CHALMERS

SKF dual axis solar tracker

From concept to product

MASTER OF SCIENCE Thesis

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The Master Thesis was performed in cooperation with SKF

Cover: An image of the prototype that was built as a part of the Master Thesis

Chalmers Repro Service
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Abstract

There has been a growing global demand for environmentally friendly energy for quite some time now and solar power is one of the definite answers. It is required that solar power becomes more cost efficient in order for it to compete with the conventional energy resources. Even though the greatly declined costs of PV-cells during 2009, when the market saturated, the prices are still too high. The concentrating solar technologies will need some time before they can reach competitive cost levels. Until then solar power will be heavily dependent on the governmental incentives.

The solar market and the solar tracker market have been growing at rapid pace since the introduction of the restructured Feed In Tariff law in Germany in 2000 and they are not showing any signs of slowing down, not even because of the global recession and the PV-cell market saturation in 2009.

The aim of this master thesis project has been to take the Twin Tracker Solar Tracker concept closer to a finished product. The project has focused on design optimization of the mechanical components to maximize the movement range and load capacity of the tracker. The movement from the actuators through the Hooke's joint has also been described theoretically.

To assure that there exists a demand for the Solar Tracker product, a market analysis has been updated continuously during the project. The market analysis identifies the driving factors of the solar energy market and maps the important voice of the customer that is fundamental in all product development.

The project has also delivered a functional prototype to showcase and verify the optimized design. This will serve as a proof of the stated, calculated and simulated azimuth and elevation movement range. The prototype also highlights the product in a practical way and it is planned to be exhibited in different SKF offices, customers and conferences around the globe.

The final steps of industrializing the Twin Tracker are; to design the control system and test a prototype in a real energy production case in order to get actual performance data. If the results are feasible, then the Twin Tracker product is ready to be launched to the solar tracker market.

PREFACE

This product development master thesis project has been carried for SKF AB, by two Mechanical engineering students at the department for Product Development at Chalmers University of Technology. Through this project the students are given an opportunity to show the competence acquired from five years of Mechanical engineering and product development studies at Chalmers. We would like to thank the following persons and companies for their help, participation, time and ideas throughout the Master thesis project:

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Martin Wahlgren	Executive Vice President

For all the ideas and work with the budget offering for the control system.

CONTENTS

ABBREVIATIONS

CAD – Computer Aided Design

CES – Cambridge Engineering Selector

ProE – ProEngineer Wildfire 4.0

CPV – Concentrating Photovoltaic's

CSP – Concentrating Solar Power, includes:
Stirling engine and Dish systems, Heliostats and CPV.

CST – Concentrating Solar Thermal

FEM – Finite Element Method

FEA – Finite Element Analysis

DOF – Degrees of Freedom

IP – Intellectual Property

MC – Mass Centre

OEMs – Original Equipment Manufacturers

PV – Photovoltaic

PV panels – Photovoltaic panels

SLA – Stereo lithography

SWOT – Strengths, Weaknesses, Opportunities, Threats

ROI – Return on Investment

ROR – Rate of Return

FMEA – Failure Mode and Effect Analysis

VOCABULARY

Solar tracker components – all the ingoing components in the solar tracker: Ground Pillar, Top Pillar, Upper Rotational Housings, Lower Rotational Housings, Rotational Joints, Solid Joint, Interface plate and bearings

Concept development project – the student Solar Tracker product development project conducted by six students during fall 2009.

Twin Tracker – The name for the dual axis, two actuator solar tracker developed in this project.

UNITS

GW – Giga Watt

m – Metres

Kg – Kilogram

MPa – Mega Pascal MW

kN – Kilo Newton

MW – Mega Watt

kW – Kilo Watt

SEK – Swedish Kronor

EUR, € - Euro

m^2 – Square meter

INTRODUCTION

BACKGROUND

SKF has together with the Department of Product and Production Development at Chalmers University of Technology initiated the Solar Tracker – From concept to Product Master Thesis. The project focus is industrialization of the Dual Axis Solar Tracker concept that was developed in the Solar Tracker product development project conducted in 2009.

The Master Thesis is conducted by two students from Mechanical Engineering and Product Development at Chalmers together with SKF personnel. The students were also members of the student group that developed the dual axis solar tracker concept.

The master thesis is a continuation of the Product Development Project: Solar Tracker conducted during study period two, three and four 2008/2009. The project was a part of the courses PPU085 and MPP126 at Chalmers Technical University. The deliverable from the project was the Dual Linear Actuator concept; a concept for tracking the sun, in order to maximize the output from Concentrating Solar Power (CSP) and Photovoltaic panels (PV). For a detailed description of the Product Development Project: Solar Tracker, see the Solar Tracker report. (M. Baysal, J. Calvert, J. Fransson, L. Kelly, V. Lindberg, J.P. Mäki, 2009)

PROBLEM FORMULATION

Energy is one of the cornerstones in our modern society. To make sure that we can provide the society with the amount of energy that is required in our everyday life, and to assure that that energy is produced without degrading our planet is one of the hottest political topics and challenges of our time. Solar power is one of the solutions to the problem. The demand for efficient renewable energy systems are growing at very rapid pace, the solar tracker market in particular is increasing with 40 % every year.

There are many different ways of generating electricity from the sun's energy. The most popular are Photovoltaic *(PV)* Panels, where silicon solar cells convert solar radiation to electricity. Keeping the PV-panels perpendicular to the sun’s radiation maximizes the output. The systems that are utilized for this movement are called Solar Trackers. The solar trackers are also a required for concentrating solar power applications to function.

The Solar Tracker product development project delivered a concept for a dual axis tracker consisting of two linear actuators. The concept used linear actuators to create both azimuth and elevation movement in a, to the market new way that was deemed interesting enough to look more into. The next step in the development of the new concept is to prove that the stated movement range can be achieved and that the concept will result in a product that qualifies for the market. This involves detailed design of the concept, simulations and keeping close track on the market development and how the voice of the customer evolves.

PURPOSE AND AIM

The master thesis aims at proving that the concept fulfills the market requirements of the PV and CSP markets. In order to do so, detailed design and optimization work needs to be done. The purpose is to take the Dual linear actuator concept closer to a product level.

GOAL

To optimize the design of the Dual Linear Actuator concept and to evaluate and prove that it qualifies as a cost efficient solution to the market. Highlight this with a new prototype. Define the relationship between the customer requirements and the technical requirements. Also update and continue the market analysis, business case and voice of the customer.

DELIMITATIONS

The delimitations for Master thesis:

- No detailed work on *logistics*
- No detailed work on *marketing*
- No detailed work on *development of sensors or control systems*
- No *programming of control systems*
- Only basic *finite element analysis* is conducted
- Only basic *force calculations* are conducted

DELIVERABLES

The deliverables from the project are:

- A comparison document between the Dual Linear Actuator concepts to existing solutions on the market.
- A market analysis document on the solar power market that is the basis for deriving an analysis for the tracking system market.
- A document with identification of key buying factors for solar trackers.
- A document ranking the Dual Linear Actuator on the market against the competition in terms of performance and cost.
- Optimized mechanical design of the concept.
- Optimize the geometry and the moving parts of the Dual Linear Actuator to minimize the load and the stroke on the actuators.
- A basic model to adapt the tracker offering due to customer requirements.
- A document that qualifies the concept to the market requirements in means of
    - Accuracy
    - Load capacity
    - Durability / lifecycle
    - Product and production cost
- A Business case document.

STAKEHOLDERS BACKGROUND: SKF AND CHALMERS

SKF

The SKF Group is a leading global supplier of products, solutions and services in the area comprising rolling bearings, seals, mechatronics, services and lubrication systems. SKF was founded in 1907 and today, SKF is represented in more than 130 countries with more than 100 manufacturing sites and sales companies supported by about 15,000 distributor locations.

SKF mainly does business through three divisions:

Industrial Division and Service Division, servicing industrial original equipment manufacturers (OEMs) and aftermarket customers as well as Automotive Division, servicing automotive OEMs and aftermarket customers.

The new focus in the SKF organization is green technology; which is to manufacture products that are used to provide the human population with services and energy production that minimizes the ecological footprint (SKF AB).

METHODOLOGY AND EXECUTION

The project has used the following methods and methodologies:

During the development phase methods taught in the product development master program, also described in *H. Johannesson, J.G. Persson and D. Pettersson book Produktutveckling, 2004* has been used. Since this project is a continuation from the concept development project conducted fall 2009, methods like Blackbox, Functional means tree and Morphological matrix won't be used since those are methods used in the beginning of a product development project and not in the late detailed design phase. The product development methods used in this project are:

PROBLEM FORMULATION

When conducting the detailed design of the chosen components, the concept generation is started with a wide and solution-neutral problem formulation.

BRAINSTORMING

To increase the creativity and to make sure that no possible solutions are missed, brainstorming sessions are held during the detailed design work of each component.

PUGH ELIMINATION MATRIX

When all the concepts have been tested against the functional requirements, the final selection process has been done with the Pugh elimination matrix.

The Pugh matrix is used to compare the concepts to an optional reference. The comparison is based on important product criteria; that are not only important to pass but to go beyond. The concepts are then given a plus, zero or negative value that determines if the concept is better, the same or worse than the reference is. The criteria can be weighted to ensure that the more important ones get a higher focus. In the end, the highest ranking concept/concepts is/are selected.

REQUIREMENT SPECIFICATION

A requirement specification is used to assure that no requirements or important wishes are overlooked. The requirement specification for this continuation development project was originally developed for the concept development project and has been updated for this project. The requirement specification is also good to establish as early as possible in the development project and then continually make sure that it is updated and new, unforeseen, requirements are inserted.

MARKET ANALYSIS

The market analysis has been conducted by gathering market data from Magazines, Industry experts, Internet databases, Market Research Institutes and Energy Agancies. The Market analysis has been done to make sure that the project has kept a close track on market development and not missed any crucial market requirements on the product.

Business Case

The Business Case has been done to show that the Solar Tracker product concept has a possibility to make a profit and also to highlight how that profit can be made.

Failure Mode and Effects Analysis

The FMEA is done to asses weak points in the product and possible dangers with the design. It serves the purpose of highlighting what the possible failure modes are and how they can affect the product. It also can be used to prepare proper actions if the failures occur.

Strengths, Weaknesses, Opportunities and Threats analysis

The SWOT analysis can be used on any particular case; such as a business case or a product concept. SWOT highlights the strengths, weaknesses, opportunities and threats. This method is used in the market analysis chapter to realize the important factors that can affect the sales of the Twin Tracker.

Other methods and applications that will be used are:

- Software :
  - Design (ProEngineer for modeling new models and Catia for old models)
  - Finite element analysis (ProMechanica) to calculate stresses
  - Mechanism simulations, for testing the movement: ProEngineer Mechanism
- Usability testing and design for installation
  - To make sure that the product is easy to use and install. A usability test in this case is when two persons assembles and uses the whole solar tracker.

Timeplan

To keep a high efficiency during the master thesis; three forms of planning are used:

- The Project plan is made as a Gantt-schedule; this includes all the important deliverables and deadlines. (See appendix C for Gantt-schedule).
- A bi-weekly schedule is performed to enable short-term planning and discussion about the direction that the project is heading.
- A daily schedule is also performed every morning in order to maximize the output.

Report Outline

This report describes the product development project: Solar Tracker – from concept to product. The report is outlined in a chronological order where the chapters, at large, follow how the project was conducted.

- *The Introduction chapter*

  Gives a basic understanding of why the project was conducted and what the goals are.

- *The Theory chapter*

  Is basic theory about solar energy technologies.

- *The Solar Energy Market chapter*

  Gives an explanation of the solar energy market.

- *THE BUSINESS CASE*

Uses the findings from the market analysis to show the profitability of the proposed Solar Tracker product.

- *THE DEVELOPMENT CHAPTER*

Explains the design work that has been done on the Solar Tracker and also how the final components were selected.

- *THE PRODUCT DESCRIPTION CHAPTER*

Describes the final product concept regarding ingoing components, material choice and cost.

- *THE ANALYSIS CHAPTER*

Follows the product description and explains the FEA and force and wind calculations that have been done on the Solar Tracker.

- *THE COMPETITOR BENCHMARKING CHAPTER*

Gives a example of a cost benchmarking against a market standard dual axis tracker solution and a picture of how the SKF solar tracker product concept qualifies to the market in performance and price.

- *THE ASSEMBLY CHAPTER*

Explains how the proposed product is thought to be installed and assembled in a solar park.

- *THE DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS CHAPTERS*

Gives closing discussion, conclusions and recommendations for the whole project.

THEORY

The theory chapter explains the basics behind the dominating solar power technologies.

SOLAR ENERGY

Production of electricity from the sun's radiation is managed by two different methods; semi-conductor materials and heat driven engines. The semi-conductor method, Photovoltaic, has become the most adopted one. The other technologies are still in varying experimental and testing phases and it is uncertain how well they can be applied commercially.

PHOTOVOLTAICS

Background

Photovoltaics are today the most widespread solar power technology. The first photovoltaic device was demonstrated as early as 1839 by the scientist Edmond Becquerel. The PV cells have dropped rapidly in price lately and the main cost-driver of these products is predicted to be the material cost. (SPIRE corp, 2010)

Technology

Solar cells are made of semi-conductor materials. They act as insulators when only low temperatures are available but at higher temperatures they act as conductors. This technology can be described with two models: the bond model and the band model (Stuart, Martin, Muriel, & Corkish, 2007)

The Bond model states that at low temperatures the bonds in the material are intact. But as the temperature rises the bonds are broken and electrons are free to move. These movements are realized by two different processes; see the arrows in *Figure 1*:

1. Electrons from broken bonds are free to move.
2. Electrons from neighboring bonds are free to move.

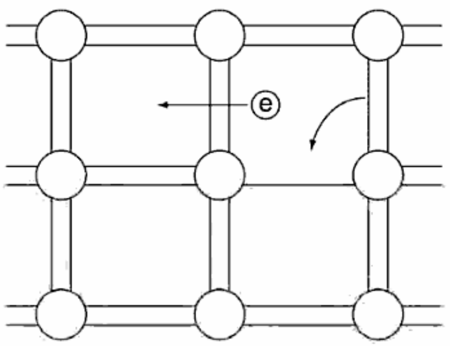


Figure 1 Shows the bond model. (Stuart, Martin, Muriel, & Corkish, 2007)

The band model states that the electron movement depends on the energy levels inside a material. When enough energy is contributed, the electron can move across the gap, *Figure 2*

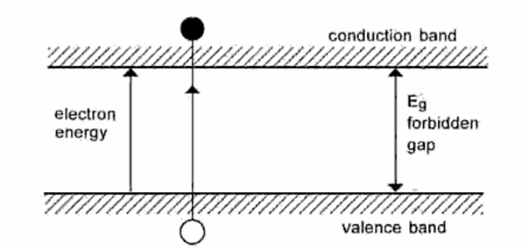


Figure 2 shows the band model. (Stuart, Martin, Muriel, & Corkish, 2007)

CONCENTRATING SOLAR POWER

There are many different technologies in the field of concentrating solar power. Of these, only parabolic through has had a major impact on the solar power market. The other technologies have not yet been adopted in any significant way. (Photon magazine, 2009)

Stirling engines

Background

The main advantage of Stirling engines are that they can be driven by any heat source. This means that there exists a wide variety of energy sources such as solar energy and biogas to drive these engines. The Stirling engines were utilized to create electricity from the sun as early as the seventies (Lindsley, 1978). However these systems have had a high cost because of their relatively complex supporting system and are still being investigated for their [electricity production/ cost] quota. In January 2010 Tessera solar and Stirling Energy Systems *(SES)* completed an installation of two solar power plants utilizing a Stirling-Dish system created by SES. Now SES expects to ramp up their volume production in late 2010.

Technology

The Stirling engines are based on gas expansion and compression through heat-transfer. A gas or liquid is expanded by transferring heat into the system, this expansion drives a piston to move. The excess heat is then transferred out from the system through a cooling unit. There exists many piston and gas/ liquid configurations but the basic principle of the function is the same.

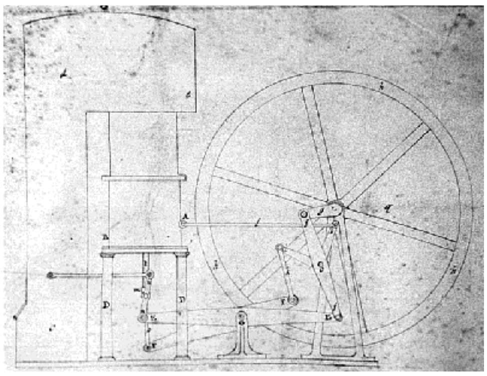


Figure 3: Original drawing of the Stirling engine made by Robert Stirling in 1816.

Naturally, in solar power applications, the heat source is the sun. The sun is reflected into the engine's heat exchanger using a parabolic mirror. As an example; mirrors of 80 m^2 have the capacity of creating temperatures up 800-900 degrees Celsius (Cleanergy).

Concentrating Photovoltaic's

Background

According to Roger G. Little, founder of Spire corp., the material cost will dominate the photovoltaic cell production cost in the near future. A means of reducing this cost is to concentrate the solar irradiation onto a smaller photovoltaic cell. These small high efficiency cells are more expensive but also contain a theoretical 40 % efficiency. These values have however only been reached in laboratory tests (Kalogirou, 2009).

Technology

Solar irradiation is focused onto the cell by utilizing a lens. These cells utilize triple junction design in order to capture a larger spectrum of the solar irradiation and are therefore more complex and expensive. CPV does not have a large market share today, but this is expected to change since the price per watt ration is lowered progressively by continuous improvements in the technology (Kalogirou, 2009).

Because the sun needs to be focused on a small area, this type of technology requires a dual-axis tracking system with a decent accuracy. The accuracy that is required is heavily dependent on the design of the concentrating system.

Heat affects PV- cells negatively. Their lifetime is decreased as well as their efficiency, this is of high importance because the irradiation is concentrated on the small cells and it increases their temperature. A direct consequence is that the system requires either passive or active cooling, further increasing their cost. (Kalogirou, 2009).

Power towers

Technology

Power towers create electricity by utilizing turbine working on a regular rankine-cycle. The irradiation is focused on a heat collector that is situated on top of a tower see *Figure 4.* The focusing is realized with hundreds or thousands of mirrors which are equipped with dual axis trackers (NREL, 2003).

The heat collector transfers the heat into salt which melts from the high temperatures. This melt is then transferred through a heat exchanger that transfers the heat into water, creating superheated vapor that drives turbine/s.

Figure 4: Solar Two, Heliostat power tower plant in Mojave dessert. (Newenergyportal)

Parabolic trough

Background

The parabolic through technology is the second most commonly adopted solar power technology. There are many facilities planned for the near future. In Spain 34 and in the US 29 parabolic through plants are under construction (Photon International, 2009)

Technology

This technology also utilizes a conventional Rankine-cycle turbine for electricity generation. The solar irradiation is focused by parabolic mirrors onto a pipe that transports a liquid. The collectors have one axis tracking in order to improve the efficient uptime of system; the tracking is managed around an axis that is located north to south. This will enable tracking the sun from East to the West.

The heated liquid transfers the collected heat in a heat-exchanger creating superheated vapor that enables the turbine/s to be driven.

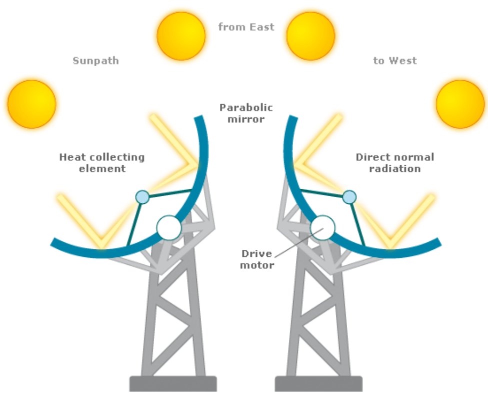


Figure 5 describes the parabolic through technology. (Radiant and Hydronics, 2006)

TRACKING SYSTEMS

The main function of all tracking systems is to provide one or two degrees of freedom in movement. This movement is utilized to keep the system directed towards the irradiation in a desired way. The main tracking types are described closer in the following chapters.

There exists a wide variety of solutions to fulfill the functional requirements. The different solar power technologies demand different solutions with varying accuracy and a general rule in what type of tracking system works best is difficult to define.

The elevation angle considers the height in which the sun can be seen on the sky. The reference plane used to define the angle is often the actual plane that the observer stands on. The azimuth angle considers the movement of the sun across the sky, from east to west. Also this movement is described from an observer's point of view on the ground.

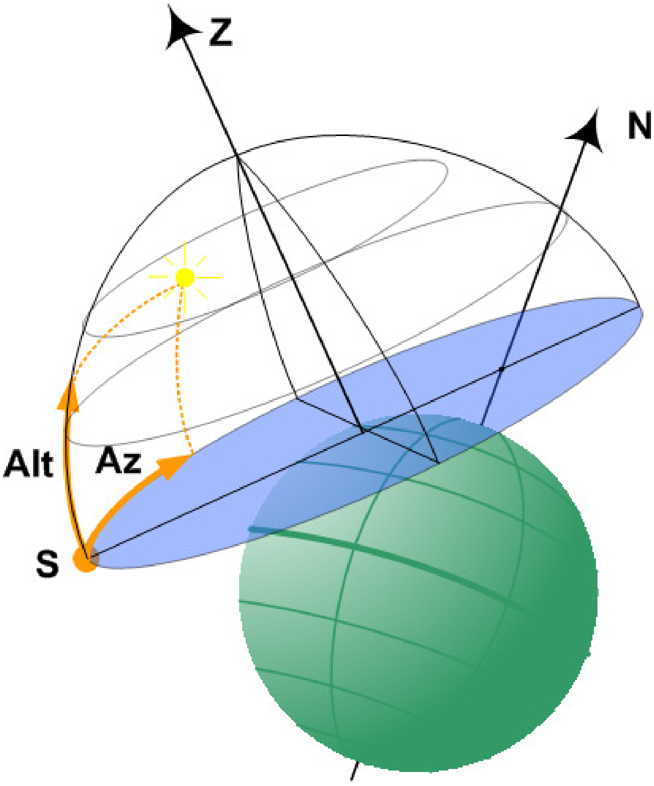
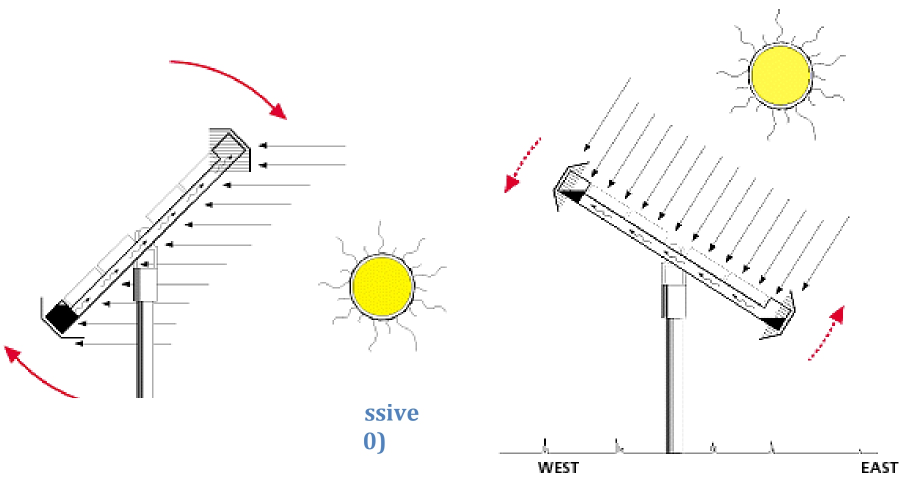


Figure 6: Shows the azimuth and elevation angle. In this figure the elevation angle is denoted as Alt. (wikimedia commons, 2007)

PASSIVE TRACKING SYSTEMS

The passive tracking system realizes the movement of the system by utilizing a low boiling point liquid. This liquid is vaporized by the added heat of the sun and the center of mass is shifted leading to that the system finds the new equilibrium position (Zomeworks, 2010).



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SINGLE AXIS TRACKING SYSTEMS

The single axis tracking systems realizes the movement of either elevation or azimuth for a solar power system. Which one of these movements is desired, depends on the technology used on the tracker as well as the space that it is mounted on. For example the parabolic through systems utilize the azimuthal tracking whereas the many rooftop PV-systems utilize elevation tracking because of the lack of space.

DUAL-AXIS TRACKING SYSTEMS

Dual axis tracking systems realize movement both along the elevation- and azimuthal axes. These tracking systems naturally provide the best performance, given that the components have high enough accuracy as well.

EARTH'S MOVEMENT

The relationship between the suns energy and the earth is a fairly complex one. The earth's path around the sun has been closely mapped and many descriptions of these movements exist. Some are heavy approximations whereas some are very exact and the equations rely on gathering the latest measured constants.

The apparent position of the sun depends on how earth rotates around the sun and how it revolves around its own axis. The path around the sun is not circular, but slightly elliptic which affects the distance to the sun. Also the axis of which earth rotates around is slightly tilted; 23,4 degrees. The tilt is called the obliquity of ecliptic and it causes the seasons in the northern and southern hemispheres. See Figure 8 below for the effects of this tilt.

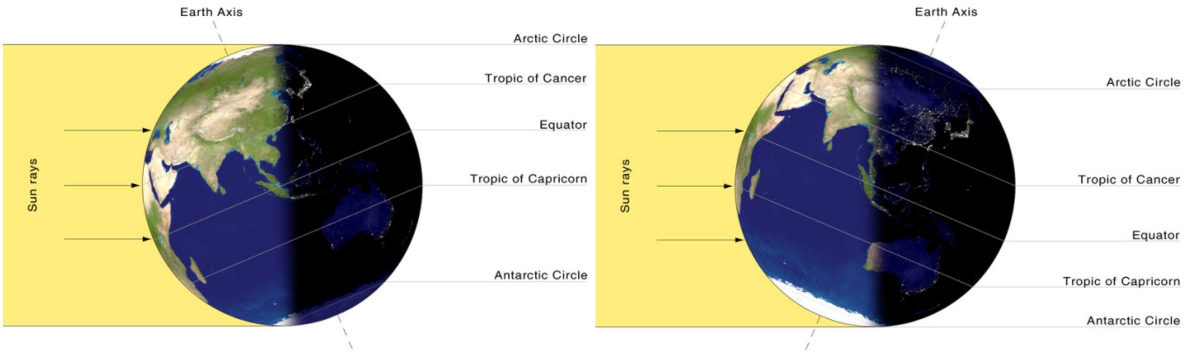


Figure 8: The effect of the obliquity of ecliptic. To the left is the summer season for example Europe. To the right it is the summer season for Australia. (wikimedia commons, 2007)

SOLAR ENERGY MARKET

This market analysis aims to create understanding of the solar tracker market by analyzing the solar energy market as a whole. The CPV and Heliostat technologies are maturing quickly which may change the market in the near future. Also the different political control measures, such as feed-in tariffs [1]and incentives, can rapidly make new markets emerge.

The solar energy market analysis focuses on the global market, the key players on that market and the key buying factors that affect the market.

THE GLOBAL MARKET

The global solar energy market is dominated by photovoltaic (PV) solar technology. The other four big technologies are Concentrating PV, Parabolic through, Power towers and Stirling Engine concentrating solar power.

The market is also, at the moment, dominated by two countries namely:

- Germany
- Spain

Japan also has some 2.15 GW of installed solar energy capacity but the installment rate in Japan has been lower than expected the last couple of years. There are many other rising stars, aspiring to become the market leader in installed capacity such as: the giant USA, People's Republic of China, India, Italy, Greece, Portugal and Korea. But they are each still far under 10 % of the market, with USA and Italy trailing closest.

CUMULATIVE INSTALLED CAPACITY

Global cumulative installed capacity of today is approximately: 15 GW (European Commission Joint Research Centre, 2009). The vast majority of installations made up of PV modules. CPV, Heliostat and Stirling systems still only make up a couple of 100 MW of the total market size.

The solar energy market has seen tremendous growth the last five years and much is because of the government introduced FIT's. The market has grown from a couple of 100 MW in the beginning of year 2000 to todays staggering 15 GW installed capacity. The most stunning increase in installment rate is Germany which in 2000 had a small annual installment rate of 70 MW which has grown to 4 GW in 2009. (Photon Magazine April 2010)

FUTURE FORECASTS

Solar energy will continue to grow huge new markets as USA, China and India pick up the pace. The market leaders of today, Spain and Germany are also expected to continue growing but the new markets have all the right geographical and political opportunities to be the new capacity leaders in the near future.

To forecast the development of the solar energy market scenarios from the International Energy Association, Greenpeace and the European Commission are summarized below.

