/ damage the tracking device. 2. Compute the compensation on tracking due to the disturbance. 3. If the magnitude of weather condition overwhelms the tracking device provide the safety measures.

4. 2. BLACK BOX MODEL

From the black box diagram as illustrated in the Fig. 3, inputs, overall function and output of the process were identified as basis for the constructing the transparent box.

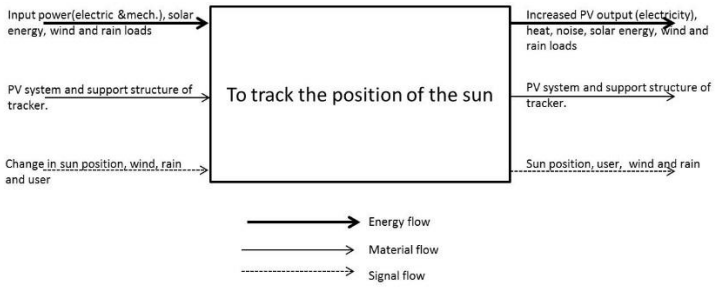


Fig. 3, solar tracking black box model

4. 2. TRANSPARENT BOX

Energy, material and signal flow is presented in diagram, *figure 6* below, the main purpose of identifying the process heuristics module (action), while maintaining a state of independence towards solution. The following are modules which later be translated into physical entities to provide actions identified; Power source (electrical, mechanical), control unit, actuation module, energy recycling module, feedback mechanism, user`s interface, positioning mechanism and environmental interference monitoring module (rain and wind protection). Among the identified heuristics module an energy recycling module which not commonly included different designs of solar tracking systems

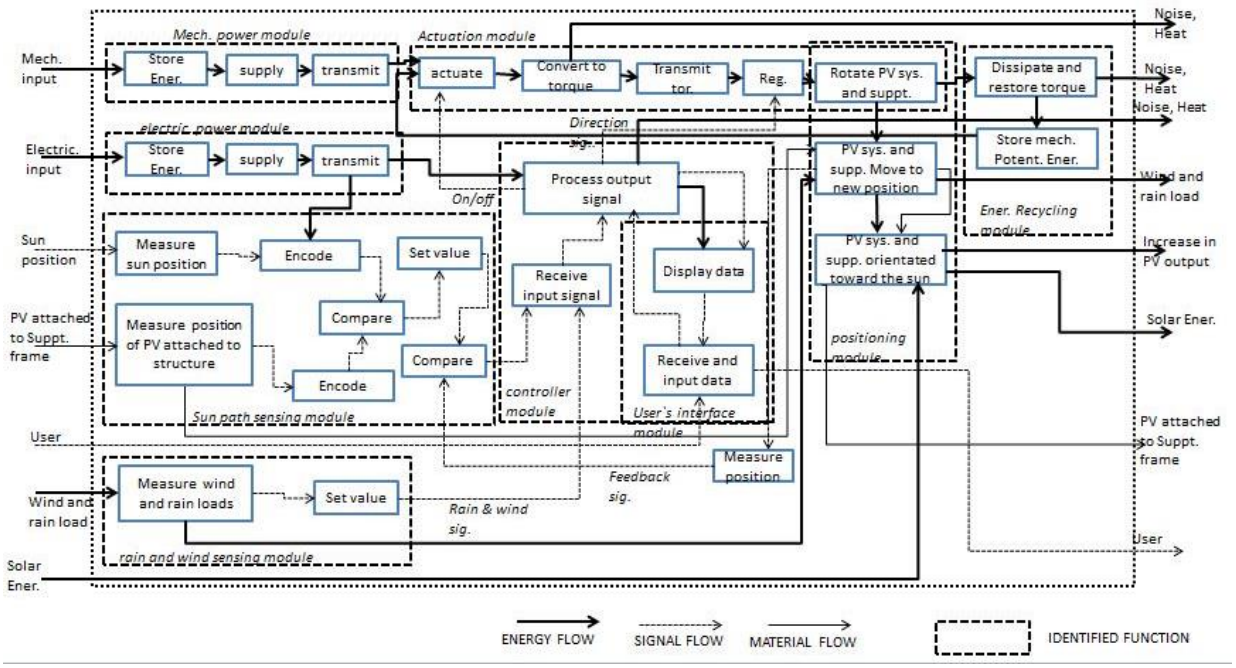


Fig. 6, Flow diagram of a solar tracking system

5. Conclusion

Through this study it can be concluded that dual tracking systems are vital for implementation to PV plants and other solar applications. Though it still faced with some challenges especially, high cost complexity in regard to design and implement irrespective of solar tracking type (i.e. passive or active). Also it was found that the current (during the period of 1997-2017) efficiency of dual tracking configuration to be about 33-43% on average basis. Furthermore active tracking systems were found to be commonly implemented for dual axis tracking than passive, though they share the same obstacle of complexity and addition expense in terms of utilisation in comparison to single axis tracking configuration. As for passive and active tracker differ with way of deploying the design trade off; the active tracking is based on accuracy while there is consumption of generated energy. As for passive the accuracy of the tracking is limited but it is more energy conservative as it uses other energy form than the generated electricity.

Lastly the Nigel Cross design model (through two first steps of process objective and function) was deployed to aid in establishment of a functional model of solar tracking system through the use of objective tree and functional analysis methods. And some of identified heuristics module developed with aid of the aforementioned methods are not common embedded in solar tracking device; that is the energy recycling module. For future; physical entities will be assigned to the identified functions to develop a tracking device concept and a prototype.

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DEVELOPMENT OF A DUAL AXIS SOLAR TRACKING CONCEPT USING MORPHOLOGICAL ANALYSIS

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***Abstract*— Solar energy is an abundant and clean resource. However, solar energy applications face the main dual challenges of low efficiency and high capital investment due to complexity in design. To mitigate low efficiencies, electro-mechanical trackers that follow the sun path to enhance reception of solar energy are used. Usually these devices are complex. The aim of this paper is to come up with a simpler and more efficient system by advancing previous work by the authors that reviewed existing dual-axis solar trackers and collated the fundamental functional objectives embodied in the most efficient ones. The fundamental functional objectives are used, in this paper, to generate different design alternatives with the aid of a morphological analysis technique. The alternatives are evaluated using a five-point Likert scale to select a simpler, more efficient, and practical dual axis photovoltaic solar tracking concept. The selected concept is to be prototyped and tested in another future investigation.**

Keywords— dual axis, solar tracking, morphological chart, conceptual design, functional objectives.

Introduction

The morphological chart is a combinatory creative design tool used to aid in generating design concepts. As a design tool, the morphological chart has found application in different multidimensional fields such as astronomy, engineering design (design of jet and rocket propulsion), social policy, etc. [1]-[2]. The power of the morphological chart lies in its bottom-up approach, whereby an overall design solution is configured from very few sub-solutions which are combined in many ways to cause an explosion of many possible solutions [3]. The most suitable one is then selected after an appropriate evaluation process.

Methodology

The conventional approach for generating a morphological chart was used in this study as discussed below.

Morphological Chart

A list of functions collated from studying the embodiment designs of the most efficient dual axis tracking devices was used. Journal, books, catalogues, fliers, internet etc. were used in an extensive search for new and existing ideas for achieving each stated function. In searching for an idea a hint search/key word or sentence for a specific function was used. For instance, for the function; **To accurately determine sun position**, search/key words such as [sun+position+sensor, etc.] were used. To guide the search process so that suitable alternatives are generated, the design checklist given in Table I was developed, complete with the set of: requirements, constraints, and functions to be met; suitable components; and evaluation criteria. The generated requirements and constraints were balanced against design requirements of an existing solar plant at Phakalane (Botswana) obtained through a field interview conducted by the author.

