Analysis and Simulation of Parallel Robots for Sun Tracking Using a CAD – Based Approach

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Jury

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This thesis is entirely dedicated to my family back in Angola, Mum, Dad and brothers & Sister, who are my unconditional supporters in every moment. Their love and encouragement kept me standing in all difficult situations throughout this journey.
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Finally, I thank Jehovah my God, for all that I am.
Abstract

This thesis investigates the application of parallel robots for sun tracking using a CAD – based approach. Different mechanical structures of parallel robots to be used for sun tracking are proposed. The models of the robots are first designed in SOLIDWORKS and later controlled using NI LabVIEW. SOLIDWORKS and LabVIEW are integrated in order to perform the virtual control of the robots.

A new approach on how to determine the workspace of a parallel robot using a CAD - based approach is proposed in this thesis. This also represents one of the major contributions of this thesis for robotics. The key of this approach is the introduction of a serial auxiliary mechanism with actuated joints that is assembled with the parallel robot in a way that the workspace of the parallel robot can easily be determined by measuring the joint variables of the serial mechanism. This approach proposes an easy way to overcome the singularities that parallel robots may present when determining their workspace.

Regarding the control of the robots, a simple control approach that consists in programming the robot to move according to a predefined trajectory based on the earth’s trajectory relatively to the sun was used.

This thesis provides a solid foundation for further development of parallel mechanisms based on solar tracking systems which may allow the sun tracking with larger panels and less energy consumption.

At the end of this dissertation the conclusions of this work and recommendations for future works are presented.

**Keywords:** Parallel Robot, Sun Tracking, Workspace, SOLIDWORKS, LabVIEW.
Resumo

A presente tese investiga a aplicação de robôs paralelos para o seguimento da trajectória solar utilizando uma abordagem baseada em modelos CAD. Neste trabalho, são apresentadas várias sugestões de estruturas mecânicas de robôs paralelos que podem ser usados para o seguimento da trajectória solar. Os modelos dos robôs são feitos no SOLIDWORKS e, posteriormente, controlados usando o NI LabVIEW através duma integração entre os dois softwares que permite o controlo virtual dos robôs.

Uma nova metodologia para a determinação do workspace de robôs paralelos usando uma abordagem baseada em modelos CAD é proposta nesta tese. Este ponto constitui um dos maiores contributos desta dissertação para a robótica. O ponto-chave desta abordagem é a introdução de um mecanismo auxiliar em cadeia aberta (série) com juntas actuadas e que é montado com o robô paralelo de modo que o workspace do robô paralelo possa ser facilmente determinado através da medição das variáveis de junta do robô série (mecanismo auxiliar). Esta abordagem apresenta uma maneira fácil de se ultrapassarem as singularidades que se podem encontrar ao determinar o workspace de robôs paralelos.

Para o controlo dos robôs, foi usada uma abordagem de controlo simples que consiste em programar o robô para que o mesmo se possa mover de acordo com uma trajectória pré definida, baseada na trajectória da terra relativamente ao sol.

Esta tese fornece uma base sólida para desenvolvimentos mais profundos de robôs paralelos baseados em sistemas de seguimento da trajectória solar, o que permitirá a utilização de painéis com maior dimensão e um menor consumo de energia para manipular tais painéis.

Na parte final da dissertação são apresentadas as conclusões deste trabalho e algumas recomendações para trabalhos futuros.
Palavras-chave: Robô paralelo, Sun Tracking, Workspace, SOLIDWORKS, LabVIEW.
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Abbreviations

CAD – Computer Aided Design

DOF – Degrees of Freedom

SPM – Spherical Parallel Mechanism

R – Revolute Joint

P – Prismatic Joint

S – Spherical Joint

U – Universal Joint

RPS – Revolute-Prismatic-Spherical

RRR – Revolute-Revolute-Revolute

UPS – Universal-Prismatic-Revolute

3D – Three Dimensions/Dimensional

N-S – North-South

E-W – East-West

CM – Center of Mass
Symbols

\(\alpha\) – Angle of rotation of the North/South axis

\(\theta\) – Angle of rotation of the East/West axis

\(n\) – Total number of links of the robot

\(f_i\) – Degree of freedom of the \(i\)-th joint

\(j\) – Total number of joints of the robot

\(L_1\) – Variable for the prismatic joint number one

\(L_2\) – Variable for the prismatic joint number two

\(L_3\) – Variable for the prismatic joint number three
Chapter 1 Introduction

This chapter marks the beginning of a thesis where studies on the parallel robots are carried out in order to apply them in a sun tracking system. This is a new application for the parallel robots that is being proposed in this thesis. Before going straight to the point, the main reasons that motivated this work and the outline of this dissertation are presented in this chapter.

It is important to note that this thesis was developed at Heriot Watt University (Edinburgh) in the United Kingdom under the supervision of Dr. Xianwen Kong through the exchange programme Sócrates-Erasmus and is now submitted at Instituto Superior Técnico (Technical University of Lisbon) in Portugal as a partial fulfillment for the degree of Master of Science in Mechanical Engineering.

1.1 Motivation for This Work

The world’s main source of primary energy is the fossil fuels. Only in the USA, according to the US Energy Information Administration [7], 83% of the total primary energy consumption is supplied by the fossil energy (by 2008). Fossil energy is a non-renewable energy and the burning of fossil fuels allows the production of around 20 Giga tonnes of carbon dioxide per year which represents twice the amount that can naturally be absorbed by natural processes [8]. This
largely contributes for the global warming problem. On the other side, oil resources are limited and knowing the relation between supply and demand, it will lead to an increase of the oil’s price throughout the years. Efforts have been done all over the world to overcome these problems related to energy, and renewable energy appears as a clean energy and a good solution for the world increasing energy demand. In 2007, the European member states made a firm commitment to increase the total share of “renewables” in primary energy consumption to 20% by 2020 [6]. Much research has been done in “renewables” in different countries to achieve this goal. Solar Energy is an important part of this group of energy.

