Independent Study Report

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Tracking Options for a Domestic Concentrated Solar Power Unit

Contents

1. Introduction

The purpose of tracking is to maximize the irradiance (energy per unit time per unit area) on a solar collector for the longest duration during the day. Particularly, when the sun's rays are not normal to the collector surface or aperture, a significant fraction of the collectable energy is lost, depending on the angle between the sun's rays and the collector surface. In sections 2 and 3, we will derive the exact quantitative relationships to look at the angular dependence of irradiance on a solar collector. Then, we will look at the various an axial mode in which tracking is possible in order to minimize the derived angle in the previous section. In the final sections, we will select a particular tracking mode and come up with a basic design of a mechanical solar tracker.

2. Solar Angles

The position of the sun at any time during the day can be described by two angles, namely the solar altitude angle α which is the angle between the sun's rays and the horizontal plane, and the azimuth angle a_s which is defined as the angle between the south axis and the horizontal projection of the line joining the site in consideration and the sun. It is taken to be positive westwards. The two angles are depicted in the figure below. In addition, we also define the solar zenith angle z which is given by the angle between the site to sun line and the vertical at the site location:

$$z = 90 - \alpha \qquad (1)$$

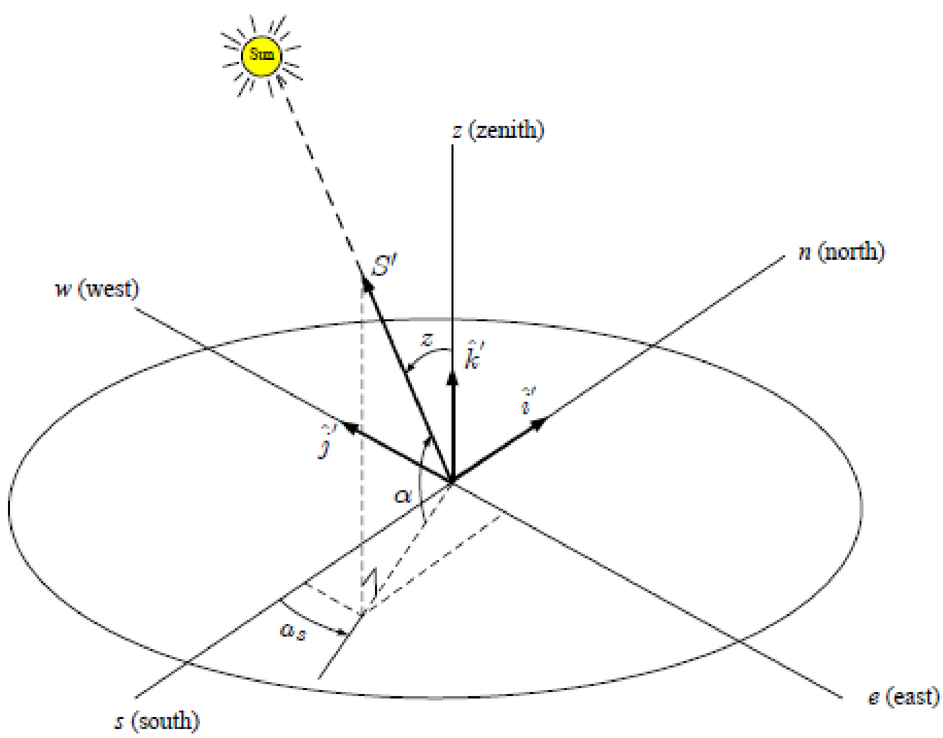


Figure 1 A depiction of the solar angles α,a_s and z with respect to S' – the vector along sun's central ray (Padilla)

3. Fundamental Angles

The solar angles are not fundamental. The information we usually have about any point where tracking is required is in the form of its location and the time of day and year. This information can be expressed in the form of three fundamental angles: the hour angle(h_s), the latitude (L) and the declination angle (δ).

