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Embodiment Design of an Azimuth-Altitude Solar Tracker

M. Culman, O. Lengerke

***Abstract*—**To provide an efficient solar generation system, the embodiment design of a two axis solar tracker for an array of photovoltaic (PV) panels destiny to supply the power demand on off-the-grid areas was developed. Photovoltaic cells have high costs in relation to t low efficiency; and while a lot of research and investment has been made to increases its efficiency a few points, there is a profitable solution that increases by 30-40% the annual power production: two axis solar trackers. A solar tracker is a device that supports a load in a perpendicular position toward the sun during daylight. Mounted on solar trackers, the solar panels remain perpendicular to the incoming sunlight at day and seasons so the maximum amount of energy is outputted. Through a preview research done it was justified why the generation of solar energy through photovoltaic panels mounted on dual axis structures is an attractive solution to bring electricity to remote off-the-grid areas. The work results are the embodiment design of an azimuth-altitude solar tracker to guide an array of photovoltaic panels based on a specific design methodology. The designed solar tracker is mounted on a pedestal that uses two slewing drives, with a nominal torque of 1950 Nm, to move a solar array that provides 3720 W from 12 PV panels.

***Keywords*—**Azimuth-altitude sun tracker, dual-axis solar tracker, photovoltaic system, solar energy, stand-alone power system.

I. Introduction

ACCORDING to economy, energy consumption increase always forces the rise of fossil [1] fuels prices in the world market. Facing an unsustainable situation, where energy demand will grow faster than new fossil fuels findings [2] and with the increasing environmental pollution, it is the academy duty to study renewable energy and energy efficiency.

Regarding solar energy, human kind has understood that it is a significant, clean, natural and renewable source of energy [3]. The sun is a giant nuclear fusion reactor and the energy supplied is equivalent to 27,000 times the total amount of energy currently produced by all other sources [4]. For reasons of atmospheric phenomena related to reflection, scattering and radiation absorption, the final amount of energy reaching the surface is much lower as it passes through the atmosphere-but not because of this, it is less significant-. This large solar radiation portion can be converted into heat or directly into electricity using different technologies; in solar collectors it is absorbed to heat water, air or any fluid, and in solar cells through photovoltaic processes to convert it into electricity.

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With photovoltaic (PV) panels we face high costs in relation to its low efficiency. However, certainly in the future this problem will be eliminated [3]. The present situation is that while a lot of research and investment has been made to try to increase the efficiency of photovoltaic cells on a few points, there is an available solution that produces an increase from 30% to 40% of the power generated nowadays: the dual axis trackers [5]. Solar panels trackers remain perpendicular panels to incoming sunlight during the day and seasons, they must have some degree of accuracy, return the panel to its original position at the end of the day and maintain their activity during cloudy periods [6]. Being compared with higher efficiency solar panels, they are relatively cheap [3], so, they are the investment a customer would definitely make to improve their photovoltaic system.

The aim of this work was to make the embodiment design of a solar tracker, whose purpose is to increase the power generated by the PV panels mounted on the structure. The stand-alone solar power system was dimensioned to supply the energy demand of a mobile computer lab which is located on a remote area and it is not connected to the national grid in Colombia.

II. Dual Axis Solar Tracker Design

In this section the development of the selected design is shown as the best option for the particular application of the mobile computer lab. The first methodology step was to assess the lab energy demand, and the second one was to review the different structures of dual-axis solar trackers. Then, the design criteria and their relevance to the particular application were defined, and these different design options were evaluated to obtain the most appropriate solar tracker design. Finally, the design calculations for the drawn structure are presented.

A mobile computer lab is an itinerant space where children of rural schools can have access to computers, internet plus other advantages of virtual education. It is mobile because this way it can be in many rural places where the existence of a built computer classroom is not possible. Due to it is necessary to go to remote areas that have a bad electricity service, a limited electricity service or are not connected to the grid, this infrastructure required an autonomous energy system to power the devices and offer a comfortable stay to kids (i.e. air conditioner in a closed space). Then as a first step of the design process, the total energy consumption of the mobile computer classroom was quantified in 38,580 Wh per day.

A. Review of Solar Trackers

In the literature, it can be found different ways of classifying which lead to two labels in general: active tracking (electric) and passive tracking (mechanical) [7], those in correspondence with the categorization made.

The passive tracker is the one that does not require power system to track [8]. Its working principle is the thermal expansion of a compressed gas fluid (e.g. freon) or memory metal alloy [8]. This passive tracker constitutes a reliable system that needs low maintenance. However, it has a low accuracy as the temperature varies from day to day and the system cannot consider this variable. Cloudy days are also a problem, as the sun appears and disappears it causes the gas in the liquid or alloy to expand and contract itself, resulting in the structure erratic movement [9]. Compared with active tracking, the passive tracker is less complex but has a lower efficiency, only about 23% [10]. Furthermore, it does not work at low temperatures [7].