“The sun provides Earth with as much energy every hour as human civilization uses every year... If the tiniest fraction of that sunlight were to be captured by photovoltaic cells that turn it straight into electricity, there would be no need to emit any greenhouse gases from any power plant” [5]. These Oliver Morton’s words published by an international journal of science [5] in 2006 perfectly illustrate the reason for the high interest in researching in solar energy field. Photovoltaic panels have been used to collect the energy (radiation) from the sun and turn it into electricity. The biggest issue nowadays is to increase the efficiency of the energy conversion of the panels (Solar radiation to electricity) which is around 12% - 19% [3]. The amount of energy produced by a photovoltaic panel depends upon the amount of solar radiation absorbed by the panel. The maximum production efficiency is reached when the sun’s rays are “delivered” perpendicularly in the panel’s surface. As the sun’s position is not constant relatively to the earth throughout the day, it means that for a panel with a fixed orientation it is not possible to keep the sun’s rays perpendicular to the panel's surface and, therefore, lower production efficiencies will be achieved. The goal is to change the panel’s orientation as the “sun’s position changes” in order to keep the panel perpendicular to the sun’s rays that will allow the maximum energy collection from the sun. In order to achieve this goal, several electromechanical tracking systems have been developed [2] – [4], yet, the efficiency can still be
largely increased. This thesis aims to investigate the application of parallel robots to undertake this task.

"Parallel robots are closed-loop mechanisms presenting very good performances in terms of accuracy, rigidity and ability to manipulate large loads" [1]. The successful development of this work will contribute for the use of bigger panels (greater electricity production) with more safety and less energy consumption. This work also shows the interest of the robotic engineers to contribute with valuable solutions for the environmental problems.

1.2 Outline of the Thesis

A description of the topics on this thesis is presented in this section:

Chapter 1 Introduces the main topic of the thesis, presents the main motivations for this works and ends by outlining what can be found by reading this dissertation.

Chapter 2 presents several proposals of parallel mechanisms suitable for sun tracking, establishes a comparison among them and selects the ones that best fit to this application. Some important details as workspace and redundancy analysis are considered in this chapter to compare the mechanism.

Chapter 3 proposes the use of CAD software to design the mechanical structures of parallel robots and supply the necessary information for modeling discarding the application of any mathematical modeling method.
Chapter 4 proposes a new approach to determine the workspace of a parallel robot based on the CAD model of the robot integrated with the CAD model of a 6 DOF serial mechanism created in this thesis.

Chapter 5 presents the results of simulating a parallel robot tracking the sun.

Chapter 6 briefly presents the conclusions of this work and gives some recommendations for future works on this topic.
Chapter 2 Analysis and Selection of the Mechanical Structure of a Parallel Robot for Sun Tracking

This chapter focuses on the analysis and selection of parallel robots to be applied in a sun tracking system.

2.1 Conceptual Design

Conceptual design is the stage of the design process where the problem is analyzed in a wider way and broad solutions are generated. In this section, it is intended to develop and/or analyze different structures for a parallel mechanism that can be used to manipulate solar panels in order to change their orientation in the 3D space. Firstly, the design specifications are outlined and later, some solutions that fulfill those specifications are presented. In the final step of the design process further details are considered and the structures that best fit to those requirements are selected. Whilst the conceptual design itself can be seen as a thick filter, the
selection of the mechanism can be regarded as a thinner filter as it takes into account smaller details in order to get closer to the desired specifications.

2.2 Product Design Specifications

The Business Dictionary [17] defines design specifications as the essential qualitative and quantitative characteristics that set criteria (such as performance requirements, dimensions, weight, reliability, ruggedness) to be satisfied in designing a component, device, product, or system.

In this section of the dissertation, a set of specifications are outlined and these will serve as a base to construct and select the mechanisms.

Regarding the application that the mechanism will be submitted to (orientate a photovoltaic panel), the main requirement is related to the number of degrees of freedom (DOF) that the mechanism must have. Two important DOF are to be considered. A rotation about a horizontal axis (that can be regarded as the axis that connects the cardinal points North and South) and another rotation about another horizontal axis which is perpendicular to the first one (that can be regarded as the axis that connects the cardinal points East and West). Figure 1 depicts an illustration of the aforementioned axes-system oriented according to the cardinal points N-S and E-W.
As the sun will move in a circular trajectory from East to West according to an observer based on the earth's surface, it is important that the sun tracking mechanism presents a wide range of motion regarding the rotation about the N-S axis. Taking the vertical axis as reference, the maximum necessary angular range to track the sun from sunrise to the sunset will be the interval \(-90^\circ \) to \(90^\circ \). The mechanism to be used for this application should then have the widest possible range of motion regarding the angle interval given above. The angle \(\theta\) in figure 1 (a) is also known as solar altitude angle and it is zero at the sunrise and at the sunset while the angle \(\alpha\) in figure 1 (b) is also known as zenith angle or angle of incidence of the beam radiation. This is just a simple way to approach the problem as more details on solar energy can be found in [31] – [33].
It is important to note that the plane that holds the solar trajectory from East to West does not remain with the same orientation all the time as showed in figure 2. This means that for a more efficient solar tracking it is desirable that the parallel mechanism to be designed for this application presents a range of motion about the E-W axis that goes from -45° to 45° taking the vertical axis as reference (0°).

It is clear that the angular intervals presented in this section as requirements for the parallel mechanism are simply the maximum necessary intervals for sun tracking and it does not necessarily mean that mechanisms with narrower intervals of motion are not selectable for this application.

The weight and the geometrical complexity of the structures are also important factors to be taken into account. The moving parts of the mechanism should be as light as possible to lead to
a lower energy consumption associated to the motors that will guarantee the desired motion. On the side, the more complex the geometry is the higher the manufacturing costs will be, therefore, the simpler the geometry is the cheaper the project will be.

The dimensions of the mechanism are also important as they play a direct influence on the total weight of the structure. However, the aforementioned angular ranges can condition the dimensions of the mechanism for they constitute a primary requirement for the project regarding the objectives.

Another important factor to be considered is the minimum number of motors necessary to provide a certain DOF. It is desirable the number of motors not to be greater that the DOF of the mechanism.

The total cost of the project is obviously an important factor to be taken into account in this project just like in any other engineering project. However, in this thesis, the costs are not evaluated explicitly.