The hour angle h_s is based on the fact that 24 hours correspond to sun's rotation of 360 degrees around the earth, which means it moves 15^o in one hour. The hour angle is defined as,

$$h_s=15(t_s - 12) \qquad (2)$$

where t_s is the solar time in hours. It is related to the local time by the following expression:

$$t_s = t + EOT + (l_{st} - l_{local})\ 4\ \text{min/degree} \qquad (3)$$

where l_{st} is the standard time meridian, l_{local} is the local time meridian and EOT is the equation of time – an empirical expression that accounts for the rotational speed of the earth.

The latitude angle L is the angle between the line from the centre of the earth to site and the equatorial plane. It is taken to be positive north of equator and shown in the following figure.

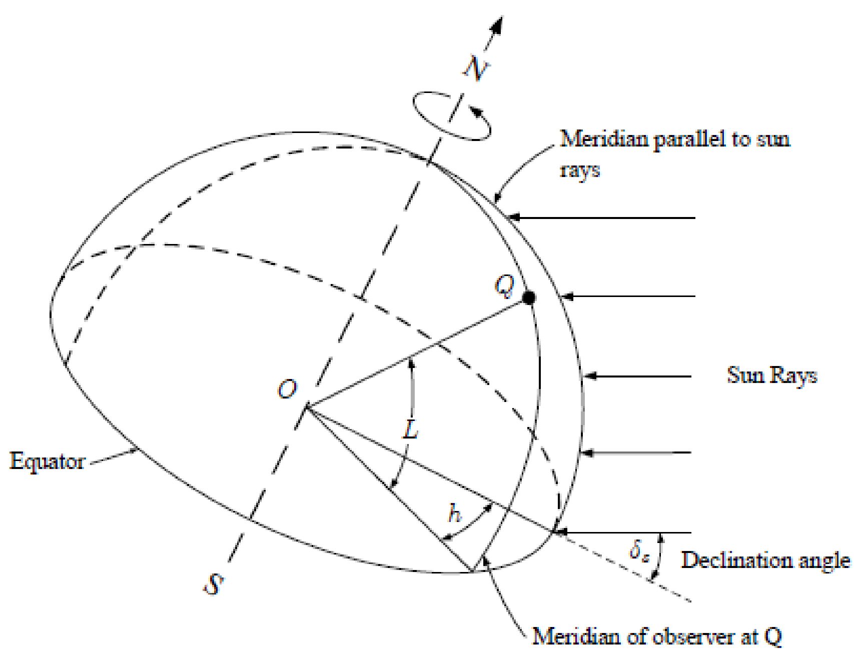


Figure 2. The latitude angle L. Source: (Padilla)

The solar declination angle δ is the angle between the earth-sun line (through their centers) and the plane through the equator. It varies throughout the year and is given by the following function, in terms of n, the number of the day of the year:

$$\delta = 23.45 \sin\left(\frac{360}{365}(284+n)\right) \qquad (4)$$

It is shown in the figure below where this angle has the value of 23.45 degrees on June 21.