Evidences have shown that the passive tracking has the same performance as electrical tracking methods. But despite passive systems are effective and less expensive; they have not been widely accepted by consumers [7].

With active tracking system power is consumed, therefore, power consumption by the tracking process should be less than the one obtained during the day [8]. By using different instrumentation, position adjustment is performed by sensors that detect when radiation does not influence perpendicularly to the panel, correcting itself by means of motors, gears and / or other solar-powered mechanical configurations. It is the most accurate method of tracking, especially for devices with optical concentrators; however, conventional photovoltaic panels may have an error margin up to 10% [11].

B. Review of Different Types of Two Axis Trackers Designs

There are three basic types of solar trackers regarding its structure and tracking points.

The elevation (altitude) and azimuth tracker mounted on a pedestal, which is used as a central support structure; movement is made by means of a gearbox that positions the cell array along a vertical axis (the change in the azimuth angle) and along a horizontal axis (the change in the elevation angle). An advantage of this configuration is its simplicity of installation since there can be drilled only a hole to then insert the pedestal and fill with concrete. On the contrary, the structure has a weak point, the wind shifts entirely to gear transmission as torque, so the gears must have large capacity [12].

The following configuration corresponds to Roll-tilt central torque tube tracker. On this, the wind loads on the drive components is considerably reduced; but it requires mechanisms and rotary bearings. Obtaining the necessary rigidity along the roll axis (shared axis) may need a large piece of horizontal support. It also requires multiple aligned bases, complicating installation. The roll axis is commonly located in North-South direction, since it minimizes the shading effect of adjacent modules along the axis [12].

Square frame Roll-tilt trackers with solar modules are oscillated between the top and bottom frame. Finally, the two axis tracker configuration on a turntable provides a lower profile and reduces wind load, so drive components and rather small media are used. But it has a more complex installation process [12].

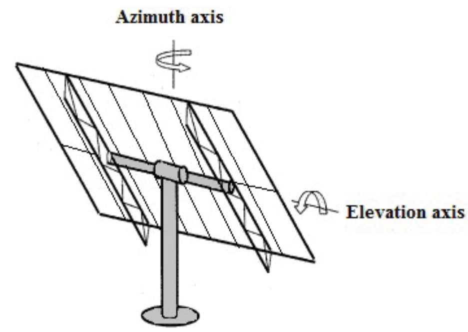


Fig. 1 Azimuth-altitude solar tracker mounted on a pedestal [12]

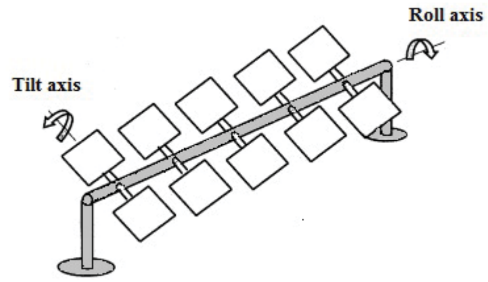


Fig. 2 Roll-tilt solar tracker using a central torque tube [12]

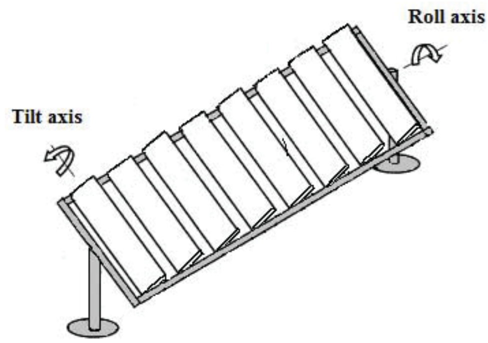


Fig. 3 Roll-tilt solar tracker using a square frame [12]

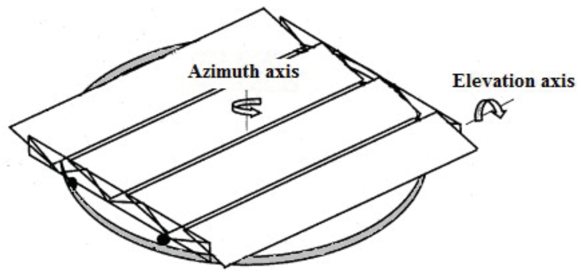


Fig. 4 Two-axis tracker on a turntable [12]

C. Mechanical Design Selection

Design methodology focused on selecting the best scheme for the solar tracker according to some design options and their evaluation according to selected design criteria. The design aspects to be considered are the different options in terms of tracking accuracy, mechanical structures, first movement actuators and second movement drives for dual-axis trackers. These options were evaluated according to operation efficiency criteria, installation area, load capacity, simple design, compliance function and manufacture ease.

A comparison was made between the characteristics selected for evaluating them as evaluation criteria (Table I), the number 1 means that the characteristic of is more important and the number 0 means the opposite. According to total number of ones in line, it is assigned a percentage to each feature to then recognize the hierarchy of these as evaluation criteria.