It is important to note that the angular ranges of motion that were mentioned in this section are related to the moving platform of the parallel robot which is the end-effector of the robot.

As a summary of what was presented in this section the essential requirements described to select the parallel mechanism are outlined in the next paragraph ordered by their importance in the project.
2.3 Outline of the Design Specifications of the Mechanical Structure

- Range of rotation about N-S axis to be the widest possible in the interval -90° to 90° where 0° is given by the vertical axis (Figure 1).
- Range of rotation about E-W axis to be the widest possible in the interval -45° to 45° where 0° is given by the vertical axis (Figure 1).
- Number of motors to be not greater than the DOF of the mechanism (redundant robots should be avoided).
- Geometry to be as simple as possible.
- Moving parts to be as light as possible.

Given the specifications above, different proposals regarding the mechanical structures of the parallel robots to be used for sun tracking will be presented in the next section.
2.4 Proposals of Mechanical Structures of Parallel Mechanisms for Sun Tracking

Along this section different proposals for the parallel mechanism for sun tracking are presented together with relevant information related to the application that is being considered in this thesis (sun tracking).

2.4.1. Proposal 1 - 1 DOF Planar Parallel Mechanism

Figure 3. 1 DOF planar parallel mechanism
Figure 3 shows the 1 DOF parallel mechanism. This mechanism is composed of three legs where two are fixed (considered as one link together with the base of the mechanism) and one is extendable through a prismatic joint. This configuration will allow the mechanism to rotate its moving platform of an angle $\theta$ about a horizontal axis that can be regarded as the N-S axis. The rotation of the platform can be achieved by using a linear motor that will act on the prismatic joint. Figures 3 (b) and (c) show the configuration of the robot for $\theta_{\text{min}}$ and $\theta_{\text{max}}$ respectively, that represent the west-facing and the east-facing maximum angular ranges, respectively.

The DOF of this planar mechanism can be calculated applying the following equation:

$$DOF = 3(n - 1) - \sum_{i=1}^{j}(3 - f_i)$$  \hspace{1cm} \text{Eq. (1)}

Where:

- $n$ is the number of links in the mechanism
- $j$ is the total number of joints
- $f_i$ is the DOF of i-th joint

Since the two revolute joints of the fixed legs are collinear they can be regarded as one joint only. Therefore, knowing that $n = 4$, $f_i = 1$ and $j = 4$, it can be confirmed that the DOF of the mechanism is equal to one.

It is important to note that the center of mass (CM) of the moving platform does not remain fixed as the platform rotates. This will require extra energy to lift the CM up which is undesirable.

Another variant of this model can be obtained by changing the positions of the fixed links in a way that the moving platform rotates about a line that contains its CM.
By optimizing the dimensions of the arms it is possible to increase both $\theta_{\text{max}}$ and $\theta_{\text{min}}$ to values very close 90°.

![Optimized configuration of the 1DOF parallel mechanism](image)

Figure 4. Optimized configuration of the 1DOF parallel mechanism

A robot based on this structure will only be able to track the sun regarding the sun’s trajectory from East to West without taking into account the angular variation about the E-W axis.

As the mechanism presents only 1 DOF, it cannot rotate about the E-W axis that would allow it to face the south or north. However, this can still be a good solution to track the sun, mainly, in locations not far from the equator.
2.4.2 Proposal 2 – 2DOF Spatial Parallel Mechanism

The structure presented in figure 5 is a variant of the structure presented in the last section. The main difference between them is that this structure has a second DOF for the moving platform that is obtained by rotating the base of the mechanism about a vertical axis that contains the CM of the base. The amplitude of this rotation can reach values greater than 270°. This characteristic leads to a more precise tracking as it allows the moving platform to face east and west as well as north and south. One important thing to note is that rotating the whole structure will lead to high energy consumption in the motor that will provide the motion.
A variant for this model can also be obtained by changing rotation axis of the moving platform in order to make the CM of the moving platform fixed when the platform is rotating similarly to the solution adopted for the mechanism in the last section.

![Figure 6. Schematic representation of a 6 DOF Parallel Mechanism](image)

### 2.4.3 Proposal 3 - 6 DOF Spatial Parallel Mechanism (4-UPS)

The mechanism showed in figure 6 is a 6 DOF parallel mechanism with four legs handling a moving platform. The legs are connected to the base through universal joints and with the moving platform through spherical joints. The legs can vary their lengths due to prismatic joints.
The DOF of this mechanism can be found by applying equation (2) that yields the DOF of a spatial parallel mechanism.

\[ DOF = 6(n - 1) - \sum_{i=1}^{j}(6 - f_i) \]  
Eq. (2)

For the given mechanism with 10 links, 12 joints of which four are universal joints, four prismatic joints and four spherical joint, the DOF is:

\[ DOF = 6(10 - 1) - [4(6 - 2) + 4(6 - 1) + 4(6 - 3)] \]

\[ DOF = 6 \]

The DOF of the mechanism shows that at least 6 motors will be needed to fully control the motion of this mechanism.

A variant of this mechanism can be obtained by using revolute joints instead of universal joints. In this case, the revolute joints should be used in the mechanism in such a way that makes them symmetric to the center point of the base. Using the equation (2) the DOF of the mechanism, given the new conditions, is:

\[ DOF = 6(10 - 1) - [4(6 - 1) + 4(6 - 1) + 4(6 - 3)] \]

\[ DOF = 2 \]

Figure 7. 2 DOF Spherical Parallel Mechanism (Original proposal in [30])
2.4.4 Proposal 4 – 2 DOF Spherical Parallel Mechanism (RR-RRR-RRR)

The 2 DOF SPM depicted in figure 7 is composed by three legs that guarantee the handling of the moving platform. This mechanism has 8 revolute joints of which two are actuated to guarantee the 2 desired DOF, a rotation about a horizontal axis that can be regarded as N-S axis and another rotation about another horizontal axis, perpendicular to the first one, that can be regarded as E-W axis. It has a total number of 7 links (including the base and the moving platform) all connected through revolute joints. The DOF of this mechanism could be found using Equation (1) (that gives the DOF for planar or spherical mechanisms):

\[ DOF = 3(n - 1) - \sum_{i=1}^{j}(3 - f_i) \]