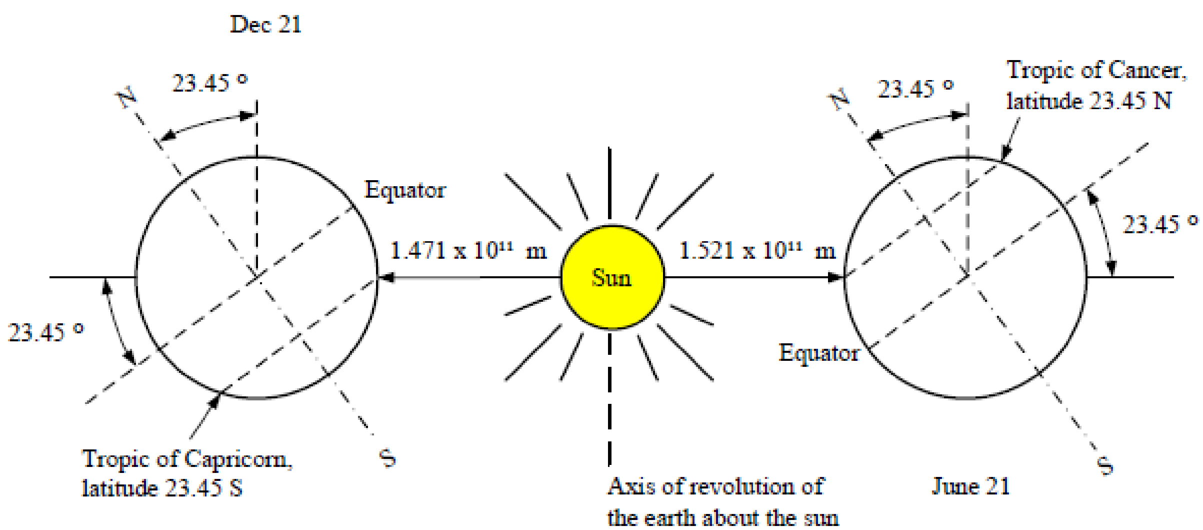
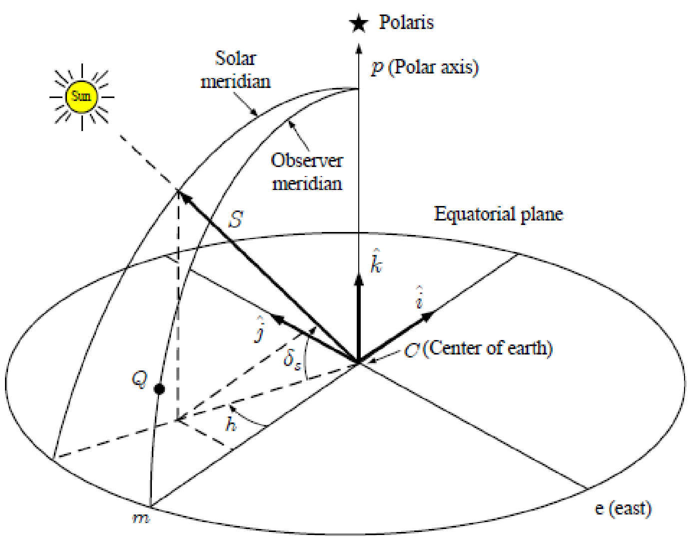


Figure 3 Solar declination angle. Source (Padilla)



Now, we need to express the solar angles discussed in the previous section, α and a_a , in terms of the three fundamental angles h_s ,L and δ. For that purpose, the figure on the left shows the fundamental angles with respect to the vector S along the sun's rays' direction.

Figure 4

It can be seen that the two coordinate systems are related by a rotation around the east axis and a translation along the earth's radius. The transformation matrix is given by,

$$\begin{vmatrix} S'_i \\ S'_j \\ S'_k \end{vmatrix} = \begin{vmatrix} \sin L & 0 & \cos L \\ 0 & 1 & 0 \\ -\cos L & 0 & \sin L \end{vmatrix} \cdot \begin{vmatrix} S_i \\ S_j \\ S_k \end{vmatrix} \qquad (5)$$

When the expressions for S and S' are substituted in the above matrices and multiplication is carried out, we obtain the following equations that essentially give the solar angles as functions of the fundamental angles:

$\cos\alpha.\cos a_s = \cos \delta.\ \text{Sin}\ L.\ \cos h_s - \sin \delta.\cos L$ (6)

$\cos \alpha.\ \sin a_s = \cos \delta.\sin h_s$ (7)

$\sin\alpha = \cos \delta.\cos L.\ \cos h_s + \sin\delta.\sin L$ (8)

Once, we have the expressions for the solar angles in terms of fundamental angles, we are in a position to look at the dependence of irradiation on these variables. For a parabolic trough solar collector, the beam radiation on the aperture area, R, is given by:

$R = (r_t H - r_d D)\cos i \,/ \sin \alpha$ (9)

Here, r_t and r_d are empirical functions of hour angle, H is the average daily total irradiation and D is the average daily diffuse radiation. Their values can be obtained either by ground measurement or satellite data (Padilla). Now, we know that the irradiation depends on the cosine of the incident angle. This means, our main task in tracking is to minimize this cosine. We'll now look at the principles of a single axis tracker to see how this can be achieved.