[1] Feed-in tariff (FIT): A feed-in tariff involves the obligation on the part of a utility to purchase electricity generated by renewable energy producers in its service area at a tariff determined by public authorities and guaranteed for a specific period of time (generally 20 years).

Table 1: IEA, EC and Greenpeace future installation capacity scenarios approximated in 2008. (IEA, 2009) (European Commission Joint Research Centre, 2009) (Greenpeace, 2010)

Year and Capacity	2000 [GW]	2010 [GW]	2020 [GW]	2030 [GW]	2050 [GW]
Geeenpeace (reference scenario)	1	10	50	86	153
Geeenpeace ([r]evolution scenario)	1	21	270	920	2900
Geeenpeace (advanced scenario)	1	21	290	1500	3800
IEA Reference Scenario	1	10	30	60	-
IEA ACT Map	1	22	80	130	600
IEA BlueMap	1	27	130	230	1150
European Commision (Current)	1	8	125	920	-
European Commision (Advanced)	1	21	211	912	-
European Commision (Moderate)	1	25	278	1864	-

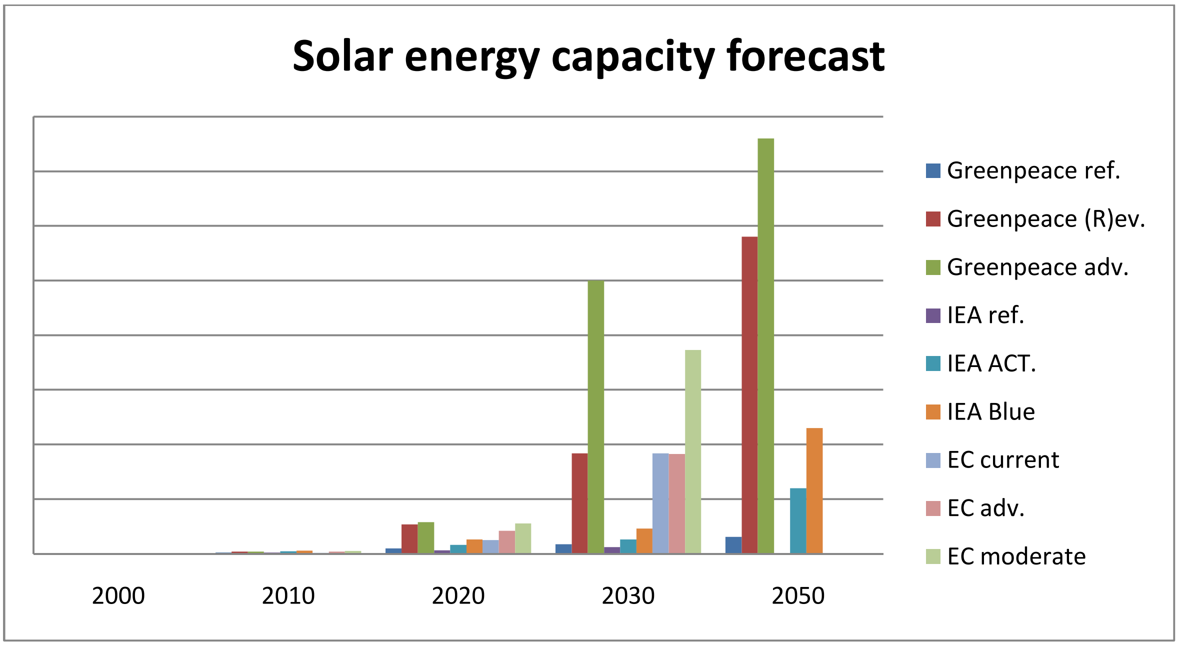


Figure 1: Forecasted solar energy capacity. (Greenpeace, 2010) (IEA, 2009) (European Commission Joint Research Centre, 2009)

As seen in the forecasts, all scenarios show continued large growth for the solar energy market. Although the most aggressive scenario forecasts a staggering 3.8 TW of installed solar energy capacity by 2050, one should keep in mind the aggressive and unexpected growth the market has seen so far. When the Prometheus Institute for example in 2005 forecasted the market to increase to 10 GW in 2010; it was seen as very aggressive but it turned out to be just what happened.

The development of the energy market is highly affected by political, technical and business factors that all are addressed in sub-chapter; *Key Buying Factors.*

GEOGRAPHICAL MARKETS

The different solar energy markets are divided into their respective geographical area. These descriptions include all technologies, their present status and future forecasts. This information is the basis for analyzing the tracker system market.

ASIA

The Asian solar energy market is very varying due to the different prerequisites for the manufacturing and installation of solar energy. Many countries such as Peoples Republic of China and India have experienced massive economical growth. This type of growth requires a very quick installment of electricity production to supply the need. China has become very dependent on coal and India is very dependent on oil import, the importance to have efficient energy processes as well as to use renewable energy has been realized not only by these nations, but by all the nations included in this report.

The most interesting about these nations is that they posess great possibilities for a future market because of either experience or a great manufacturing capacity of the different PV – technologies.

JAPAN

The Japanese market had well defined goals formulated from 1997; the end result however has fallen short of the expectations. By the end of 2008 the goal was to have 4.8 GW installed solar energy, but only 2.15 GW had been installed. To counter this slow progress; new goals were formulated as well as new methods in order to bring results forth. Feed in tariffs coupled with the new subsidies cover systems that have a complete cost-range of 10.000 – 100.000 ¥ (559 – 5590 €)((European Commission Joint Research Centre, 2009) The trend in Japan is to install PV-modules on houses, this trend seems to continue. The Japanese 2030+ plan states that it is intended that smaller houses utilize the electricity generated from the sun until 2020. This coupled with the strong trend to install PV-modules on houses will make the market for higher efficiency systems such as Stirling-engine and CPV-systems small. Considering the constraints that the cost range for the subsidy and the actual integration with a building forms; the Japanese market seems only open for smaller trackers.

The future however might favor CPV systems because the 2030+ plan clearly states that a high amount of effort is to be spent on researching highly efficient PV panels.

CHINA

The economical explosive growth that China has had will by estimates result in 2.5 times higher energy consumption by 2020, compared to the year 2000 (European Commission Joint Research Centre, 2009). This increase has coupled with the crisis that the Chinese PV-module production is experiencing has triggered incentives to install renewable energy at a much quicker pace than earlier stated. The original plan was to have 1% of the consumption from renewable energy sources, but 2005 the value was boosted up to 10%. The effects of this will surely impact the amount of installed PV greatly since China possesses the largest manufacturing of capabilities PV-technology in the world (European Commission Joint Research Centre, 2009).

China became is the largest manufacturer of PV technology with an estimated manufacturing capacity of 8.9 GW by the end of 2009. However the Chinese export business started to suffer during 2009 when the supply for PV-modules became larger than the demand. To partly counter the effects the decreased export and to reach the stated renewable goal; the Chinese ministry of finance formulated a plan to have 20GW installed PV technology by the year 2020. However, the documentation for this plan does not include any information of feed in tariffs, or the maximum or minimum values to be installed per year. This political indecisiveness may lead to Chinese domestic market gets confused about what can be expected from the government in stimulus. However if the tariffs are stated clearly alongside with the guaranteed time-plan for the tariffs, then the market has the expected to grow quickly.

South Korea

The strong incentives South Korea formulated in 2006 made the market boom during 2008 when 278MW was installed. Compare this to 2007 when approximately 48 MW, this means an almost six fold increase. In order to get control of the installment pace, the feed in tariffs were adjusted and a maximum cap was introduced. From now on the market is awaited to grow more steadily; 98 MW in 2009, 132 MW in 2010 and 160 MW in 2011 (Solarplaza, 2009).

The *one million green homes* program intends to install renewable energy to one million homes. As a part of this program, smaller rooftop systems will be installed. The exact amount of rooftop PV systems is uncertain since all areas will be provided with different technologies (Global Solar Thermal Energy Council, 2009).

Also the larger installations are not in the scope for South Korea. According to the new feed in tariffs in place, the support will be lessened for systems larger than 3MW (PV-tech, 2009).

India

India has been one of the fastest growing economies for many years, only slightly slowed down by the financial crisis. The energy consumption has risen alongside the economic growth and will keep rising greatly in the future. Today India gets approximately 53 % of its energy from coal and 31 % from oil, while the renewables alongside with hydroelectricity forms a mere 7 %. A difficulty with the quick growth has been to offer stable electricity, today 70 % of the villages and cities suffer from regular blackouts. Also approximately 40 % of the citizens still do not have electricity (IEA, 2009).

Even though India is the sixth largest oil consumer in the world, they lack any significant production for their own. This makes them very dependent on import. In order to provide electricity for cities and businesses, the Indian government has stated goals of installing 20 GW of solar energy by the year 2020. For this to be reached, SolarPlaza (SolarPlaza - The Indian PV market report, 2010) states that the market is required to grow 68 % annually until 2020, setting a future stable market.

The actual size of the installations is difficult to predict since these will partly be off-grid as well as grid connected and will be built on demand in many cases.

Europe

In June 2009, The European Union's framework for renewable energy strategy came to effect. The purpose of this strategy is to make sure that all members reach their obligation of having 20 % of the consumption to come from renewable energy (European Commission Joint Research Centre, 2009). The effect of this will surely become evident for the solar energy market. The PV Status Report 2009 continues to state that during 2009 the total installments of new solar energy in Europe was 4.59 GW PV (19 % of new installments) and 100 MW (0.4 % of new installments) CSP.

Of the total amount of installed solar energy, the most is in Germany and Spain. The reason for this dominance is the incentives that the respective governments enforced to boost the solar energy market. As of the end of 2009, 17 of the member countries of the European Union have introduced feed in tariffs. The specific amounts and the guaranteed time that these tariffs are paid vary between the countries (European Commission Joint Research Centre, 2009). Investing in solar energy is going be a very lucrative business in Europe, the same kind of growth that Germany had is expected to apply to many other countries in the near future.

GERMANY

The German market is difficult to assess because of the lack for a register of the installed amount of solar energy. This kind of register was put in effect during 2009 and therefore future information will be precise, as the reported 3.8 GW installed PV power in 2009 (Germany's Federal Network Agency, 2009). Total installed capacity in Germany in the end of 2009 is 10 GW (Photon Magazine April 2010).

According to Norbert Röttgen (Photon magazine, 2009), the Feed in Tariffs in Germany market are to be adjusted. How the cuts will affect the solar energy market is unknown, but FIT's will probably be adjusted to the lowered PV-module prices (Green Tech Media, 2009). The outcome of the proposed cut is still unclear since the magnitude of the downward adjustment is still under discussion. The latest draft however shows that the cuts are *"... rather moderate and won't impact growth dramatically this year – at least if the latest draft is passed."* according to an editorial in the April issue of Photon Magazine by Editor in Chief Michael Schmela. Considering how stable the German market is, see Figure 9 below, it does not seem probable that it will get affected largely by these adjustments. It is fair to assume that the market demand in Germany for 2010 won't be less than in 2009. The fact that the total installed solar energy capacity in Germany is approaching the 20 GW mark makes solar start reaching a level where it is big enough to have significant effects on the stability and pricing of the country's energy supply. (Photon Magazine April 2010).

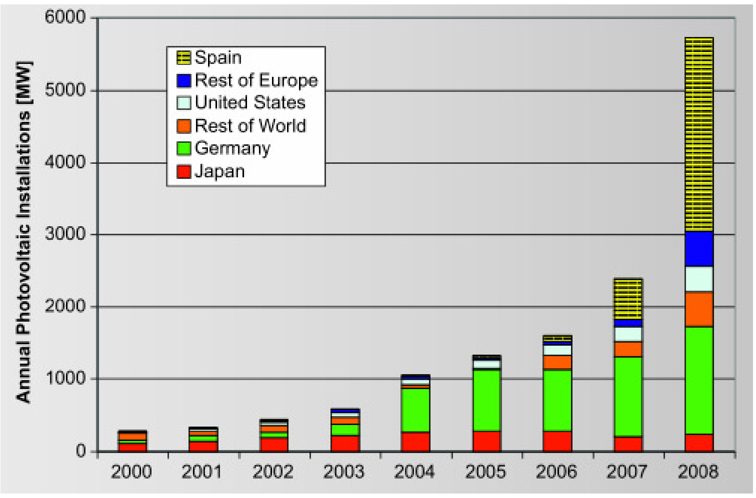


Figure 9: The annual installed PV capacity in the world 2000-2008. This graphs clearly shows how the German market has been stable since 2004. The values for 2009 are not included but they are expected to be around 1.5 GW. Source : (European Commission Joint Research Centre, 2009)

Spain

Spain increased its solar energy installation capacity greatly during the period 2006 – 2008. This large increase was due to the *Plan de Energias Renovables en Espana* (Energía, 2005). This incentive was coupled with generous financial aid which has lead to a dramatic increase of solar energy, from 560 MW in 2007 to 2.7 GW in 2008. After this rapid increase, a maximum annual installation amount of 500 MW was introduced. These new regulations also include that two thirds of new installations is required to be roof-top mounted and that no more free field systems may be installed. The outcome of these new rules will in smaller and simpler installations that probably are cheaper than the earlier ones.

Italy

Since the Feed in Tariffs in Italy went into play in 2005, the installed energy has reached to around 900 MW in 2009 (European Commission Joint Research Centre, 2009). The largest portion of these installments has come since 2007, when the goal of having 3 GW of installed power from PV by 2016 was stated by the *Gestore del Sistema Elettrico* (GSE, 2005).

The future looks bright for solar energy in Italy with the 3 GW of installed power goal and the guaranteed feed in tariffs for 20 years, with a 2% deviation for new systems each year.

France

France has not yet managed to install a substantial amount of solar energy. The Feed in Tariffs only managed to interest investors to install 20.4 MW by 2008. During 2009, 44.3 MW was installed, these relatively low amounts made France boost its goals to have 5.4 GW installed PV by 2020 (European Commission Joint Research Centre, 2009).

The Feed in Tariffs are legit until 2012, when they will be revised. Considering that there are no size obligations (minimum or maximum) to meet for the PV installations to enjoy these incentives, makes this a very lucrative opportunity to invest in solar energy.

Greece

Greece is making good progress to start the installment of PV energy. Today the installed base is very small approximately 20 MW (European Commission Joint Research Centre, 2009). But since the Feed in Tariffs, which started in January 2009, over 3GW of installations have been applied for but not yet processed. The FIT's are guaranteed for 20 years, for installments that cost more than 100.000 € which will give a solid base for larger installations. Also measures have been taken for smaller rooftop installations; these do not have any limitations to the size or the amount of installations per year.

How much the Greek market will grow is difficult to predict since no official goal on the desired amount exists yet. But legislation from 2006 states that 20.1 % of the energy consumption should come from renewable sources (CRES, 2006). How much of this energy should come from PV installations is unknown.

USA

In 2008 the US market grew with 342 MW installations to an installed capacity of 1.15 GW PV (European Commission Joint Research Centre, 2009). The US market is also expected to grow 50% annually and reach 5 GW installed capacity in 2013 (SPIRE corp, 2010).

The solar market in the USA is, as the rest of the world, dominated by PV. But the American market also has much focus on Heliostat, Stirling and CPV systems. With Stirling Energy Systems (SES), the US is also the technology leader in Stirling concentrating solar power. There are also a stunning 6 GW CSP systems, among many Stirling systems, with signed power purchase agreements waiting to be built (CleanEdge, 2009).

It also needs to be clear that the US market is not even close to its full potential. It is a huge market considering the energy consumption coupled with good geographical prerequisites for solar energy. A lot of things have happened politically the last years; with the Energy Bill, aimed at solving the growing energy problem, being passed in 2005 and many government and state incentives being passed after that. For a description of incentives and subsidies see the online Database of State Incentives for Renewables & Efficiency: www.dsireusa.org.

Solar energy is also covered in president Obama's American Recovery and Reinvestment Act of 2009. The act states that solar energy investors can apply for investment tax credit, loan guarantee and tax incentives.

Other markets (Africa, Australia)

The African and Australian markets are still very small in relation to their sun irradiation potential.

Africa

Interesting countries that can be mentioned in Africa are Nigeria, Israel, Egypt and Morocco. Israel did in August complete its first megawatt-scale PV system (Photon Magazine, 2009). Nigeria is also developing a new FIT system that aims at installing 75 MW by 2015 and 500 MW by 2025. (Photon Magazine, 2009).

Australia

The Australian solar energy market has been affected by many new and rapidly changing government incentives. Australia has very good geographical possibilities and still is trying to live up to its potential. Total installed capacity was in 2008 only 105 MW according to information from the Australian PV Association. (Photon Magazine, 2009). Australia is for the future looking into possibilities to build large scale solar power plants and after the small boom in 2009, this year will be a test to see where the Australian market is heading.

Jobs and price development

For every produced MW,10 jobs are created For every installed MW, 38 jobs are created. The solar energy manufacturing and installation occupy approximately 100.000 employees in Europe alone, which is a substantial amount of people.

Approximately 80 % of the current PV technology is based on Silicon and the recent material shortage has shifted focus to developing methods to both increase efficiency and minimize to material consumption, according to Roger G. Little CEO of Spire corp. The production costs for PV-modules are 86 % material based.

Due to fierce competition, the cost per watt needs be reduced. Many R&D efforts are made to both minimize the material requirement for production and to raise the efficiency of the modules. The material shortage also made companies to realize the benefits of thin film PV and CPV. Both of these technologies are expected to gain a considerably larger market share.

Solar Trackers

The solar tracker market is directly coupled to the development of the solar energy market. The market drivers for the different technologies differ since PV panels do not require a tracker to function but Heliostat, Stirling and most CPV systems do. In order to highlight the different markets PV is analyzed separately from the other prioritized technologies.

Photovoltaic panels

For PV panels, the tracker market has seen huge growth the last five years and this has also driven the development of many diverse tracker solutions and technologies. In the PV market however trackers face a big challenge since PV modules do not require a tracker to function. This means that the amount of increased energy that is produced because of the tracker needs to give a profit that is bigger than the cost of the tracker compared to just buying more panels.

The competitiveness of a PV tracker has been affected negatively the last year because of the rapid drop in PV panel prices. The price drop puts a direct demand on reduction of the tracker prices, so that the investing in a tracker system makes economical sense.

The requirements on the trackers for the PV market are also quite different depending on the application. Trackers for big, open field solar farms are very different for smaller commercial roof-top installations.

The PV tracker market is, by far, the largest tracker market and it has through the years been fueled by FIT's and incentives. The FIT's ensures the utilities the possibility to sell the solar energy to a high price, has given trackers a big advantage. The trackers deliver at best approximately a 40 % efficiency increase. With a high energy price, the payback of the tracking systems are easily fulfilled. This said however, now with talks of lowering the FIT's in Germany and changes also happening in Spain, the PV tracker market is really up for the test of producing smarter systems with lower cost.

Heliostat, Stirling and CPV

For the other prioritized technologies the market for trackers looks very differently since the tracker is required. This is of course very good for the overall market but the cost/efficiency comparison here against competitors is always very important.

The market for Heliostat, Stirling and CPV are mostly large solar parks. Stirling and Heliostat technologies also require a minimum amount of sun irradiation [W/m^2] to be able to function at all. Which is why the most interesting market for these technologies are sun intensive areas such as parts of the US, Spain, Africa, India and Australia.

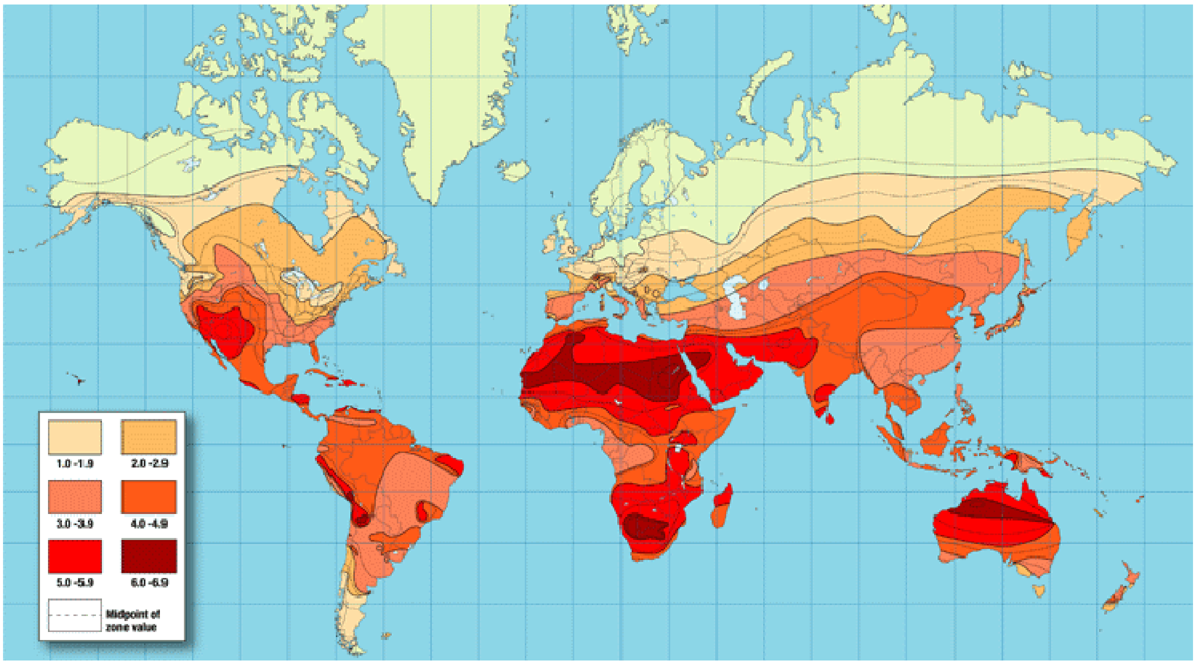


Figure 10 Amount of solar energy in hours, received each day on an optimally tilted surface during the worst month of the year. Source: SunWize Tehnologies.

One technical aspect that differs a lot between the tracker market for Heliostat, Stirling and CPV and the PV tracker market is the precision requirement. For PV, precision of the tracker is not really an issue. But for Heliostat, Stirling and CPV high precision is a requirement otherwise the system will not function at all and vital parts could also be damaged by misdirected heat.

Key Buying Factors

To be able to develop and sell a product it is important to understand what factors that are influencing the customer's choice of product. It is even more important to understand and identify the *key* factors that the customer is interested in and uses to compare products.

For the solar tracker market the buying factors differ depending on which of the four prioritized technologies that are analyzed. These technologies are:

- Photovoltaic's
- Heliostats
- Stirling Engine and Dish (Concentrating Solar Power)
- Concentrating Photovoltaic's (CPV)

In order to highlight the factors for each technology in an understandable way, a table for each of the four prioritized technologies was created. These tables identify the buying factors that influence the solar tracker product in the respective market area and also give an approximated ranking of the factors. The factors are also categorized into three categories:

- Business
- Technology
- Political

The key buying factors are the ones with the highest ranking and are also summarized in the beginning of each sub-chapter.

The Political factors however affect the four different technologies in the same way and therefore they are listed here to avoid repetition.

POLITICAL

Here the key political buying factors for all the four technologies are listed.

Feed in tariff (FIT)

A feed-in tariff involves the obligation on the part of a utility to purchase electricity generated by renewable energy producers in its service area at a tariff determined by public authorities and guaranteed for a specific period of time (generally 20 years). FIT's has been the single most important driver for the development of the solar markets worldwide, since it basically guarantees the return on investment for utilities investing in solar parks.

Subsidies

Government subsidies are important factors since they can have big effect on the solar market as it can make investments in solar parks more profitable.

Will to achieve energy independence

The political will to achieve energy independence is one of the driving political factors for granting feed in tariffs and subsidies for solar energy.

Environmental public opinion

The public opinion for renewable energy such as solar energy is also of the driving factors for the political investments in solar energy.

PHOTOVOLTAIC'S

Here are the key buying factors for the Photovoltaic's solar energy market addressed and explained. All identified buying factors are also listed in Table 1.

BUSINESS

Price of trackers compared to delivered output

The price of the tracker compared to the gained profit from the higher electricity manufacturing is a very important buying factor. Since this profit is the basis for calculation of the return on investment. For example if the tracker increases the energy production with 40 % the cost of the tracker compared to cost in just buying new panels need to be less than 40 % of the panel and panel installation price. Off-course sometimes also available space also is an issue, where putting up more panels on a building or field just is not possible. Then investing in trackers could be the only solution to increase the energy production of that installation.

Price of PV modules

The market has changed for PV; for the moment PV modules have a larger supply than demand. This has natural effect of reducing prices on PV modules which puts a requirement on the tracker systems to also decrease in price.

Prices of competing solar energy technologies

The price of competing solar technologies will directly affect how attractive the PV technology is.

TECHNOLOGY

Quality of the product

The perceived quality of a tracker plays a great role as a buying factor. These systems have an expected lifetime of 20-25 years. The product design needs to display this kind of robustness.

Efficiency increase

The efficiency increase is a common criterion that is displayed when promoting trackers for PV. It makes it easy for customers to quickly compare trackers, which makes it an important factor. The efficiency increase of the PV system from the tracker is dependent on the accuracy and range of angles that the tracker can produce.

Table 2: Buying factors for the trackers for the PV-market.

Buying factors for trackers for Pv-market					
Business	**Rank**	**Technology**	**Rank**	**Political**	**Rank**
Price of trackers compared to delivered output- complete system price	5	**Design options -** Customize the system to different market demands	2	**Legislation -** Force utilities to invest in renewable energy	4
Grid parity comparison	4	**Quality**	5	**Subsidies**	5
Price of land & land availability - Compare the total plant cost with and without trackers	4,5	**Installation support -** Offer qualified subcontractor for installation	3	**Will to achieve energy independence**	5
Price of PV panels	5	**Test facility that verifies claims -** Increased efficiency and angle-ranges	4	**Environmental public opinion**	5
Brand Name - How the brand name increases attraction of the product	4	**Cheap dismantlement costs**	1	**Grid connection availability**	3
Service - Offer solutions prior and after installation	3	**Easy maintenance of the tracking system**	3	**Feed in tariff**	5
Geographical area - W/m² and amount of sun days	3	**Customer familiar components**	3		
Other cheaper energy options - renewable and non-renewable competing energy	4	**Customer familiar solution**	3		
Price of competing solar energy technology	5	**Low total environmental impact**	1		
		Efficiency increase	5		
		Logistics	4		
		Volume production capacity	4		
		Easy, fast and cheap installation	4		
		Possibility to facilitate other technologies such as radio base stations	1		
		Possibility to facilitate both heat and electricity production	1		
		Easy maintenance for the PV-system	1		

Heliostats

Here are the key buying factors for the Heliostat concentrating solar power market addressed and explained. All identified buying factors are also listed in Table 2.

Business

Price of complete system [$/W]

This is a measurement of how much money the investor needs to pay per watt installed capacity. This factor is affected by the price of the complete system i.e. Heliostat tower, trackers, mirrors and installation, compared to the amount of energy the system will deliver. A Heliostat CSP system cannot function without a tracker system which is why the price of the Heliostat tower, mirrors and tracker system are not cost compared individually. The $/W is an easy way of comparing different energy technologies.

Price of competing solar energy technology

The price per watt of other competing solar energy technology is always an affecting factor, if other technologies are cheaper in the $/W comparison then they are preferred.

Technology

Here the key technology buying factors are listed.

Accuracy – resolutions of the system

The accuracy of the tracker system is vital for the function of the Heliostat power station. The tracker needs to be able to follow the motion of the sun very precisely so that the focal point always is kept in the center of the Heliostat tower. If the focal point misses the tower no energy will be produced.

Range of angles - Azimuth and Elevation

The range of angles that the tracker system can fulfill is important so that the mirror can follow the sun during the entire energy production day and focus the sun irradiation to the Heliostat tower.

Quality

The quality of the tracker is also very important so that it will last the whole lifetime of 20-25 years.

Table 3: Buying factors for trackers for the Heliostat-market.

Buying factors for trackers for Heliostat market					
Business	**Rank**	**Technology**	**Rank**	**Political**	**Rank**
System price compared to delivered output [$/W] - Complete system price.	5	**Design options** - Customize the system to different market demands	2	**Legislation- force utilities to invest in renewable energy**	4
Grid parity comparison	4	**Quality**	5	**Subsidies**	5
Brand Name - How the brand name increases attraction of the product	4	**Installation support -** Offer qualified subcontractor for installation	3	**Will to achieve energy independence**	5
Service - Offer solutions prior and after installation	3	**Test facility that verifies functional claims**	4	**Environmental public opinion**	5
Geographical area - W/m² and amount of sun days	3	**Cheap dismantlement costs**	1	**Grid connection availability**	3
Price of competing solar energy technology	5	**Easy maintenance for the tracking system**	3	**Feed in tariff**	5
		Customer familiar components	3		
		Customer familiar solution	3		
		Low total environmental impact	1		
		Logistics	4		
		Accuracy - resolutions the system	5		
		Range of angles - Azimuth and Elevation	5		
		Volume production capacity	4		
		Easy, fast and cheap installation	4		
		Possibility to facilitate both heat and electricity production	1		
		Easy maintenance for the mirror	1		

Stirling Engine concentrating solar power

Here are the key buying factors for the Stirling Engine concentrating solar power market addressed and explained. All identified buying factors are also listed in Table 3.