Knowing that \( n = 7 \) and that all 8 joints are revolute, the DOF of the mechanism is:

\[ DOF = 3(7 - 1) - 8(3 - 1) \]

\[ DOF = 2 \]
The two greatest advantages of this mechanism are the fixed position of the CM and the wide range of motion that can be provided by the two actuated joints. Rotations about N-S and E-W can reach values very close -90° and 90° for their $\theta_{\text{min}}$ and $\theta_{\text{max}}$ (and $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$), respectively (figure 8). The reason why both $\theta_{\text{min}}$ and $\theta_{\text{max}}$ (and $\alpha_{\text{min}}$ and $\alpha_{\text{max}}$) cannot be -90° and 90°, respectively, is that for those angles the mechanism will present a singular configuration.
2.4.5 Proposal 5 – 3 DOF Spatial Parallel Mechanism (3-RPS)

Depicted in figure 9, the 3 DOF spatial parallel mechanism is also presented as a solution for the sun tracking problem. It was also presented in [37] for a different application. It is composed by three extendable legs that handle a moving platform. The legs are connected to the base (ground) through revolute joints and to the moving platform through spherical joints. The orientation and position of the moving platform is controlled by manipulating the variables \(L_1\), \(L_2\) and \(L_3\) of the prismatic joints associated to the legs.

Figure 9 (b) shows the mechanism with the platform oriented in a direction that can be regarded as the E-W axis, i.e., facing east and rotating about N-S axis by simply varying the length \(L_1\). The maximum angular displacement that can be achieved by this motion will be denoted by \(\theta_{\text{max}}\). On the other hand, (c) that also shows the platform oriented in a direction that can be regarded as E-W axis, depicts the mechanism with its moving platform facing west and rotating...
about an axis that can be regarded as the N-S axis by varying simultaneously the lengths \( L_2 \) and \( L_3 \) with the same magnitude. The maximum angular position that can be achieved when performing this motion will be denoted by \( \theta_{\text{min}} \).

It is important to note that the N-S and E-W reference axes showed in figure 9 (a) are simply to illustrate their directions but the origin of the frame is not necessarily located as showed in the figure.

To change the orientation of the moving platform in the N-S direction the lengths \( L_2 \) and \( L_3 \) must present different values (figure 10).

Figure 10. 3 DOF spatial parallel mechanism with the moving platform facing the south (\( \theta_{\text{min}} \))

The DOF of the mechanism can be found by applying the equation (2) knowing that \( n = 8 \), \( j = 9 \) and three joints are revolute, three are prismatic and other three are spherical:

\[
DOF = 6(8 - 1) - \left[ 3(6 - 1) + 3(6 - 1) + 3(6 - 3) \right]
\]

\[
DOF = 3
\]
This mechanism allows the tracking of the sun taking into account the sun’s trajectory when it is varying its position both along east to west and north to south.

The CM of the moving platform does not remain fixed as the platform moves. This constitutes a drawback for this mechanism.

2.5 Selection of the parallel mechanism

This section presents the selection of the parallel mechanisms to be used for sun tracking among the proposed mechanisms presented in the previous section. The selection is done after all proposed mechanisms are compared based on the design specifications presented in the beginning of this chapter.

Table 1 summarizes the relevant information on the mechanisms that will be taken into account to choose the right mechanisms for this application.
Table 1. Main characteristics of the parallel robots proposed for sun tracking

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Proposal 1</th>
<th>Proposal 2</th>
<th>Proposal 3</th>
<th>Proposal 4</th>
<th>Proposal 5</th>
</tr>
</thead>
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<tr>
<td>DOF</td>
<td>1</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Number of Linear Motors</td>
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<td>4</td>
<td>0</td>
<td>3</td>
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<tr>
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<td>θmax [degree]</td>
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<tr>
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<td>3</td>
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<tr>
<td>Number of spherical joints</td>
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<td>4</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Number of universal joints</td>
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<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cost (qualitative comparison)</td>
<td>Expensive</td>
<td>Expensive</td>
<td>Very expensive</td>
<td>Less expensive</td>
<td>More expensive</td>
</tr>
<tr>
<td>CM status</td>
<td>Not fixed</td>
<td>Not fixed</td>
<td>Not fixed</td>
<td>Fixed</td>
<td>Not fixed</td>
</tr>
</tbody>
</table>

Considering the requirements presented in the design specifications and comparing with the information presented in table 1 the following conclusions are derived:

- Proposal 1 will not be selected as the mechanism has only one DOF and the minimum DOF required for the application is two. However, it is important to note that it can still be a good solution to track the sun in locations close to the equator.

- Proposal 2 presents a mechanism with two DOF which is the required DOF for the application. However, rotating all the mechanism to achieve a second rotation can be very costly in terms of energy to power the motor that will provide such rotation.
Therefore, this proposal will be excluded from this thesis. However, in terms of price, there is not much difference comparing to the first proposal as rotary motors are much cheaper than linear motors.

- Proposal 3 presents a high redundancy as the DOF of the mechanism is 3 times greater than the DOF of the task. This will require a large number of linear motors to control the mechanism which implies a very high cost and overconsumption of energy. Therefore, this proposal will be excluded from this thesis.

- Proposal 4 is the best option in terms of the required workspace and also for keeping the CM of the moving platform fixed while it is moving. The DOF of the mechanism matches the DOF of the task. In some configurations, the arrangement of the legs can limit the dimension of the panel to be handled. The geometry of the moving platform can also be a reason to increase the weight of the structure. However, the first drawback can be overcome by inverting the mechanism up-side-down in a way that the moving platform becomes the base and the base becomes the moving platform. It is also possible to reduce the effect of the second drawback by using a moving platform with holes. One important fact is that this proposal uses rotary motors only which being much cheaper than linear motors greatly reduce the cost of the mechanism. This mechanism is selected for the application that is being considered in this thesis.