4. Single Axis tracking

In this kind of tracking, a drive system rotates the collector about an axis of rotation until the sun central ray and the aperture normal area are coplanar. We define ρ as the tracking angle by which the system needs rotation at any point. We now require the incident angle I and the tracking angle ρ in terms of the collector orientation and the solar angles. For this purpose, we transform the coordinate system such that the tracking axis is one of the three orthogonal axes. The second axis is parallel to the surface of the earth and the third is orthogonal to the first two as shown below.

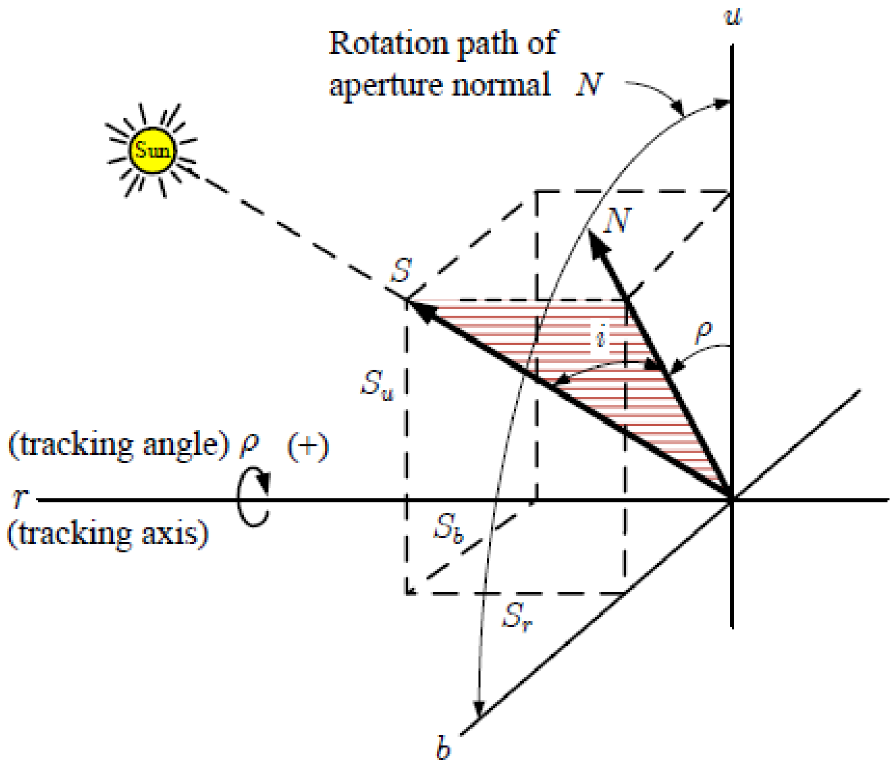


Figure 5 Single axis tracking coordinates (Padilla)

Transformation to our desired coordinate system is achieved by the following matrix

$$\begin{vmatrix} S_r \\ S_b \\ S_u \end{vmatrix} = \begin{vmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} S'_i \\ S'_j \\ S'_k \end{vmatrix} \qquad (10)$$

γ is the angle between the tracking axis and the collector normal. Substitution in (10) and solving gives us the incident angle as well as the tracking angle in terms of the solar angles.

$$\cos i = \sqrt{1 - \cos^2 \alpha \cos^2(\gamma - a_s)} \quad \textbf{(11)}$$

$$tan\rho = \frac{\sin(\gamma - a_s)}{tan\alpha} \quad \textbf{(12)}$$

The last two equations give essentially the parameters that we need to control in any tracking system.

5. Tracking Modes

There are two modes of tracking depending on the direction of rotation of the trough:

1) North-South tracking. In this case, the tracking axis is along the east-west direction
2) East-West tracking. In this mode, the tracking axis is along the north-south direction.