BUSINESS
Here the key business buying factors are listed.

System price compared to delivered output [$/W] - Complete system price
This is a measurement of how much money the investor needs to pay per watt installed capacity. This factor is affected by the price of the complete system i.e. Stirling engine, tracker, support structures and installation, compared to the amount of energy the system will deliver. A Stirling engine CSP system cannot function without a tracker system which is why the price of the Stirling engine and tracker system is not cost compared individually. The $/W is an easy way of comparing different energy technologies.

Price of competing solar energy technology
The price per watt of other competing solar energy technology is always an affecting factor, since if other technologies are cheaper in the $/W comparison they are also preferred. This depends a lot on the geographical factor. For example Stirling system need at minimum amount of W/m^2 to be able to function properly and that can only be found in some areas of the world.

Technology
Here the key technology buying factors are listed.

Accuracy – resolutions of the system
The accuracy of the tracker system is vital for the function of the Stirling engine system. The tracker needs to be able to follow the motion of the sun very precisely so that the focal point always is kept in the center of the Stirling engine. If the focal point misses the heat exchanger no energy will be produced and the Stirling engine also faces the risk of burning vital components.

Range of angles - Azimuth and Elevation
The range of angles that the tracker system can fulfill is important so that the Stirling engine system can follow the sun during the entire energy production day.

Quality
The quality of the tracker is also very important so that it will last the whole lifetime of 20-25 years.

Easy maintenance for the Stirling engine
The Stirling engine needs maintenance from time to time. The tracker system therefore needs to be able to give maintenance personnel easy access to the engine; so that maintenance can be done quick and cheap.

Table 4: Buying factors for trackers for the Stirling-market.

Buying factors for trackers for Stirling-market					
Business	**Rank**	**Technology**	**Rank**	**Political**	**Rank**
System price compared to delivered output [$/W] - Complete system price.	5	**Design options -** Customize the system to different market demands	2	**Legislation- force utilities to invest in renewable energy**	4
Grid parity comparison	4	**Quality**	5	**Subsidies**	5
Brand Name - How the brand name increases attraction of the product	4	**Installation support -** Offer qualified subcontractor for installation	3	**Will to achieve energy independence**	5
Service - Offer solutions prior and after installation	3	**Test facility that verifies function and performance**	4	**Environmental public opinion**	5
Geographical area - W/m² and amount of sun days	3	**Cheap dismantlement costs**	1	**Grid connection availability**	3
Price of competing solar energy technology	5	**Easy maintenance for the tracking system**	3	**Feed in tariff**	5
		Customer familiar components	3		
		Customer familiar solution	3		
		Low total environmental impact	1		
		Logistics	4		
		Volume production capacity	4		
		Easy, fast and cheap installation	4		
		Accuracy - resolutions of the system	5		
		Range of angles - Azimuth and Elevation	5		
		Possibility to facilitate both heat and electricity production	3,5		
		Easy maintenance for the Stirling - engine	5		

Concentrating Photovoltaic's (CPV)

Here are the key buying factors for the Concentrating Photovoltaic's solar power market addressed and explained. All identified buying factors are also listed in Table 3.

BUSINESS

System price compared to delivered output [$/W] - Complete system price

This is a measurement of how much money the investor needs to pay per watt installed capacity. This factor is affected by the price of the complete system i.e. concentrated PV cell, tracker, support structures, mirror and installation, compared to the amount of energy the system will deliver. Almost all CSP system cannot function without a tracker system which is why the price of the system components and tracker system are not cost compared individually. The $/W is an easy way of comparing different energy technologies.

Geographical area

The geographical area plays a big role since this technology is heavily dependent on where it is placed. The placement will give a certain set of demands that are important to capture and compare to the performance of the tracker.

Price of competing solar energy

The most competing solar energy is PV. The selling point of CPV is that it has a higher efficiency and thus requires less space. This might affect the economics enough to make CPV to be the more profitable choice.

TECHNOLOGY

Quality

The perceived quality of a tracker plays a great role as a buying factor. These systems have a expected lifetime of 20 or more years. The product needs to display that.

Accuracy

The focal area of a focused sunbeam is relatively small, therefore high accuracy is important. If you can claim a very high accuracy, it will make the product attractive.

Range of angles - Azimuth and Elevation

The range of angles that the tracker system can fulfill is important so that the CPV system can follow the sun during the entire energy production day.

Buying factors for trackers for CPV-market					
Business	**Rank**	**Technology**	**Rank**	**Political**	**Rank**
System price compared to delivered output [$/W] - Complete system price.	5	**Design options -** Customize the system to different market demands	2	**Legislation - force utilities to invest in renewable energy**	4
Grid parity comparison	4	**Quality**	5	**Subsidies**	5
Price of land & land availability - Compare the total plant cost with and without trackers	1	**Installation support -** Offer qualified subcontractor for installation	3	**Will to achieve energy independence**	5
Brand Name - How the brand name increases attraction of the product	4	**Test facility that verifies function and performance**	4	**Environmental public opinion**	5
Service - Offer solutions prior and after installation	3	**Cheap dismantlement costs**	1	**Grid connection availability**	3
Geographical area - W/m² and amount of sun days	3	**Easy maintenance for the tracking system**	3	**Feed in tariff**	5
Price of competing solar energy technology	5	**Customer familiar components**	3		
		Customer familiar solution	3		
		Low total environmental impact	1		
		Logistics	4		
		Accuracy - resolutions the system	5		
		Range of angles - Azimuth and Elevation	5		
		Volume production capacity	4		
		Easy, fast and cheap installation	4		
		Possibility to facilitate other technologies such as radio base stations	1		
		Possibility to facilitate both heat and electricity production	2		
		Easy maintenance for the CPV-system	1		

Competitors

The tracker market is still a fairly new market with many small players and many different technologies. There are a couple of solutions aspiring to be dominating in the different solar technology areas but the amounts of different companies that compete on the market are many. For a listing of the biggest and most important competitors, with technical description of their product see Excel document: Solar tracking systems OEM.xls.

Summary and Future forecasts

The solar power market continues to outclass prognosis makers' growth scenarios. Germany is the huge market leader and driver, but the USA is now showing some real signs of waking up; with some 8 GW (Green Tech Media, 2010) of planned installments in the pipeline.

The market for tracker systems is expected to continue to grow with the all growing solar energy market. The only cloud on the sky is the question whether trackers will continue to be interesting for the PV market or not and how quickly the Heliostat and Stirling markets will grow. The challenge here is to keep the tracker price low enough to pay off to invest in, but here the possibilities are many. For the Heliostat, Stirling and CPV the market has potential for huge growth, from low levels, because of growth in geographically optimal markets such as the US, India and Australia.

The FIT's in Germany and Spain are going to be cut and this will affect the market negatively but the latest FIT drafts from Germany show that the cuts will probably only have moderate negative effect.

Business Case – Solar Tracker

Executive Summary

Today's solar energy market continues to grow at a rapid pace and so does the tracker market. Of the four prioritized solar energy technologies: Photovoltaic's, Heliostats, Stirling engines and CPV's, PV is still the by far dominant technology. With the dual axis solar tracker, that this project aims to industrialize, SKF has the opportunity to enter all four markets with one product. But the challenge is to prove that the product that is cost efficient and has the correct technical abilities.

The cost of this project is 8.000 EUR and the complete market introduction project costs are approximately 1.6 million EUR. With a potential market share of 1 % in a conservatively growing market the product will reach earnings of 7.9 million EUR in 2011 and a ROI of over 79 %.

A SWOT analysis shows that the Twin Tracker concept has potential to be very competitive because of its cost efficiency and robust design. The analysis also showed that the threats and weaknesses are; the technology might not function as intended since it has not been physically tested and the solution is unfamiliar to the market.

By introducing a solar tracker product to the market it is expected to generate a profit as well as gain better understanding of the market and voice of the customer and develop its technical abilities. After the first solar tracker is introduced to the market the internal learning outcomes from that project will enable easier future solar tracker product development and market launches.

Situational Assessment

The solar tracker market has seen tremendous growth the past five years. Many different companies are active on the market and selling their solar tracker products. To be a competitive player on this market requires both market understanding - the voice of the customer, as well as the engineering knowledge to deliver competitive products. SKF has both these abilities and has the opportunity to enter this lucrative market – it is also high time to do so.

The solar tracker market consists of four dominating solar energy technologies:

- Photovoltaic's
- Heliostat concentrating solar power
- Stirling engine concentrating solar power
- Concentrating Photovoltaic's

SKF here has the opportunity to enter all four markets. The solar tracker master thesis project aims to industrialize an existing concept that will be competitive in all four mentioned markets. The challenge is to produce a product that has the correct technical performance and durability but at the same time is outstanding in the cost/performance comparison.

By introducing a solar tracker product to the market SKF has possibilities to take a market share and also experience spin-off effects such as:

- Increased customer contacts
- Better mapped voice of the customer

- Deeper technical understanding of the systems
- Easier other similar product development such as products for:
    - Single axis tracking
    - Roof-top deployment
    - Large customer specific products
- Developed commonality systems
    - Sensor systems
    - Control systems
    - Frames

Direct component competing companies to SKF such as IMO, Elero and Linak are already selling components and sometimes even systems to the solar tracker industry and it is now time to rise to face the competitors.

Cost Analysis

The costs of the product development for the Solar Tracker product will be:

- Market analysis costs
    - Visits
    - Magazines fees and other sources
- Prototypes manufacturing costs
- Sensor and control systems costs

These costs are all covered by the budget of 8.000 EUR.

The approximated costs for the market introduction for 2011 will be:

Table 5: Cost Approximation market introduction.

Sales and market activities	300 000 €
5 Full scale prototypes	20 000 €
Testing	100 000 €
Validation of prototypes for customers	24 000 €
Supplier start-up costs (pre-series etc.)	300 000 €
Labor costs/year (five full time employees)	672 000 €
Other costs	200 000 €
Total cost	1 616 000 €

Sales and Market Scenarios

Market forecasts or prognosis's are always a guessing game. In order to highlight what market developments that can be expected from the project; three different scenarios are presented.

The prototype of the finished product is introduced to the market on exhibitions, magazines and by direct customer contacts. For the three market scenarios it can be expected that the product is introduced in quarter 4, 2011. It is also assumed that 50 % of all new PV installations use trackers, 60 % for Europe and 40 % for rest of the world.

Conservative Scenario

In the scenario, the prototype of the finished product is introduced to the market on exhibitions, magazines and by direct customer contacts.

In this scenario it can be expected that the solar tracker takes a 1 % market share in 2011, in a market that grows slower than in recent years.

Table 6: Conservative Scenario.

Amount of trackers/MW	Expected new market installations	2011 [MW]	Trackers	SKF Sales 1 % market share
114	PV	5 000	285 000	2 850
109	Heliostat	40	4 360	22
40	Stirling	50	2 000	10
105	CPV	50	5 250	26
Tracker Manufacturing price		1.280 €		
Sales price (20 % margin)		2.048€		
Other investments		1 616 000 €		
Profit		617 344 €		
Return On Investment		38 %		

As seen from table 2, the profit in 2011 will be over 600.000 Euros. Since the initial investment needed to develop the product is small and considering that it will be produced by a supplier, the ROI is reasonable.

Basic Scenario

In this scenario it can be expected that the product takes 5 % market share in 2011, in a market that grows as in past years.

Table 7: Conservative Scenario.

Amount of trackers/MW	Expected new market installations	2011 [MW]	Trackers	SKF Sales 5 % market share
114	PV	6 000	342 000	17 100
109	Heliostat	40	4 360	22
40	Stirling	50	2 000	10
105	CPV	50	5 250	26
Tracker Manufacturing price		1.280 €		
Sales price (20% margin)		2.048 €		
Other investments		1 616 000 €		
Profit		11 561 344 €		
Return On Investment		715 %		

As seen from table 2, the profit in 2011 will be over 11.5 million Euros. Since the initial investment needed to develop the product is small and considering that it will be produced by a supplier, the ROI is very large.

AGGRESSIVE SCENARIO

In this scenario it can be expected that the product takes a 10 % market share in 2011, in a market that grows aggressively.

Table 8: Aggressive Scenario.

Amount of trackers/MW	Expected new market installations	2011 [MW]	Trackers	SKF Sales 10% market share
114	PV	10 000	570 000	57 000
109	Heliostat	1 000	109 000	10 900
40	Stirling	500	20 000	2 000
105	CPV	500	52 500	5 250
Tracker Manufacturing price		1.280 €		
Sales price (20% margin)		2.048 €		
Other investments		1 616 000 €		
Profit		56 099 200 €		
Return On Investment		3 471 %		

As seen from table 1, the profit in 2011 will be more than 56 million Euros. Since the initial investment needed to develop the product is small and considering that it will be produced by a supplier, the ROI is huge.

DO NOTHING SCENARIO

In this scenario, no market and sales activities are undertaken. The master thesis will deliver market data and a prototype of a finished product that will be shown on exhibitions without resulting in any sales.

The dual axis tracker market will then continue to evolve without SKF being one of the key players. The downfall of this scenario is that SKF will not be an active part of the solar tracker market and will miss opportunities to earn profits and new technical abilities from the market.

If no market and sales activities are undertaken the project will result in market data, a prototype and documented finished product.

APPROXIMATIONS

The market growth in 2011 is approximated by extrapolating historical market data and analyzing the factors affecting the market at the time and comparing it to what political control measures are in affect today and tomorrow. This gives a quantified approximation of the future market growth.

In the conservative scenario the biggest expected differences from 2009 is that Europe with Spain and Germany are expected to grow slower but new markets such as the USA and Asia are expected to pick up instead. The conservative market growth in 2011 is therefore approximated to 5 GW down from approximately 10 GW in 2009. The Basic scenario is expected to have almost the same growth pace as in 2009.

In the aggressive scenario the German and Spanish markets experience the sales as in the conservative are approximately. The new markets in USA, Asia and Europe are expected to grow faster. The aggressive market scenario is therefore approximated to 10 GW market growth in 2011.

Risk Assessment and Critical Assumptions

The risks with the solar tracker project are assessed in the Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, see chapter SWOT. The major risks are also discussed under table 9.

Table 9: SWOT-analysis Solar Tracker Business case.

Strengths	Weaknesses	Opportunities	Threats
Linear actuators as drive units	Unproven technology	Rapidly growing market	Other cheaper and simpler solutions
New and promising solution	No customer feedback on the product yet	Heliostat gets commercialized	Trackers will stop being interesting for PV
Modularized design – easy to adapt	No ready to use SKF actuators	CPV gets commercialized	Unknown future of PV-module sizes
Large SKF organization	No partner company that can test the product and provide feedback	Market requires cheaper solutions for PV trackers	Solution might be too different for the market
Cost effective solution	No contracted suppliers yet	Market leaning towards bigger panels	Unknown how tracker solution fares in cost against the Asian market
Robust design solution	No physical testing done	CPV becomes more cost efficient than PV	Dropping PV panel prices
High quality	Possible programming difficulties	The EU electrical Grid to Sahara is established	Competitor patents the same solution
SKF brand name	Tricky to acquire the same movement range as slewing drive ring and actuator solution		Other renewable energy becomes dominant

The strengths of the product are; it is a new and promising solution that aspires to be more cost efficient and robust than the competition. The weaknesses are; the technology is unproven, especially considering movement range and no physical testing has been done yet as well as no customer has given feedback on the product. Mentionable opportunities are the rapid growing solar energy market and the promising rise of Heliostat, Stirling and CPV technologies. Threats from the market are other cheaper solutions from competitors and of course if trackers stops being interesting for PV panels.

Conclusions and Recommendations

The solar tracker market has now been growing at an enormous pace for more than five years, almost doubling the installed capacity each year. The market is still growing very fast but starting to show signs of consolidation, mostly due to FIT's in Germany and Spain are being cut. It needs to be understood that the introduction of a product to the market is important because taking market shares in fast developing markets is much cheaper than doing the same in a consolidated and crowded market. Also, by producing a dual axis solar tracker based on two linear actuators SKF is making somewhat of a internal technology leap, which is seen as positive.

By industrializing a product now and introducing it to the market, SKF has the possibility to both generate profit and take market shares as well as gain better understanding of the market and develop its in house technical abilities. It is therefore strongly recommended that the solar tracker master thesis project is followed up by aimed market introduction and production projects; as well as a whole product family (both single and dual axis trackers) for the solar market is developed.

PRODUCT DESCRIPTION

The Solar Tracker is designed in three different size versions relating to the actuators forces. This chapter will outline the main dimensions of the different designs as well, material choice and the main manufacturing processes will be mentioned.

The chosen designs of the components from the development phase resulted in a final product concept consisting of the following components:

- The Pillar
  - Top pillar
  - Bottom pillar
  - Pillar arms
- The new Solid Joint, Hooke's Joint
- Upper Rotational Joints
  - Housing
  - Rotation joint
  - Ball bearings
  - Bushings
- Lower Rotational Joints
  - Housing
  - Rotation joint
  - Ball bearings
  - Bushings

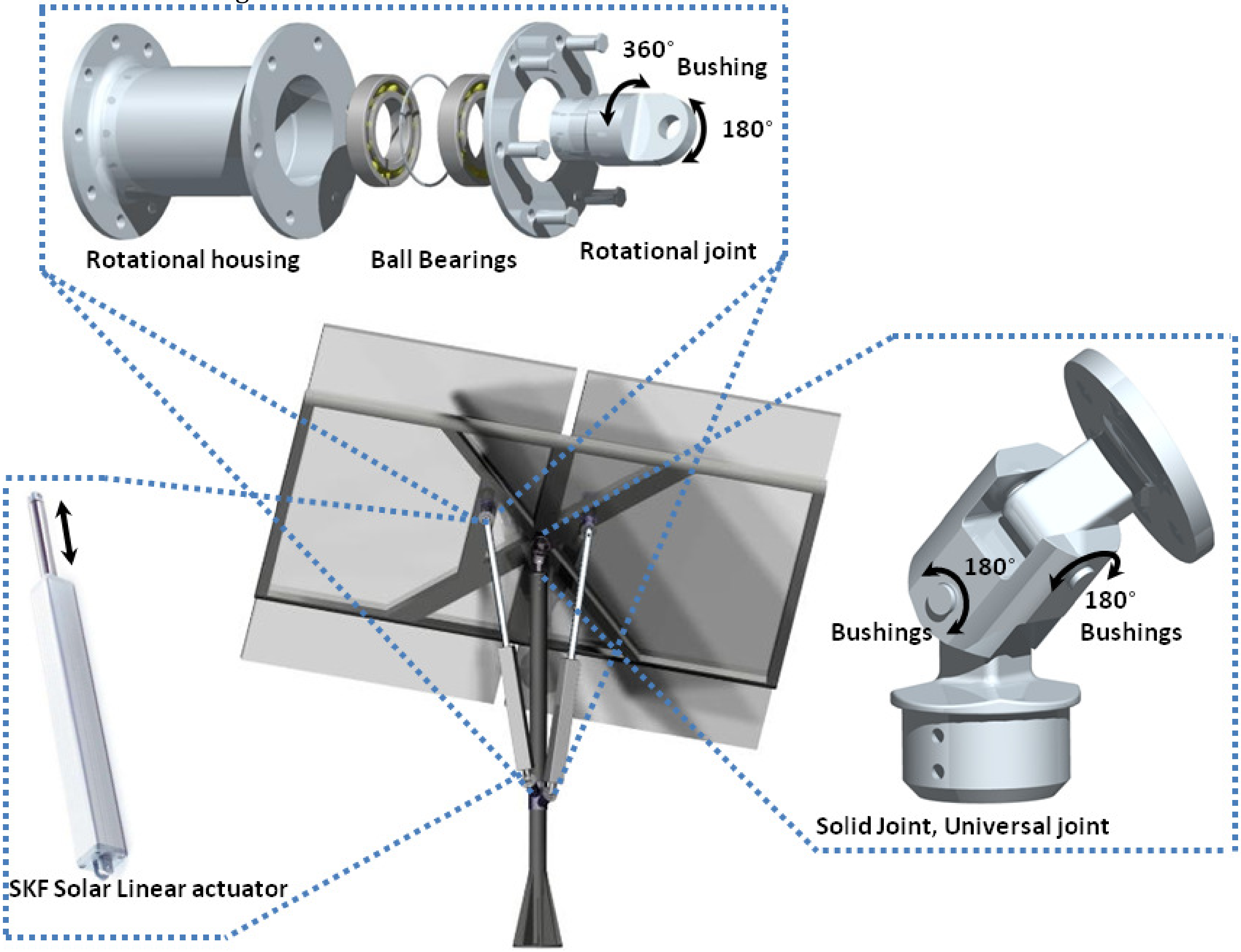


Figure 2: Final product concept.

Material selection

The goal of the material selection is to provide materials for the Twin Tracker product. The suggested materials should enable the product to fulfill its function at the lowest possible materials cost.

Material selection method

The material selection process for the Twin Tracker was done utilizing Cambridge Engineering Selector (*CES*). This process was guided by the main properties that the material should possess;

1. Stiff enough, Youngs modulus, tested with FE-analysis
2. Strong enough, yield strength, tested with FE-analysis
3. Fracture toughness, at least 20 MPa.m$^{1/2}$
4. Elongation, at least 8 %
5. Ductility
6. As cheap as possible
7. A high [yield strength/ price] value
8. Suitable for:
    a. Welding
    b. Machining
    c. Casting
9. A specific material for cast components will be selected

The search was limited to only cover metals.

Results

The results are presented in the two main categories of the manufacturing method; cast material and other components.

Cast material

The cast components are made of cast iron P70-02. CES shows that this material has the following main properties:

- Young's modulus of 153-179 GPa.
- Yield strength of 530 – 660 MPa.
- Fatigue strength at 10^7 cycles of 290-330 MPa.
- Price of 4.42 – 4.86 SEK/kg.

Cast components

- The solid joint

Other components

CES search resulted in a large variety of steels. For the rest of the product AISI 6150 was selected as the most appropriate material. AISI 6150 is low alloy tempered steel with a very good performance (since it is tempered and oil quenched).

The main properties of the AISI 6150 steel are:

- Young's modulus of 201-212 GPa.
- Yield strength of 1.52 – 1.86 GPa.

- Fatigue strength at 10^7 cycles of 629-726 MPa.
- Price of 7.08 – 7.78 SEK/kg.

The exact specifications of the AISI 6150 steel can be seen in appendix M (*Materials data)*.

AISI 6150 components

The components to be manufactured from AISI 6150 are the rest of the tracker. This steel provides extremely affordable performance and is therefore a great material choice for the rest of the components.

- Pillar
- Arms
- Rotational housings
- Pins

DESCRIPTION OF THE DESIGNED COMPONENTS

The Twin Tracker product is presented here with a description of every component. The images in this chapter are of illustrative nature, for complete overview see Appendix E for CAD drawings.

THE PILLAR

The pillar is separated into four different components:

- Ground pillar
- Small top pillar
- Medium top pillar
- Large top pillar

Ground pillar

The ground pillar serves as a basis for the whole product. It is therefore crucial to guarantee that this component is robust enough to carry the rest of the system. For the large and medium trackers it has been designed to be wider than the top pillars. This will enable higher load carrying capacities for the whole tracker without the mechanical integrity being compromised.

The flange that is welded on the top of the ground pillar is used as a screw jack for fastening the pillar components together. The flange has been designed with a hole in order to easily fill the ground pillar with concrete to make the foundation sturdy.

The general dimensions for the ground pillar are the same for all three versions and are:

Table 10: Outer dimensions ground pillar.

Tracker	Measure (mm)
Height	**1500**
Outer diameter	**400**
Thickness	**10**
Flange Thickness	**20**
Flange diameter	**600**
Hole diameters	**20**

Manufacturing method

The ground pillar is ordered as a pipe from a supplier, it is then cut into the correct dimensions and the flange is welded to one of the openings. The hole for filling the pipe with concrete is bored.

Top pillars

The rest of the tracker's components are mounted on the top pillar. In order to speed up the installment process; the top pillar is pre-installed with the correct wiring. These wires are connected to the proper interface both in the top and the bottom of the top pillar. This minimizes the work that is required on-site.

The top pillars are manufactured in three different sizes according to the three offerings. The height of the pillar is dependent on the dimensions of the solar technology connected to the tracker. This makes it easy to modify them to match the proper height.

The product holds high requirements on the mechanical properties of the design and the material. The load carrying capacity has been ensured with a FE-analysis

Table 11: Outer dimensions top pillar.

Large Tracker	Measure (mm)	Medium tracker	Measure (mm)	Small tracker	Measure (mm)
Height	**6150**	Height	**5400**	Height	**2600**
Outer diameter	**250**	Outer diameter	**250**	Outer diameter	**250**
Thickness	**10**	Thickness	**10**	Thickness	**10**
Flange Thickness	**10**	Flange Thickness	**10**	Flange Thickness	**10**
Flange diameter	**600**	Flange diameter	**600**	Flange diameter	**400**
Hole diameters	**18**	Hole diameters	**18**	Hole diameters	**18**

Manufacturing method

The top pillars are bought as pipes according to the specific dimensions. The flange and the stiffener are welded to the top pillar with preferably an under dimensioned weld to minimize the risk for cracks in the welded area. The holes for the wiring are manufactured with a regular boring operation, with low demand on tolerance.

THE ROTATION HOUSINGS

The rotational housings' design is driven by two factors; the proper bearing size and the strength of the corresponding housing. Three different bearings were selected to be used in the different sized trackers. These control the width of the housings. The length varies because the tracker design is adapted to the specific actuators.

Figure 11 Image of the prototype rotational housings with the rotational joint assembled.

The upper housings are fastened to the solar technology frame with a screw unit. The most important part of this assembly is to make sure that the hole pattern is correctly placed on the frame. This is a very crucial part of how the control system of the tracker will work; an error here will affect the functionality.

The arm housings are welded to the pillar ring, and therefore they are cut to match the pillar ring components outer diameter.

Tabell 12: Outer dimensions of the Rotation Housings.

Large Tracker	**Measure (mm)**	**Medium tracker**	**Measure (mm)**	**Small tracker**	**Measure (mm)**
Height	**300/250**	Height	**260/216**	Height	**126/105**
Outer diameter	**150**	Outer diameter	**140**	Outer diameter	**105**
Thickness	**11.5**	Thickness	**11.5**	Thickness	**9.25**
Flange upper diameter	**230**	Flange upper diameter	**220**	Flange upper diameter	**185**
Hole diameters	**18**	Hole diameters	**18**	Hole diameters	**8**

THE ROTATIONAL JOINT

The rotational joints connect, together with the actuator pin, the housings and the actuators. These joints have a very simple design; they consist of a metal bar that has been machined to the correct dimensions. The design varies slightly between the different offerings due to different bearing dimensions.

Figure 12 The rotational joints used in the prototype.

Manufacturing method

The rotational joint is easily manufactured. It is a metal bar that is machined into the correct dimensions.

Table 13: Outer dimensions of the Rotational Joints.

Large Tracker	Measure (mm	Medium tracker	Measure (mm	Small tracker	Measure (mm
Height	**132**	Height	**130**	Height	**116**
Outer diameter	**80**	Outer diameter	**75**	Outer diameter	**60**
Hole diameter	**40**	Hole diameter	**40**	Hole diameter	**30**

The Actuator Pin

The actuator pin is a very simple component. The main purpose is to connect the rotational joints together with the actuators. It also allows them to rotate in their connection joint.

Figure 13 The actuator pin used in the prototype.

Manufacturing method

The actuator pin is best to be ordered as metal bars with specific tolerances on its straightness and then machined to its final design.

The dimensions for the actuator pin are the same for all size versions and are:

Table 14: Outer dimensions of the actuator pin.

Tracker	Measure (mm
Length	**70**
Outer diameter	**30**

The Pillar Ring

The welding process of attaching the lower rotational housings to the top pillar was simplified by creating another component; the Pillar Ring. The large sized pillar would have been very difficult to control in a welding process and thus requiring very large support structures for this relatively short process. Therefore this component has been designed to be slid into the correct position and fastened with a screw jack

Figure 3: Pillar ring.

Manufacturing method

The Pillar Ring is manufactured from a pipe that has the same inner diameter as the top pillar's outer diameter is. The flange is welded on the back-side of where the lower rotational housings are welded.