- Proposal 5 presents a workspace that although being much smaller than the workspace required in the design specification is still considerable for the application. The mechanism presents a simple geometry and a very light moving platform due to empty space bounded by the three bars that form the moving platform (Figure 9). Having one more DOF than the DOF of the task, a moving CM of the moving platform and three linear motors constitute the the major drawbacks of the mechanism. However, in general, this proposal showed to be a better option than the first three proposals. Therefore, it is also selected for the purpose of studies of this thesis.
It is important to remark that for the ranges of motion presented in table 1 this mechanism can be a good solution to track the sun in places located in the region between the tropics.

It is important to note that the comparison in terms of costs presented on the table is based on the cost of the motors only. As linear motors are much more expensive than rotary motors then structures with more linear motors are presented as more expensive than others with less.

After the parallel mechanisms are selected (proposals 4 and 5) to be used for sun tracking, some considerations regarding their kinematics and dynamics will be presented in the next section of this chapter.

2.6 Kinematics and Dynamics

Considerations

The application of a parallel robot for sun tracking requires solutions for the inverse kinematics problem. Given the desired orientation $\theta$ and $\alpha$ for the moving platform of the robot the values of the joint variables have to be determined so that the robot may perform the motion that will lead to such orientation of the moving platform. This thesis will not derive any equations of the kinematics or dynamics of the parallel robots as a CAD – based approach will be used to get all necessary information of the kinematics and dynamics of the mechanism. This constitutes one of the big advantages of using this approach to simulate and control mechanisms. This
approach may help reduce product development time. Proposals in how to derive the kinematics and the dynamics of the mechanisms can be found in [1], [10] – [16], [23], [34] and [35].
Chapter 3 CAD - Based Modeling

Although many solutions to derive the kinematics and dynamics models of parallel robots have been proposed ([1], [10] – [16], [23], [34] and [35]), in this thesis a CAD-based modeling is used to acquire all necessary information of the kinematics and dynamics of the parallel robot to be used to program motion.

This approach can actually be regarded as virtual system identification provided that the CAD model will generate all important information about the system once it is fully designed. This can be a very useful approach and is presented as an alternative option to the mathematical modeling that may sometimes involve a very complex analysis. Provided that the CAD model of the robot has been designed with high accuracy, this approach will lead to simulations with high degree of accuracy as well. Another advantage of using this approach is that it may lead to reduction in the product development time.

SOLIDWORKS is the CAD software used in this thesis to design the mechanical structures of the parallel robots that have been proposed for sun tracking. Afterwards, NI LabVIEW is used to design all logic part of the manipulators.

Using a CAD model to simulate a mechanical structure is an economic way to guarantee that the project works well before incurring the costs of physical prototypes. By simulating the 3D CAD model, the simulation of the mechanical dynamics of the mechanism can be carried out and it will include mass and friction effects, cycle times, individual performances of the components [22]. This information is later managed by a virtual instrumentation program and
used to provide a perfect control of the system. Following paragraphs will explain how the two programs (SOLIDWORKS and LabVIEW) are integrated to work together and fulfill the desired task.

As stated in the previous section, the mechanical structures of the parallel robots used in this project were designed with the aid of SOLIDWORKS. SOLIDWORKS appeared to be a very powerful tool for a complete design of a mechanical structure. Geometrical, structural and motion analysis can be done on the mechanism before going for the physical prototyping stage discarding the use of another mechanical or structural design software.

The connection between SOLIDWORKS and LabVIEW can be regarded as a Master – Slave communication model. LabVIEW works as the Master for it is LabVIEW, who has the general control of the system such as starting the communication between the two programs, abort the simulation, receive the inputs, etc. Outputs can be obtained both from SOLIDWORKS and LabVIEW. Figure 11 shows a LabVIEW project manager where all main settings for the connection of LabVIEW and SOLIDWORKS are done. The motors defined in the SOLIDWORKS Assembly are then actuated by LabVIEW NI SoftMotion axes that are also added to the project manager.

If certain motion is to be performed by more than one motor simultaneously then a coordinate space formed by the axes of the respective motors has to be added to the LabVIEW project.

To perform a perfect integration of SOLIDWORKS and LabVIEW, a set of requirements have to be satisfied by both programs. A SOLIDWORKS 2009 Service Pack 2.1 version or later is required to connect it with LabVIEW. Any version released before this will not work. When playing a simulation (motion study) of a model in SOLIDWORKS 2009 version or any later, three options for the type of motion are available to simulate a motion.
The difference between one type of motion and the others is in the amount of reality that can be assigned to the motion study. The first option named "Animation" is just a simple motion study more appropriate to observe how the model works without taking into account physical properties such as mass, gravity and others, relying simply on geometry. It more appropriate to analyze the geometry only. The second option is named "Basic Motion" and is a more realistic study than the first one as it allows the input of some properties to the motion such as gravity. The third type of motion study, the “Motion Analysis” is the most realistic type of motion and takes into account properties like mass, friction forces, materials, gravity and is the most appropriate for a more accurate analysis of a mechanism.
To connect SOLIDWORKS with LabVIEW, it is required to choose Motion Analysis as the motion study type. Any other option, but this, will not work with LabVIEW. In order to have the third option of the motion study available in SOLIDWORKS, it is necessary to have a special add-in named “SOLIDWORKS Motion”. Another important configuration that must be set in SOLIDWORKS in order to prepare it for a later use with LabVIEW is the motors’ configuration. There are different options for configuring the motors in SOLIDWORKS but for this specific application the velocity configuration has to be defined by a distance and a time interval. This is applicable both for a rotary motor and for linear motor. The difference is that for a rotary motor an angle is chosen instead of a linear distance. Any other option chosen, but this, will make the connection of the two software fail [21].

On the other hand, there are also few requirements to be met by LabVIEW in order to access a SOLIDWORKS model. A 2009 LabVIEW version (or any later) is required for this specific application plus a special add-in called SoftMotion (version 2009 or later). Any other versions released before these will not work with SOLIDWORKS. SoftMotion is actually the responsible for the connection of SOLIDWORKS and LabVIEW as it serves as a bridge to bring SOLIDWORKS control to LabVIEW [21].