The two modes are illustrated in the following diagram

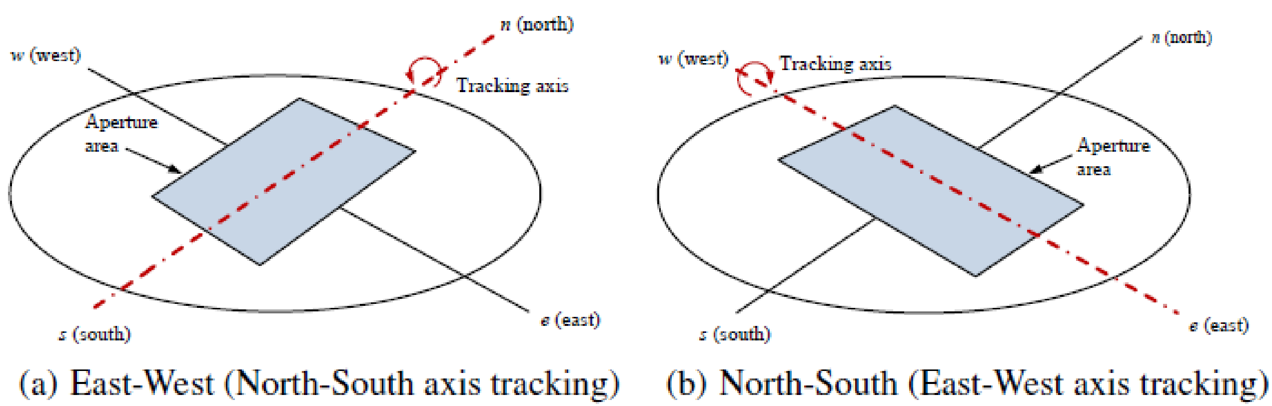


Figure 6 Tracking modes (Padilla)

6. The case for East-West (North South axis) tracking

Literature survey (Stine and Geyer) shows that there are certain advantages of single axis East-West tracking besides cost saving. The difference between a day's solar radiation energy captured by a N/S oriented single axis tracking aperture and that by a two-axis tracking is only about 2%. For E/W tracking, the only time the aperture points directly toward the sun is at noon. Such a system is only about 73% efficient. On the other hand, if the demand for energy in a specific design is higher in the summer than in the winter, then N/S axis tracking is preferable. The following are results from an experimented conducted by a graduate student at the University of Florida (Padilla) showing the effect of tracking axis on the solar radiation collected by a parabolic trough at a certain location. The results clearly show that the average monthly radiation collected in the case of N/S axis tracking is higher as compared to E/W axis.