The above helped to generate the four main evaluation criteria of: serviceability, availability, interfacing, and reliable in cloudy weather, that were used in the five-point Likert scale developed to select the most suitable design from the morphological chart of Table II. Each alternative was scored against all the criteria. Then points scored by each alternative were aggregated. Alternatives scoring high points were ranked first choice and selected.

Alternatives evaluation

The alternatives evaluation criteria from the preceding section are based on the 3Ps (people, profit and planet) approach, as illustrated in fig. 1. This method was incorporated in this study because it assigns appropriate measures to profit, social (people) and environment (planet) aspects of a product, such that customer needs and profitability are met without causing any destruction to the environment.

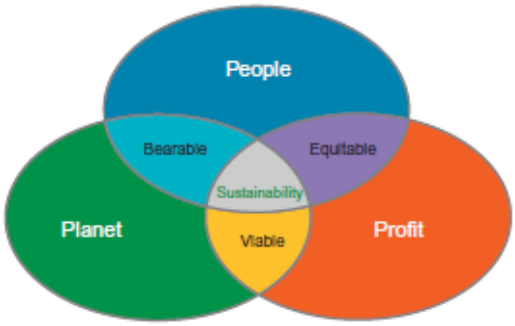


Fig.1. Venn diagram defining sustainability [4]

Lastly a concept was developed from the highest scoring selected alternatives. To further enhance the concept, supplementary components were added at the interfaces of selected components. These components include power storage devices (battery for electrical power) and air compressor to store and supply pressurized air to the pneumatic system

Some of the design measures that are normally used for evaluation of concepts are as defined below.

- *Serviceability/ maintainability*

This attribute describes the timeliness, relative cost and availability of skilled personnel in the local areas to carry out replacement and/or repair of the component.

- *Reliability*

The ability to maintain an expected functional behavior at all time and specific conditions

- *Interfacing/ compatibility*

This measure describes various ways in which a component can be applied (i.e. configurations and strategies) in order to achieve a specific function.

- *Scalability*

The ability of a component to be re-sized for a specified application.

- *Cost*

The price value of a component will affect the total cost of device hence its economic feasibility.

- *Availability*

Ease of access locally or less difficulties in sourcing the component

Table 0-1 A map of design checklist, requirements, constraints, functions, components and evaluations measures

CHECKLIST QUESTIONS	REQUIREMENTS	CONSTRAINTS	FUNCTIONS	COMPONENTS	EVALUATION MEASURES
FUNCTIONAL ASPECTS					
What defines a best performing solar tracking devices?	• Should have low tracking error. • Should consume minimum energy as possible.	• Environmental disturbance (cloudiness, wind, rain etc.). • Internal disturbance (interfacing of components). • Power consumption.	• To accurately determine sun position • To precisely calibrate positioning mechanism • To rotate the panel towards the sun using low amount of energy	• Sensors • Control unit • Support structure • Actuator • Energy recycling	• Reliable in Cloudy conditions. • Accuracy and precision of control • High response rate • Power consumption
How is the solar tracking going to be operated i.e. manually, semi-automatic automatic?	Should be fully automated.	Technical know-how of operator	• To monitor the tracking effects • To precisely calibrate positioning mechanism	•Control unit •User`s interface	Adaptability to different control techniques.
In which environmental conditions is the device going to operate?	Should be robust to extreme weather and instant changes.	Environmental conditions Cost	To monitor the tracking effects	Feedback sensors Wind, rain and cloud sensors Support structure	Reliability
Is the device profitable (i.e. what is it payback)?	Should be at an optimum profit return	Financial budget for production	All functions	All components	Cost
What level of maintenance and repairing is required?	• Should be made of components available within the locality of operation. • Should be easy for locals to repair or maintain.	Technical know-how of operator	All functions	All components	Maintainability (cost and timeliness)
What type of technology is required to operate the device?	Should not be obsolete or too advanced for local uses.	Available technological aspect	All functions	All components	Scalability Availability Assemble-ability
NON-FUNCTIONAL ASPECTS					
• What method of waste disposal will be used after product life cycle? • How will the operation of the device after wildlife, birdlife and water sources?	• Should be environmentally friendly (reduced water, wild and birdlife pollutant) • Should be made of material easy to reuse and recycle	Environmental regulations	All components		Sustainability
What size of land is available of the system?	Should cover minimal land as possible	Available land	N/A	Support structure	Land coverage ratio
What level of aesthetics is required for the system?	Should be appealing to consumers	Budget Time	N/A	All components	Versatility (different application of the device e.g. car parks, roof top etc.)