Table 15: Outer dimension of the Pillar Ring.

Large Tracker	Measure	Medium tracker	Measure	Small tracker	Measure
Height	**400**	Height	**400**	Height	**400**
Outer diameter	**270**	Outer diameter	**270**	Outer diameter	**270**
Thickness	**10**	Thickness	**10**	Thickness	**10**
Hole diameters	**18**	Hole diameters	**18**	Hole diameters	**12**

THE SOLID JOINT

The solid joint the heart of the system; it allows movement in 180 degrees in both of its rotational axes without any clashes. This gives it the theoretical possibility to cover a 360 degree azimuth- and a 90 degree elevation range.

The solid joint is a heavily modified Hooke's joint that allows for a good range of motion in both the azimuth and elevation angles.

The solid joint is to be manufactured in the same size for the large and medium trackers because of the small load difference between these versions and to minimize costs for new casting tools. For the small tracker the size of the solid joint is reduced to minimize the weight and the cost.

The joint consists of three main components; the upper arm, middle component and the lower arm.

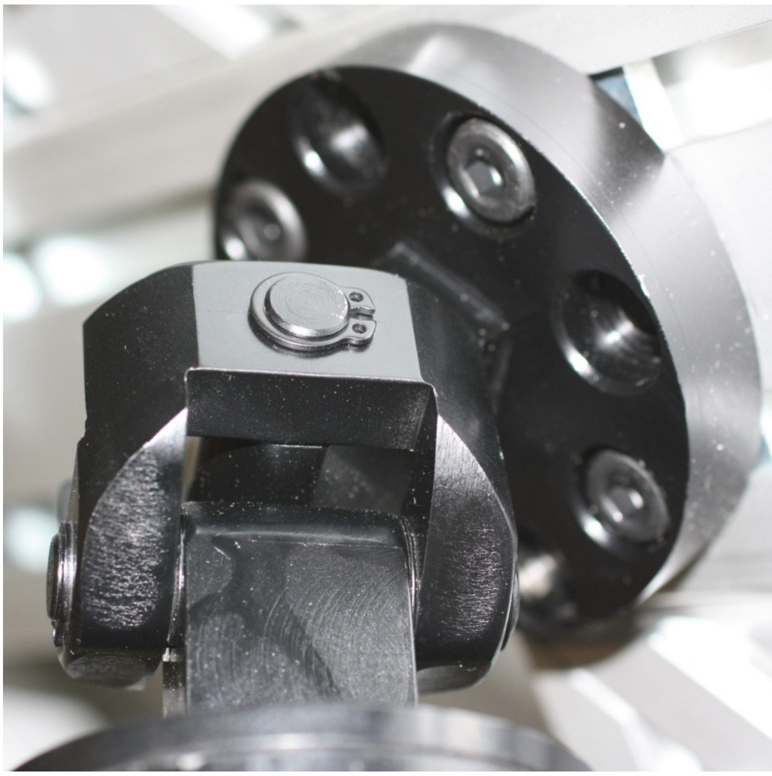


Table 16: Dimensions of the Solid Joint.

Large Tracker	Measure	Medium tracker	Measure	Small tracker	Measure
Complete height	**558**	Height	**558**	Height	**450**
Diameter	**230**	Diameter	**230**	Diameter	**230**
Thickness	**98**	Thickness	**98**	Thickness	**60**
Hole diameters	**20**	Hole diameters	**20**	Hole diameters	**12**

Manufacturing method

The Solid Joint is made from cast iron, except for the rotational pins. The geometry of the joint requires for it to be cast in order to reach reasonable manufacturing costs. A machined part would be extremely expensive because of the large amount of work that needs to be done. The backside of casting is that cast iron strengths are weaker than the AISI steels. This poses tighter requirements for the component to pass the FE-analysis.

COMPONENTS SELECTION

This chapter describes the ingoing components of the system that have not been specially designed as a part of the project. These components are crucial for the function of the Twin Tracker product as they realize the movements between the different components.

Fiber weave bushing

Bushings are products that are placed in joints to minimize the wear and friction in the system. Bushings are either flanged or un-flanged. The selected variant to the Solid joint are the SKF Fiber Weave (FW) bushings. These are especially adapted for high loads and dirty environments such as excavators on digging sites.

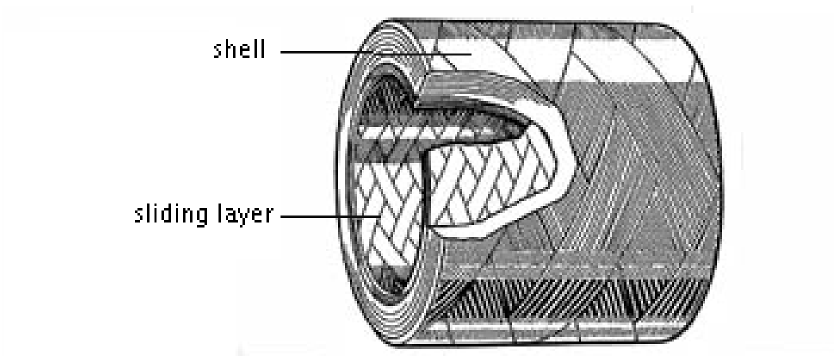


Figure 14 Shows a fiber-weave (FW) bushing from SKF. ***(SKF)***

Utilization

The fiber weave bushings will be placed in the Hooke's joint in order to provide the rotational movements required from the joint. The exact fastening of the Bushings can be seen in the drawings appendix E.

Specifications

The operating temperature range for the FW-bushing is between -50 to +140°C degrees. For temperatures – 30°C there will be an increase of friction in the bushing.

The running in behavior of the bushing is very short and is characterized by higher friction. After the running in period the friction will stay at a constant low value.

The load rating for the selected bushing is high duty, that is over 300 kN static load and 100 kN dynamic load. These are well above the loads that will be experienced in the joints, guaranteeing that this component will not fail under the specified lifetime.

Cost

The cost of the bushing in large volumes can be assumed to 50 SEK per piece. This cost is low because this product is produced in high volumes and in-house.

Bearing selection

The SKF bearing selector online software was used when selecting the bearings. This was done together with SKF expertise, who guided the selection work in order to select appropriate bearings.

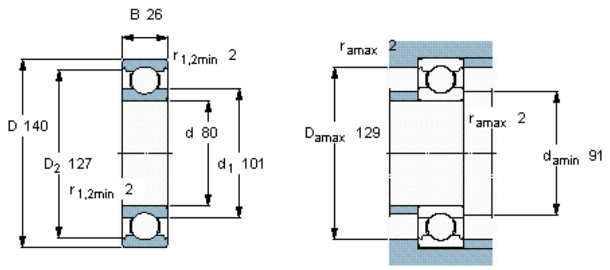
Three different bearings were selected for the different tracker offerings. The selected bearings are presented below.

Large tracker bearings

Deep groove ball bearings, single row
Product information

Tolerances , see also text
Radial internal clearance , see also text
Recommended fits
Shaft and housing tolerances

Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings		Mass	Designation
			dynamic	static		Reference speed	Limiting speed		
d	D	B	C	C_0	P_u				* - SKF Explorer bearing
mm			kN		kN	r/min		kg	-
80	140	26	72,8	55	2,2	9500	6000	1,40	**6216 ***



Calculation factors

k_r 0,025
f_0 15

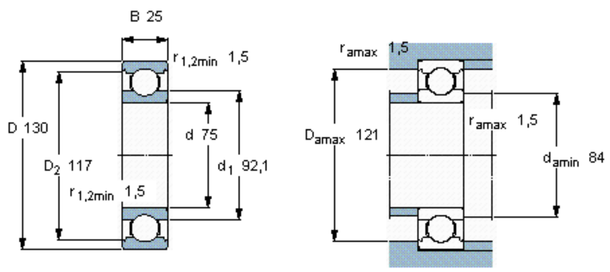
Figure 15 The SKF deep groove ball bearing 6216

Medium tracker bearings

Deep groove ball bearings, single row
Product information

Tolerances , see also text
Radial internal clearance , see also text
Recommended fits
Shaft and housing tolerances

Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings		Mass	Designation
			dynamic	static		Reference speed	Limiting speed		
d	D	B	C	C_0	P_u				* - SKF Explorer bearing
mm			kN		kN	r/min		kg	-
75	130	25	68,9	49	2,04	10000	6700	1,20	**6215 ***



Calculation factors

k_r 0,025
f_0 15

Figure 16 The SKF deep groove ball bearing 6215

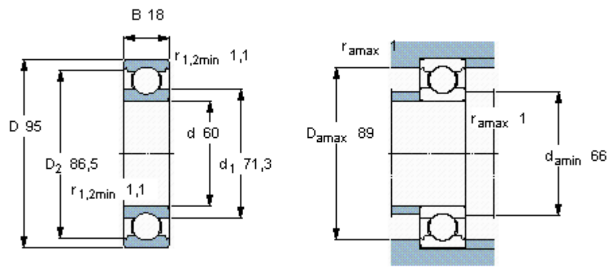
Small tracker bearings

Deep groove ball bearings, single row

Product information

Tolerances , see also text
Radial internal clearance , see also text
Recommended fits
Shaft and housing tolerances

Principal dimensions			Basic load ratings		Fatigue load limit	Speed ratings		Mass	Designation
			dynamic	static		Reference speed	Limiting speed		
d	D	B	C	C_0	P_u				* - SKF Explorer bearing
mm			kN		kN	r/min		kg	-
60	95	18	30,7	23,2	0,98	15000	9500	0,42	**6012** *



Calculation factors

k_r 0,025
f_0 16

Figure 17:The SKF deep groove ball bearing 6012

Utilization

The bearings will be placed in the upper and lower rotational houses. These bearings are used in pairs of two in order to manage the loads that the rotational housings are subjected to.

Cost

The cost of these bearings can be assumed to be between 40-200 SEK. This price is lowered greatly due to high volumes and because these are purchased directly from a SKF factory. For detailed calculations see the cost analysis appendix B.

ASSEMBLY

The assembly of the Twin Tracker product is described in this chapter. The components are assumed to be manufactured according to the drawings in the drawing appendix. The assembly is first discussed as each individual assembly and then a suggestion of the complete product assembly process is made in the sense of pre-assembly and on-field assembly

GROUND PILLAR AND TOP PILLAR ASSEMBLY

The ground pillar is mold to the ground with concrete. When the concrete is dry, the top pillar is placed on the ground pillar and fastened with a screw jack that is placed in the flanges that surrounds the ground and top pillars.

ARM AND ROTATIONAL HOUSINGS JOINTS ASSEMBLY

The spherical bushings or the bearings are placed with a squeeze fit into the arms-housing and the rotational joint. These components are locked in place with the fastening cap.

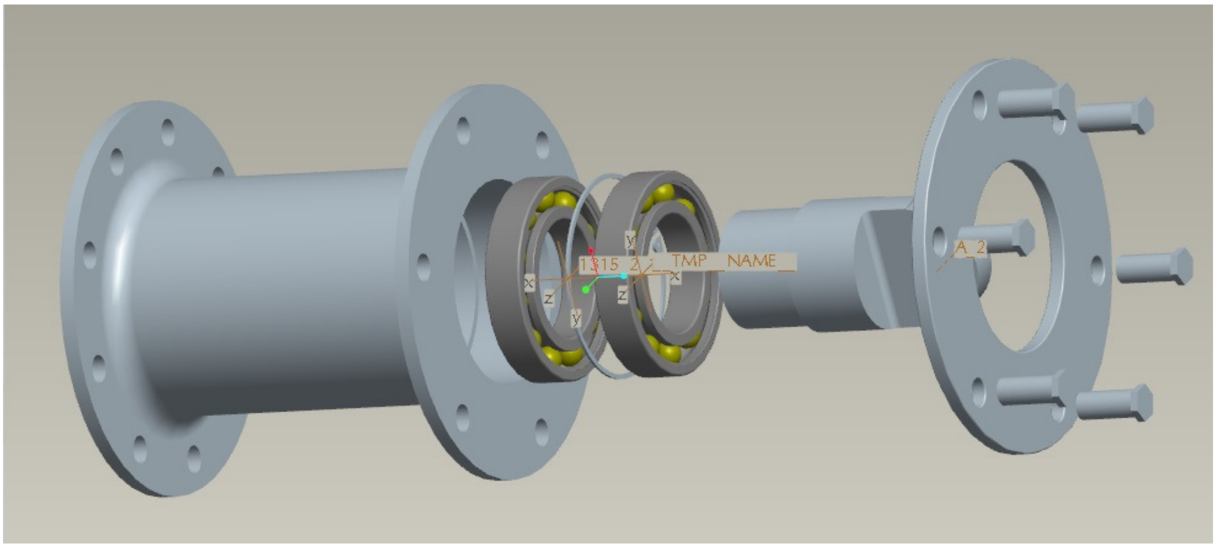


Figure 18 an exploded view of the Housing and arms assembly.

SOLID JOINT ASSEMBLY

The Solid Joint is pre-assembled before it is fastened to the interfaceplate and the pillar. The lower arm is placed on a table where it is fixed together with the middle component by utilizing the pin and locking ring . Between the components, a bushing is placed to minize the friction in the joint as well as to minimize the wear of the joint. The upper arm is then fixed together with the middle component, also with a pin, a locking ring and bushings.

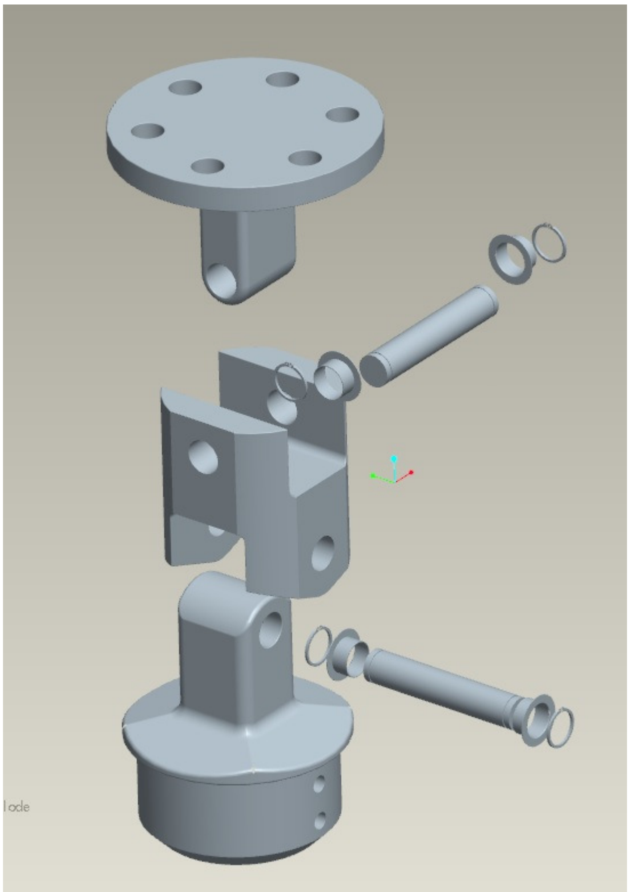


Figure 19 An exploded view of the Solid joint and its components

FASTENING AND PILLAR ARMS ASSEMBLY

The pillar arms are welded together with the Pillar Ring before it is delivered for the assembly. The Pillar Ring is then placed at the appropriate height on the top pillar. It is then fastened with a screw jack that is located on the backside of the Pillar Ring.

FASTENING THE ACTUATORS ON THE ARMS AND HOUSINGS

The actuators are fastened to the arms by utilizing bushings, a pin and locking rings. The actuator is placed so that the ears of the fastening element cover the rotational joint. The pins are slid into place, through the holes and locked with a locking ring.

PRE-ASSEMBLY

The pre-assembly is done to minimize the actual installation time on-site. This pre-assembly process offers value to the customers since they can have a cost efficient installation.

- The arms are assembled together with the affected joints
- The fastening component is assembled to the pillar
- Actuators are fastened to the arms and this enables the product to be shipped efficiently in easy to assemble pieces.

ON-SITE ASSEMBLY

The on-site assembly consists of the following steps.

- The Ground pillar is cemented to the ground
- The top pillar is fastened on the ground pillar
- The solar technology to be used is fastened on the frame
- The frame, together with the Solid joint and the rotational housing assemblies are placed on the pillar.
- The solid joint is fastened to the pillar as are the two actuators fastened to the rotational joints in the housing assembly.

The mounting of the top pillar and the frame requires a crane.

The solar technology to be used is assembled on site on the tracker. How this installation is realized depends on the size of the applied technology.

TRACKING TECHNOLOGY SELECTION

This chapter discusses the selection of the tracking technology used in the Twin Tracker product. A wide perspective was kept when selecting the tracking technology in order to cover as many aspects as possible.

The choice rested between active tracking with sensors or chronological tracking using equations and known relationships between the direction vectors from a specific position on the earth towards the sun. In order to select the most appropriate technology a strengths and weaknesses analysis was made.

Tabell 17: Strengts and Weaknesses comparison for tracking technology selection.

Active sensor tracking		**Chronological tracking**	
Strengths	***Weaknesses***	***Strengths***	***Weaknesses***
Always directed to the brightest spot in the sky	Sensitive to disturbances such as leaves, bird droppings and dirt.	Accuracy depends on the equations = very high, up to 0.00003 degrees accurate	Does not consider the error in the tracker alignment during time
Diameter	Might use more energy while searching bright spot	One processors can calculate many trackers direction	Manual calibration might be needed when rain affects the ground around the tracker
Thickness	One processor is required for each tracker	Never deviates from the solar path	

Both technologies have their strengths and weaknesses. The chronological tracking method is more suitable for the Twin Tracker since it allows one CPU to calculate many trackers position, further pushing the cost down. As well as the accuracy is unprecedented and it is not sensitive to outer factors such as dirt, leaves and bird droppings.

CHRONOLOGICAL TRACKING EQUATIONS

It is required to know the position of the sun in real time. This can be managed with equations that were provided by the National Renewable Energy Laboratory (*NREL)*. These equations are very precise, NREL claims to have an accuracy of ±0,000003 degrees in both azimuth and elevation calculations.

These solar path equations are very extensive and are therefore placed in appendix G Solar path calculations. The equations cover both the Topocentric (the suns position as seen from the middle of earth) and Geocentric (the suns position as seen from an observer's eye on earth) calculations so that both methods can be used if deemed fit. The equations can be used to calculate the azimuth end elevation angles while considering the following factors:

- Date
- Time
- Longitude
- Latitude
- Height of the system from the sea level
- Orientation of the system (is facing directly south or is it turned)
- Tilt of the ground where the system is placed

Customer to technical requirements

Since the solar tracker product is designed to work for four different technologies (as explained in the Technologies chapter) it is important to understand that major customer requirements, like which technology to choose and what panel size to use results in different technical requirements on the product.

In order to manage these requirements, an easy sales support model that chooses the best tracker specification has been developed. This model divides the tracker into three different designs depending on solar technology and three different size ranges, in relation to the new actuators, depending on which panel, mirror or dish area. For the complete requirement specification concerning the solar tracker see the Requirements chapter.

The major customer requirements are (see chapter Key buying factors for more customer requirements):

- Solar technology: PV, Heliostat, Stirling or CPV
- Panel, mirror or dish size or desired Energy Production
- Tracker range (Azimuth and Elevation)
- Maximum wind speed that the tracker can withstand
- Price vs. performance ratio

The customer requirements affect the design and dimensions on all ingoing components in the solar tracker. For example the forces that the actuators needs to push and the loads the bearings and solar tracker components need to withstand are directly correlated to the size of the e.g. PV panel area. To manage these diverse customer requirements in an easy way, the tracker has been designed for three different size ranges (for each technology). The three size ranges are linked to the three new SKF solar tracker actuators. For example if a customer needs a tracker for a 70 m^2 PV panel area he can choose the medium version of the solar tracker. The medium version is then already optimized to handle loads derived from 25 – 85 m^2 panel area and wind speeds up to 20 m/s when tracking, see calculation chapter for load calculations. The optimization is done by selecting the most suitable actuators and dimensioning ingoing parts like pillar and arms; making sure that material use and weight is minimized.

Product selection model

What the product selection model does then is that it allows a sales person, or person on exhibitions talking to a potential customer, to easily understand which version of the solar tracker that is best suitable for each situation. The sales person uses the product data sheets as support when explaining to the customer the correct version of the tracker. Each version of the solar tracker has been calculated and FEM tested to withstand corresponding forces. It has also been simulated in ProE Mechanism and physical testing on the 1/3.5 scale prototype to assure the stated movement range. Movement range chart and product data sheets can be found in Appendix A and D.

THE EQUATIONS OF MOTION

In order to connect the solar position equations to the product it is required that the motion is described by utilizing equations. These equations consider the solar Azimuth and Elevation as inputs to and the outputs are the strokes on the actuators.

All the following equations are described in the manner as if the tracker was an industrial robot arm. Therefore the coordinate axis on the interface plate is placed so that the Z-axis always point out perpendicular from the surface.

All the equations are based on the theory and formulas in the book Dynamics (Jansson & Grahn, 1995)

The main equations to be used in the controlling of the product are the equations that define the Solid joint and the paths through each actuator to the fastening paths.

HOMOGENEOUS MATRICES

Every individual components is given their own coordinate system in order to describe them in relation to the global coordinate system. A homogeneous matrix describes the component coordinate system to the global coordinate system.

PILLAR AND ARM PLACEMEMENT

Two separate coordinate systems are placed on where the arms begin with the z-axis pointing in the direction of the pillar. I.e. there is a translation L_{R1} and L_{L1} along the axial direction of the pillar.

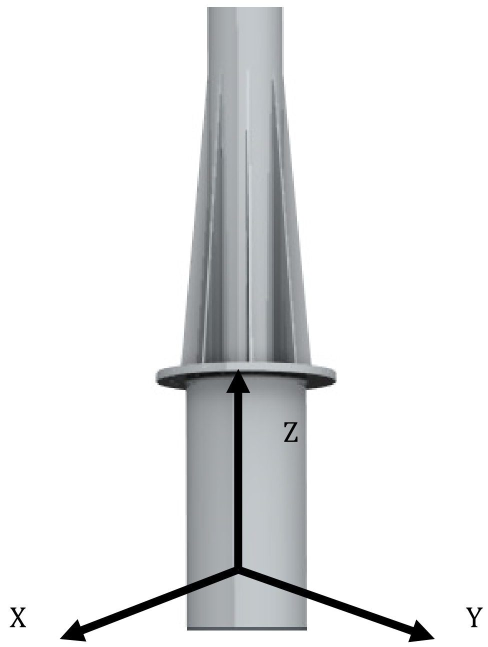


Figure 20 The world coordinate axis

$$T_{L1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{L1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{R1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{R1} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The arms are rotated around the z-axis in the following manner:

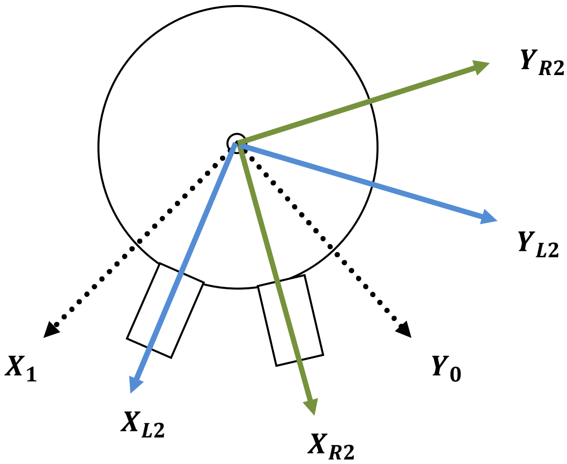


Figure 21 Shows the rotated coordinate axes of the lower rotational housings

$$R_{ZL1} = \begin{bmatrix} Cos\alpha_{L1} & -Sin\alpha_{L1} & 0 & 0 \\ sin\alpha_{L1} & cos\alpha_{L1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{ZR1} = \begin{bmatrix} Cos\alpha_{R1} & -Sin\alpha_{R1} & 0 & 0 \\ sin\alpha_{R1} & cos\alpha_{R1} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

TOP OF THE LOWER ROTATIONAL HOUSINGS

The two coordinate systems are placed on top of the arms. They are only translated in this matrix.

The first matrix defines the direction of the arm and the second defines the translation alongside the laft lower rotational housing.

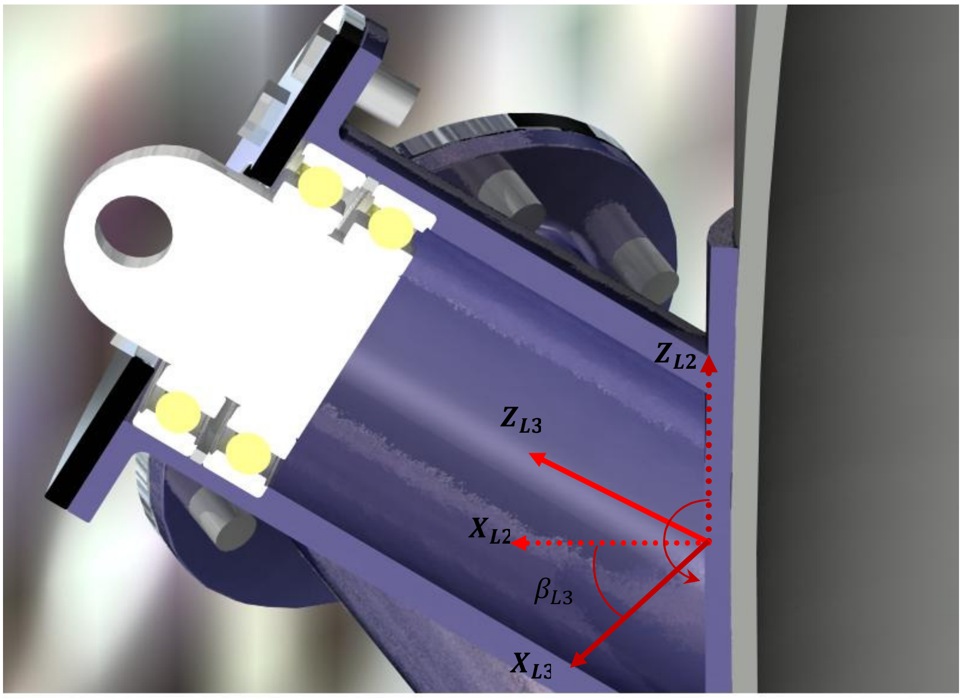


Figure 22shows the left lower rotational housing's exchange in coordinate frames

$$R_{LY2} = \begin{bmatrix} cos\beta_{L2} & 0 & sin\beta_{L2} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{L2} & 0 & cos\beta_{L2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{L2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{L2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The first matrix defines the direction of the arm and the second defines the translation alongside the right lower rotational housing

$$R_{RY2} = \begin{bmatrix} cos\beta_{R2} & 0 & sin\beta_{R2} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{R2} & 0 & cos\beta_{R2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{R2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{R2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Lower rotational joints

The coordinate system rotates around the Z-axis, as described by the matrix.

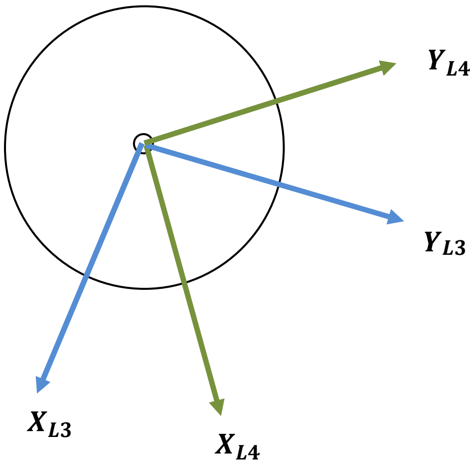


Figure 23 The rotational join t coordinate frame transfer

$$R_{ZL3} = \begin{bmatrix} Cos\alpha_{L3} & -Sin\alpha_{L3} & 0 & 0 \\ sin\alpha_{L3} & cos\alpha_{L3} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{ZR3} = \begin{bmatrix} Cos\alpha_{R3} & -Sin\alpha_{R3} & 0 & 0 \\ sin\alpha_{R3} & cos\alpha_{R3} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

ACTUATOR BOTTOMS

The actuator can rotate around the Y-axis, as described by the matrix.