Continuing now with the assessment of different possibilities, through the assessment made from -1, 0 and 1 among the available options and design criteria (each one with an assigned weight), it was obtained the scoring matrix (Table II) where the design aspects were taken from, to be applied to the dual axis solar tracker. The rating carried out to each option is derived from the information collected and the particular installation needs. As noted, the options were not qualified in all the criteria set, as not applying to be assessed regarding the six characteristics. The highest scored options in every aspect constitute the solar tracker design.

TABLE I
ASSESSMENT CRITERIA FOR EVALUATING THE BEST SOLUTION

Characteristics	Operation efficiency	Installation area	Loading capacity	Design simplicity	Function compliance	Manufacture ease	**Total**	**Weight (%)**
Operation efficiency		1	1	1	1	0	4	25.00
Installation area	1		0	1	0	0	2	12.50
Loading capacity	0	1		0	1	1	3	18.75
Design simplicity	1	0	0		0	1	2	12.50
Function compliance	0	0	1	1		1	3	18.75
Manufacture ease	0	0	1	1	0		2	12.50

TABLE II
BEST DESIGN DECISION MATRIX

Design aspects		**Characteristics**						**Total points**
		Operation efficiency	Installation area	Loading capacity	Design simplicity	Function compliance	Manufacture ease	
Tracking accuracy	Passive tracker	0			1	0	1	6.25
	Active tracker	1			1	1	0	14.06
Two axis tracker design	Azimuth-altitude solar tracker mounted on a pedestal		1	-1	1		1	4.69
	Roll-tilt solar tracker using a central torque tube		-1	0	1		1	3.13
	Roll-tilt solar tracker using a square frame		-1	0	1		1	3.13
	Two-axis tracker on a turntable		-1	1	-1		1	1.56
First rotation electric driver	Worm drive		1	1	1		1	14.06
	Swivel head gear		1	0	1		1	9.38
	Reducer and drive sprocket on vertical axis		0	1	0		0	4.69
	Crown-wheel and pinion		-1	1	0		0	1.56
Second rotation electric driver	Linear actuator		1	0	1		1	9.38
	Crown-wheel and pinion		0	1	0		-1	1.56
	Worm drive		1	1	1		1	14.06

To finally combine energy dimensioning result and the conditions that the photovoltaic system can have in a rural area, it was the procedure to make an initial estimate of the number of panels, regardless of supply issues (reliability on cloudy days, battery bank, sensibility, etc.). Using:

$$Number\ of\ \text{panels} = \frac{E_{daily}}{h_{sp} * W_{panel} * \eta_s} \tag{1}$$

where E_{daily} is the energy that the installation consumes daily, h_{sp} is the number of hours per day at an average irradiation of 1,000 W/m^{2}hours, W_{panel} is the power delivered by the PV panel and η_s is the efficiency of the fixed or motional photovoltaic system.

The first calculation parameter indicates that a photovoltaic system average efficiency is 70%, given regulator efficiency, investors, batteries, etc. The second parameter is based on maps of sunshine in Colombia, Santander specifically, which identified that the average annual solar peak is 5.5 hours [13]. According to a polycrystalline panel characteristics ReneSola Virtus II, to standard test conditions (STC Standard Test Conditions - Air Mass AM1.5, Irradiance 1000W / m2, Cell Temperature 25°C), the output power is 310 W [14]. It was found that the photovoltaic system should have 32 panels, regardless the energy gain that would have the system mounted on the solar tracker. To ensure flexibility in the trackers installation, it was determined that the array of panels should be greater than one, so that the number of panels should not be grouped into a single set.

D.CAD Design

This section describes the basic calculations made in terms of mechanical structure, this one dimensioned from the primary calculation of electricity demand from a computer room and different environmental conditions. From an initial design that fulfils the above references, the following two design considerations were the wind load and operating torque. Coming through continuous iterations to a final structure with materials and preliminarily selected drives.

The next step was thinking of drive structure, in other words, the fit between fixed parts, moving parts and device operation regarding the worm drive (slew drive). In terms of the first freedom degree, its configuration was made according to Fig. 7. For the second freedom degree, the most appropriate process was the creation a drive basis that would keep it upright and concentric to a base for supporting the framework of ensemble panels as shown in Fig. 8.

Material selection was based on information from trackers in development process and solar trackers at market level. It was found that all structures are built in carbon steel or steel alloys because they have good mechanical properties and lower prices. Since trackers are always exposed to ambient conditions, the corrosion factor is a vital criterion when selecting materials. Moreover, to reduce the risk of corrosion reaction and some problems as regards of thermal expansion in the structure, it is a good decision to have all the made of the same material [15]. Following these indications and the choice made by [16] for building the solar tracker with AISI 6150 alloy steel.