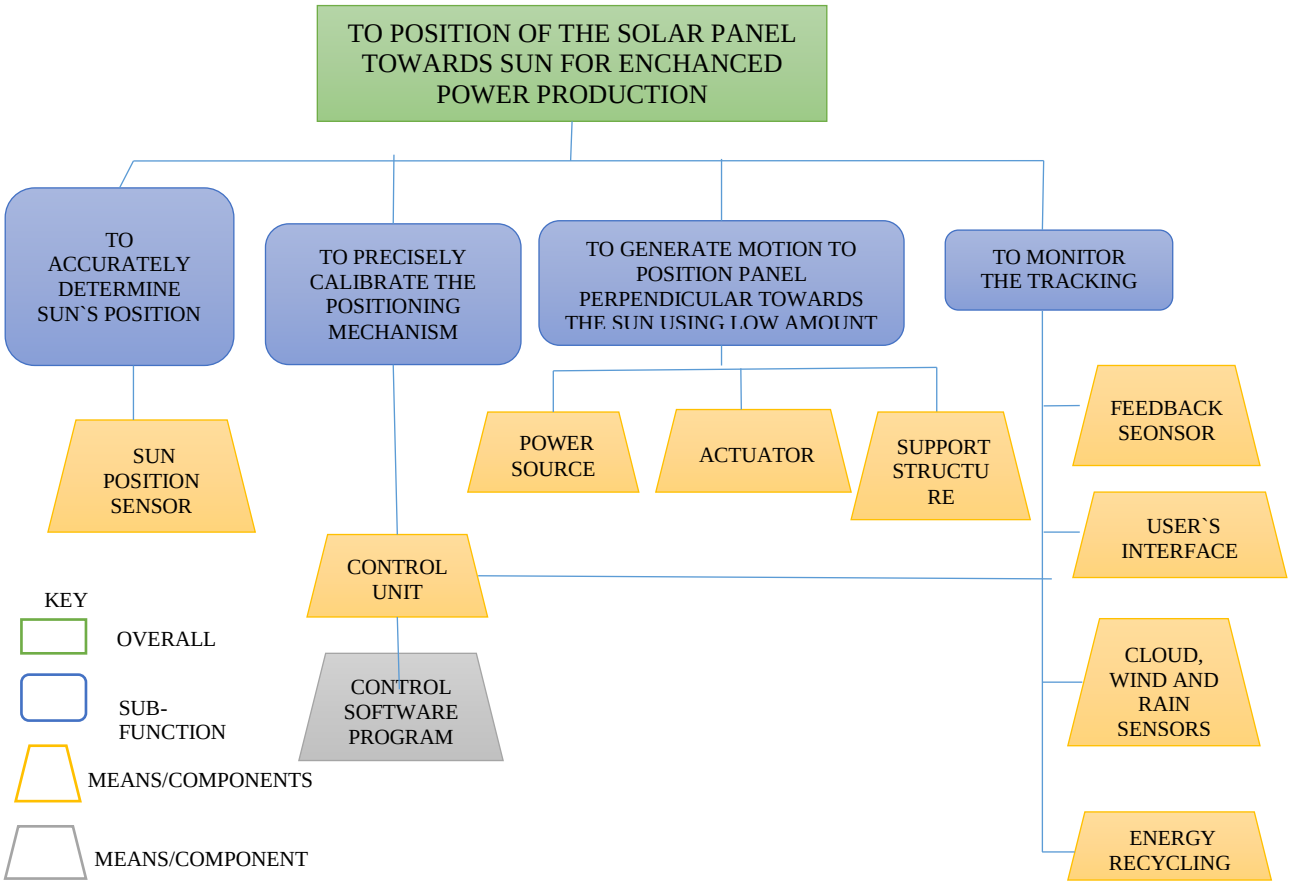


Fig.2 Function-Means Tree of a solar tracking device

MORPHOLOGICAL CHART OF DUAL AXIS SOLAR TRACKING SYSTEM

Previous work by the authors, see Mpodi et al (2019) [5], identified four main modules as very important in the design of an efficient dual tracking system. Fig.2 shows the four main functions and the appropriate means/components needed to achieve them. Sun position sensor determines the change in sun position and sends a signal to a control unit. Then control unit which is equipped with a software program then calculates the output signal and calibrates the motion generating components (i.e. power source, actuator and support structure) to start the positioning of the PV panels towards the sun. Also the control unit measures the tracking effects by monitoring the following components; energy recycling module which reduces energy consumptions by using passive energy form when necessary. Feedback sensor measures the position of the support structure and panel while referencing the desired position of the structure. User`s interface is an interaction platform between the user and the machine. Rain, cloud and wind sensors detects change in environmental conditions that are not conducive for tracking (e.g. unbearable storms).

Table II presents possible practical design alternatives (marked: ALT 1, 2…) for each main function. Equation (1) was used to compute the number of possible solutions, where M denotes the number of alternatives, for each function; N. For this work, the number of possible solutions is equal to: 4, 147, 200.

Possible combinations

$$= \prod_{i=1}^{n} M \quad (1)$$

$$= 5 \times 2 \times 3 \times 4 \times 4 \times 2 \times 5 \times 4 \times 4 \times 2 \times 3 \times 2$$

$$= 4,147,200$$

Table 0-2 Morphological chart of dual axis solar tracking

FUNCTION (FUNC.)	**ALTERNATIVES (ALT.)**				
	ALT 1	***ALT 2***	***ALT 3***	***ALT 4***	***ALT 5***
Sun position sensor (Sun Pos.)	Photo sensors	Real time clock (RTC)	Camera	Global positioning system device (GPS)	(RTC+ photo sensor)
Power source (elec.)	Mini PV panel	Grid electricity			
Power source (mech.)	Solar engines	Spring system	Gravity engines		
Control unit (CU.)	Micro controller	Personal computer (PC)	Programmable Logic controller (PLC)	Field Programmable Gate Array (FPGA)	
Actuator (Act.)	Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	Stepper motor	
User`s interface (UI.)	Keypad and LCD screen	Safety switch and LED flash light			
Support structure (SS.)	Cable mount	Parallel kinematics device (PKD)	Rotating platform (RP)	Polar mount	Counter balance mount (CBM)
Energy recycling system (ER.)	Spring system	Piezoelectric system	Spring return fluid power actuators	Energy recovery wheel (ERW)	
Feedback sensor (FS.)	Inclinometer	Accelerometer	Magnetometer	Gyroscope	
Wind sensor (WS.)	Electronic Anemometry (EA)	Air flow sensors			
Rain sensor (RS.)	Weighing precipitation gauge (WPG)	Optical rain gauge	Water Sensors		
Cloud sensor (CS.)	Optical sensor	Ceilometer			

Table 0-3 Evaluation of design alternatives

FUNC.	**CRITERIA**	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**
Sun Pos.		Optical sensor	RTC	Camera	GPS	RTC+ photo sensors
	Serviceability	4	5	1	3	4
	Availability	5	5	1	3	4
	Interfacing	4	5	1	3	3
	Reliable in cloudy weather	3	2	4	1	5
	Point scored	16	17	7	10	16
	Rank	2	1	4	3	2
Electric.		Mini PV panel	Grid			
	Serviceability	5	4			
	Availability	5	5			
	Reliability	4	3			
	Points scored	14	12			
	Rank	1	2			
Mech.		Solar engines	spring system	gravity engines		
	Serviceability	5	5	4		
	Availability	4	5	2		
	Reliability	5	2	2		
	Points scored	14	12	8		
	Rank	1	2	3		
Act.		Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	stepper motor	
	High response	3	4	2	5	
	Controllability	4	4	2	4	
	Interfacing	4	5	2	3	

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
	Minimal energy consumption	3	4	3	5	
	Compatible to support structure	5	5	3	4	
	Points scored	19	22	12	21	
	Rank	2	1	3	2	
CU.		Micro controller	PLC	FPGA	PC	
	Interfacing	5	3	2	3	
	Accuracy and Precision	3	5	4	4	
	Availability	5	4	3	5	
	Serviceability	5	4	2	2	
	Adaptability to control	4	5	5	5	
	Point scored	22	21	16	19	
	Rank	1	2	4	3	
UI.		Keypad and LCD screen	LED and switch			
	Accessibility of information	5	3			
	High alarm rate	4	4			
	Compatibility	5	4			
	Points scored	14	11			
	Rank	1	2			
SS.		Cable mount	Polar mount	Parallel kinematics devices	CBM	RP
	optimal land coverage	4	3	2	5	1
	Versatile utility	3	4	2	5	1
	Assemble-ability	5	3	1	5	3
	Optimal material consumption	5	3	1	4	2
	Robust mechanical	1	4	5	3	5
	Points scored	18	17	11	22	12
	Rank	2	3	4	1	5
ER.		Springs	Piezoelectric	Spring load cylinders	ERW	
	compatibility to control	5	3	5	1	
	ease of use	4	1	5	2	
	Maintainability	5	2	4	1	
	Availability	4	2	5	1	
	Points scored	18	8	19	5	
	Rank	2	3	1	4	
FS.		Accelerometer	Inclinometer	Magnetometer	Gyroscope	
	Interfacing	4	5	1	2	
	Cost	5	5	1	1	
	Availability	5	5	2	2	
	Points scored	14	15	4	5	
	Rank	2	1	4	3	
WS.		Electronic anemometry	Air flow sensor			
	Interfacing	4	4			
	Availability	3	5			
	Scalability	3	4			
	Cost	4	5			
	Points scored	14	18			
	Rank	2	1			
RS.		WPG	optical gauge	water sensor		
	Interfacing	1	1	5		
	Availability	2	3	5		
	Scalability	2	4	5		
	Cost	2	1	5		
	Point scored	7	9	20		
	Rank	3	2	1		
CS.		Optical sensor	Ceilometer			
	Interfacing	5	2			
	Scalability	4	3			
	Availability	5	1			
	Cost	5	1			
	Points scored	19	7			
	Rank	1	2			