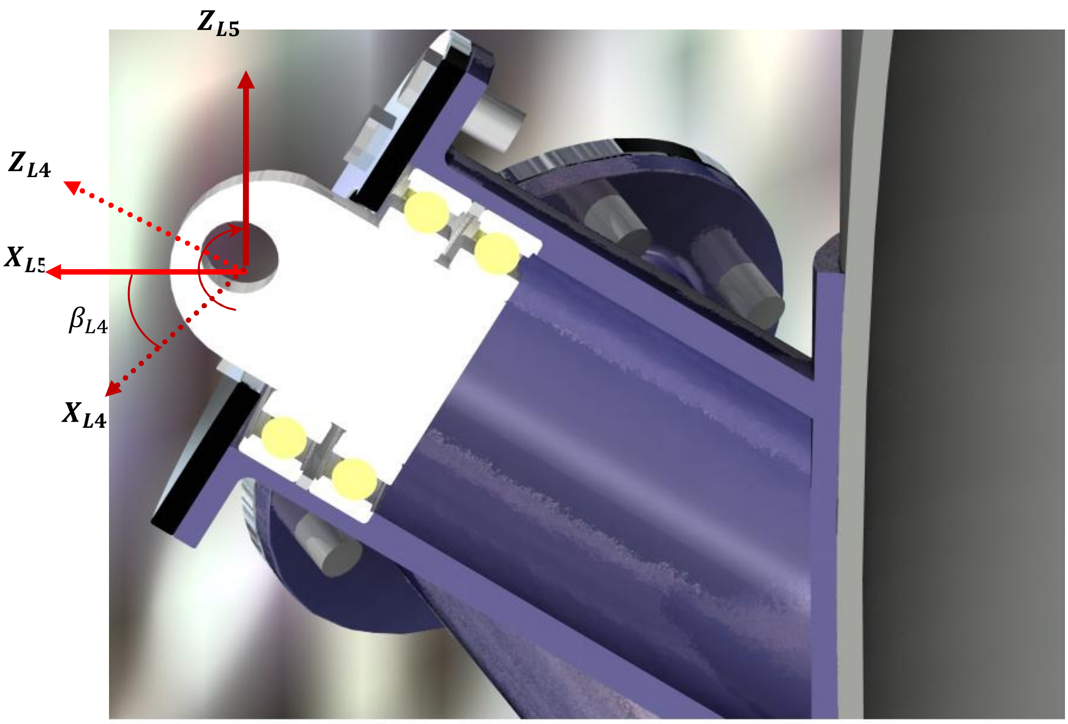


Figure 24 the coordinate frame transfer from the rotational joint to the actuator

$$R_{LY4} = \begin{bmatrix} cos\beta_{L4} & 0 & sin\beta_{L4} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{L4} & 0 & cos\beta_{L4} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{RY4} = \begin{bmatrix} cos\beta_{R4} & 0 & sin\beta_{R4} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{R4} & 0 & cos\beta_{R4} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

ACTUATOR TOPS

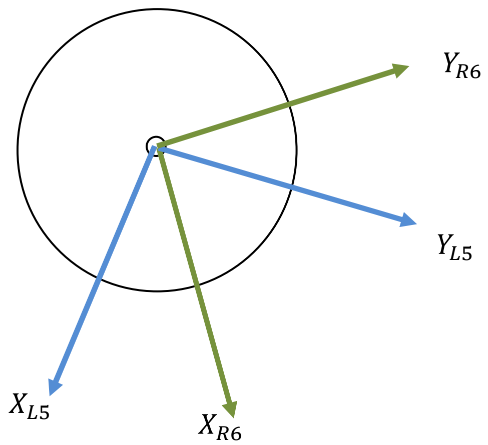
The coordinate system is placed on top of the actuators and therefore has one fixed translation and one that is described by the stroke of the actuators.

$$T_{L2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{L2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{R2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_{R2} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

BOTTOM OF THE UPPER ROTATIONAL JOINTS

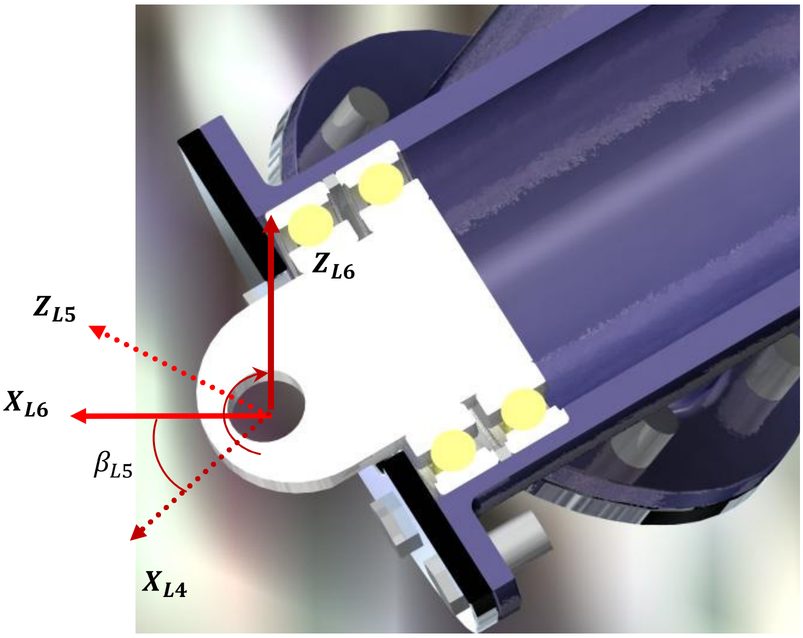
The coordinate system can rotate around the Z-axis, as described by the matrix.



$$R_{ZL5} = \begin{bmatrix} Cos\alpha_{L4} & -Sin\alpha_{L4} & 0 & 0 \\ sin\alpha_{L4} & cos\alpha_{L4} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{ZR5} = \begin{bmatrix} Cos\alpha_{R5} & -Sin\alpha_{R5} & 0 & 0 \\ sin\alpha_{R5} & cos\alpha\,{}^{L}_{R5} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

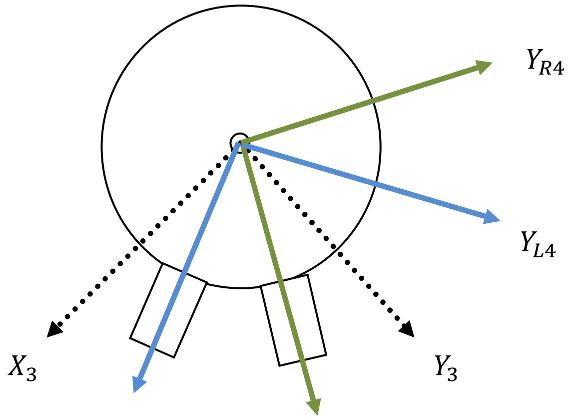
The middle component of the joints can rotate around the y-axis:



$$R_{RY6} = \begin{bmatrix} cos\beta_{R5} & 0 & sin\beta_{R5} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{R5} & 0 & cos\beta_{R2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{LY6} = \begin{bmatrix} cos\beta_{L2} & 0 & sin\beta_{L2} & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_{L2} & 0 & cos\beta_{L5} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

And finally around the z-axis again



$$R_{ZL7} = \begin{bmatrix} Cos\alpha_{L4} & -Sin\alpha_{L4} & 0 & 0 \\ sin\alpha_{L4} & cos\alpha_{L4} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R_{ZL7} = \begin{bmatrix} Cos\alpha_{L4} & -Sin\alpha_{L4} & 0 & 0 \\ sin\alpha_{L4} & cos\alpha_{L4} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

COMBINING THE MATRICES

in order to complete the equations, the matrices need to be combined together. This is done by multiplying the matrices with each other. It is paramount that the matrices are multiplied together in the right order, otherwise the end result will not describe the movement at all but just provide false equations.

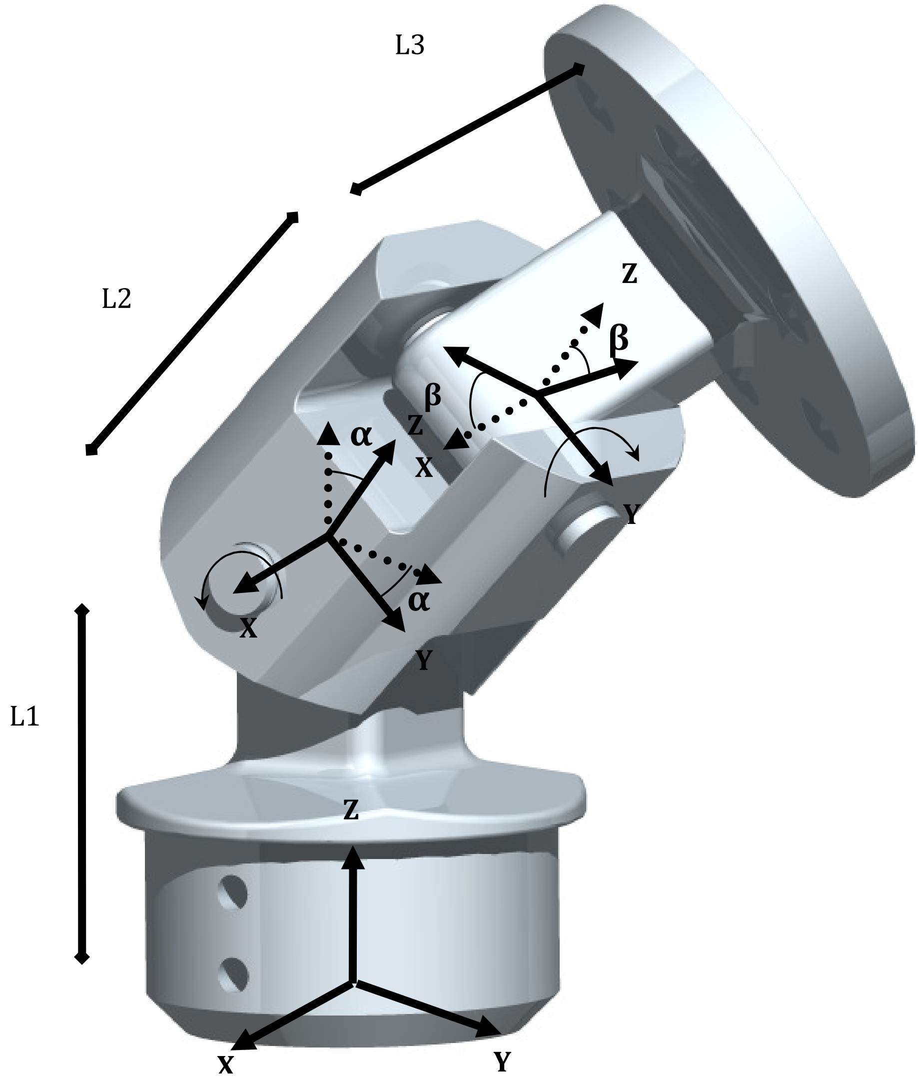
The order of multiplication is:

RL= T_{L1}*R_{ZL1}*R_{LY2}*R_{LY2}*R_{ZL3}*R_{LY4}*R_{ZL5}*R_{lY6}*R_{ZL7}

RR=T_{L1}*R_{ZR1}*R_{RY2}*R_{RY2}*R_{ZR3}*R_{rY4}*R_{Zr5}*R_{RY6}*R_{Zr7}

Solid joint equations

The equations to describe the solid joint movement consist of three translations and two rotations.



$$T_{Hookes\,1} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{Hookes\,2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\alpha_H & -sin\alpha_H & 0 \\ 0 & sin\alpha_H & cos\alpha_H & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{Hookes3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{Hookes\,4} = \begin{bmatrix} cos\beta_H & 0 & sin\beta_H & 0 \\ 0 & 1 & 0 & 0 \\ -sin\beta_H & 0 & cos\beta_H & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T_{Hookes\,5} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

These matrices are easiest to multiply together in a software since the complete equations will become very cumbersome to handle. The order in which these are to be combined is:

RHookes=$T_{Hookes\,1} * T_{Hookes\,2} * T_{Hookes\,3} * T_{Hookes\,4} * T_{Hookes\,5}$

DEVELOPMENT

The main objective during the development phase was to improve the performance, i.e. mainly movement range and load capacity and reduce the cost of each individual component in the tracking system. Focus was also kept on design for manufacturing.

It is important to point out that the main design of the tracker with two linear actuators was for this project already decided and the development has focused on detailed design of the ingoing components to optimize the product concept.

The development chapter describes the different concepts that were generated and how it was done as well as the requirement specification for the product. From these concepts the best were selected through selection processes according to the well-recognized product development methodologies taught at Chalmers University of Technology.

THE TWIN TRACKER CONCEPT

The concept that has been redesigned consists of two linear actuators that realize the tracking of the sun through pushing and pulling e.g. PV panels centrally stored in a universal joint. This concept has been further developed to optimize the design so that tracker can move without clashes and also while withstanding 20 m/s wind speeds when tracking.

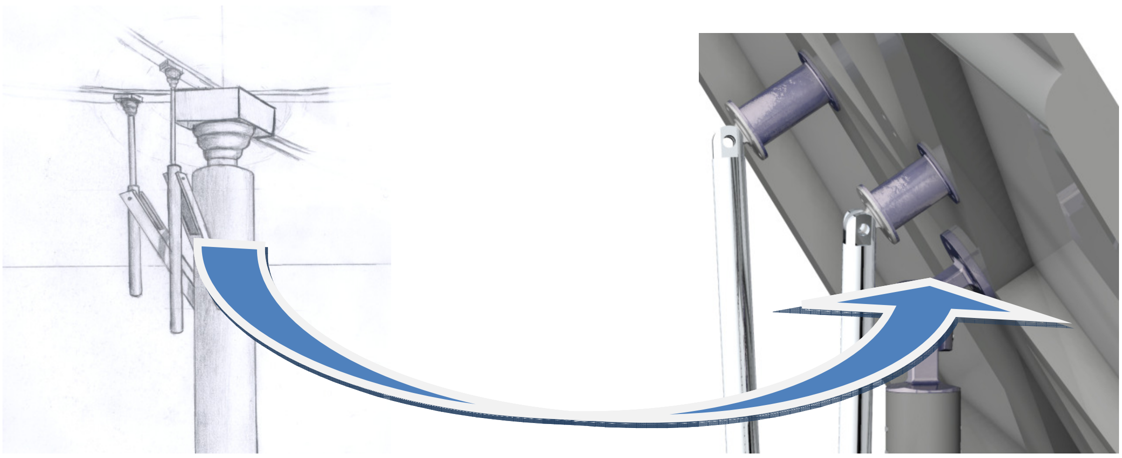


Figure 4: From concept to product.

COMPONENTS TO BE DEVELOPED

During the development phase of the project, the following components were identified for detailed design work:

- The Hooke's Joint
- Upper Rotational Joints
- Lower Rotational Joints
- The Pillar
    - Top pillar
    - Bottom pillar
- The Interface Plate

For all these components the basic requirements were stated and brainstorming was utilized to form ideas. These ideas were tested with ProEngineer or Catia in order to see the possibilities and limitations with every concept. The most interesting concepts for each component where printed as 3D SLA models to physically compare their performance.

THE HOOKE'S JOINT

The Hooke's joint that was suggested in the report SOLAR TRACKER. This joint is a crucial part of the Twin Tracker product; any improvements on the function of this joint will greatly affect the value of the Twin Tracker.

Requirements on the Hooke's joint

- Facilitate rotation around two different axes
- Easy to manufacture
- Easy to install
- As cheap as possible
- Carry the specified load cases
- Possible to control with a processing unit

The brainstorming sessions resulted in 7 new concepts that all fulfill the functional requirements. These concepts where all tested and evaluated for movement in ProEngineer Mechanism.

The Hooke's joint concepts

The concepts that were generated are:

1. 45 Degree Hooke's
2. 90 Degree Hooke's
3. Pillar rotation
4. Hooke's moon
5. Hinges
6. Course
7. T-axis
8. Solid joint

The description of these concepts can be found in Appendix J concepts.

Evaluation

The different concepts were evaluated in the CAD software for function and then compared to the reference case; the Hooke's joint. This comparison was done with a Pugh matrix. For further evaluation, the models were printed out with a 3D-printer and tested as small scale prototypes.

In the end the joints that emerged as the best were the original Hooke's joint and the solid joint.

The Hooke's joint

There are two versions of The Hooke's joint, one version that was originally suggested in the report SOLAR TRACKER in the course mpp126, that has been optimized and one new version called the Solid Joint. The old Hooke's joint with brackets and one ring with two axes is relatively cheap and easy to manufacture. The negative aspect of this joint is that it is more time-consuming to assemble than the solid joint and it does not give the same quality impression as the new Solid Joint.

The Hooke's joint consists of the following components:

- 1x Ring with 4 pins creating two axis
- 2x Lower brackets
- 2x Upper brackets
- 2x Support brackets
- 4x SKF Heavy duty fiber weave bushings
- 1 x Lid

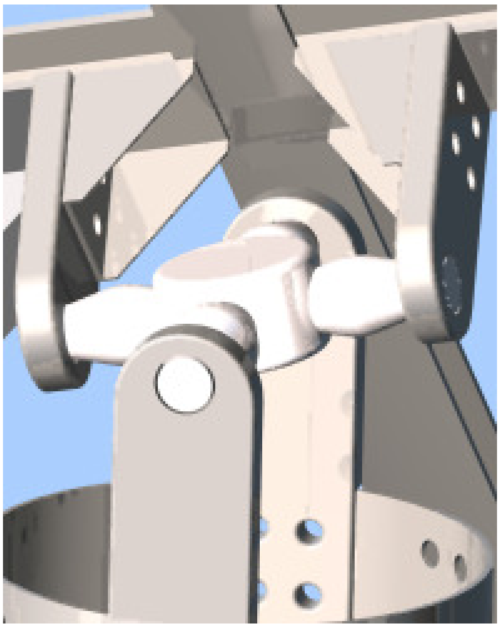


Figure 5: Hooke's Joint, bracket version.

Manufacturing

The ring is to be cast into the approximately proper dimensions and thereafter it is machined in holes where the axes are to be inserted. The machining is important because the pins require a sturdy fastening to the ring and they may not be subjected to unnecessary stresses due to unnecessary sharp edges, which is also why the holes that the axes are inserted into are coned.

The brackets are manufactured out of standard metal bars that are cut and machined into the right shape. The angle support brackets are also manufactured in the proper dimension and holes for screws are machined. It is important that these brackets are able to support the required loads without succumbing to deformations.

The Solid joint (Hooke's Joint)

The solid joint was a further development of the Hooke's joint. The development was done in co-operation with Hans Lindén and resulted in a solution that is very robust and showed very small stresses in the material in the FE-analysis.

The Solid joint is consists of the following components:

- 1x Lower arm

- 1x Joint middle
- 1x Upper arm
- 4x safety collar
- 4x SKF Heavy duty fiber weave bushings

Figur 6: Solid Joint (Hooke's Joint)

Manufacturing

The arms and the middle component of the joint are made of cast iron that is machined to create the fine enough surface tolerances in the holes to make sure that bushings and axes fit and to.

Selection of joint

The solid joint was selected as the better joint because of its superior performance; no clashes and it is very robust; it can withstand heavy loads. The FE- analysis, see FE chapter, showed that this joint can withstand the loads created by the wind and the actuators.

INTERFACE PLATE

The interface plate needs to facilitate the following technologies; PV-modules, CPV-modules, Heliostat mirrors and Strirling-dish systems.

The plate needs to be easily scaled to match the different tracker offerings. Considering the loads and the different connections that are required.

Requirements on the interface plate

- Withstand loads that are created on the different solar technologies.
- Enable easy connectivity to different technologies
- Easy to install
- Minimize cost
- Easy to manufacture

Interfaceplate concepts

- Triangle
- Square
- Frame

Evaluation

The evaluation was based on a Pugh matrix that enabled a comparison of the three concepts considering their most important aspects; see Appendix C for Pugh matrix.

Selection of interface plate concept

When evaluating the different concepts for the interface plate in the Pugh matrix it became clear the most reasonable choice is to incorporate the plate into the frame; carrying the PV panels or other solar energy technology. This is because it does not make much sense to just have a plate between the frame and the Solid Joint, which only purpose is to make sure that there is a correct hole picture for the universal joint. It is both easier and more effective to make sure that the frame that is used for either PV, Stirling Dish, Heliostat Mirror or CPV has the correct hole picture that will fit with the Solid Joint. Therefore it is concluded that when a customer chooses which panel and frame to use for the Solar Tracker, SKF solar tracker is purchased for a solar park it is easiest to contact the frame manufacturer and make sure that the frame is reworked with plates and holes that fit for the actuators and Hooke's joint.

THE ROTATIONAL HOUSINGS (UPPER AND LOWER)

The rotational joints are crucial components of the solar tracker. They are the link that transfers the forces from actuators to the solar technology array and thus needs to be very robust so that it does not fail during the products lifespan.

Requirements on the rotational housing

The requirements are:

- Withstand loads that are specified in the FE- analysis chapter
- Easy to install

Rotational housing concepts

- Spherical bushings
- Bearings
- Bearing housing

Evaluation

The rotational housings were analyzed mainly by their load carrying capacity and life expectancy.

Spherical bushings

The spherical bushings seemed at first to be the definite solution for the housings; offering a maintenance free joint for just 30% higher cost than the bearing solution. The value for the customers of a maintenance free joint would be great. But as it turned out in the play calculations; the spherical bushings are inferior to the bearing solution (see play calculations chapter). The play was just too large for the system to function properly.

Bearings
The main advantage of the bearing solution is the lower friction in the system. This lower friction will minimize the power use of the tracker and enable to increase the PV-gain percentage slightly; it also minimizes wear on joints.

The main disadvantage however is the uncertainty on how well the bearings will perform in the low rotational speeds. Bearings are designed for certain minimum velocities in order to function properly and not catch internal faults such as; false Brinelling[2] on the rollers or racers, caused by fretting (that can arise when the tracker is standing still and is subjected to small vibrations from wind). When bearings are standing still the risk of column corrosion is increased when water creeps inside the racers or rollers aren't greased continually. This also makes the expected lifetime extremely hard to calculate since the calculation models do not consider these extremely low rotational speeds.

Bearing housing
The bearing housing is a slightly cheaper solution than the bearing one because the upper rotational housings would have been eliminated as a component. It however has other limitations; the housings are the weak point. They cannot support the forces in the system unless a very large housing is used.

A maximum load of 120 kN for the proper housing in this application. This limit is surely enough to handle the instantaneous loads for the Twin Tracker, but it may be difficult to guarantee a lifetime of 20 years for an affordable solution.

Selection of rotational housing concept
The bearings were selected as the best solution for the rotational housings. The selection of the spherical bushings seemed to be the ideal choice at first but as it turned out in the play calculations chapter; they were not applicable at all in the Twin Tracker tracker.

The bearings have the benefit of guaranteeing the lowest friction in the system and a very high accuracy. The real lifetime of these bearings are however up for discussion since the calculation models available do not incorporate the extremely low rotation speeds experienced in the Twin Tracker tracker.

THE PILLAR
The pillar is the main support structure of the tracker that holds all parts together. The tallest pillar for the 100 m^2 panel area needs to be 7.6 m high in order to make sure that the tracker can function properly. For the three different versions of the tracker the pillar height also varies from 3.6 m to 7.1 m which makes it easier to divide the pillar into two sections. One bottom section, that is mould into the ground with concrete, and one upper section that is connected to the lower section through a large screw unit.

Requirements on the pillar
The requirements are:

- Withstand loads that are Specified in the FE-analysis chapter

[2] False Brinelling is damage caused by fretting; wear or corrosion damage at the asperities (surface roughness), on the material.

- Easy to install
- Minimize actuator clashes
- Carry three different sizes of the panels without making the panels clash into the ground when standing diagonally

Pillar concepts

- Tripod
- Truss structure
- Cylindrical pillar

Evaluation and selection

The pillars where not evaluated in a Pugh elimination matrix because the testing in ProEngineer easily showed that the best shape for the pillar is the cylindrical, since this shape minimizes the area where the actuators clash into the pillar. The two divided cylindrical pillar was selected since the other concepts didn't fulfill the clash requirement well at all.

Figure 7: Selected Pillar concept.

THE LOWER ROTATIONAL HOUSINGS

The lower rotational housings are the mechanical components that connects the bushings and actuators to the Pillar structure. The pillar arms should be as small and thin as possible but at the same time robust enough to take up the forces from the actuators into the pillar.

Requirements on the lower rotational housings

The requirements are:

- Withstand loads that are Specified in the FE- analysis chapter
- Easy to install
- Minimize clashes
- Make sure that actuators are positioned optimally to carry loads
- Hold the bearings or bushings in place
- Easy to manufacture

Lower rotational housings concepts

- Cylindrical arms welded to the pillar at the correct height
- Cylindrical arms mounted on the ground
- Cylindrical arms welded on a ring that is clamped to the pillar at the correct height (Pillar ring)

Evaluation and selection

The lower rotational housings were not evaluated in a Pugh elimination matrix because the testing in ProEngineer eliminated concept #2 and also showed that the best shape for the pillar is the Pillar ring. This shape minimizes the area where the actuators clash into the pillar. Welding the arms on a ring is the best solution for this since performing a weld on a very large pipe would require a large and robust fixture.

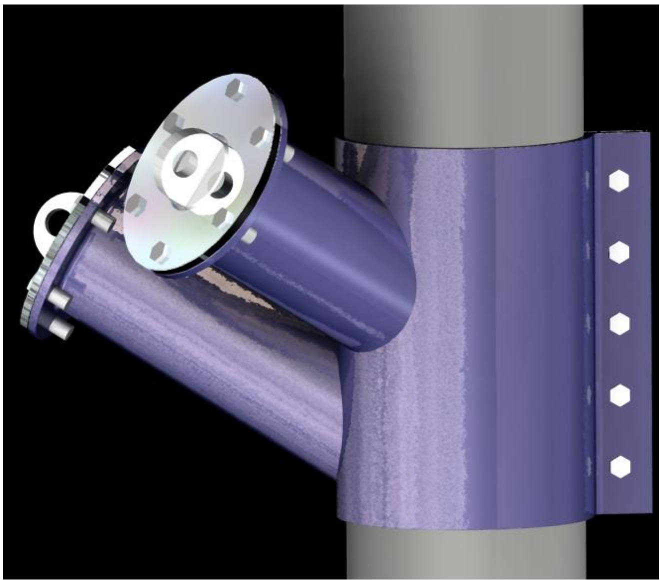


Figure 8: Selected pillar Arms concept.

Conclusions

The development process resulted in new designs for the Hooke's joint, rotational housings, the pillar arms as well as placement of the actuators in order to maximize movement and load taking capability. These new designs are more robust and can guarantee a good performance for the Twin Tracker product. The detailed drawings for all versions of the new components can be found in appendix E.

Requirement Specification

When developing the solar tracker product there are many different requirements that must be fulfilled. To capture all these requirements; a requirement specification was made and continuously updated during the project. This requirement specification is naturally a continuation of the specification originally developed during the concept development project in fall 2009.

This chapter will highlight the most central requirements for the dual axis solar tracker. For the complete requirement specification see Appendix C.

Design

- Dual axis tracking
- Azimuth range, 0° - 210°
- Elevation range, 10° - 90°
- Minimum life-time of the product > 20 years, i.e. the tracker moves east to west and back 14.600 times.

The criteria *Dual axis tracking* states that the solar tracker shall be able to track the sun by movement around two axes; azimuth and elevation.

The Azimuth range is the east to west tracking ability and Elevation is the observed zenith angle change. If the specified values are fulfilled they enable a product to be competitive on the tracking system market.

The *Minimum lifetime* is identified from benchmarking and it is an extremely important criteria to consider since it is has become an outspoken criteria that the product has a lifetime of at least 20 years. Since the lifetime reflects the profitability of the product greatly.

Production

The production capacity and the production costs reflect the profitability of the Twin Tracker.

- Maximum manufacturing cost of 1200 Euro for the Twin Tracker configurations
    - Small tracker 723 €
    - Medium tracker 1.280 €
    - Large tracker 1.714 €

The *Manufacturing Capacity* is a demand that must be met by the manufacturing company. This criteria is important since the solar tracker market has had an explosive expansion, it is also to ensure the capability to meet the expected market demand.

Max Manufacturing Cost per Unit is a benchmarked value that the product needs to be under otherwise it is not competitive on the market.

Distribution

- Minimum units per truck, 8 Solar Trackers per truck.

The *Minimum number of units per truck* is an important criterion to assure that the product will be able to be supplied to the customer in an efficient way.

Installation

- Installation is handled by two persons and a crane

The *Installation is handled by two people and a crane* criterion is to make sure that the installation process of the tracker is easy and quick.

Use

- Minimize tracking system power usage

The criterion *Minimize tracking system power usage* is important to make the system as energy efficient as possible and is aimed at choosing a power smart solution for the azimuth and elevation systems.

Maintenance

- Max maintenance interval, 1 year.

The maintenance interval is for the moving parts of the tracker system are expected to be done once every year and is aimed at lubrication. For the stationary parts , no maintenance during the whole lifetime is expected.

Disposal of the Product

- The product should be recyclable, to 90 %.