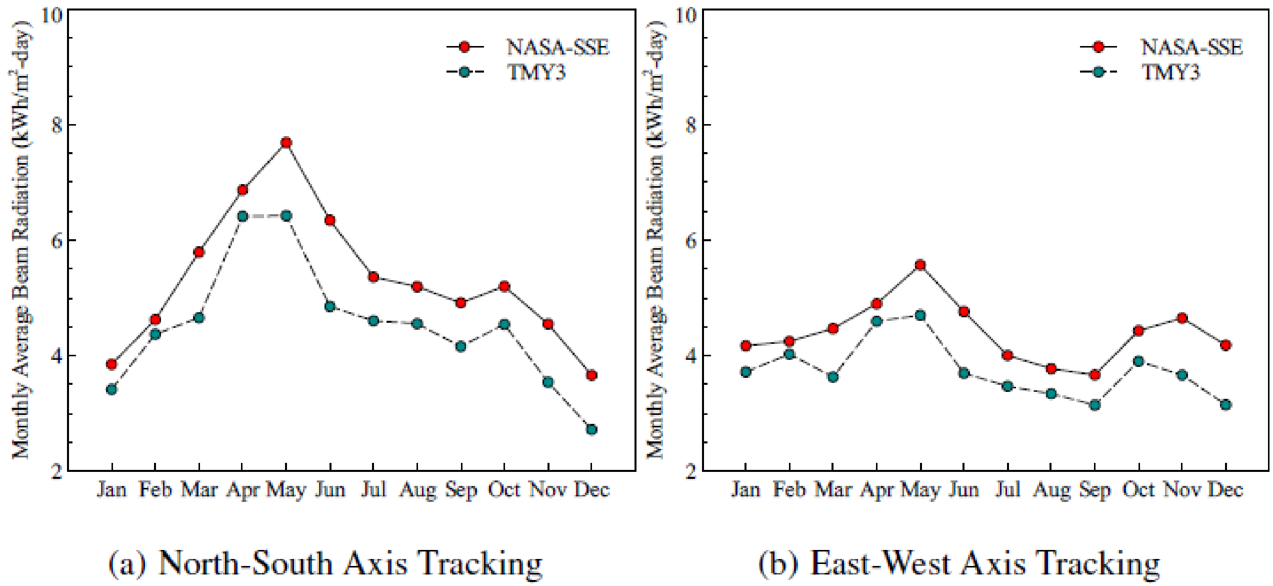


Figure 7 Effect of tracking axis on monthly average beam radiation. Source (Padilla)

7. Tracking Methods

Various methods of tracking that employ either electrical or mechanical means were studied. The findings are summarized in the following table.

Electrical Methods	Mechanical Methods
Consist of a photo-sensor, a control unit, a motor and an actuator.	Sensors use physical differential processes based on pressure or temperature and extend to a positioning mechanism such as hydraulic cylinders, bimetallic strips etc.
Consume power from the system and therefore decrease the efficiency (Mousazadeh, Keyhani and Javadi)	Difficult to calibrate and not as accurate as electrical.
Tracking is real-time and accurate	Cheaper and do not consume energy from the system.

8. Proposed Design

It was eventually decided to settle on a purely mechanical gear-based tracking system that will require minimum cost and energy and yet able to provide a rotation of the trough at the rate of approximately 10 – 15 degrees per hour.

The basic idea is depicted in the following figures. The parabolic trough will be resting on a curved support that will have its ends attached to two more taught strings that will in turn be partially mounted on a rotating rod. The rotation of the rod will cause the strings to wrap around it further, resulting in a change in their extended length which will result in the motion of the trough supports and hence the trough itself. The key is controlling the rotation of the rod which will be accomplished by a clock work mechanism involving gears.