DEVELOPMENT OF CONCEPT

From the evaluation, a simpler and more efficient design should embody a real time clock, and a mini-PV cell. The PV cell is used to supply power to a sensor that marks the change in sun position, and also to detect the shade due to cloud cover. The power supplied is stored in a battery to

also supply other subsystems. Equations (2) and (3) which calculate the sun azimuth (α_s) and elevation (γ_s) are programmed in a micro-controller to compute the position of the sun. In the equations, where (δ), denotes solar declination angle. It describes the angle between the equatorial plan and the line to the sun or the inclination of the earth axis to an orbit of about 23.45˚. Its value oscillates with the period of a year between 23.45˚ and -23.45˚. Whereas (φ) is Latitude coordinate of geographical location of the tracking devices. Lastly, (h) is the solar time based on the apparent angular motion of the sun across the sky.

$$\alpha_s = \sin^{-1}[\sin\delta \ \sin\varphi + \cos\delta\cos\varphi\cos h] \quad (2)$$

$$\gamma_s = \cos^{-1}\left[\frac{\sin\delta\cos\varphi - \cos\delta\sin\varphi\cos h}{\cos\alpha_s}\right] \quad (3)$$

The output of the process is used to control the direction and speed of the pneumatic actuator which is powered by fluid power system, through solar engine. The solar engine runs the air compressor which drives the pneumatic cylinder to smoothen operations as the power source generate varying power. As the orientation of PV attached to the support structure reaches the maximum azimuthal position at sunset or maximum tilt during winter season, a spring system within the pneumatic actuator is engaged to return the sunset position or the minimum tilt orientation during the summer season. In case of unfavorable weather conditions the air and rain sensors will send signals to the controller to switch the operating mode into safe mode, i.e. the tracking will stop. Table IV and fig.3 illustrate the components and working principle of the proposed concept respectively.

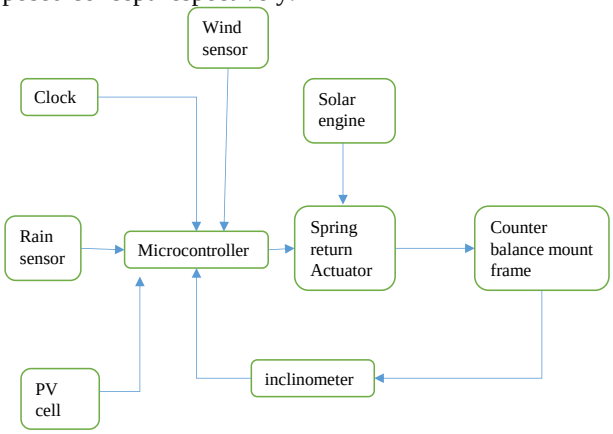


Fig.3. Solar tracker concept embodiment

Table 0-4 Diagrammatic sketch of a simple and efficient dual-axis tracker

FUNC.	ALT.				
	ALT 1	***ALT 2***	***ALT 3***	***ALT 4***	***ALT 5***
Sun Pos.	Photo sensors	RTC	Camera	GPS	RTC+ photo sensor
elec.	Mini PV panel	Grid electricity			
mech.	Solar engines	Spring system	Gravity engines		
CU.	Micro controller	PC	PLC	FPGA	
Act.	Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	Stepper motor	
UI.	Keypad and LCD screen	Safety switch and LED flash light			
SS.	Cable mount	Parallel kinematics device	RP	Polar mount	CBM
ER.	Spring system	Piezoelectric system	Spring return fluid power actuators	ERW	
FS.	Inclinometer	Accelerometer	Magnetometer	Gyroscope	
WS.	EA	Air flow sensors			
RS.	WPG	Optical rain gauge	Water Sensors		
CS.	Optical sensor	Ceilometer			

CONCLUSION

In this study the diagrammatic design of simple and more efficient solar tracking concept was developed through the use of morphological analysis. Over 4 million design ideas were found to be possible. After an evaluation process a simpler and practical concept of dual axis solar tracking system was developed. The proposed tracker is a hybrid system with passive solar power. In a future study, the concept will then be modelled, prototyped, and further investigated.

Acknowledgment

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IMPROVING PRODUCT QUALITY THROUGH A FUNCTIONAL ANALYSIS APPROACH: CASE OF DUALAXIS SOLAR TRACKER

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Abstract

Product quality determines how well a product meets the customer's requirements. One way of measuring and ensuring that the product's quality is achieved is through incorporating the functional analysis approach in the design process of the product, especially at early stage of lifecycle. A case study involving the design of a dual axis solar tracking system is used to illustrate the approach. In the study, the designed solar tracking concept was compared to existing mechanisms. The designed concept was found to be, generally, less complex than existing models.

Keywords: design, quality, complexity, solar energy, functional analysis.

1. Introduction

Since the industrial age, product development has evolved greatly from the primitive craft approach in which design and manufacturing were interlinked to the new enhanced approach in which design and construction are separate. The product development process is often achieved in six (06) steps as illustrated in Figure 1. Whereby **Strategic definition** is the identification of the need or a niche in the market, **Research** is the competitive analysis of products related to the one being developed in order to understand the dynamics of the product market and demands, **Product design and manufacturing** transforms ideas into functional objects (physical or virtual). **Production evaluation and selection** is the stage at which the choice of the engineered product is done influenced by factors such as; cost, user preference, product quality, etc. **Use and recycling of product** is the stage at which the product is put to use, encounters tear and wear, it is repaired until it reaches the end of life after which it is disassembled and some parts might be used for other purposes. Finally, **Market feedback** is the input from the market to help improve future generations [1]

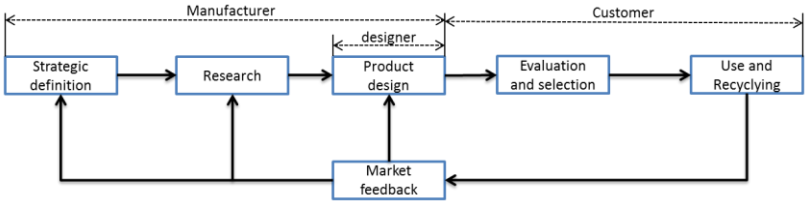


Figure 1: Product lifecycle [1]

2. Design process model

There are many design models. For instance, French's descriptive model has four stages, namely; a) analysis of problem, b) conceptual design, c) embodiment of schemes, and d) detailing [2]. Cross' model is four staged too. The four stages are; a) Exploration, b) generation, c) evaluation and d) communication [3]. So is Ullman's model consisting of; a) product planning, b) conceptual design, c) product development and d) product support [4]. The stages of all the three models above are nearly similar and apply the general framework given in Table 1. Other models comprise of Axiomatic design, the VDI model, quality loss function, and quality-function deployment, and many others.

Design stage (descriptive)	Sub-stages (prescriptive)	Relative techniques
Planning	Deriving customer's needs	Questionnaires, usability lab studies, ethnographic field studies, etc.

	Setting design objectives	Checklists, objective and key results (OKR), Specific, measurable, actionable, realistic and time-based (SMART) framework, mind maps, etc.
Generation	Functional analysis	Function-means tree, Becoming-the-flow, Converter-Operator-Transmitter-Control model (COTC) Bond graph model, etc.
	Setting technical specification	Quality function deployment, design for assembly, design for manufacture, theory for inventive problem solving (TRIZ) matrix etc.
	Generating design alternatives	Morphological analysis, brainstorming, biomimetic, design by analogy, 6-3-5, etc.
Evaluation	Testing and validation of product	Simulations, mockup, prototyping, mathematical models, miniaturized models etc.
	Product improvement	Value engineering, Failure mode effect, Fault tree analysis, design for environment, design review, Strength, weakness, opportunities and threads (SWOT) analysis, Pros-cons analysis etc.
Documentation	Detailed design	Technical drawings, designs portfolios, procurement plans etc.
	Design documenting	Design database, patents, product manuals, design report etc.