In a brief, to connect SOLIDWORKS and LabVIEW, the following software and configurations settings are required:

- **SOLIDWORKS 2009 SP2.1 or later**
  - Add-in: SOLIDWORKS Motion 2009
  - Motion study type: Motion Analysis
  - Motor’s configuration: Velocity defined by a distance (linear or angular) and a time interval
- **LabVIEW 2009 or later**
  - Add-in: SoftMotion 2009
In the next chapter a new approach on how to determine the workspace of a parallel robot is presented. SOLIDWORKS and LabVIEW are used together to achieve the desired objective.
Chapter 4 Workspace Determination and Analysis Using a CAD - Based Approach

The workspace of a robot (manipulator) is one of its most important features as it defines the points (or angles) of the space that can be reached by the end-effector of the robot when it is at work. It is a geometrical property that will depend upon the type, geometrical and mechanical (types and number of joints) characteristics of the robot [24].

In this chapter, the workspace topic will be presented and analyzed. A new approach for the workspace determination of parallel robots using SOLIDWORKS and LabVIEW is proposed in this text.

4.1 Principle of the Approach

A 6 DOF serial mechanism was created in SOLIDWORKS to serve as the main tool to determine the workspace.

Figure 12 depicts the 6 DOF serial mechanism proposed to be used for workspace determination. It is composed by a planar base with two translational DOF which is connected
to a 1 DOF rotational cross-like (cross-shaped) link. The other side of the cross link is connected to a 1 DOF rotational bar similarly to an inverted pendulum. The bar itself serves as axis of rotation for a cylindrical joint that contributes with 2 DOF to complete the total number of DOF of the mechanism. All DOF are represented in Figure 12 (a) by the straight and curve arrows for translation and rotation respectively.

The motion of any body in a 3D space with a reference frame OXYZ can be fully defined by 6 DOF, a translation and a rotation about the axis OX, translation and rotation about the axis OY and another translation and rotation about the axis OZ. Therefore, this thesis suggests that the 6-DOF serial mechanism can be integrated with a parallel robot without interfering or constraint the motion of the parallel robot. This offers the possibility of measuring or observing some important properties of the motion of the parallel robot through the serial mechanism.

Figure 12. 6 DOF serial auxiliary mechanism
4.2 Case Study

In figure 12 (c) a SOLIDWORKS model of the 3-DOF spatial parallel mechanism integrated with the 6-DOF serial mechanism is depicted. They are assembled together in a way that the cylindrical joint of the serial mechanism stays concentric and perpendicular to the moving platform (end-effector) of the parallel mechanism (figure 12 b)). This means that by knowing the orientation of the axis of the cylindrical joint, the two desired orientation angles of the platform are consequently known.

This thesis will only be focused on determining the angular workspace of the parallel robot (angular range of motion) regarding the application that the robot is presented for. Two rotations will be considered for the moving platform of the parallel robot, a rotation $\theta$ about the N-S axis and another rotation $\alpha$ about the E-W axis. This can be easily achieved and measured by simulating the integrated system of the Figure 13 (c) by assigning two virtual rotary motors to the joints 3 and 4 of the 6-DOF serial mechanism. Considering the axis of rotation of joint 3 as the N-S axis and the axis of rotation of joint 4 as the E-W axis, the angular ranges of motion of the platform can be determined by measuring the amplitude of the joint variables $\alpha$ and $\theta$ at joints 3 and 4, respectively.

In the following paragraphs the procedure to determine the workspace of the 3 DOF spatial parallel robot will be described.

The moving platform is set horizontally and both $\alpha$ and $\theta$ are considered to be zero at this configuration (figure 13). Fixing the angle $\alpha$ of the joint 3 of the parallel mechanism and rotating the joint 4 (angle $\theta$) until SOLIDWORKS detects any interference in the model, the maximum/minimum value of $\theta$ is found for the fixed value of $\alpha$. This process is repeated for different values of $\alpha$. 
Table 2 shows the values of the E-W ranges ($\theta_{\text{min}}$ and $\theta_{\text{max}}$) of the moving platform for fixed values of the angle ($\alpha$). By convention, the limit amplitude of the angles $\alpha$ and $\theta$ is said maximum (and positive) if it is measured in clockwise direction and minimum (and negative) if it is measured in anticlockwise direction. Figure 14 (a) and (b) show the angles $\alpha$ and $\theta$ measured on the 6 DOF serial mechanism. A graphical representation of the workspace of the 3-DOF spatial parallel mechanism is plotted in figure 15.
### Table 2

Ranges of the E-W angles given a fixed value of the N-S angle

<table>
<thead>
<tr>
<th>North-South angle (α) [Degree]</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17,1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-15</td>
<td>-8,3</td>
<td>5,5</td>
</tr>
<tr>
<td>-10</td>
<td>-11,5</td>
<td>15</td>
</tr>
<tr>
<td>-5</td>
<td>-11,7</td>
<td>17,8</td>
</tr>
<tr>
<td>0</td>
<td>-11,9</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>-11,7</td>
<td>17,8</td>
</tr>
<tr>
<td>10</td>
<td>-11,5</td>
<td>15</td>
</tr>
<tr>
<td>15</td>
<td>-8,3</td>
<td>5,5</td>
</tr>
<tr>
<td>17,1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Figure 14.** Rotation angles of the 6 DOF serial auxiliary mechanism
The joint variables L1, L2 and L3 of the parallel robot can be measured directly in SOLIDWORKS by associating dimensions to each of the variables. As the simulation is played, the values of the variables change and they can be seen in SOLIDWORKS.

Tables 3 and 4 show the corresponding values of the joint variables of the 3 DOF spatial parallel robot for the pairs $\alpha - \theta_{\text{max}}$ and $\alpha - \theta_{\text{min}}$. The same procedure can be done to determine the value of the joint variables of the parallel robot for any pair $\alpha$ and $\theta$. 