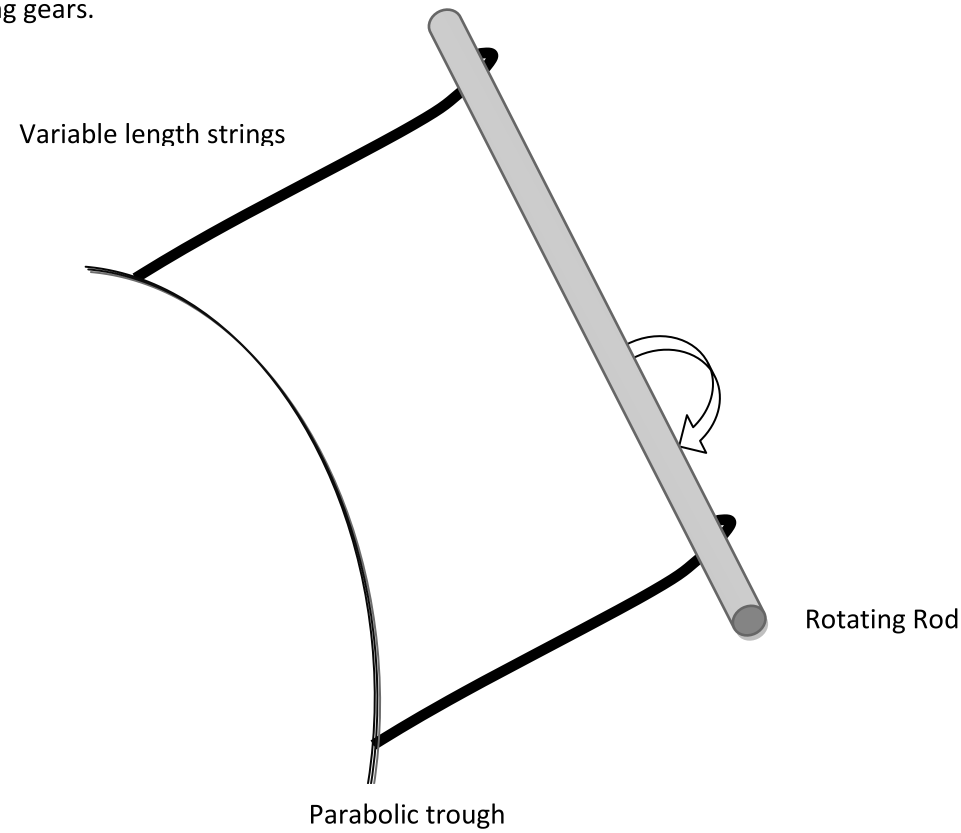


Figure 8 Rotational support of the trough

The rotation of the rod is controlled by mechanical gears which in turn respond to the motion of a falling weight. It is the rate of the fall of this weight that is to be predetermined and preset such that the desired rate of rotation (roughly 15^{o}/hour) is achieved. The main parameters to be incorporated in such a design are to be derived out of the following mechanics problem. The quantity following each arrow is to be determined by the one preceding it.

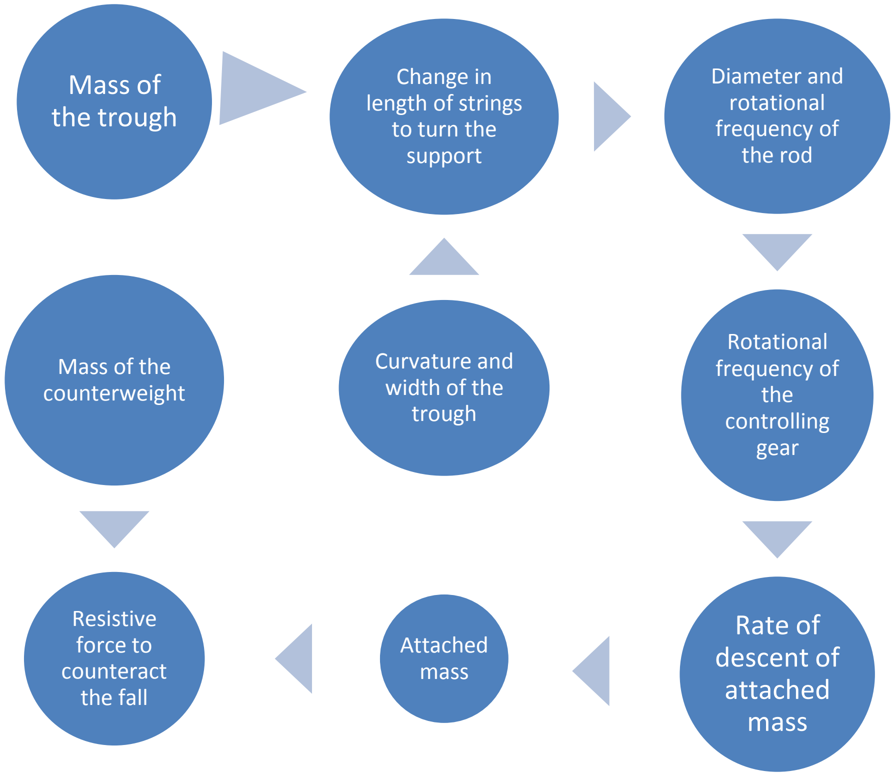


Figure 9 Parameters and their interdependence

9. Conclusion

The theory of tracking has been discussed in detail and based on that a basic sketch of a low-cost mechanical solar tracker is presented. Though, the proposed design has not been constructed or tested so far, this report has sufficient information to serve as a stepping stone towards making an attempt towards construction in future by making improvisations to the proposal.

Works Cited

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Padilla, Ricardo Vasquez. "Simplified Methodology for Designing Parabolic Trough Solar Power Plants." Graduate Thesis. 2011.

Stine, William B. and Michael Geyer. Power From The Sun. 2001.