Table 1: summary of theoretical design framework

2.1 Design quality

Quality is defined as the ability of the supplier/producer to meet the specified and measurable requirements of the customers. From this definition of quality, design quality is then defined as a practice of ensuring that products developed in a process of design meet the expectation of customer (without imposing any harm to the social and natural environment of society). It is important to control and monitor quality of products in order to minimize cost, resource, time and relative environmental impact of product development.

A five-level hierarchy of design quality was proposed by reference [6]. The attributes outlined in the reference are namely; functionality, reliability, usability, maintainability, and creativity. Functionality of products is considered paramount in controlling, managing, and ensuring that high quality designs are achieved [6].

Simplicity and complexity are also concepts used to define quality of design products. Simplicity is the exact converse of complexity. Simplicity of an artifact is defined as the use of the lowest possible number of lines, shapes, components, etc. without compromising its functional requirements.

2.1.1 Functional Analysis

Functional analysis transforms customer's requirements into functional means (physical components). In the approach, the designer surveys the prospective customer's market to develop a product that is suitable for their need. Often, simpler and competitive products than existing ones are realised by this approach [7].

2.1.2 Design complexity

Design complexity is a field in design engineering which focuses on analysing and managing uncertainties of designs (i.e. process and product) due to many interwoven elements and attributes which make an object difficult to understand. Managing complexity in design is important as it reduces effort and resources used when developing products. Design complexity metrics measure a number of design aspects such as; structural complexity: (i.e. physical arrangement and interactions of constituting components), functional complexity: (i.e. number, variety, and interactions of basic and support functions), behavioural complexity: (i.e. predictability and understand-ability of product's behavioural in the field) [8].

Three complexity metrices exist. Bashir and Thompson (1999) developed a design complexity metric system that uses a functional analysis approach [9]. The devices are broken down from basic to advanced functions. This approach considers a linear relationship of functions at each level, but the number of assemblies and components in a device are neglected. Roy et al (2010)'s complexity metric method was formulated to address the demand of the device with regard to the commonality of components used to construct the device [10]. Whereby product commonality is the number of parts being used for more than one product and is measured for all product family. Keating (2000) developed a complexity metric system which is based on the number of components and their interaction in a device [11]. Table 2 gives a summary of the metrics and reasons for disregarding some and choosing one.

Reference	Description	Formula	Comments
[9]	Number of functions	$C = \sum_{j=1}^{l} F_j k_j$ Where; C =complexity L= number levels F_j = number of functions at level j K_j = weight of level j; 1,2,	Not selected because only a few of the publications reviewed in this study disclosed the functional analysis of their designs.
[10]	Demand	$C = {}^{d_i}/_{d}$ Where; d_i=demand of part variant d = total demand of product	This approach is based on the availability of product components in the market. Therefore, this method is not relevant for use in this study.
[11]	Number of components and interaction	$C = M^2 + I^2$ Where; M= Module/components I= interactions	Since most publications describe their devices in terms of assemblies, components, and their interactions, this method was found to be the most suitable for this research.

Table 2: Design complexity metric system

3 A Case study: Design and complexity evaluation of dual axis solar tracking concept

To illustrate how the functional analysis technique can be used to remove complexity and ensure that product quality is achieved at the early stages of product development of an engineered system, a design case study for the design of a dual axis solar tracking system is used. Figure 2 gives the general design framework used.

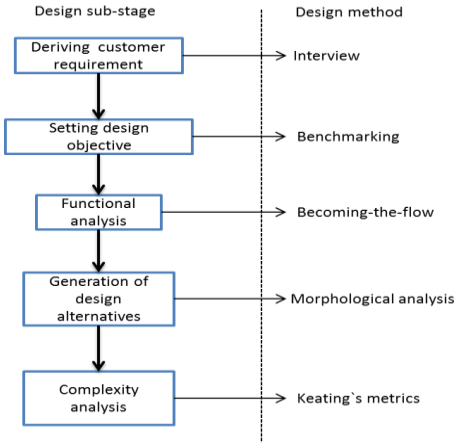


Figure 2: design approach for developing a solar tracker

3.1 Deriving customer's requirements

The requirements of a dual axis tracker were established from an interview conducted with a facility technician at the Phakalane solar plant (Botswana). This was to understand the requirements of a dual axis solar tracker from an expert. The following questions divided into two categories, namely, functional and non-functional aspects were asked in the direct interview:

Functional aspects: The following six (06) questions were asked under functional aspects

1. What defines the best performing solar tracking, in terms of its;
    a. Level of efficiency
    b. Power consumption
    c. Tracking accuracy
2. How is the solar tracking going to be operated i.e. manually, semi-automatic or automatic?
3. Under which environmental conditions is the device going to operate?
4. Is the device profitable (i.e. what is it payback)?
5. What level of maintenance and repairing is required?
6. What type of technology is required to operate the device?

Non-functional aspects: the following four (04) questions were asked under this non-functional aspect

1. What method of waste disposal will be used after product life cycle?
2. Is the 3Rs (reuse, reduce and recycle) approach embedded in the product?
3. How will the operation of the device affect wildlife, birdlife and water sources?

4. What level of aesthetics is required for the system?

The requirements described in table 3 were identified during the interview.

Design requirements	Description
Low tracking error	A highly efficient tracking is the one that can position towards the sun with relatively high accuracy, for an improved energy output.
Low energy consumption	For an economically feasible product, the tracking device should consume as little energy as possible or use a mechanism which saves energy.
Fully automated	A machine with little human interface of daily operation, but with ease of use by an operator.
Operational in Array setup (On-Grid)	The tracker should be used on national electrical grid-connected PV system.
Optimum Power output	The solar tracking device should generate enough power either equal or slightly lower than the theoretical expectation, for economical and functional viability.
Optimum Payback period	For an economically viable system there is a need that it has a lower payback period as the profit will be realised in the early period lifetime of the machine.
Environmentally Friendly	Solar energy aids in reducing pollution emission. Therefore, the device should not harm its surroundings e.g. ecological system, water sources, wildlife and birds through generation of toxic waste materials
Aesthetically appealing	Growth in the use of renewable energy technology has led to an increasing interest in many people to comprehend the technology. Therefore, the solar tracking should be aesthetically attractive to attract tourists (i.e. technological tourism)

Table 3: identified design requirement for dual axis solar tracker

3.2 Setting design objectives

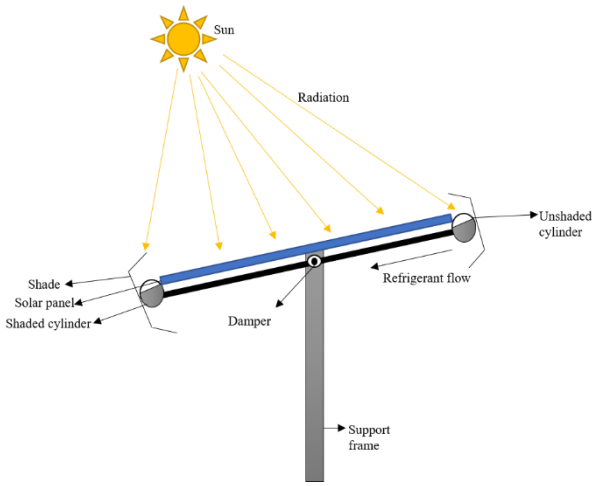


Figure 3: ZomeWorks passive solar tracker [12]

Firstly, the Universal Track Racks™ by ZomeWorks (in figure 3) was used to come up with the basic functions of a solar tracking system due to its popularity. The tracking system uses two or four *(if is dual axis)* identical cylinders on the edges of a panel frame. These contain a working thermo-fluid (normally a refrigerant). As the position of the sun changes with time, one cylinder receives more thermal power than the other. Due to this, the refrigerant expands and flows to another cylinder through a duct. From this process the function identified is the ability to detect the new position of the sun at a reference point. As the fluid accumulates in the other cylinder, there is difference in weight of the two cylinders. Since system is designed to detect imbalance through a centre pivot, then motion is generated by this effect. To avoid shock on the system, a damper is used to guide and regulate; as other components rotate towards the desired position [12]. From this process four main sub-functions can be summarised as follows;

a) To precisely determine the position of the sun.
b) To calibrate the positioning mechanism.
c) To generate the tracking motion.
d) To monitor tracking effect.