The Solar Tracker product is expected to be made up of materials that are possible to be recycled to at least 90 %.

ANALYSIS OF THE DUAL LINEAR ACTUATOR PRODUCT

This chapter describes the performance of the dual linear actuator. The following analyses were made:

- Finite element analysis
- Force calculations
- Movement range analysis
- Prototype analysis
- Cost analysis
- Manufacturability analysis
- Play approximation

FINITE ELEMENT ANALYSIS

The aim of the finite element analysis is to dimension the ingoing components and to prove that the structure of the product can withstand the loads that are applied to it during usage.

ANALYSIS METHOD

For the analysis the most extreme positions and load directions were considered, these are described in each individual case. If the structure holds for these positions; it will also hold for all other positions. The FE- analysis is conducted for all the different configurations with the small, medium and large actuators. Also, a wind speed of 20 m/s is calculated with. Each load case will be explained individually for each component.

LOAD CASES AND RESULTS

The different load cases with the corresponding results are described below. The full results with larger images can be found in appendix H.

Pillar

The load cases

1. Large tracker:
    a. 100 kN static and 20 kN dynamic actuators
    b. Panel area of 100 m^2
    c. Wind speed of 20 m/s
    d. Wind load of 45 kN
2. Medium tracker
    a. 60 kN static and 20 kN dynamic actuators
    b. Panel area of 85 m^2
    c. Wind speed of 20 m/s
    d. Wind load of 32 kN
3. Small tracker
    a. 16 kN static and 4 kN dynamic
    b. Panel area of 25 m^2
    c. Wind speed of 20 m/s
    d. Wind load of 1.000 kN

The wind load is placed on top of the pillar at an arbitrary direction. The twisting forces created by the actuators were also applied to the top of the pillar, where the screws transfer the loads to the pillar.

Results

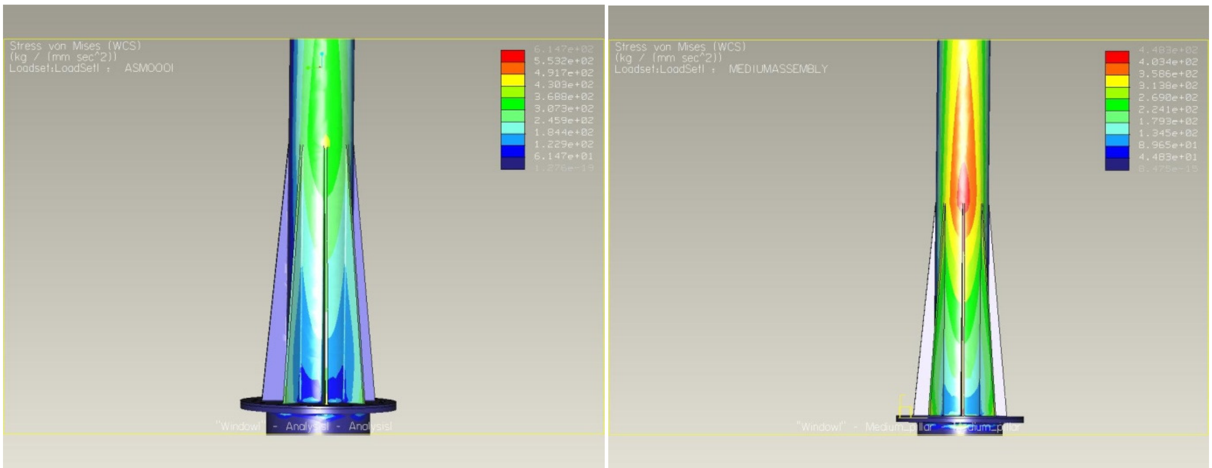


Figure 25: To the left; the large pillar. To the right; the medium pillar. The color coding shows that the medium tracker has its largest stresses near the flanges. The large pillar has its largest stresses in the screw holes at the top (not visible in this figure).

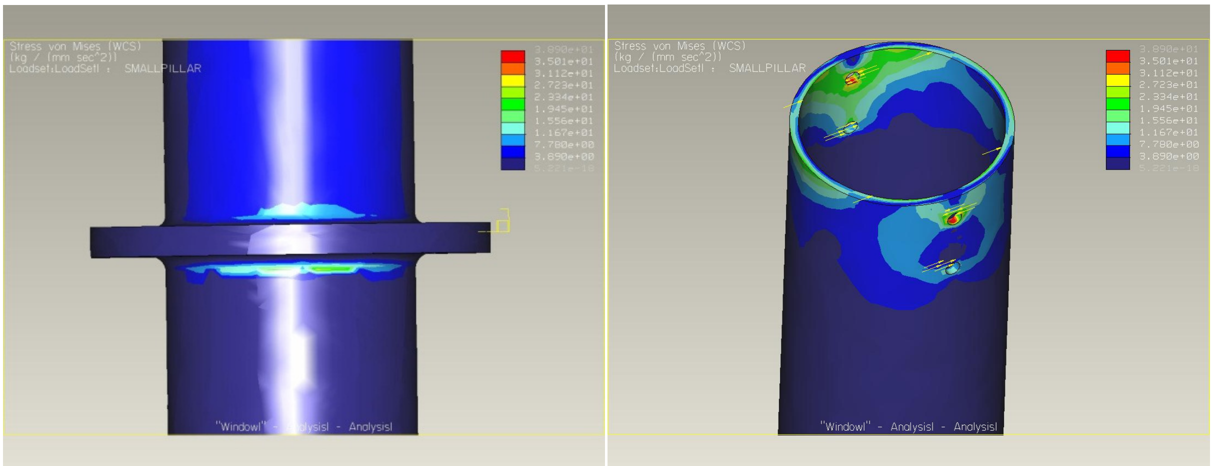


Figure 26 The stresses in the small pillar. The highest stresses are at the screw holes at the top of the pillar.

The stresses in the pillar are within the yield strength limit of the AISI 6150 material. For the medium and large trackers the pillar is a relatively high structure. If any problems surface with the durability of the pillar; the ground pillar can be made higher. Its wider base makes it more sturdy against the torques created by the loads.

- The large pillar has a safety margin of 1.7 before it yields.
- The medium pillar has a safety margin of 2 before it yields.
- The small pillar has a safety margin of 6 before it yields.

Solid joint

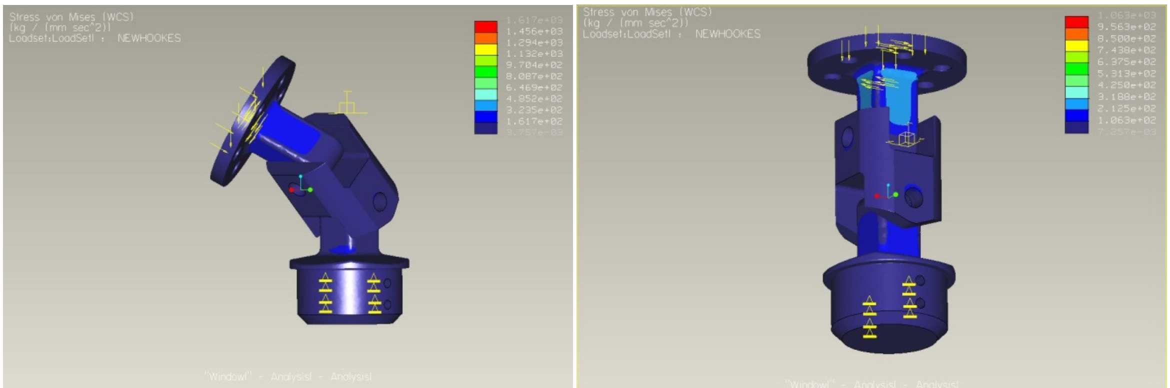
Load cases

1. Large tracker:
   a. Wind load of 45 kN

    b. Weight load of 35 kN
    c. Torsion by a force couple of 120 kN on the top of the Solid joint
2. Medium tracker
    a. Wind load of 32 kN
    b. Weight load of 25 kN
    c. Torsion by a force couple of 70 kN on the top of the Solid joint
3. Small tracker
    a. Wind load of 1000 kN
    b. Weight load of 10 kN
    c. Torsion by a force couple of 20 kN on the top of the Solid joint

The Solid joint was analyzed as an assembly and thus the forces and the stresses will distributed realistically.

Results



The maximum stress arises around the joint pins. Here the material yields a little, but after a small plastic deformation it will not yield any more. These deformations are very small and it will not affect the performance of the joint.

The maximum stress in the arms is 350MPa for the highest loads, this will give a safety margin of 1.89. Since the Solid Joint will only be made in one size; the smaller trackers' Solid Joints will carry the loads easily.

Rotational Housings

Load cases

1. Large tracker:
    a. 100kN static and 20kN dynamic actuators
    b. Panel area of 100 m^2
    c. Wind speed of 20 m/s
    d. Wind load of 45kN
    e. Weight load of 35kN
2. Medium tracker
    a. 60000kN static and 20kN dynamic actuators
    b. Panel area of 85 m^2
    c. Wind speed of 20m/s
    d. Wind load of 32kN
    e. Weight load of 35kN

3. Small tracker
    a. 16kN static and 4kN dynamic
    b. Panel area of $25m^2$
    c. Wind speed of 20m/s
    d. Wind load of 1000kN
    e. Weight load of 35kN

The rotational housing are loaded radially at the top of the housing, in the spherical bushing placement. This will create the highest possible load case for the housings.

Results

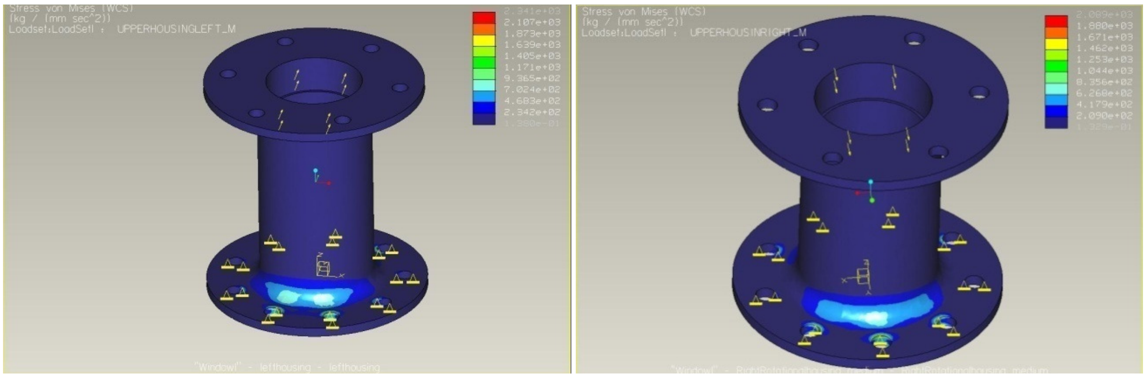


Figure 27 **To the left: The left large rotational housing. To the right: The right large rotational housing**

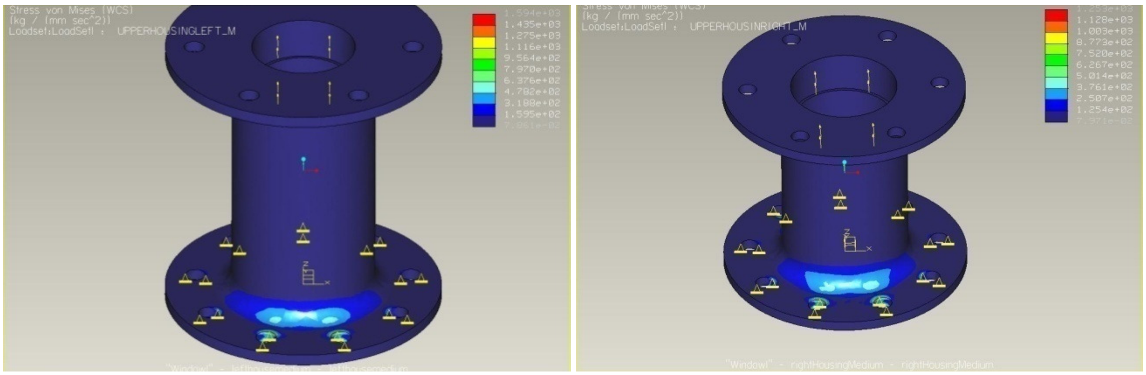


Figure 28 **To the left: The left medium rotational housing. To the right: The right medium rotational housing**

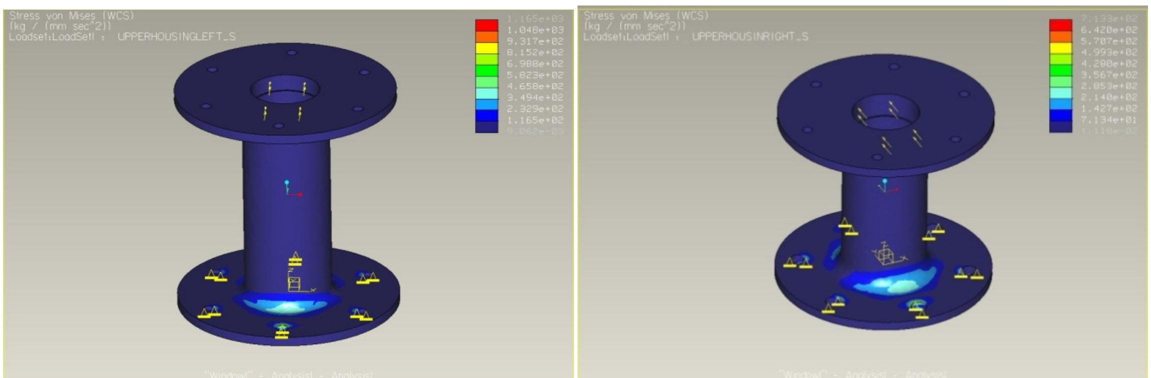


Figure 29 **To the left: The left small rotational housing. To the right: The small medium rotational housing**

The rotational housings do not have any problems in managing the loads on the system. The weakest area is the weld. This weld is preferably under dimensioned and thus a little weaker than the AISI 6150 is, so that there won't be any stress concentrations in the weld where the weld could shed from the weld metal. A low strength assumption would be 600 MPa as the welds yield limit. The welds at worst have a safety factor of 1.7 before any yielding occurs.

The weld safety factors are:

- The large housings' welds have a safety margin of 1.7 before they yield.
- The medium housings' welds have a safety margin of 2 before they yield.
- The small housings' welds have a safety margin of 6.3 before they yield.

The highest stresses arise in the screw holes that are used to fasten the housings to the interface plate. There is a risk that a very small area near the screw holes will deform plastically. This area is however very small.

Except for the small possible plastic deformation around the holes, there exists no risk that the housings will fail due to the loads.

Lower rotational housings

Load cases

1. Large tracker:
    a. 100kN static and 20kN dynamic actuators
2. Medium tracker
    a. 60000kN static and 20kN dynamic actuators
3. Small tracker
    a. 16kN static and 4kN dynamic

The Lower rotational housings are loaded with the highest force that the actuators can withstand without breaking. That is, this is the maximum load that they will be subjected to during use. The three suggested tracker sizes have different load specifications and therefore the arms can be dimensioned after these specifications.

Results

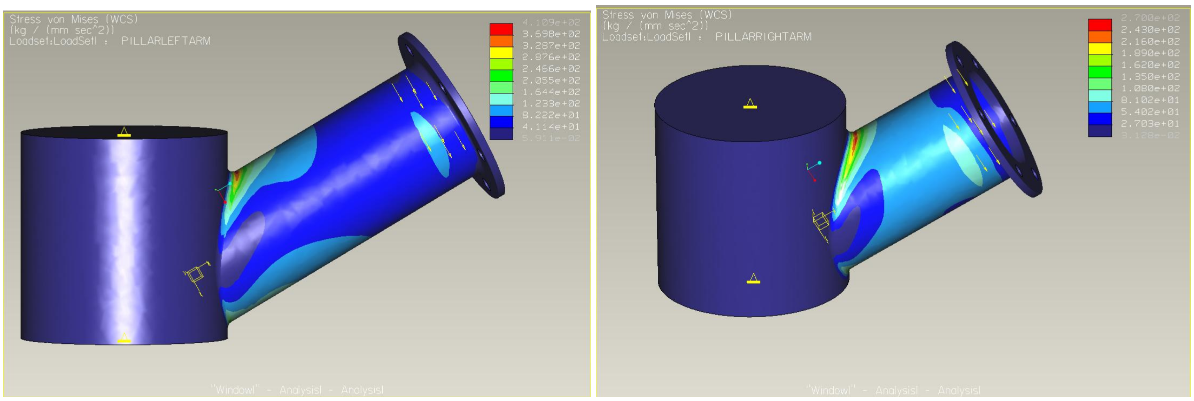


Figure 30 **To the left: The large left arm. The maximum stress at the weld is 411MPa**
To the right: The large right arm. The maximum stress at the weld is 270MPa

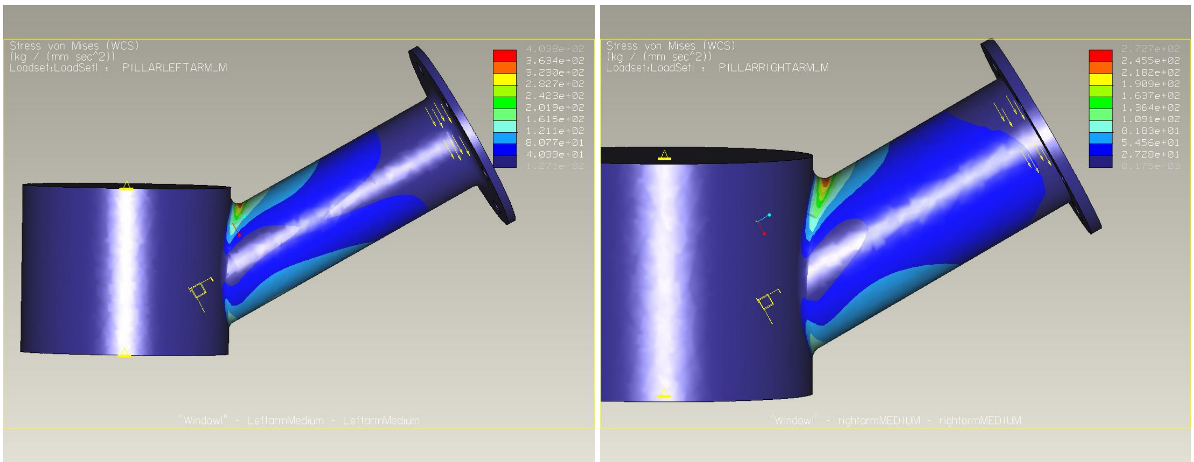


Figure 31 **To the left: The medium left arm. The maximum stress at the weld is 400MPa**
To the right: The medium right arm. The maximum stress at the weld is 272MPa

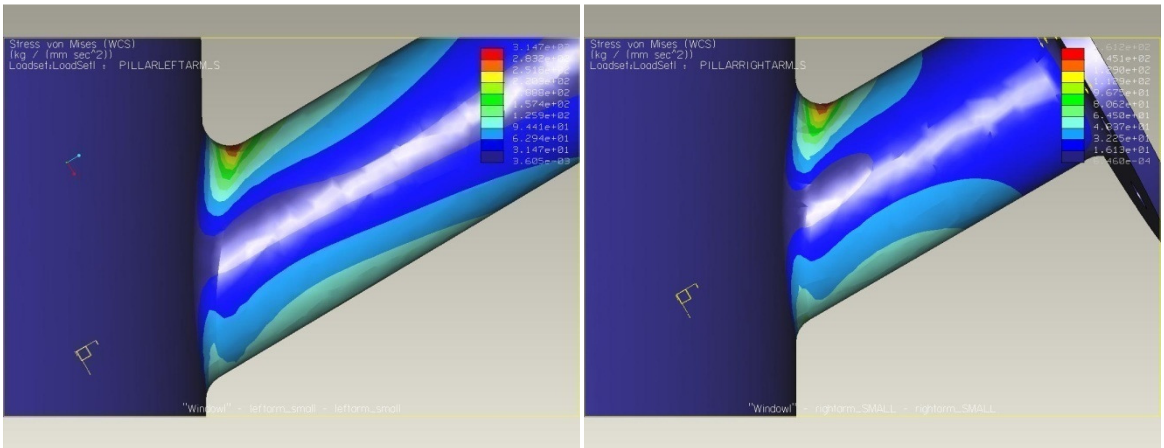


Figure 32 **To the left: The small left arm. The maximum stress at the weld is 314MPa**
To the right: The small right arm. The maximum stress at the weld is 162MPa

The location of the highest stresses is also the weakest area. Assume that the weld is under-dimensioned and has maximum yield strength of 600MPa. With this suggested case, the stresses have a safety margin of 1.45 to the welds.

The safety margins for the most affected arm welds are:

- The large arms' welds have a safety margin of 1.45 before they yield.
- The medium arms' welds have a safety margin of 1.5 before they yield.
- The small arms' welds have a safety margin of 1.9 before they yield.

All the three pillar arm solutions manage to handle the loads. The highest stresses arise in the welding of the Pillar Ring and the arms. This weld is under dimensioned to 1400MPa yield strength limit. As seen on the figures, the stresses pose do not affect the welds at all.

Rotational joints

The rotational joints connect the actuators to the interface plate. Since the maximum load that these joints need to withstand equals the maximum force that each actuator can push with; the joints where loaded with 120 kN. The maximum stress that arose in the joints where 554 MPa, as seen in the picture, this gives an elastic safety factor of 4.07 against the AISI 6150 material yield strength.

Results

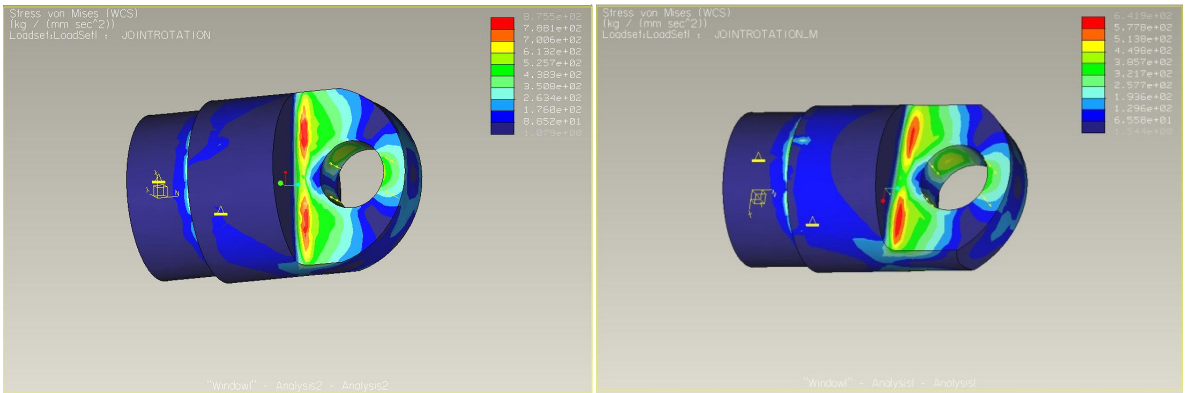


Figure 33 shows the FE analysis of the rotational joints. The large to the left and the medium to the right. The highest stresses are located at the simulated fastening point. These do not occur in real life and are discarded.

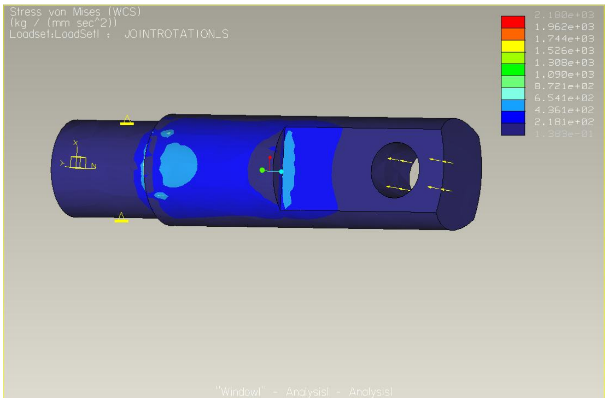


Figure 34 Shows the FE analysis of the small rotational joint. The highest stresses are located at the simulated fastening point. These do not occur in real life and are discarded.

The stresses that occur the rotational joints are much lower than the AISI 6255 yield limit. No plastic deformation will occur on these components.

The safety margins for the rotational joints are:

- The large rotational joints have a safety margin of 2.6 before they yield.
- The medium rotational joints have a safety margin of 3.5 before they yield.
- The small rotational joints have a safety margin of 26 before they yield.

Fastening cap

The load cases

1. Large tracker:
   a. 100 kN static and 20 kN dynamic actuators
2. Medium tracker
   a. 60 kN static and 20 kN dynamic actuators
3. Small tracker
   a. 16 kN static and 4 kN dynamic

Results

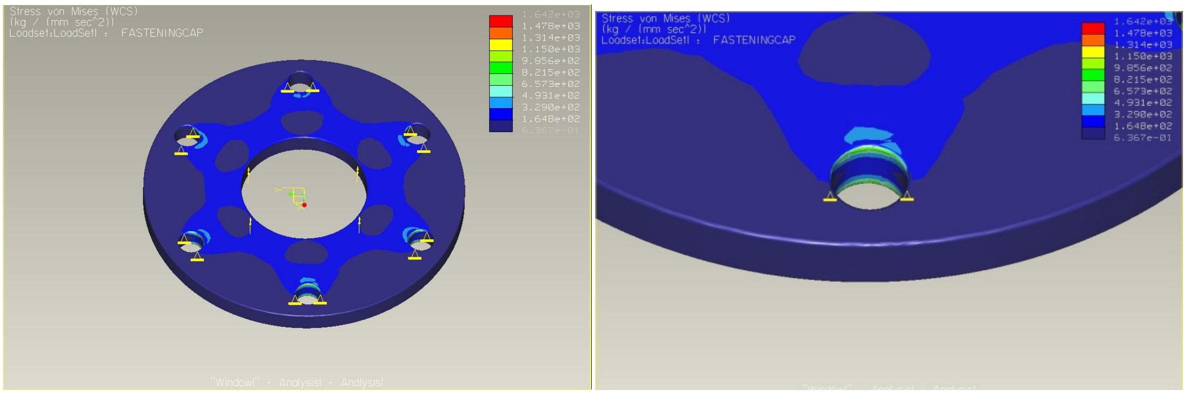


Figure 35 The large fastening cap FE-analysis results

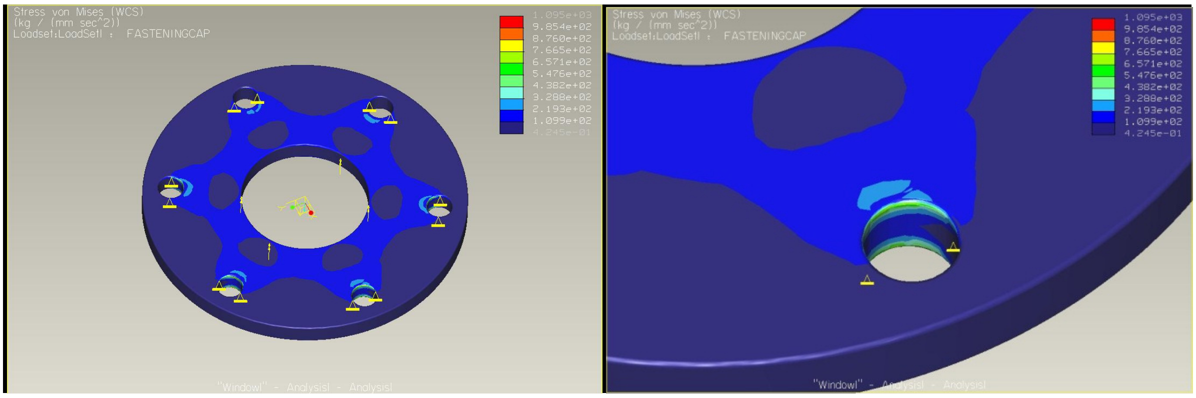


Figure 36 The medium fastening cap FE-analysis results

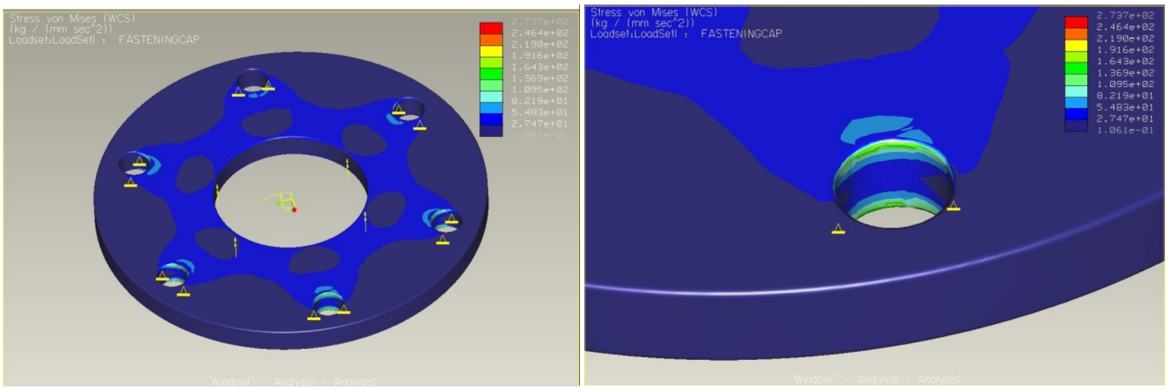


Figure 37 The small fastening cap FE-analysis results

There will be no plastic deformations on the fastening cap , on any sizes of the tracker. The maximum stress in the large fastening cap is 1.642 MPa at the screw holes and will give a slight plastic deformation at these areas but it will not be significant. The safety factor on the other areas than the screw holes is 4.6.