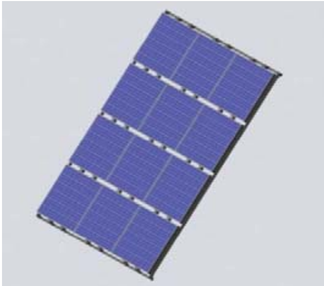


Fig. 5 Array of twelve PV panels on support structure, view 1

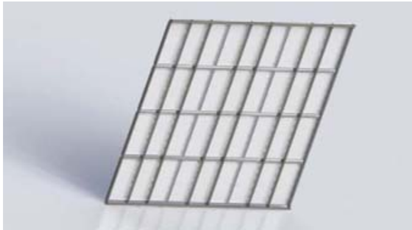


Fig. 6 Array of twelve PV panels on support structure, view 2

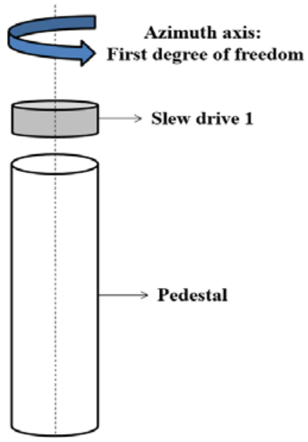


Fig. 7 Drive adaptation for the first degree of freedom

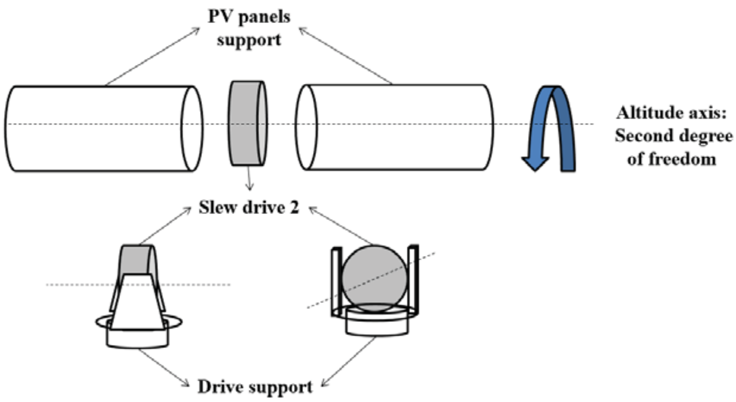


Fig. 8 Drive adaptation for the second degree of freedom

With features such as high torque, low rotation speed output and small set, height and diameter, slew drives have great advantages when generating rotational movement of heavy loads [17]. Through information collected, the selection was based on the products presented by the German company IMO in a Slew Drive comprehensive catalogue. Among the final design parameters taken into account [15], certain requirements were taken to ensure the solar tracker robustness.

The first two calculated from the design were frontal and side wind force on the structure, and the torque by the panel assembly weight.

TABLE III
FINAL DESIGN PARAMETERS

Condition	Value	Reference
Mass settlement panels and its support (kg)	553.1	Calculated
Critical follower operating condition	Fix upright panels	Calculated
	Front and side wind directions	[14]
Service factor fa for general mechanical applications.	1.25	[16]
Axial load to resist (kN)	116	[14]
Radial load to resist (kN)	40	[14]
Wind speed to resist(km/h)	140	[14]

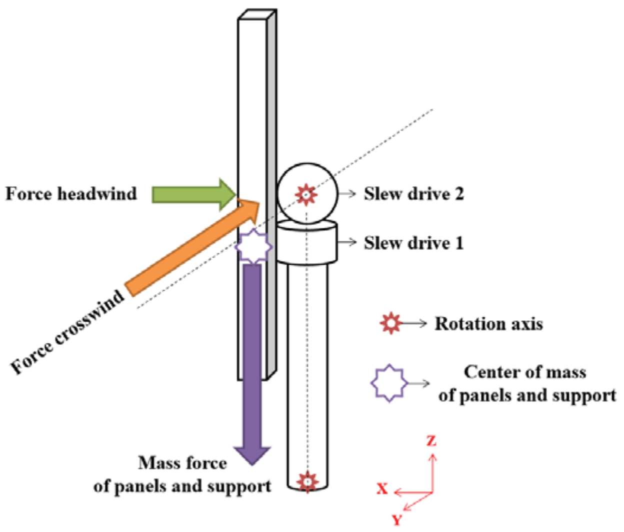


Fig. 9 Force diagram on the solar tracker

Since it is very difficult to simulate wind [16], there are many approaches, for this design it was implemented the expression described in [18]:

$$F_{wind} = A*C_d*V_{wind}^2*\rho_{wind}*0.5 \quad (2)$$

where A is the object area facing the wind, C_d is the resistance drag coefficient, which is 1 for panels, V_{wind} is the wind speed and ρ_{wind} is the air density, which is 1185 at 25°C and 1 atmosphere.

- Headwind force: $F_{front\ wind} = 132.034\ lb_f$
- Crosswind force: $F_{Side\ wind} = 3.821\ lb_f$

The torque represents the vector product with the force application (Regarding the point at which the moment is taken) by the force vector, in that order. A force moment with respect to a specific point, leads to know to what extent it exists capacity in a force or forces system to change the status of body rotation about an axis passing through the point, that is, the ability the drive must have to cause panel movement. It is defined as:

$$\tau = F \times r \quad (3)$$

where F is the force and r is the radius to rotation axis.