3.3 Functional analysis

Form follows functions approach was used at this stage. That is, functions establishment should be independent of geometrical state to broaden the solution space [4]. A function is a task that transforms input to output in the system [13]. Therefore, functional modelling is a framework that relates functions in a flow, processes, and the operations to a system.

Using *"to become the flow"* heuristic approach, the transparent box model was developed to identify the *"function chains"* (i.e. related tasks often performed by a single physical component). Table 4 shows a thought aid process (e.g. the retrieval questions) used in the "*becoming the flow"* approach. "*Becoming the flow"* approach is based on the flow of energy, signal and material in a system. The first step engaged in this process was to identify the inputs, outputs and following their interactions in the solar tracking system. Inputs in this study are defined as fundamental *"causes"* that ensure that the overall function of the system is performed. Output is the *"effect"* produced in the system i.e. these include; desired and undesired effects. Some of the inputs remain unchanged, while others change (i.e. they are consumed) in a process carried out by a system. These inputs were traced until they exit the system as outputs. To identify inputs and outputs the following guidelines were used, a consideration of the requirements (i.e. functional aspect of system), environmental conditions and designer's understanding of the problem.

Retrieval questions	**Description**	**Inputs identified**	**Type of input (energy, material or signal**	**Output**
Why is there a need to track the sun for PV application?	There is change in position the sun (triggers the need to measure the change in sun position).	Sun position	Signal	• Sun position • Signal for control
	To increase output of PV by tracking (PV generates electrical energy from sunlight directly)	PV system	Material	• Electrical energy • PV • Solar energy
		Solar energy	Energy	
Can PV system rotate on itself?	There is a need for support structure to provide facilitate motion and solid orientation (the support structure is coupled to the PV)	PV system coupled to the support structure	Material	• PV system + Support structure
How is automation of the system going to be achieved?	The level of interaction with human is low. That is the user only monitors the machine at time of maintenance and unforeseen operations	User	Signal	User
Is the system environmental conditions proof?	The environmental conditions such as wind, rain and cloud shade will affect the tracker	• Wind load • Rain load • Measure of wind • Measure of rain • Measure of cloud shade	• Energy (Wind and rain loads) • Signal (Measure of rain, wind and cloud shade)	• Wind load • Rain load • wind • rain • cloud shade
How is the energy going to be minimized?	This is based on choice of input energy and mechanism (there selection of mechanical energy for providing torque with recycling of waste energy and electrical energy used for power calibration devices can minimize energy)	• Mechanical Energy • Electrical Energy	Energy	Waste energy (heat and noise)

Table 4: Thought aid process applied for becoming the flow

Transparent box model of a solar tracking device is shown in figure 4. In this model, energy, material, and signal are traced from input to their relative output state. The model was used to identify function chains to achieve relevant tasks. In the stated figure the (SS.) stands for support structure, (tor.) is torque, (sys.) is system, (Ener.) is energy, (mech.) is mechanical, (elec.) is electrical, (Pow.) is power, (Enviro.) is environmental, (Pos.) is position and (Prot.) is protection [14]

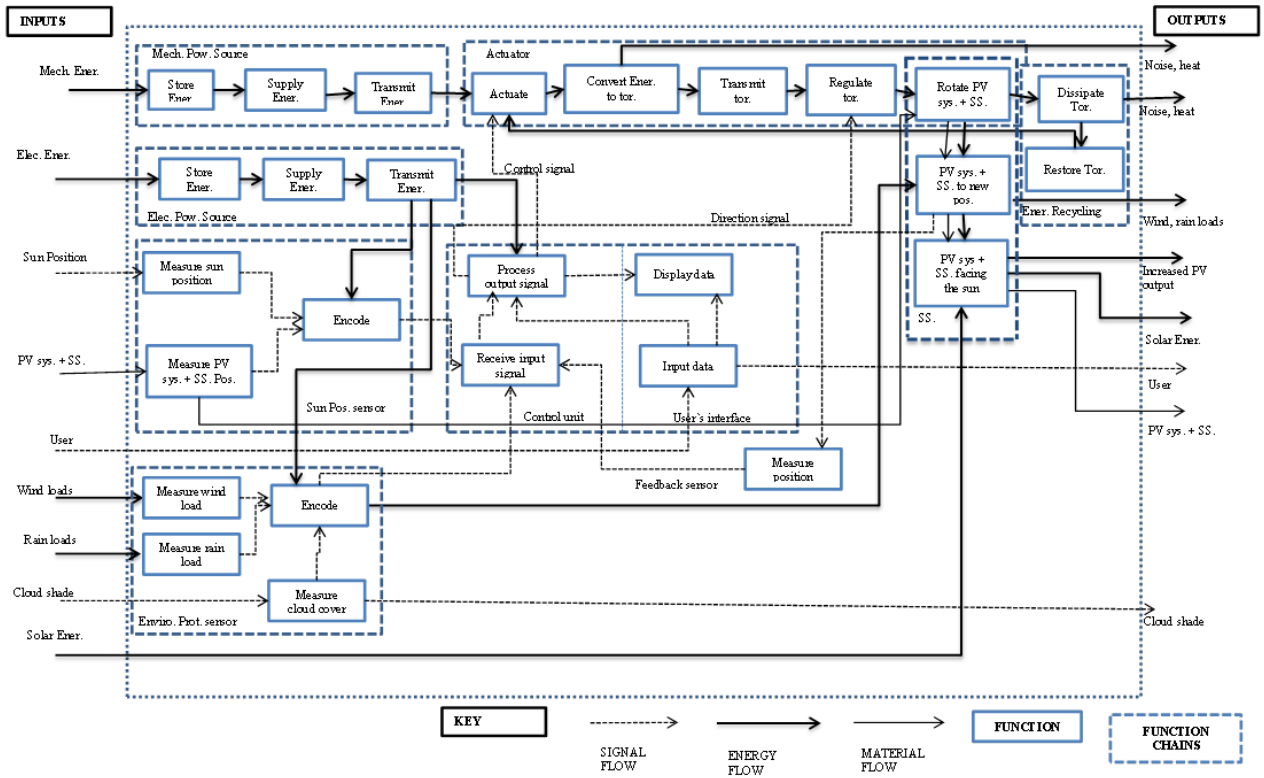


Figure 4: Transparent box model of a dual axis solar tracking [14]

3.4 Generation of design alternatives

A morphological Chart was deployed to perform this transitional process, i.e. to present design alternatives generated in this research. Firstly, the function chains identified with the aid of transparent box model were listed in the column of morphological chart (grid). Then possible alternatives (i.e. these are physical components available in market) to perform the tasks of the function chains were identified. Through brainstorming, the grid of the morphological chart was filled by noting (with text) ideated alternatives alongside their relevant function chains (i.e. on the row of the function chain). For example, two alternatives; electronic anemometry (alt 1) and airflow sensor (alt 2) were brainstormed for the function chain; wind sensor [15].