In conclusion, the safety margins for the fastening caps are:

- The large fastening caps have a safety margin of 2 before they yield.
- The medium fastening caps have a safety margin of 2.5 before they yield.
- The small fastening caps have a safety margin of 93 before they yield.

Conclusions

The FE analysis has enabled the components to be designed and dimensioned to be able to withstand the loads applied to the tracker during usage.

None of the components experience stresses higher than the yield limit in the crucial areas. The yield strength is passed in some cases, but these areas only slightly deform plastically and do not affect the performance of the system. These areas are located on the edges of the screw holes of the fastening areas. These areas are also affected negatively by the boundary conditions; the boundaries in each analysis are infinitely stiff and therefore cause higher stresses than they would have in real life. This means that the stresses in the screw hole are higher than they will be in real life.

The main result from the FE analysis is that the system has a safety factor of 1.45 in the weakest component. The largest trackers weakest component can therefore carry 45% the load than it is suggested to by the winds. The medium tracker has the lowest safety factor of 1.5 before it yields; the small tracker has 1.9 before it yields. If a safety factor of e.g. 2 is requested for all the tracker versions. The individual components material thickness could be optimized through detailed FEA but the project was limited from not focusing on that, in the project scope, since it would have been very time consuming.

Movement Range

The range of motion for the solar tracker is highly dependent on the design of the tracker. Small changes in for example placement of the actuator joint on the interface plate, how the pillar arms are designed or how the Hooke's joint is positioned (rotated) affects when clashes between parts appears, i.e. clashes between the actuators and the pillar when moving from east to west. When the geometry of the ingoing components of the tracker are designed optimally against clashes, the forces on the tracker, during usage, also needs to be calculated to make sure that the actuators can control the motion of the panel in every position. What has been found, and can be seen in the force calculations chapter. Is that the biggest challenge when maximizing the motion range in azimuth and elevation is to make sure that there are long enough lever arms to the actuators in all positions of the tracker's movement. If the lever arms that the actuators can utilize around the two axis of the Hooke's joint are small the actuators have problems counteracting the wind load.

Limiting factor

What needs to be explained about the motion range of the tracker is that the limiting factor is when the force from the wind becomes greater than the force that the actuators can push with. The actuators are very strong and can push with 120 kN and the wind of 20 m/s only creates a direct force of 45 kN on a 100 m2 panel area, so wind forces distributed uniformly over the panel area are no problems. But if the wind strikes only a portion of the panel area, it creates high torques around the Solid joint that have to be counteracted by the actuators. The weakest areas of the tracker are when the points, where the force of the actuators is affecting, are in line with one of the axes of the Solid joint of the pillar. This reduces one of the lever arms for creating counteracting torque, *see force calculations chapter for detailed description*. This problem is however decreased with smaller panel areas and as the panel areas are decreased the azimuth range increases.

Actual motion range

In order to highlight the movement range in an understandable way the following table explains the azimuth and elevation range in relation to three different panel areas:

Table 18: Solar Tracker movement range.

Wind m/s	Panel area m^2	Azimuth range	Elevation range
20	120	213	4 – 90*
20	100	220	4 – 90*
20	70	225	4 – 90*
20	50	233	4 – 90*
10	120	252	4 – 90*
10	100	252	4 – 90*
10	70	253	4 – 90*
10	50	254	4 – 90*

The range however that can be achieved if the wind is not considered is 360 degrees azimuth and 4 – 90 degrees elevation.

Force calculations

The force calculations has three objectives:

1. To verify that the actuators can provide the needed force in order for the product to function properly.
2. Calculate the maximum panel area and wind speed for tracking.
3. To calculate the forces applied in the Solid joint in order to enable bearing or bushing selections and to support the FE-analysis.

Method

Matlab and ProE were the main tools of this analysis. Measurements were used in the CAD model to provide for geometrical information about positions of interest in the Twin Tracker product. This data was input to Matlab, where the calculations were performed.

The analysis of actuator forces are heavily coupled with the wind speed and panel area calculations. The two variables; panel area and wind speed were varied and it was checked if the actuators could deliver enough force to counter the loads. This check was performed utilizing an easy to overview Boolean function which returns a true whenever the actuators could give sufficient force to counteract the loads.

The equations that these calculations are based on are torque equilibrium calculations around the Solid joint, these are described in detail in the chapter below.

Equations

The equations that were used in the numerical calculations are presented in this chapter. Most of the equations are based on the equations found in the book Mekanik, (Per-Åke Jansson, 2002).

Wind speed equation

The wind is very difficult to simulate, therefore an approximation was used. The equation is described in the book Fluid Mechanics, (White, 2006).

$$F = Area_{Panel}[m^2] * C_d * v_{wind}{}^2 \left[\frac{m}{s}\right] * \rho_{Air} \left[\frac{kg}{m^3}\right] * 0.5 \quad [\text{N}] \qquad eq.1.$$

This approximation, where C_d accordingly is approximated to 1, gives sufficient accuracy for the calculations performed on the Twin Tracker tracker. More accurate wind simulations are used for cars, aircrafts and trains in order to decrease the air resistance in their design. This level of accuracy was not needed here, because the fluid dynamics around the panels are not of interest but only the load on the panels.

Torque equilibrium equations

These calculations are based on torque equilibrium around the Hooke's joint. This is a natural selection for calculating the torque since the two rotations, around the X- and Y-axes cannot counteract any torque and the resulting torque is zero. The Z-axis of the joint however will be subjected to a torque from the loads and the actuators. This magnitude was solved with numerical values from Matlab and the Finite Element Method (FEM) analysis was made with the highest values for this torque in mind.

The equations are presented here and the solutions were solved numerically in Matlab. Torque is in equilibrium around the Hooke's joint if the loads and the actuators create the same amount of torque, which leads to that the system is able to withhold its position.

$$\boldsymbol{T}_{mass} + \boldsymbol{T}_{wind} = \boldsymbol{T}_{West\ actuator} + \boldsymbol{T}_{East\ actuator} \qquad eq.2$$

The torque created from the mass is described as:

$$\boldsymbol{T}_{mass} = \begin{vmatrix} \boldsymbol{e_x} & \boldsymbol{e_y} & \boldsymbol{e_z} \\ 0 & 0 & m * g \\ X_m & Y_m & Z_m \end{vmatrix} = (-Y_m * m * g)\boldsymbol{e_x},\ (X_m * m * g)\boldsymbol{e_y},\ (0)\boldsymbol{e_z} \qquad eq.3$$

The torque from the wind is described as:

$$\boldsymbol{T}_{wind} = \begin{vmatrix} \boldsymbol{e_x} & \boldsymbol{e_y} & \boldsymbol{e_z} \\ F_{wind,x} & F_{wind,y} & F_{wind,z} \\ X_{wind} & Y_{wind} & Z_{wind} \end{vmatrix} = \left(F_{wind,y} * Z_{wind} - F_{wind,z} * Y_{wind}\right)\boldsymbol{e_x},\ \left(-F_{wind,x} * Z_{wind} + F_{wind,z} * X_{wind}\right)\boldsymbol{e_y}, \left(F_{wind,x} * Y_{wind} - F_{wind,y} * X_{wind}\right)\boldsymbol{e_z} \qquad eq.4$$

The torque that the west actuators can create is stated as:

$$\boldsymbol{T}_{west,Actuator} = \begin{vmatrix} \boldsymbol{e_x} & \boldsymbol{e_y} & \boldsymbol{e_z} \\ F_{W.act,x} & F_{W.act,y} & F_{W.act,z} \\ X_{W.act} & Y_{W.act} & Z_{W.act} \end{vmatrix} = \left(F_{W.act,y} * Z_{W.act} - F_{W.act,z} * Y_{W.act}\right)\boldsymbol{e_x}, \left(-F_{W.act,x} * Z_{W.act} + F_{W.act,z} * X_{W.act}\right)\boldsymbol{e_y}, \left(F_{W.act,x} * Y_{W,act} - F_{W.act,y} * X_{W.act}\right)\boldsymbol{e_z} \qquad eq.5$$

The torque that the east actuator can create is stated as:

$$\boldsymbol{T}_{East,Actuator} = \begin{vmatrix} \boldsymbol{e_x} & \boldsymbol{e_y} & \boldsymbol{e_z} \\ F_{E.act,x} & F_{E.act,y} & F_{E.act,z} \\ X_{E.act} & Y_{E.act} & Z_{E.act} \end{vmatrix} = \left(F_{E.act,y} * Z_{E.act} - F_{E.act,z} * Y_{E.act}\right)\boldsymbol{e_x},$$

$$\left(-F_{E.act,x} * Z_{E.act} + F_{E.act,z} * X_{E.act}\right)\boldsymbol{e_y}, \left(F_{E.act,x} * Y_{E.act} - F_{E.act,y} * X_{E.act}\right)\boldsymbol{e_z} \qquad eq.6$$

In order to calculate the torques it is needed to define the direction of the force and the lever-arm for each individual case.

Force vector equations

The force magnitude is given by the three actuator suggestions, this force acts in the direction that the actuator is pointing. To know the different components of this force, the unit vector is needed. This unit vector can be calculated by using measurements from the CAD model.

$$\boldsymbol{u}_{E.act} = \frac{(\Delta X_{E.act}, \Delta Y_{E.act}, \Delta Z_{E.act})}{\sqrt{(\Delta X_{E.act}^2 + \Delta Y_{E.act}^2 + \Delta Z_{E.act}^2)}} \qquad \text{eq.7}$$

$$\boldsymbol{u}_{W.act} = \frac{(\Delta X_{W.act}, \Delta Y_{W.act}, \Delta Z_{W.act})}{\sqrt{(\Delta X_{W.act}^2 + \Delta Y_{W.act}^2 + \Delta Z_{W.act}^2)}} \qquad \text{eq.8}$$

This now enables us to efficiently calculate the directions that the force from the actuators is applied in.

$$\boldsymbol{F}_{E.act} = F * \boldsymbol{u}_{E.act} \qquad \text{eq.9}$$

$$\boldsymbol{F}_{W.act} = F * \boldsymbol{u}_{W.act} \qquad \text{eq.10}$$

Lever arm equations

For the force calculations, the origin of the coordinate system is placed in the middle of the Hooke’s joint. In the assembly the origin is in the pillar’s bottom and therefore it is required to be moved mathematically by the formulas described in this chapter.

The denotation $\boldsymbol{O}_{Hooke's}$ describes the mass centre of the Hooke’s joint, where the origin is also placed. This point is always fixed in space and it does not move even if the Hooke’s joint rotates.

$\boldsymbol{O}_{Interface\ plate}$ is the mass centre of the interface plate

$\boldsymbol{O}_{East\ actuator}$ and $\boldsymbol{O}_{West\ actuator}$ are the affecting points of the force from the actuators.

Equations used to calculate the lever arms are described below

$$\Delta\boldsymbol{O}_{\boldsymbol{mass\ Load}} = \boldsymbol{O}_{Interfaceplate} - \boldsymbol{O}_{Hooke's} \qquad \text{eq.11}$$

$$\Delta\boldsymbol{O}_{\boldsymbol{Wind\ Load}} = \boldsymbol{O}_{Interfaceplate\ load\ point,\ \ i} - \boldsymbol{O}_{Hooke's} \qquad \text{eq.12}$$

Where the *i* stands for the different load points (1, 2, 3, 4, 5, 6 and 7).

$$\Delta\boldsymbol{O}_{\boldsymbol{East\ actuator}} = \boldsymbol{O}_{East\ actuator} - \boldsymbol{O}_{Hooke's} \qquad \text{eq.13}$$

$$\Delta\boldsymbol{O}_{\boldsymbol{West\ actuator}} = \boldsymbol{O}_{West\ actuator} - \boldsymbol{O}_{Hooke's} \qquad \text{eq.14}$$

LOAD CASES

Different solar courses were analyzed in order to calculate the appropriate configurations for the panel size and wind speed.

Each case was analyzed with the following approximations:

Seven points of interest for the wind loads. These points are spread out over the panel area as shown in figure 24.

1. The wind force was applied horizontal and perpendicular to the projected area, seen from the ground.

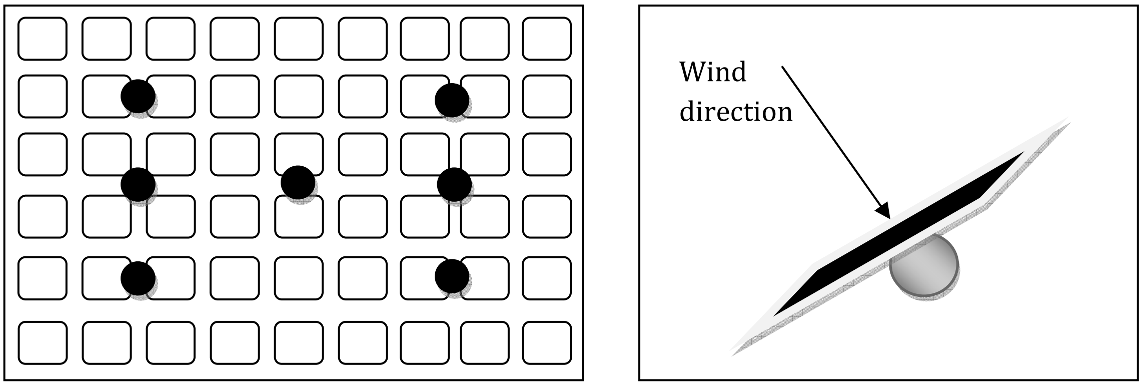


Figure 24: shows the measurement points on the simulated panel and the assumed wind direction. The wind is always facing towards the flat surface of the panels.

Tested solar path

The tracker moved with an azimuth range of 360 degrees with an elevation angle of 88 degrees. This can be seen as one of the most extreme load cases, considering the torques needed to lift the panel with the actuators, because the lever arms for the actuators are the shortest. These calculations will show if the actuators can deliver enough force to realize this movement.

Results

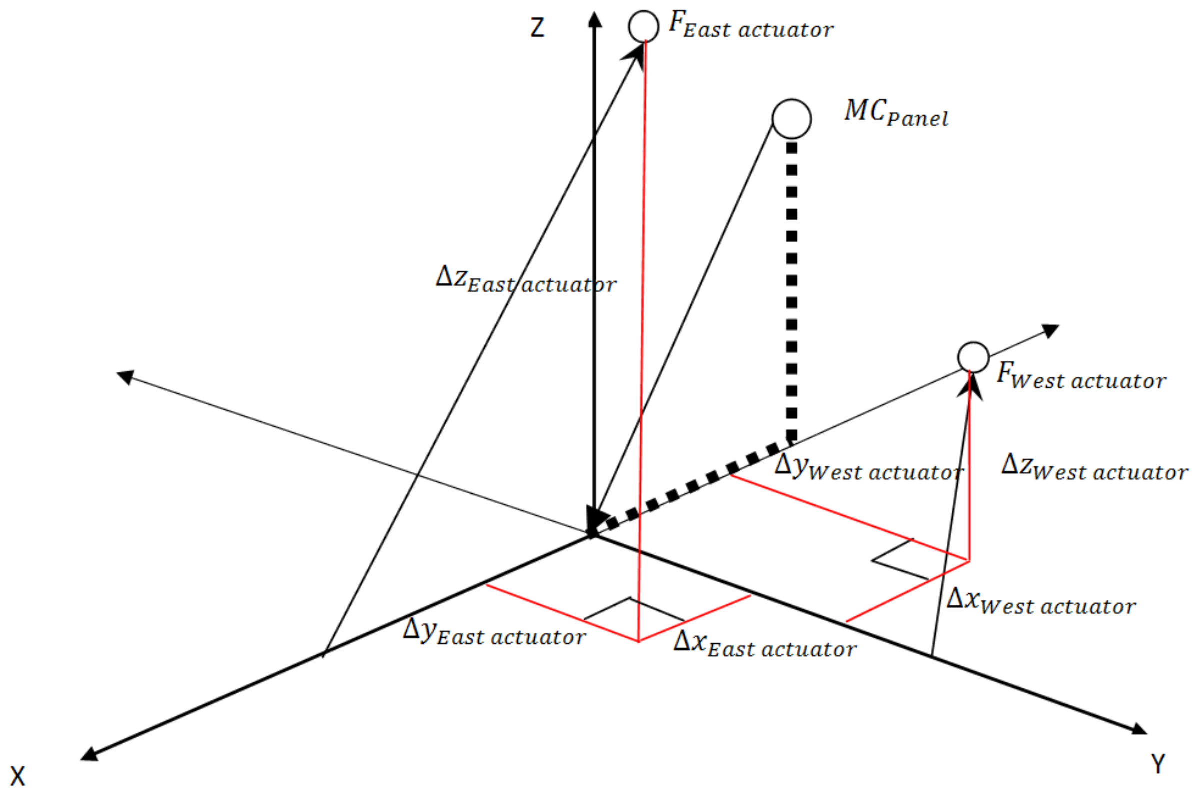
The main results from the force calculations were:

- Initial design was too weak to carry the loads for the 100 m^2 panel areas in 20 m/s winds when tracking; redesign needed to be done.
- An unsymmetrical design enables the actuators to carry the required loads.
- The highest torque created around the Solid joint can be simulated with a force couple of 120 kN that twists the joint.
- The Twin Tracker can be very competitive for Heliostat application.

Complete results can be seen in the appendix E.

The calculations showed that the original configuration was too weak to cover the solar paths in the afternoon. The reason for this was that the lever-arm's to the Solid joint was minimized. Modifications were made in order to ensure that there always exists a lever-arm between the actuator force application point and the Solid joint axes. The tracker can, with these modifications, track the sun in the stated movement range, as shown in the actual tracking movement range chapter.

Figure 2 shows how the lever arms are affected by the movement. At the weak positions the lever arms in the x-and y-directions are minimized creating a problem for the actuators to produce enough torque around the solid joint to withstand the wind.



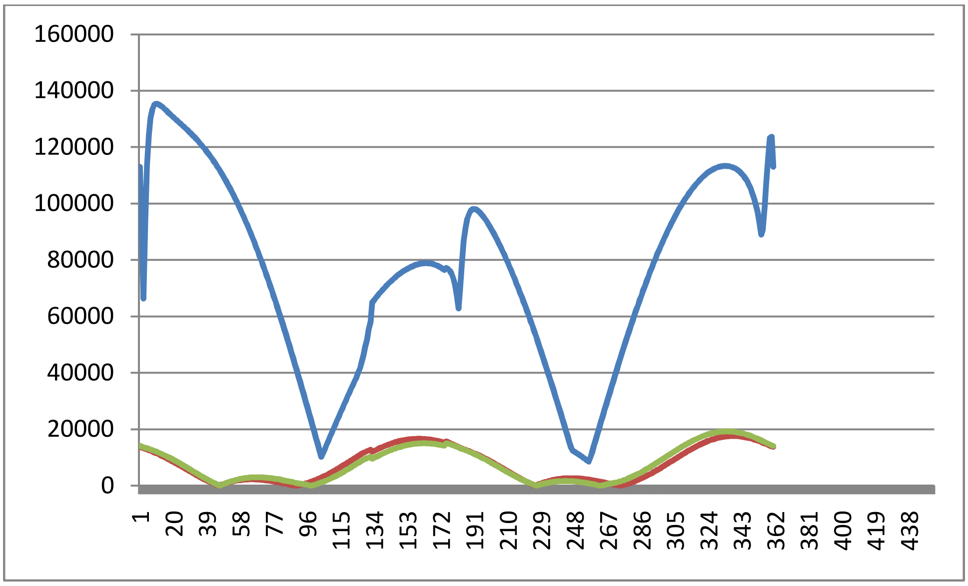
Figur 25: Lever arms geometry.

Calculations show that for the two 120kN trackers, the best combination is a 100 m^2 panel and a wind speed limit of 20 m/s (72 km/h). Higher speeds can be tolerated in many positions, especially during the midday, but for the weakest positions in this configuration the wind speed can be at maximum 20 m/s.

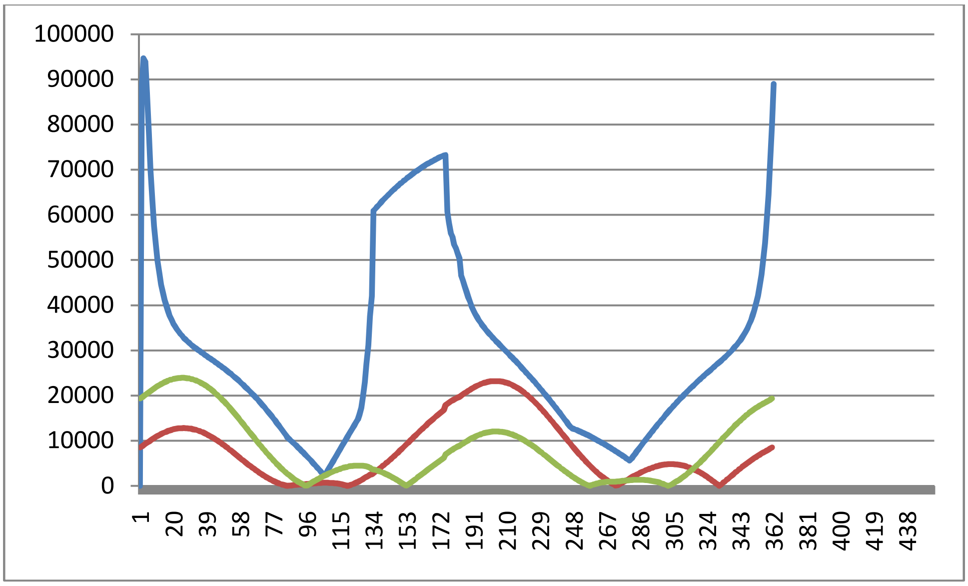
Asymmetrical design

The knowledge gained from the force calculations supported of having an asymmetrical design in the system. The housings are therefore manufactured in different lengths as well as their placement is asymmetrical both in the supporting frame and the pillar. These alterations produced enough lever-arm for the system to be able to carry the loads from the winds and the weight of the solar power system used.

The placement of the actuators also makes the tracker possible to withstand higher forces during the midday than it can during the morning and evening, see appendix K force calculations. This variance in performance should be exploited to boost the performance around 10 am to 2pm. This could be realized with a simple trigger in the controlling software that raises the wind trigger input higher values during these hours. Also this gives the possibility for the Heliostat version of the tracker to withstand much higher wind speeds than, since it can be designed to almost only needing to track in the strong areas. For Heliostat this also means that the tracker could be even more cost competitive since to smaller actuators that cost less can be used for bigger mirror areas. The performance of the system can be seen in graphs 1 and 2. The blue line represents the torque created around the Solid joint.



Graph 1 **Blue line: the torque that the actuators can create around the Solid joint**
Green line: Torque created around the x-axis of the Solid joint because of the wind.
Red line: Torque created around the x-axis of the Solid joint because of the wind.



Graph 2 **Blue line: the torque that the actuators can create around the Solid joint**
Green line: Torque created around the y-axis of the Solid joint because of the wind.
Red line: Torque created around the y-axis of the Solid joint because of the wind.

Conclusions

The asymmetrical design allows the system to carry the required loads. These calculations are however not absolute proof that the system will perform in the described manner. Some physical testing is required to complement these calculations as well to provide valuable information for further design optimization.

The tracking range is dependent on the wind load; therefore it is preferred to have a variable wind triggers that makes the tracker go to table position on different wind speeds, depending on the azimuth range. The tracker can endure very high loads in its midday positions since the lever arms here are very generous.

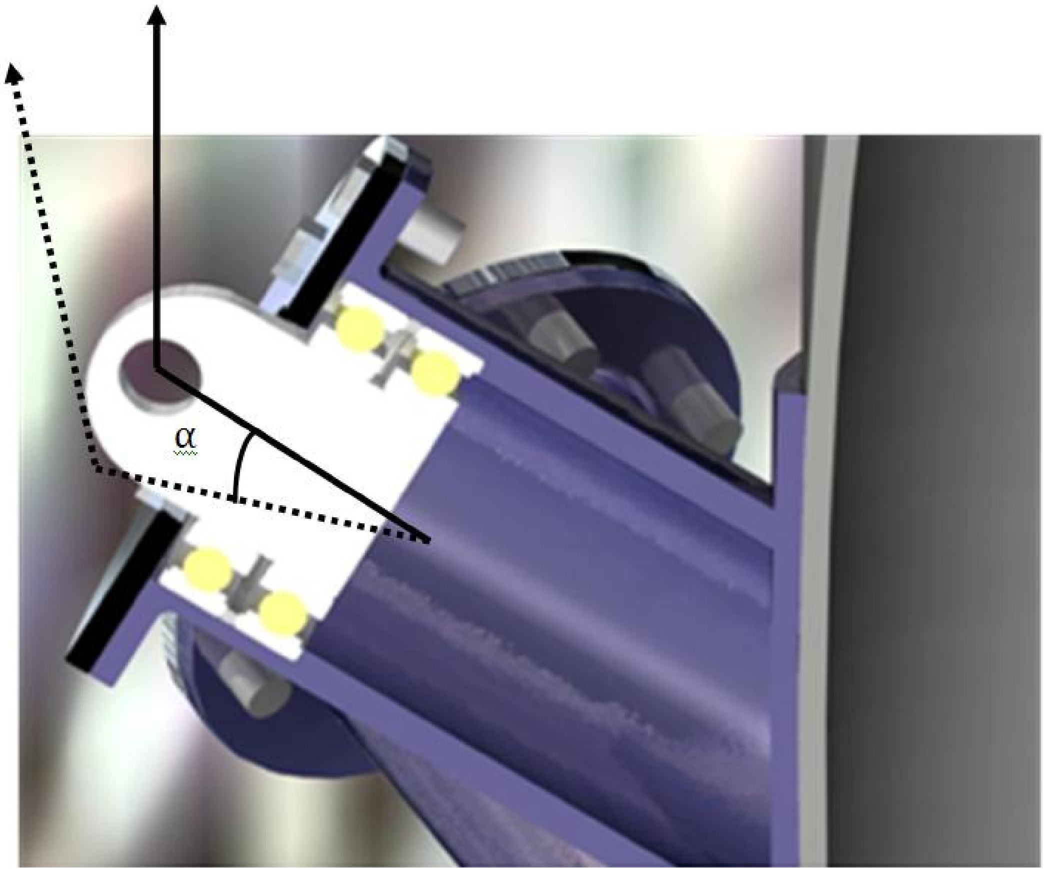
PLAY CALCULATIONS

These precision calculations are based on the components' known precision. These calculations will provide an approximate view on how precise the Twin tracker can be.

The precision can be affected by changing tolerances of the individual components and increase the precision of the calculations that the motions are based on. Tight tolerances are coupled with high manufacturing costs because the tools must hold a very high precision themselves.

BEARING SOLUTION

Utilizing two bearings in each solution will give a very high accuracy on the tracking system. The radial clearance in the bearings is at maximum36 μm, which according to the calculations below will give a very small variation on the accuracy of the tracker.



Figur 26: Shows the greatly exaggerated radial clearance of the bearings.

Since the radial clearance is very small in the bearings, it is possible to use a simplification of how the angle affects the placement of the actuators. The output based on the radial clearance is linearly related to the angle and the length of the actuator. The actuators are assumed to have a play of 0.5 mm in their length.

The approximate play of the actuator fastening position around the Solid joint is 0.514 mm. This does not consider the play caused by tolerances. This play of the actuator positions would cause a total variable tilt of the system of about 0.5 degrees. When adding the tolerances this play will be slightly higher.

Bushing solution

The following play assumptions have been made in the CAD-models in ProE and are approximate and should not be interpreted as definite values.