The first freedom degree torque is not significant since the structure weight is parallel to the axis of rotation.

Torque to the second degree of freedom:

$$\tau_2 = 2083.33\ lb_f\,.ft$$

For drive selection, there was the must to compute the forces on the spindles in radial forces, axial forces and tilting moments. The ones above finally represent the Slew Drive capacity. In terms of axial load (Fax), all the rolling elements are loaded in the same direction. In the case of radial loads (Frad), a segment of the rolling elements receives the load. In the case of overturning moment load (Mk), a segment of one side and a segment on the opposite side, receive the load. Commonly, a combination of loads and tilting moments occur during the drive [17].

TABLE IV
DESIGN FORCES FOR THE SOLAR TRACKER

Forces on the first rotation axis	
Axial forces: $F_{axial1} = 29885.6\ lb_f$	$F_{axial} = F_{axial\,design} + F_{panels,\ support,\,drive\,1}$
Radial forces: $F_{radial1} = 9128.21\ lb_f$	$F_{radial} = F_{radial\,design} + F_{radial\,wind}$
Forces on the second rotation axis	
Axial Forces: $F_{axial2} = 26081.6\ lb_f$	$F_{axial} = F_{axial\,design} + F_{axial\,wind}$
Radial forces: $F_{radial2} = 12691.5\ lb_f$	$F_{radial} = F_{radial\,design} + F_{radial\ panels,\,support}$

There were not considered tilting moments for any of the two rotation axis, as these are related to the load inertia around the rotation- its rotation speed-and this is not a major factor in solar tracking applications. It is considered that the torque is more critical than system inertia due to the high gear relation these systems use [13]. It was then defined that the solar tracker must count with two slew drives (reference WD-H 0146 / 3-00020 of the company IMO), whose characteristics are given in Table V.

TABLE V
WORM DRIVE (SLEW DRIVE) FEATURES [16]

Module	m	[mm]	3
Number of starts of the worm		[-]	1
Gear ratio	i	[-]	68
Máximum torque	$M_{d\ max}$	[lb.ft]	2,957
Nominal torque	$M_{d\ nom}$	[lb.ft]	1,438
Static load rating, radial	$C_{0\ rad}$	[lb X 1000]	101
Static load rating, axial	$C_{0\ ax}$	[lb X 1000]	271
Dynamic load rating, radial	C_{rad}	[lb X 1000]	38
Dynamic load rating, axial	C_{ax}	[lb X 1000]	44
Weight		[lb]	139
Output speed	n	[rpm]	3

To conclude the solar tracker embodiment design, there were some corrections on pedestal size diameter and frame support base for PV panels. The final version is shown in Figs. 10 and 11.

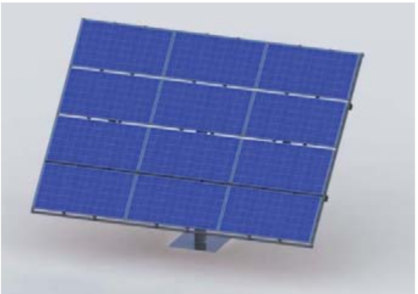


Fig. 10 Final design of the two axis solar tracker

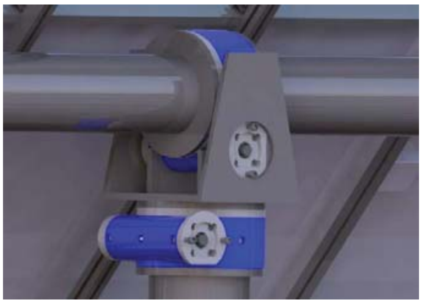


Fig. 11 Details of the drives in the final two axis solar tracker

E. Kinematics

Structure kinematics solution is essential when solving dynamics. With MATLAB software support, it was first solved the solar tracker position to different rotation degrees of both first and second freedom degree, to then generate trajectories that resemble the structure on the daily solar tracking movement.

In Fig. 12, the structure initial position is observed with zero degrees of rotation.

The pedestal (B) corresponds to the base of the fan plus the height of the first drive, which corresponds to the red line. The first "link" (L1) is the distance from the rotation axis 2, which is located in the second drive centre and corresponds to the blue line. As a second "link" (L2) is considered the panels distance to the frame that corresponds to the green line. To finally draw the set of panels in relation to the height that has its basis as the black line (P).