$$\text{Possible combinations} = \prod_{i=1}^{n} 0 \tag{1}$$

$$= 5 \times 2 \times 3 \times 4 \times 4 \times 2 \times 5 \times 4 \times 4 \times 2 \times 3 \times 2$$
$$= 4,147,200$$

FUNCTION CHAIN (FUNC.)	ALTERNATIVES (ALT.)				
	ALT 1	*ALT 2*	*ALT 3*	*ALT 4*	*ALT 5*
Sun position sensor (Sun Pos.)	Photo sensors	Real-time clock (RTC)	Camera	Global positioning system device (GPS)	RTC+ photo sensor (Hybrid)
Power source (elec.)	Mini PV panel	Grid electricity			
Power source (mech.)	Solar engines	Spring system	Gravity engines		
Control unit (CU.)	Micro controller	Personal computer (PC)	Programmable Logic controller (PLC)	Field Programmable Gate Array (FPGA)	
Actuator (Act.)	Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	Stepper motor	
User's interface (UI.)	Keypad and LCD screen	Safety switch and LED flashlight			
Support structure (SS.)	Cable mount	Parallel kinematics device (PKD)	Rotating platform (RP)	Polar mount	Counterbalance mount (CBM)
Energy recycling system (ER.)	Spring system	Piezoelectric system	Spring return fluid power actuators	Energy recovery wheel (ERW)	
Feedback sensor (FS.)	Inclinometer	Accelerometer	Magnetometer	Gyroscope	
Wind sensor (WS.)	Electronic Anemometry (EA)	Airflow sensors			
Rain sensor (RS.)	Weighing precipitation gauge (WPG)	Optical rain gauge	Water Sensors		
Cloud sensor (CS.)	Optical sensor	Ceilometer			

Table 5: Morphological chart present design alternative [15]

The evaluation measures formulated at the planning stage of the design process were then deployed to judge the alternatives. As a way of guiding selection of best alternatives, that will be used to develop a concept. Some of the evaluation measures, which are normally used for evaluation of concepts, are defined below:

- Serviceability/ maintainability: This attribute describes the timeliness, relative cost and availability of skilled personnel in the local areas to carry out replacement and/or repair of components.
- Reliability: the ability to maintain an expected functional behaviour at all times and under specific conditions.
- Interfacing/ compatibility: the ability of the component to be useable with different configurations and strategies to achieve the desired function.
- Scalability: can a component be easily down or up sized for a specified application.
- Cost: the price value of a single component will affect the total cost of device hence its economic feasibility.
- Availability: ease of access of a component locally or less difficulties in sourcing it.

Evaluation of alternatives was then carried after a five-point Likert scale was established. Then each alternative was scored against the evaluation measure in a relevant manner (i.e. according to

the knowledge and discretion of the designer). Points scored by each alternative were aggregated, and the alternative scoring high points were ranked as first choice (refer to tables 6 and 7) [15].

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
Sun Pos.		Photo sensor	RTC	Camera	GPS	Hybrid
	Serviceability	4	5	1	3	4
	Availability	5	4	1	3	4
	Interfacing	4	5	1	3	5
	Reliable in cloudy weather	3	2	4	1	4
	Point scored	**16**	**16**	**7**	**10**	**17**
	Rank	**2**	**2**	**4**	**3**	**1**
Electric.		Mini PV panel	Grid			
	Serviceability	5	4			
	Availability	5	5			
	Reliability	4	3			
	Points scored	**14**	**12**			
	Rank	**1**	**2**			
Mech.		Solar engines	spring system	gravity engines		
	Serviceability	5	5	4		
	Availability	4	5	2		
	Reliability	5	2	2		
	Points scored	**14**	**12**	**8**		
	Rank	**1**	**2**	**3**		
Act.		Hydraulic cylinder	Pneumatic cylinder	Motor and gearbox	stepper motor	
	High response	3	4	2	5	
	Controllability	4	4	2	4	
	Interfacing	4	5	2	3	
	Minimal energy consumption	3	4	3	5	
	Compatible to support structure	5	5	3	4	
	Points scored	**19**	**22**	**12**	**21**	
	Rank	**2**	**1**	**3**	**2**	
CU.		Microcontroller	PLC	FPGA	PC	
	Interfacing	5	3	2	3	
	Accuracy and Precision	3	5	4	4	
	Availability	5	4	3	5	
	Serviceability	5	4	2	2	
	Adaptability to control	4	5	5	5	
	Point scored	**22**	**21**	**16**	**19**	
	Rank	**1**	**2**	**4**	**3**	

Table 6: Evaluation of design alternatives for solar tracking [15]

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
UI.		Keypad and LCD screen	LED and switch			
	Accessibility of information	5	3			
	High alarm rate	4	4			
	compatibility	5	4			
	Points scored	**14**	**11**			
	Rank	**1**	**2**			
SS.		Cable mount	Polar	Parallel mech.	CBM	RP
	optimal land coverage	4	3	2	5	1
	Versatile utility	3	4	2	5	1
	Assemble-ability	5	3	1	5	3
	Optimal material consumption	5	3	1	4	2
	Robust mechanical	1	4	5	3	5
	Points scored	18	17	11	22	12
	Rank	2	3	4	1	5
ER.		Springs	Piezoelectric	Spring return fluid power actuators	ERW	
	compatibility to control	5	3	5	1	
	ease of use	4	1	5	2	
	Maintainability	5	2	4	1	
	Availability	4	2	5	1	
	Points scored	**18**	**8**	**19**	**5**	
	Rank	**2**	**3**	**1**	**4**	
FS.		Accelerometer	Inclinometer	Magnetometer	Gyroscope	
	Interfacing	4	5	1	2	
	Cost	5	5	1	1	
	Availability	5	5	2	2	
	Points scored	**14**	**15**	**4**	**5**	
	Rank	**2**	**1**	**4**	**3**	
WS.		Electronic anemometry	Airflow sensor			
	Interfacing	4	4			
	Availability	3	5			
	Scalability	3	4			
	Cost	4	5			
	Points scored	**14**	**18**			
	Rank	**2**	**1**			
RS.		Weighing gauge	optical gauge	water sensor		
	Interfacing	1	1	5		
	Availability	2	3	5		
	Scalability	2	4	5		
	Cost	2	1	5		
	Point scored	**7**	**9**	**20**		
	Rank	**3**	**2**	**1**		
CS.		Optical sensor	Ceilometer			
	Interfacing	5	2			
	Scalability	4	3			
	Availability	5	1			
	Cost	5	1			
	Points scored	**19**	**7**			
	Rank	**1**	**2**			

Table 7: Continuation of evaluation of design alternatives [15]

Lastly, a concept was developed from aggregating the best-selected alternatives. This resulted in the final design which was modelled using a SolidWorks® platform (figure 5 shows the developed concept).

