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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.

I. 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.

II. 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 were 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.

Lastly a concept was developed from the highest scoring

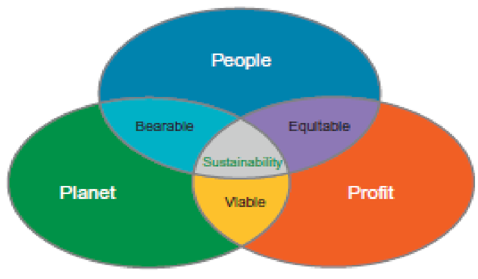

Fig. 1. Venn diagram defining sustainability [4]

selected alternatives. To further enchance the concept, supplimentary 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 pressurised air to the pneumatic system

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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

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Table I 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.)

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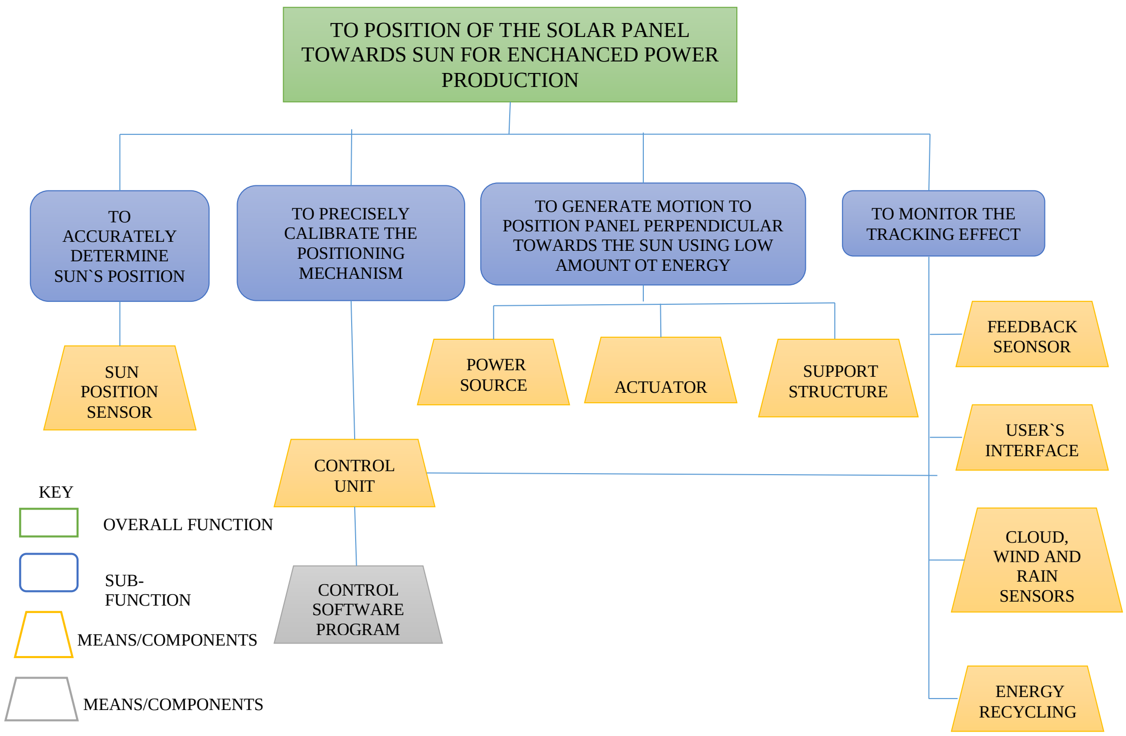

Fig. 2. Function-Means Tree of a solar tracking device

III. 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 II 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			

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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 III 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	
	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	

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FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
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			

FUNC.	CRITERIA	Alt 1	Alt 2	Alt 3	Alt 4	Alt 5
	Availability	5	1			
	Cost	5	1			
	Points scored	19	7			
	Rank	1	2			

IV. 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.

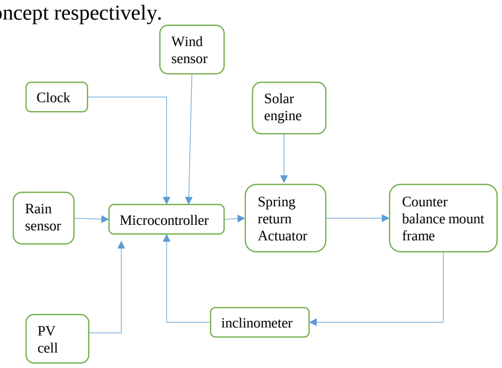

Fig. 3. Solar tracker concept embodiment

Table IV 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	Piezoelectr ic system	Spring return fluid power actuators	ERW	
FS.	Inclinomet er	Accelerom eter	Magneto meter	Gyrosco pe	
WS.	EA	Air flow sensors			
RS.	WPG	Optical rain gauge	Water Sensors		
CS.	Optical sensor	Ceilometer			

V. 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.

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