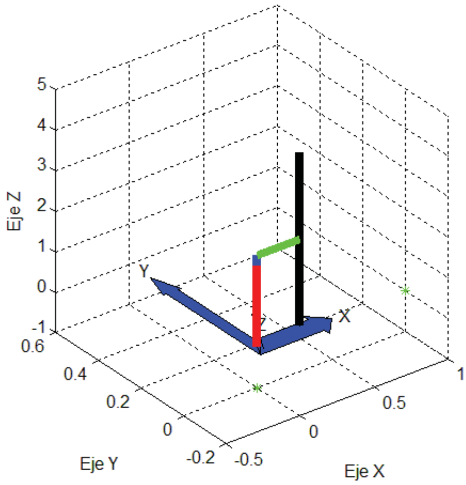


Fig. 12 3D solar tracker simplified MATLAB image

Forward kinematics using homogeneous transformation matrices

Rotations secession and translations that link the solar tracker structure:

1. Translating the $\boldsymbol{z}_i$ over a distance B,
2. $\boldsymbol{z}_i$ rotation about the angle axis θ_1,
3. Translation along one $\boldsymbol{z}_i$ distance L_1,
4. y_i rotation about the axis θ_2 angle + 90 °,
5. Translation along one $\boldsymbol{z}_i$ distance L_2.

$$^{0}\boldsymbol{A}_1 = \boldsymbol{S}_0\ \boldsymbol{T}(0,0,B)$$
$$^{1}\boldsymbol{A}_2 = {}^{0}\boldsymbol{A}_1\ \boldsymbol{T}(\boldsymbol{z},\theta_1)\ \boldsymbol{T}(0,0,L_1)$$
$$^{2}\boldsymbol{A}_3 = {}^{1}\boldsymbol{A}_2\ \boldsymbol{T}(\boldsymbol{y},-\theta_2+90°)\ \boldsymbol{T}(0,0,L_2)$$

Kinematic chain of the solar tracker:

$$^{0}\boldsymbol{A}_3 = \boldsymbol{S}_0\ \boldsymbol{T}(0,0,B)\boldsymbol{T}(\boldsymbol{z},\theta_1)\boldsymbol{T}(0,0,L_1)\boldsymbol{T}(\boldsymbol{y},-\theta_2+90°)\ \boldsymbol{T}(0,0,L_2)$$

F. Dynamics

The solid rigid body dynamics of the solar tracker is denoted as:

$$M(q)\ddot{q}+C(q,\ \dot{q})+G(q)+F(\dot{q})=T(u) \qquad (4)$$

where M represents the inertial terms, C represents the centripetal and coriolis forces, G represents gravity and F friction. T represents the torque generated by the engine, which is one of its voltage functions.

The solar tracker is a highly coupled system. The mass matrix is not diagonal as regards of most configurations, this means that the torque applied by one of the engines will result in all the joints movement. Centripetal and Coriolis forces are proportional to the product of the squared speed product, which means they are very important terms when the tracker movement is at high speeds.

Regarding the following information, the dynamic was resolved through MATLAB SimMechanics tool, where it was proved that drives have the ability to move the structure.

To assess each of the differential equation parameters described above, it is necessary to know two-axis solar tracker:

Lengths of the base and the links:

$$B = 1.934\ m \quad L_1 = 0.2575\ m \quad L_2 = 0.28551\ m$$

The masses of the links:

$$m_1 = 49.23\ kg \quad m_2 = 1677.34\ kg$$

Each link mass centres and inertia tensors obtained in the mass centre of each link.

When checking the correct actuators selection, the Slew Drive WD-H 0146/3-00020 working speed was taken as an input variable, according to the manufacturer, this one works to 3 rpm in what would be 18 degrees per second deg / s. Through simulation blocks, it was generated an angular position as speed signal integral and angular acceleration, as derived from the speed signal. The input signals are shown on Figs. 13 and 14.

Speed signals were created arbitrarily, the only value taken into account was the speed actuator output.

As a result of the structure character, it is generated a torque that should give each drive to move it according to the input signals. As shown in Fig. 15, the torque on the first drive is not as critical as the torque on the second drive, so that the design was not the first measured value. It then shows that the defendants torques are within the drive limit, the nominal torque is 1950 Nm and the maximum torque is 4009 Nm.