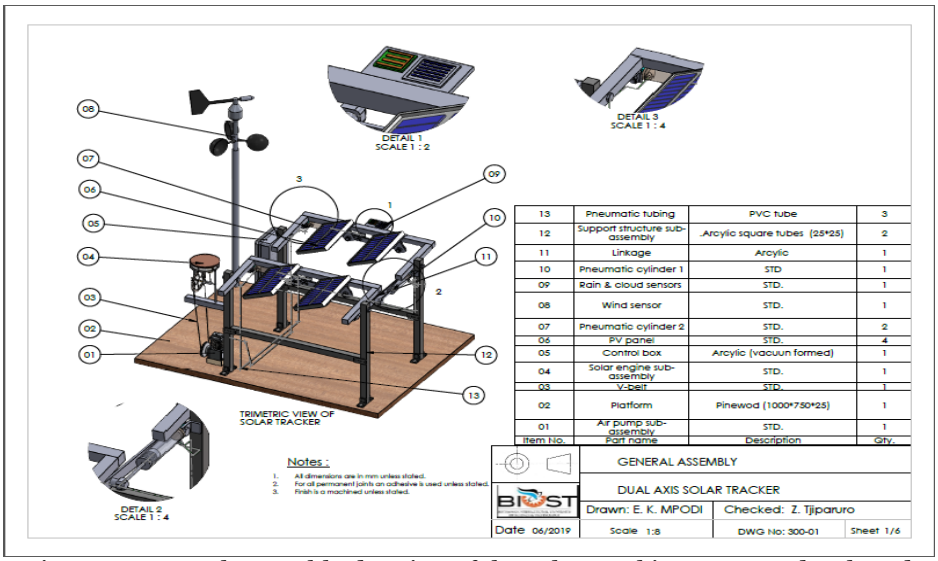


Figure 5: General assembly drawing of the solar tracking concept developed

3.5 Complexity analysis

The analysis was carried out by comparing the existing systems' design complexity with the developed concept. In the comparison, the approach used in reference [11] was adopted. This approach uses modules and interactions between the modules to compare design products. A typical Keating's model is given in Figure 6 whereby the number of components/ modules (M), and number of interactions (I), in the design are counted and the inherent complexity computed using (*Eq. (2)*).

$$C = M^2 + I^2 \tag{2}$$

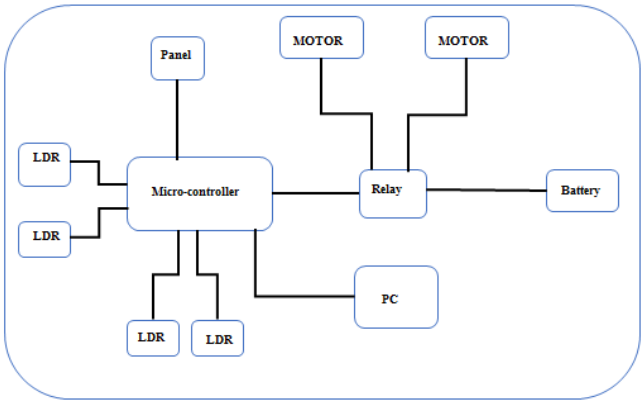


Figure 6: A block diagram showing module and interaction of system developed by Akbar et al, (2017)

Table 8 shows a complexity metrics of systems developed in the period, 1997-2017. The average complexity of these systems was found to be 221.43 in this study.

Reference	M	I	C
[16]	4	6	52
[17]	7	8	113
[18]	5	4	41
[19]	10	11	221
[20]	15	18	549
[21]	4	3	25
[22]	6	8	100
[23]	10	10	200
[24]	14	16	452
[25]	13	11	290
[26]	10	10	200
[27]	10	9	181
[28]	10	12	244
[29]	12	11	265
[30]	9	10	181
[31]	10	11	221
[32]	11	13	290
[33]	14	15	421
[34]	9	10	181
[35]	9	11	202
[36]	11	10	221
Average			221.43

Table 8: Design complexity study of existing solar trackers

Figure 7 shows a diagrammatic embodiment design of the designed system. Plotting the complexity index of the developed concept against the complexity values of the existing systems give Figure 8. The trend illustrated the graph shows a relatively constant increasing pattern at the beginning of the study period up to the year 2005-2007.Generally the system designed is more complex when compared with developed between 1997 and 2004. While from 2005 to 2011 the existing systems are more complex the concept developed in this research study. For period between 2012 and 2017 the system developed and existing system are generally equal in

complexity. The pattern was realised because of the advancement which were made to the dual axis tracking such as including weather intelligent features (wind and rain shield systems). In summary the developed system, firstly, falls within the average complexity of existing systems, and secondly, it is 10% less complex than the existing systems

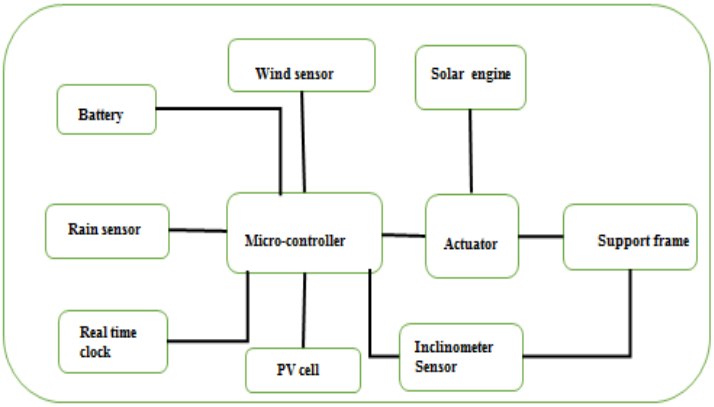


Figure 7: Embodiment diagram of a solar tracking concept developed

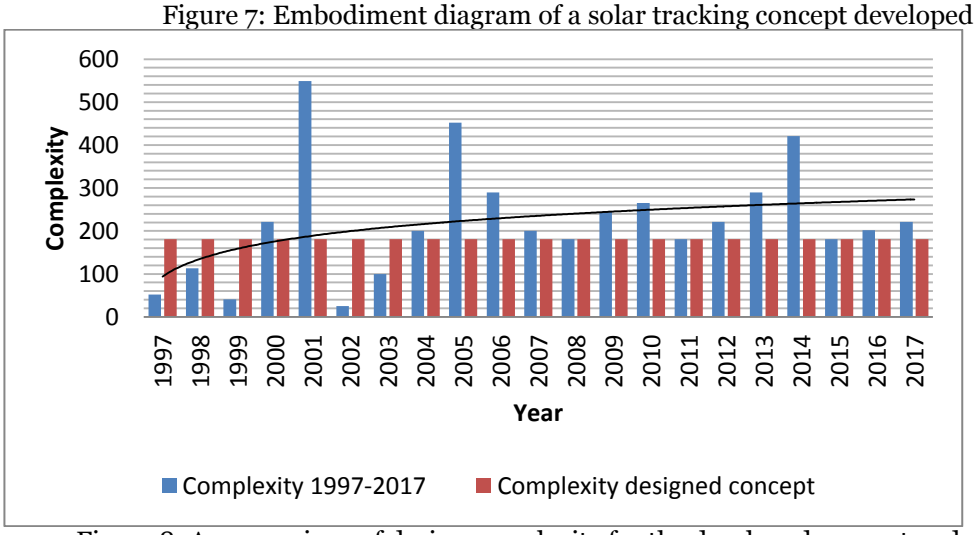


Figure 8: A comparison of design complexity for the developed concept and existing mechanisms

Conclusion

In this chapter a design of a dual axis solar tracker was used to describe a way of enhancing product's quality, during the early stage of product design. A design and complexity analysis undertaken resulted in a less complex solar tracker. The developed concept was evaluated against the existing solar tracking systems. Therefore, carrying out an analysis of complexity on system at an early stage of product design is important in improving the product functionality and simplicity factor. Consequently, this will relatively reduce the product's cost and design effort.

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Conflict of Interest

The author(s) declared no potential conflict of interest in regard to this research, authorship and/or its publication.

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