Figure 15. Orientation workspace of the 3 DOF spatial parallel robot determined using CAD – based approach (For the stroke of the joint variables Limin=0 and Limax=100mm)
### Table 3. Relation between the orientation angles of the moving platform ($\alpha - \theta_{\text{min}}$) and the joint variables of the parallel robot

<table>
<thead>
<tr>
<th>North-South angles ($\alpha$) [degree]</th>
<th>$\theta_{\text{min}}$</th>
<th>L1 [mm]</th>
<th>L2 [mm]</th>
<th>L3 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>88.21</td>
</tr>
<tr>
<td>-15</td>
<td>-8.3</td>
<td>37.53</td>
<td>0</td>
<td>77.66</td>
</tr>
<tr>
<td>-10</td>
<td>-11.5</td>
<td>51.83</td>
<td>0</td>
<td>52.09</td>
</tr>
<tr>
<td>-5</td>
<td>-11.7</td>
<td>52.72</td>
<td>0</td>
<td>26.14</td>
</tr>
<tr>
<td>0</td>
<td>-11.9</td>
<td>53.62</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>-11.7</td>
<td>51.83</td>
<td>26.14</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>-11.5</td>
<td>51.83</td>
<td>52.09</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>-8.3</td>
<td>37.53</td>
<td>77.66</td>
<td>0</td>
</tr>
<tr>
<td>17.1</td>
<td>0</td>
<td>0</td>
<td>70</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 4. Relation between the orientation angles of the moving platform ($\alpha - \theta_{\text{max}}$) and the joint variables of the parallel robot

<table>
<thead>
<tr>
<th>North-South angles ($\alpha$) [degree]</th>
<th>$\theta_{\text{max}}$</th>
<th>L1 [mm]</th>
<th>L2 [mm]</th>
<th>L3 [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-17.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>24.15</td>
</tr>
<tr>
<td>-15</td>
<td>5.5</td>
<td>0</td>
<td>24.15</td>
<td>30.03</td>
</tr>
<tr>
<td>-10</td>
<td>15</td>
<td>0</td>
<td>45.15</td>
<td>45.15</td>
</tr>
<tr>
<td>-5</td>
<td>17.8</td>
<td>0</td>
<td>67.29</td>
<td>59.37</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
<td>0</td>
<td>88.21</td>
<td>88.21</td>
</tr>
<tr>
<td>5</td>
<td>17.8</td>
<td>0</td>
<td>59.37</td>
<td>67.29</td>
</tr>
<tr>
<td>10</td>
<td>15</td>
<td>0</td>
<td>45.15</td>
<td>45.15</td>
</tr>
<tr>
<td>15</td>
<td>5.5</td>
<td>0</td>
<td>30.03</td>
<td>24.15</td>
</tr>
<tr>
<td>17.1</td>
<td>0</td>
<td>0</td>
<td>24.15</td>
<td>0</td>
</tr>
</tbody>
</table>
The 3-DOF spatial parallel mechanism presents a limited angular range of motion with the geometrical configuration presented here. However, an optimization can be done in the geometry of the robot to increase the workspace. For instance, the geometry of the spatial parallel mechanism aforementioned presents its three revolute joints symmetric to the center of the base (Figure 16 (a)). If the arrangement (layout) of the three revolute joints is modified in a way that two joints will have their axes of rotation parallel and simultaneously perpendicular to the axis of rotation of the third joint (Figure 16 (b)) the workspace increases as shown in figure 17.

Other constructions’ details could be modified in order to obtain a larger workspace. The optimization of geometry and dimensions of the mechanism deserves further investigations. This creates a high potential for geometrical optimization and possibly an enlargement of the workspace.

![Figure 16. Comparison of the effect of the layout of the R-Joints in the workspace of the mechanism](image-url)
4.3 Summary of the Approach

The main ideas of this approach can be outlined as follows:

- Design of a 6DOF serial mechanism from where the rotations about the N-S axis ($\theta$) and E-W ($\alpha$) axis will be managed by assigning rotary motors to the joints that provide those motions.
- Integrate the serial mechanism with the parallel robot in a way that the moving platform of the robot stays concentric and perpendicular to the last link of the serial mechanism (counting from the base)
- Associate, in SOLIDWORKS, dimensions to the joint variables L1, L2 and L3
- Simulate the model for a fixed value of the angle $\alpha$ (aforementioned) and get the maximum value of $\theta$ (aforementioned) that will be achieved when SOLIDWORKS detect any interference. The interference here means any collision between parts of the assembly which means that no more rotation can happen.

- LabVIEW can be used to control the inputs for the angles $\alpha$ without having to stop SOLIDWORKS.

As described in this text, this approach proposes the determination of the workspace of a parallel robot without deriving any equations as that can sometimes be very complex according to the robot that is being studied. Therefore, this approach constitutes a valuable contribution as it is presented as an alternative option to the analytical determination of the workspace.

One important characteristic to remark is that this approach allows the determination of the parallel robot's reachable workspace without having to face any singularity that the parallel robot may present as the workspace is calculated. The motion of the assembly (parallel robot and serial mechanism) was conducted by the serial mechanism, i.e., the actuated joints were in the serial mechanism. It allowed all the joints of the parallel robot to be passive and, therefore, there was no need to solve any problem with the (possible) singularities of the parallel robot.

Knowing the workspace of the mechanism allows one to know what to expect from the mechanism given a certain task. In the next chapter, simulations will be done to analyze the mechanisms working according to the trajectory of the sun relatively to an observer on the earth surface throughout the day.
Chapter 5 Simulations

This chapter will be dedicated to the simulations of the parallel mechanism using NI LabVIEW to monitor the models in SOLIDWORKS. The chapter starts with the planning of the trajectory desired for the robots to perform and ends with the analysis of the behavior of the system when performing the required task.

5.1 Trajectory planning

As it has been mentioned from the beginning of this dissertation, the robots that have been presented here are proposed to orientate photovoltaic panels to allow them to track the sun as the sun’s position relatively to an observer based on the earth’s surface is not constant throughout a day. Therefore, the robot must be capable to perform an angular trajectory that matches the trajectory of the sun relatively to the location of the robot, i.e., that keeps the face of the photovoltaic panel perpendicular to an imaginary line that connects the center of the sun with the location of the panel.

Two approaches can be considered to make the robot track the sun. The first approach consists in programming the robot to move according to a predefined trajectory that is derived from the knowledge of the sun’s trajectory relatively to the desired location. This is an open-loop control
strategy. The second approach, a more complex one, makes use of a communication system based on sensors located on the panel that will “inform” the system about the current position (orientation) of the sun relatively to the panel and make it track the sun. In this thesis, simulations will be done considering the first approach only.