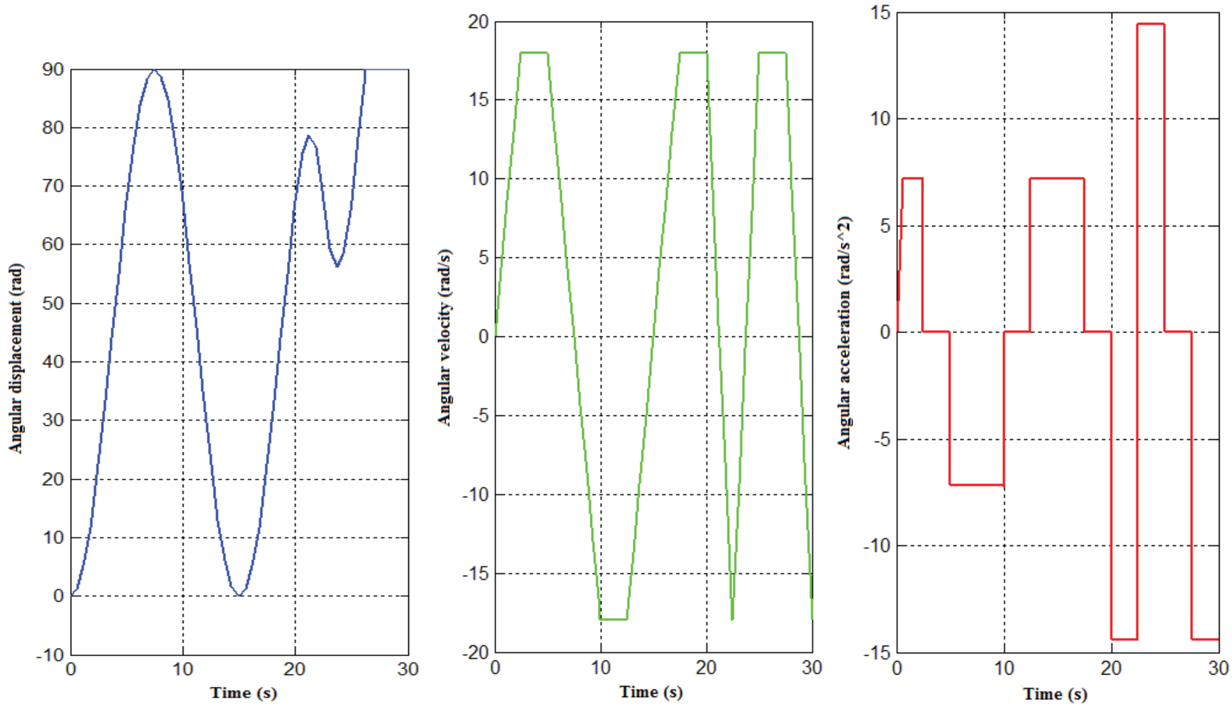
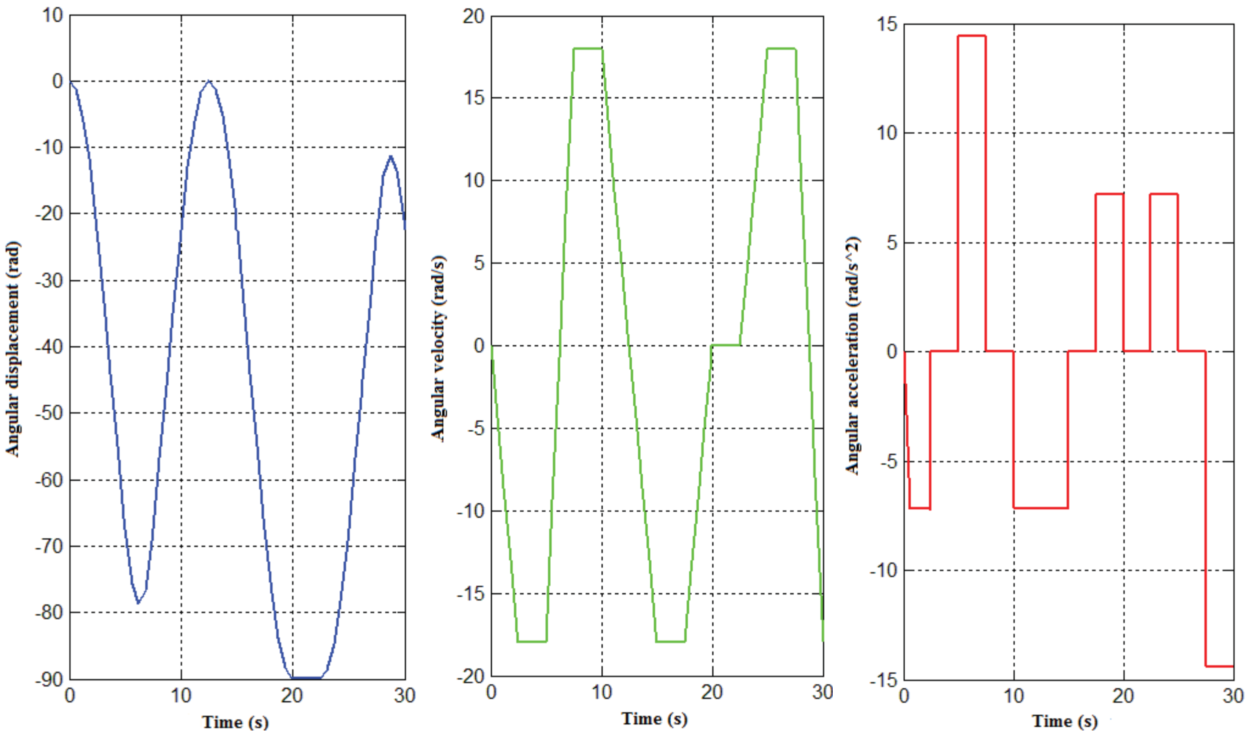


Fig. 13 Input signals on Slew Drive 1: (a) angular displacement, (b) angular velocity and (c) angular acceleration

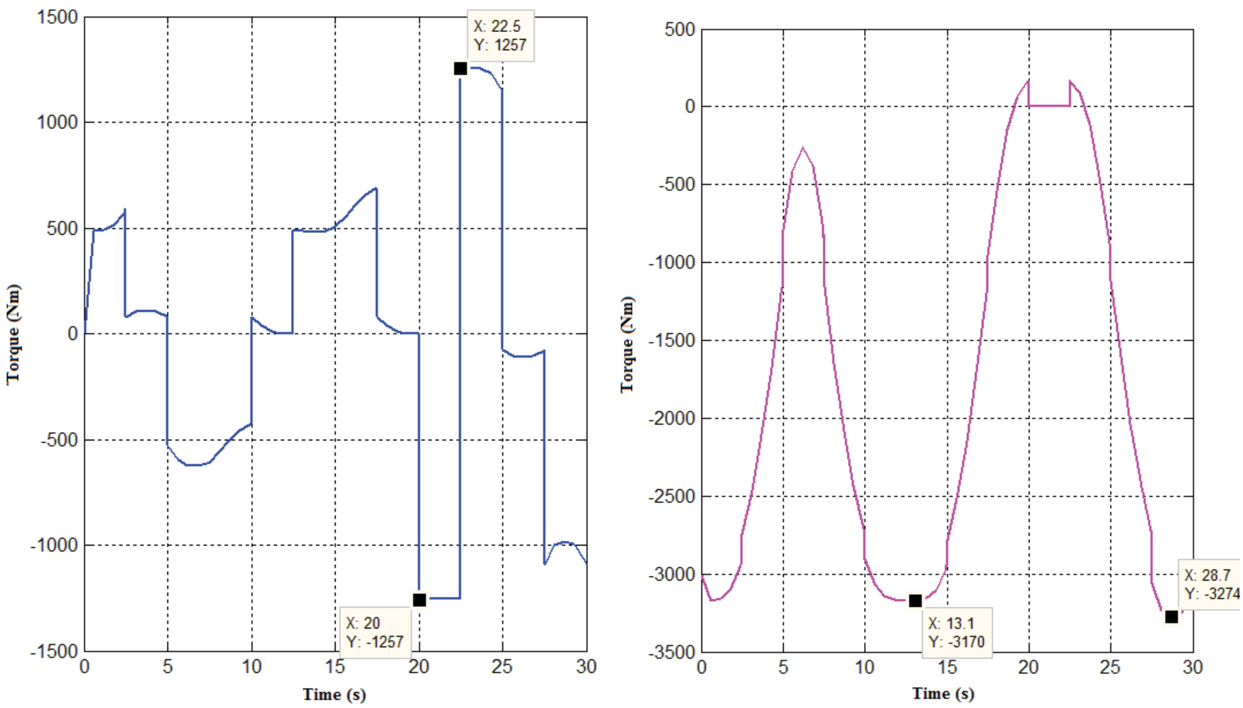
III. Conclusions

As the product of the performed work, it was achieved the embodiment design of a small solar tracker, ideal to be installed in further inaccessible areas. One of the design goals was to reach a model with the ability to meet the demands of a mobile computer lab that does not represent a complicated structure in a building process, nor a large-scale dimension since simplicity and space are challenges for alternative energy systems. It should be noted that this is an initial idea that emerges from two criteria, the calculated energy demand and the selection of the most appropriate structure, this one as a literature review result on trackers, both commercial level and research level. Thus, in a design process, it is the first step to an optimal solution for improving the system energy efficiency.



(a) (b) (c)

Fig. 14 Input signals on Slew Drive 2: (a) angular displacement, (b) angular velocity and (c) angular acceleration



(a) (b)

Fig. 15 Computed torques on: (a) slew drive 1 and (b) slew drive 2

Through the established methodology and the information considered, it was carried out an exercise that can be replicated not only in a simple design but also as a mechatronic one that goes beyond engineering. As a vital element in its implementation, this approach requires having the largest amount of documents to be able to consider, weigh and rate different solutions to the problem; an issue that requires time and objectivity. Moreover, it also demands for the ability of recognizing a significant, pure document that truly contributes and has the authority to do so. The available software resources were decisive when achieving the objectives. Furthermore, the integration process that design and simulation programs currently offer, provokes that every day studies and generation of solutions, can have more virtual details, establishing more elaborated schemes that enable faster processes and reliable designs. Using SolidWorks and MATLAB was an essential strategy for this procedure.

The achieved results evidence the necessity to research on local studies of climatic variables that help renewable energy projects. There can be found interesting projects worldwide, even with contradictory conclusions in the solar trackers implementation. It is popularly accepted that dual axis trackers are not needed in the areas of Ecuador due to stable weather conditions; however, that does not characterize all regions over Ecuador. The presence of different -valleys reliefs, rivers, mountains, plains- that draw the physical map and climate variations in Colombia makes it possible to research on it.

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