It is possible to program the trajectory of the moving platform by using NI LabVIEW graphical programming. LabVIEW offers two possibilities to program the type of motion desired for sun tracking problem. The first option is to perform the motion with a set of straight lines (where straight lines can be understood as the move from one point to another) connected in series using the NI LabVIEW function _Straight-Line Move_ (Figure 18 (a)). This function uses the coordinate space as the reference frame to perform the straight line whenever more than one axis is presented. The straight line will obviously link two points where the coordinates of the points are given by the coordinates of joint variables in the defined coordinate space [19].

![a) Straight-Line Move Function   b) Contour Move Function](image)

Figure 18. LabVIEW functions for motion programming
Another option to perform the motion is by using the function *Contour Move* (Figure 18 (b)). The contour move function performs a contour along a finite number of points. In fact, a contour is a set of straight lines reunited in one function only. This is a more efficient way of programming a move along several points. To perform a contour move, a table containing the coordinates of the points (joint variables) that form the contour has to be provided. A time interval has to be defined in LabVIEW in order to set the velocity that the mechanism will move from one point to another.

When planning a contour move for sun tracking, this time interval from one point to other depends on the tracking ranges and on the number of divisions of this range, i.e., the mechanism starts moving from east to west with an orientation of \( \theta_{\text{min}} \) and varies its orientation gradually by adding \( \Delta \theta \) when the contour-move jumps from one point to another until the value \( \theta_{\text{max}} \) is achieved. One has to decide the value of \( \Delta \theta \) that will consequently define the time interval knowing previously the time that the “sun takes to rotate from \( \theta_{\text{min}} \) to \( \theta_{\text{max}} \).

As both the Straight-Line Move and the Contour Move functions will need the joint variables it is necessary to know their values for a given orientation of the platform. In other words, this means that the inverse kinematics problem has to be solved first. This can be done Using SOLIDWORKS and LabVIEW together and was already described in the previous chapter and the values of the joint variables L1, L2 and L3 are presented in tables 3 and 4 for the limits of the workspace.

A simple simulation was done by moving the platform from \( \theta_{\text{min}} \) to \( \theta_{\text{max}} \) for \( \alpha \) equal to zero, moving in ten steps. Figure 19 shows the values of the joint variables, used in LabVIEW to program this motion, obtained by applying the procedure shown in the previous chapter. First, second and third column represent L1, L2 and L3, respectively.

The values of the joint variables presented in figure 19 (input) represent the motion of the platform changing its orientation (output) from east to west, starting from the value of \( \theta_{\text{min}} \) and
finishing with the value $\theta_{\text{max}}$ for $\alpha$ equal to zero, both provided in tables 3 and 4 for the 3–DOF spatial parallel mechanism. This means that the platform will not be facing south neither north at any point of the trajectory.

![Contour Move points for a rotation from min to max in ten steps](image)

Figure 19. Contour Move points for a rotation from min to max in ten steps

## 5.2 Control

Figure 20 depicts a scheme that shows how SOLIDWORKS and LabVIEW cooperate to control the virtual system. The system uses PID controllers embedded in the NI SoftMotion axes where the values of the gains are automatically updated as LabVIEW receives the information about the model from SOLIDWORKS (Figure 22). This process occurs internally and one only has to define an error limit as showed in figure 21. This helps to guarantee a good control of the mechanism as it reproduces exactly the required output in the motors to perform the desired motion.
Figure 20. Schematic representation of LabVIEW and SOLIDWORKS cooperating to control the system

Figure 21. NI SoftMotion axis configuration window
Figure 2. PID controller in LabVIEW

Figure 23 is an illustration of the graphical programming in LabVIEW. It shows a program to perform a contour move.
Figure 23. LabVIEW block diagram and front panel programmed to perform a contour move
Chapter 6 Conclusions

As result of the studies carried out by this thesis, a set of conclusions is presented in this chapter. At the end of this chapter recommendations for future works are also presented.

6.1 Contribution

The main conclusions of this work will be focused on the contributions that this thesis added to the field of robotics.

Regarding the integration of SOLIDWORKS and LabVIEW, the following can be concluded:

Using LabVIEW to simulate and analyze a parallel robot CAD model showed to be a very good alternative to explicit mathematical modeling as it eliminates the complexity that is normally associated to the mathematical modeling of systems and also allows the visual monitoring of the system while working through the virtual visualization provided by SOLIDWORKS that is very close to reality.

Physical prototyping of the mechanism can later be done with high certainty of success.
This approach may lead to a reduction on the robot development time.

Regarding the workspace determination and analysis using a CAD – based approach, the following can be concluded:

The CAD – based approach proposed in this thesis for workspace determination of parallel robots worked perfectly and appears to be a good solution for easier determination of the workspace of parallel robot regarding the complexity that analytical approaches may have. One important characteristic to remark is that this approach allows the determination of the parallel robot's reachable workspace without having to face any singularity that the parallel robot may present as the workspace is calculated by actuating the joints of the serial mechanism leaving parallel robot's joints passive.

Regarding the sun tracking with parallel robots, the following can be concluded:

This thesis provided solid foundations for sun tracking using parallel robots as it was presented as a new application for parallel robots. Building prototypes of the robots proposed in this thesis and carrying out a series of real time simulations could help to obtain further conclusions about the topic. Parallel robots present a considerable angular workspace that is suitable for efficient sun tracking.

Larger panels can, through the aid of parallel robot, track the sun and produce more electricity per each unit of tracking system.
6.2 Recommendations for Future Work

- Further studies on the geometry of the mechanism can be done in order to increase the range for tilting the structure, i.e., workspace can become larger through a further geometrical work on the structure.

- The second control strategy proposed on this work was not implemented due to limited time for this work. It is certainly worthy to implement that control strategy to make the control system more robust and operational everywhere in the globe without having to set parameters again as it can be based on the photoelectric detection tracking.

- The virtual reality appeared to be working very well. Therefore, it is worthy to go for the prototyping stage to allow further investigation on the topic.
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