The spherical bearings together with the actuators are the controlling part of the tracker's precision. The spherical bushings can be angled at maximum 6 degrees. This with the actuators fully extended will give an approximated variation of 250mm of the actuator fastening positions. This is not acceptable and cannot thus be used because this will cause the whole system to become unstable and high retardation forces will occur because of this allowed movement.

Conclusions of the play calculations

When considering the spherical bushings in the sense of load carrying capacity and the minimized maintenance that they require, they seem to be a good choice for this product. But as seen in the play calculations, the spherical bushing solution is inferior and will most likely cause the tracking system to fail because of fatigue. The retardation forces will just simply be too large due to the relatively large play.

The bearing solution is the superior choice of these two. This is in line with the recommendations received by SKF expertise Erich Mayer and Nils Manne.

FMEA

The Failure Mode and Effects analysis conducted on the Solar Tracker product shows that the most vulnerable systems are the two linear actuators and the solid joint. These are the components that are most likely to break first in harmful environmental conditions and if an annual inspection is done of the trackers in a solar park it most important to check these three components.

For the complete FMEA excel-sheet see Appendix C.

Prototype

The new prototype was manufactured with the purpose of proving that the movement range, simulated in the ProEngineer Mechanism, is possible to realize.

Testing and validation

Movement range

The first testing of the prototype was done with all components assembled except for the actuators. The prototype was then moved by tilting the panel frame by hand, highly approximate simulating the movement from east to west. This movement worked without any problems which also shows that the design with the frame mounted in its center on the Hooke's joint. This movement test also shows that there are no issues with clashes or looking of the Hooke's joint when moving in azimuth or elevation ranges.

What then needed to be proven was if the frame could be moved by pushing and pulling with the two actuators. This has not yet been possible to test, because the new Magdrive actuators are finished from the manufacturing plant in Liestal, Switserland on Friday the 4th of June, 2010 and will arrive, by express transport, in Gothenburg on Monday the 7tht of June.

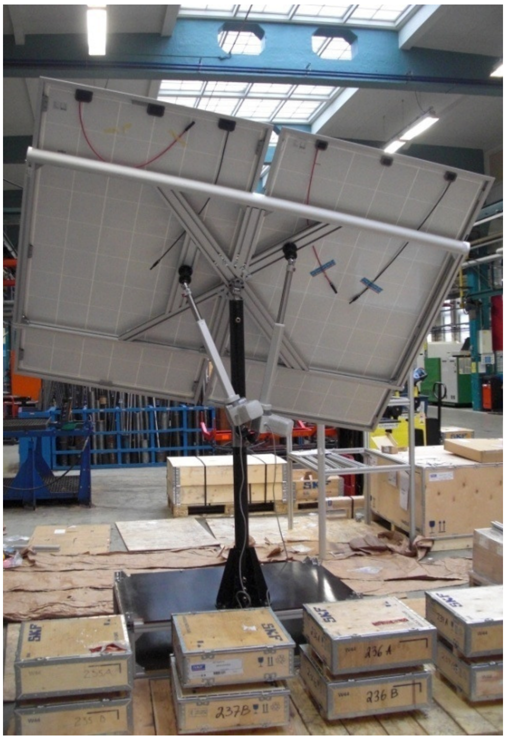


Figure 9: Showing the two old Matrix actuators, that are too big for moving the prototype without clashes.

The movement with the actuators pushing has however been, in a very simple way tested by pushing and pulling on the joints; with hand force. The result of that test is positive and shows no problems with the movement at this point.

Play in the system

The prototype is also a good validation tool for testing the supposed play in the system. All mechanical components have an internal play to different extent, even high precision SKF bearings. In solar tracking applications this mechanical play has a direct effect on the precision of the tracker. High precision is not required for PV applications, but all other concentrating technologies demands precision tracking. The play in ProEngineer Mechanism is by default zero so the play needs to be tested on the prototype. This has been done by hand, in a very simple manner on the assembled prototype. The prototype yielded no noticeable play, when pushing and pulling on the panels – when the rotational joint where locked in the axial directions as bearing and not with bushing that have the play because of the stop rings. This can be seen as a very good result, since other solar trackers on the market has a play that by hand can be approximated to 100 mm when lifting on the panels.

Costing and Investment (Qualification Market requirements)

To calculate the cost of the solar tracker product the ingoing components are divided into mechanical components, control system and SKF components. Each mechanical component has been cost estimated regarding material cost and machine operation cost. The cost for the SKF components such as bearings and actuators are taken from SKF sales prices and the control system is cost calculated from the budget offering from Consat AB.

The mechanical components are cost calculated for material cost and machining operations cost, for details see Appendix B. The total cost for the mechanical component that needs to be manufactured is (Large|Medium|Small version):

647€ | 432€ | 625€

For detailed price estimations see appendix G.

The prices on the SKF PWM Bushings and Spherical bushings are considered for high volume and as follows (Large|Medium|Small version):

153€ | 99€ | 80€

For detailed price estimations see appendix G.

The cost for the actuators, used on the tracker, are based on information from the development team for the actuators and are (Large|Medium|Small version):

(2x43=)86€ | (26x2=)52€ | (2x9=)18€

For detailed price estimations see appendix G.

The price on a new control system for the dual axis solar tracker is based on a budget offering from Consat AB where the development would cost approximately 10.000 € and the target price for the control system per tracker would be 100 €. For complete budget offering see appendix G.

Total cost for the SKF dual axis solar tracker will be dependent on which of the three different sizes that is selected and the prices are:

Tabell 19: SKF dual axis tracker cost and price.

Version	Small	Medium	Large
Target cost (Euros)	723 €	1.280 €	1.714 €
Target sales price (Euros)	1.157 €	2.048 €	2.742 €

The targeted sales price is with a 60 % sales price margin, which is seen as SKF standard and the prices are for low volume of 1.000 pieces. Prices on mechanical components and actuators are expected to decrease when volume increases because of economies of scale, prices for the bushings are however already considered for higher volume since.

INVESTMENT ANALYSIS

When investing in a solar farm, choosing the technology that has the lowest price per watt of energy production is of interest. When investing a solar park with solar panels, today the lowest prices on panels are 1.44 €/W. If the investor wants to increase the production on the solar PV park he can also invest in a tracker to the panels. The dual axis tracker increases the power production of the PV panels with up to 40 % which puts a clear requirement on the price of the tracker to be under 40 % of the panel price; this is what the SKF dual axis tracker needs to meet. When investing in the other solar technologies, Heliostats, Stirling Engines or CPV, having a tracker or not is not optional since those systems wont function without a tracker. So for the other technologies the interesting investment factor to compare against is competitor's price/performance ratio. For competitor analyses see the Benchmarking chapter, but as an investment analysis for the tracker it can be said that the SKF dual axis solar tracker is a very competitive product since it fulfills the movement range that is needed to follow the sun and the ingoing components have relatively low price.

PV PANELS

For a basic investment calculation, the sales price of the largest version of the dual axis tracker is 2.742 € and that tracker, mounted with panels that produce 134 W/m², has a maximum energy production of 13.4 kW for the 100 m² panel area. This gives the tracker cost per watt of 0.2 €/W and the cheapest panel price per watt is today 1.44 €/W. The dual axis tracker gives an increase in energy production of the panels of 40 % by tracking to movement of the sun. The tracker increases the price per watt of energy of 0.2 €/W which is only 14 % of the panel price per watt. Therefore one can easily state that the investing in the SKF dual axis solar tracker is a very sound investment.

The following table shows how the three different size versions of the SKF solar tracker relate to panel euro per watt price:

Table 20: price per watt for PV panels and tracker.

Version	Small	Medium	Large
Tracker sales price [€]:	1.157 €	2.048 €	2.742 €
Tracker panel area [m²]:	25 m²	85 m²	100 m²
Tracker production increase:	40 %	40 %	40 %
Tracker energy production:	3.4 kW	11.4 kW	13.4 kW
PV panel €/W price:	1.44 €/W	1.44 €/W	1.44 €/W
PV panel price total:	4.896 €	16.416	19.296
Tracker €/W price:	0.34 €/W	0.18 €/W	0.20 €/W
Tracker price / PV panel price:	23.6 %	12.5 %	13.9 %
Cost efficiency:	16.4 %	27.5 %	26.1 %

The table shows that when buying the small version of the solar tracker the production is increased with 40 % and the price of the total solar park is only increased with 23.6 %. For the medium version the price is increased with 12.5 % and for the large version the price is increased with 13.9 % because of the larger panel areas. This shows that the SKF solar tracker is a very good investment for PV solar parks and the most economically feasible size choice is the Medium version with panel sizes ranging up to 85 m².

The price of the solar tracker for the PV panel market is always related to the price of the panels. Since the dual axis tracker increases the production of a PV panel with 40 %, the price of the tracker can never be larger than 40 % of the panel price; because otherwise it would make more sense to only invest in more panels if you want to increase the production of the solar park.

COMPETITOR BENCHMARKING

On today's market there is a vast amount of companies selling and manufacturing trackers, both dual and single axis versions ranging from 5 m² up to 400 m². So the market supply of tracker can be said to be quite large.

The traditional and most common trackers on the market is the single axis tracker using a slewing ring as drive unit and the dual axis tracker using a slewing ring for azimuth motion and a linear actuator in the elevation direction.

Figure 10: Commonly used tracker solution with slewing ring and actuator.

For CSP systems there are also many solutions with a slewing drive for the elevation movement. To compete on the market with a solution similar to the commonly used solutions on the market it is needed to be better quality components or be more cost efficient; concerning price, durability and maintenance. However, the dual linear actuator solution, that uses two actuators for motion in both azimuth and elevation angles has a benchmarking advantage in the sense that it diversifies from the traditional solutions already out on the market.

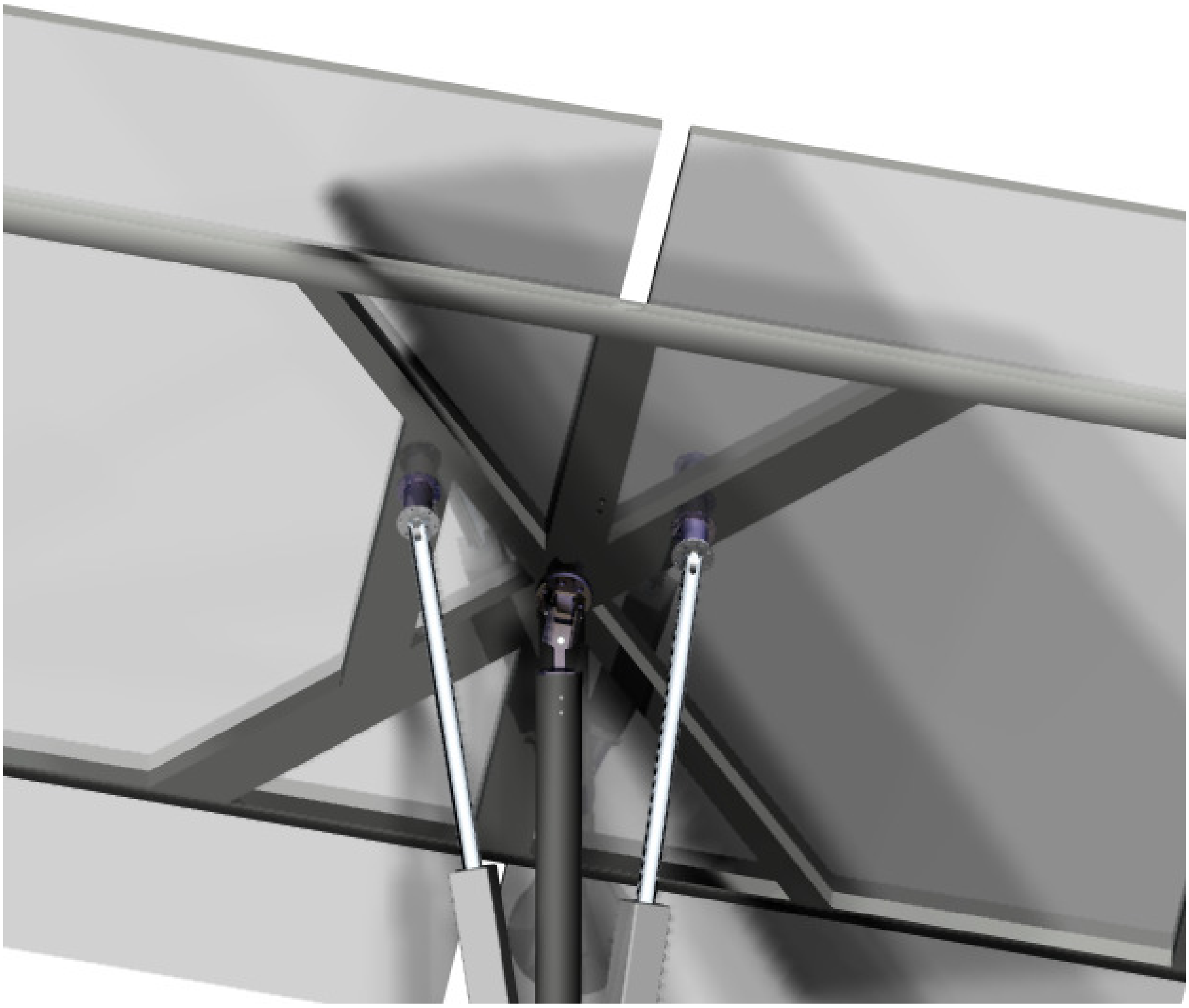


Figure 11: Dual linear actuator solution.

To highlight the differences, advantages and weak points the dual linear actuator solution has, benchmarking have been done regarding the complete system and drive units; slewing drive or linear actuator.

THE SLEWING RING DRIVE

The slewing drive has the advantages that it is a proven solutions that customers are used to see in a tracker as the drive unit for the azimuth movement. The slewing ring can easily be placed in the middle of the trackers pillar, making sure that there are no problems with clashes when rotating the panels. The slewing drive does however need maintenance with grease and the price is expected to be higher than for a linear actuator doing the same work.

THE LINEAR ACTUATORS

The linear actuators are proven components in solar tracker for facilitating the elevation movement. Using actuators for accomplishing both the elevation and azimuth movement is however new to customers. The advantage with using linear actuators are that they are more cost efficient that slewing drives, they require less maintenance and are easier to get higher precision with. The disadvantages are that there is an issue with internal clashes and the programming of the actuators is more complex than for the slewing ring.

THE COMPLETE TRACKER

The Twin Tracker, with two linear actuators can achieve 250 degrees azimuth movement in 4 – 90 degrees elevation. This can be seen as well within the market standards for movement and is also what is needed to be able to follow the sun during the day. Achieving this movement with two linear actuators is however more challenging than when using a slewing ring and one actuator. One advantage with using two actuators is though that loads from uniform wind or wind gusts are taken up from both actuators working together, this decreases the risk of the drive units breaking in extreme conditions.

ACTUAL PRICE BENCHMARKING

In order to give a good understanding of how the price of the SKF Twin Tracker compares to other trackers on the market a price comparison example have been conducted. The price comparison highlights the following scenario:

A customer wishes to invest in a PV panel solar park and wants the panels to be mounted on trackers. The customer is considering two suppliers for trackers: SKF dual axis tracker or a commonly used tracker solution on the market using a slewing drive and a actuator. The customer wishes to invest in the commonly used size of 85 m^2 panel area.

The three trackers ability to follow the sun can be considered to be the same and the price comparison is then the important factor. The prices for the traditional tracker and SKF's tracker are: as follows:

Traditional: 2.600 € (Actuator: 500 €, Slewing Drive: 800 € Mechanical components: Pillar, Pillar Rings, etc: 300 €)

SKF dual axis tracker: 2.048 €

This basic price benchmarking shows that the SKF dual axis tracker has a very competitive market price.

CONCLUSIONS

The advantage with two linear actuators can be summarized into the following points:

- A more cost efficient solution than market leaders today through cheaper drive units.
- Lower to none maintenance requirements, compared to annual maintenance on traditional drive units.
- Longer service life of the tracker due to more robust drive units.

The performance and cost benchmarking can also be highlighted with the following figure:

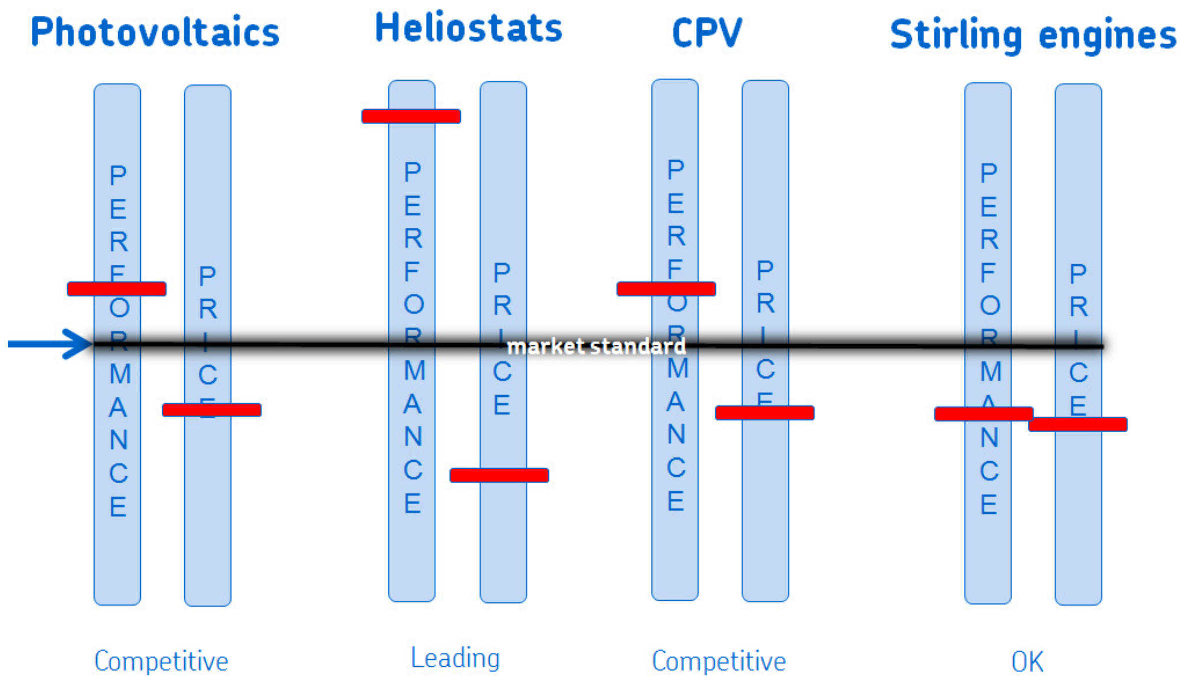


Figure 12: Competitor benchmarking.

The disadvantages of the dual linear actuator tracker it to a customer, is a new way of tracking and complex solution to program and also there are issues with the actuators clashing into the pillar when trying to achieve more than 250 degrees azimuth movement in low elevation degrees. But this is seen as minor issues that can be overcome.

PATENTS

To make sure that the dual axis solar tracker doesn't infringe on other patented dual axis tracker solution a patent search has been conducted. The patent search has been done in two steps. The first step is search through free patent search engines online such as esp@cenet and Google Patents, the second step is through a professional SKF news search that was ordered for 1.500 €.

The first search resulted in many different hobby solutions, no one with two linear actuators however and one serious company patent pending from Hispano Tracker, see Project CD for complete patent. The Spanish company Hispano tracker has applied for a patent for a dual axis tracker using hydraulic actuators. The Hispano tracker is similar since it uses two linear actuators to achieve both azimuth and elevation movement. What differentiates SKF dual axis tracker is that it uses electrical actuators and a Hooke's joint as a pivot point.

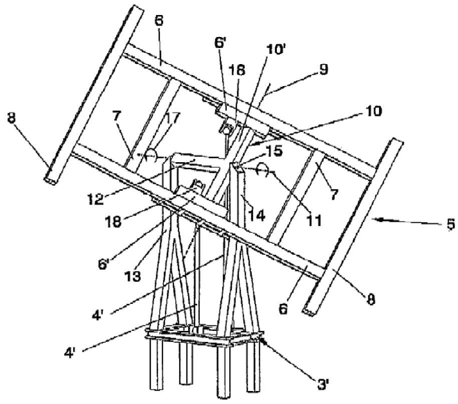


Figure 13: Hispano dual axis tracker.

After analyzing the Hispano tracker patent application and what is claimed in the application(see claim 1- 11 in Appendix P); it is concluded that there is a risk that the SKF tracker can infringe on Hispano's patent, if the patent is granted, and the risk is seen as medium.

The second step in the patent search was done by using SKF's internal patent department. The department conducted a news search with focus on other patents and patent applications that uses two linear actuators. That closest patent or patent pending that the ordered search resulted in was also the Hispano Tracker patent pending. For the complete patent search results, see Project CD.

The patent searches conclude that there is a medium risk that the SKF dual axis tracker can infringe on Hispano Trackers' patent pending.

DISCUSSION

The result from the project proves that the design with two linear actuators, moving the solar energy system; centrally mounted on the Hooke's joint, in both azimuth and elevation directions works. The force calculations and FEA show that the loads from e.g. 100 m^2 PV panels in wind speeds of 20 m/s, while tracking, can be taken up by the system. It is however important to clarify that it is the asymmetrical placement of the actuators that ensures that the loads can be handled even in the extreme east and west positions. The asymmetrical placement of the actuators gives the effect that the actuators lever arms against un-uniform wind gusts are never minimal at the same time. So that there is always one actuator that can handle loads from sudden wind shears.

The prototype that has been built and sent to Holland, Canada and the USA is highlighting the concept and it has worked as a validation for the stated movement with the two actuators. But it would have been preferably to have finished to prototype earlier in the project so that testing would not have been rushed in the end.

GOAL AND AIM ASSESSMENT

The following goals were stated for the master thesis:

- Optimize the design of the Twin Tracker concept, developed in fall 2009
    - Highlight the new design with a prototype
- Qualify the Twin Tracker to the market requirements
- Define relationships between the customer requirements and the technical properties of the Twin Tracker
- Conduct a market analysis and map the voice of the customer
- Conduct a business case

DESIGN OPTIMIZATION

The design optimization goal is fulfilled through the design changes, which ensure that the tracker can reach the stated movement range; while withstanding wind speeds of up to 20 m/s with a 100m^2 panel area when tracking. The detailed design optimizations has produced; reworked and new mechanical components that are more robust and eliminates clashes. The internal clash of the Hooke's joint has completely been eliminated with the new solid Hooke's joint design and the load capability has been optimized through asymmetrical positioning of the actuators.

The mechanical properties of the tracker were greatly improved during the project, at first the structure barely passed the FE analysis but now the large tracker has on the weakest component a safety factor of approximately two. The other size versions are perhaps even over dimensioned, but that could be remedied by conducting a more detailed FEA.

PROTOTYPE

The goal to highlight the new design with a prototype is realized through the new prototype with PV panels and the Magdrive actuators. There are always things that can be adjusted and made better on a prototype and in this case it would have been great to have the prototype finished much earlier in the project, so that testing and validation of the movement could have been completed in advance of the final presentation. This was also the original plan but due to the fact that the prototype build was put to a stop for three weeks at the SKF mechanical workshop at the Gothenburg plant, because of internal projects with higher priority, the time schedule was heavily overstepped. This fact had very negative effects on the prototype testing. The testing was now rushed in the end which is not optimal. The prototype did however prove the movement range of the Solar Tracker, which was pre-simulated in ProEngineer Mechanism, when testing it by hand. However, the exact same movement range was not possible to achieve on the prototype with the Magdrive actuators since the pillar showed to be too short compared to the length of the actuators and since the prototype build was delayed it was not enough time in the project to fix the problem. This was unfortunate but not a disaster since the prototype still is possible to highlight the product concept and show how it will track the sun in a good way.

MARKET QUALIFICATION

The Twin Tracker product was qualified to the market by utilizing a large competitor analysis, key buying factors of the customer and other market requirements. What can be seen from that benchmarking is that the Twin Tracker solar tracker can be said to be performance-wise competitive since it fulfills the required movement range. Price-wise the product can be said to be very competitive since using two linear actuators instead of a slewing ring and actuator yields a lower price. The product also qualifies better than market standard in other qualifiers such as maintenance and durability; actuators require less to none maintenance compared to a greased slewing ring.

LINKING CUSTOMER REQUIREMENTS TO TECHNICAL

The relation between the customer requirements and product specifications was simplified in order to facilitate an easy selection process. The main relationships are the links between the desired energy production to the size of the panels. The tracker size is then derived from this information. In this process, the main focus was to produce three different size-classes; Large, Medium and Small that can be adjusted to different panel areas. These three size-classes also correspond to the sizes of the three new solar actuators.

MARKET ANALYSIS

The market analysis was based on different reports and news that were collected and analyzed in order to build a comprehensive image of the solar power market situation. The market analysis proved to be satisfactory and important to understand the possibilities of the tracker market today and in the future.

The market analysis also maps the voice of the customer through listing the Key buying factors; business, technical and political factors. These factors fulfill the voice of the customer goal.

BUSINESS CASE

The business case was performed to highlight the possible winnings if launching the Twin Tracker product to the solar market. Three different sales scenarios were assumed and the possible profits from them show that the stated business case is feasible. These scenarios show the possible profits that can be made in the solar tracker market. It serves as a good incentive to invest in solar trackers.

CONCLUSIONS

Market analysis

The market analysis shows that the solar energy market is growing rapidly with expected new large emerging markets in Europe, China and the US. The tracker market however is more difficult to analyze since the registers of the installations are poor and in many cases non-existent. The market analysis can be summarized as:

- The PV market increases approximately 40% annually.
- CSP is expected to become a more competitive technology in the future. Many CSP installations are under construction in Spain and the awakening giant USA.
- PV installations will continue to be market leading for at least the nearest years to come.
- The USA is expected to become a huge new market for solar power; solar news sites such as Photon Magazine, GreenTechMedia and SolarPlaza talk about tens of GW in the installation planning pipeline.
- China is expected to be a large future market, how and when it will boom is not possible to foresee today.
- Germany and Spain planning to cut their feed-in tariffs to adapt to the boom and also lowered PV panel prices. This is however only expected to have moderate affect on the global solar demand. Other countries are instead looking into facilitate a large growth for solar power.
- India is expected to become a large market for stand-alone systems since more than 60 % of its energy market is off-grid systems.

BUSINESS CASE

The business case was done in order to give understanding of what kind possibilities for profit there exists in the solar tracker market.

The main findings from the business case are:

- Even with a small share of the total market, the possible profits are great.
- It is financially sound for SKF to invest in solar power and the earlier SKF gets out on the solar tracker market with a competitive tracker product the easier it is to take market shares.

OPTIMIZED DESIGN

The design of the Twin Tracker product has been optimized by detailed design work an all components. The design is now optimal for PV panels or CPV panels and fulfills stated movement range. For the other prioritized technologies: Heliostat mirrors and Stirling engine and dish systems the design needs to be looked over to ensure best possible solution.

For Heliostat the movement range that the tracker needs to move is smaller which makes it an easier application to track. This also enables the positioning of the actuators to be widened increasing their load carrying ability which would enable the heliostat tracker version to withstand much higher wind speeds than 20 m/s while tracking.

Knowledge of the Twin Trackers' mechanical properties was obtained during the design process. The main findings are:

- The design and the high quality material choice enable the product to fulfill its function in at least 20 years.
- The large tracker can facilitate panels up to 100m^2 with the maximum wind load of 20 m/s
- The medium tracker can facilitate panels up to 80m^2 with a maximum wind load of 20 m/s
- The small tracker can facilitate panels up to 25m^2 with a maximum wind load of 20 m/s
- The range of the 100 m^2 PV/CPV tracker is 220 degrees in azimuth and 86 degrees in elevation for 20 m/s wind speed and 252 degrees in azimuth for 10 m/s wind speed when tracking.

MARKET QUALIFICATION

It can be concluded that the Twin Tracker solar tracker qualifies itself very competitive to the market with the biggest advantages that it is price efficient and needs minimal maintenance.

LINKING CUSTOMER REQUIREMENTS TO TECHNICAL

The highlighting of the customer requirements is good for understanding the voice of the customer but it is also concluded that a closer cooperation with actual customer would greatly have increased the understanding; and actual customer feedback on the Twin Tracker is still highly needed.

PROTOTYPE

The prototype was built to test the Twin Trackers' range performance and to create curiosity and interest internally and externally for the product concept. The prototype has been showed at SKF conference in Holland, in SKF internal newspaper Lagerbladet in Gothenburg, at the 6th University CDIO[3] conference in Montreal, Canada and it will be highlighted in the US at SKF offices and for potential customers. It can therefore be concluded that the prototype has served its purpose of highlighting the product concept but the movement range testing could have been done much better and more thorough if the prototype build would have been finished in time Also the movement range for the prototype is not really fulfilled with the too long Magdrives and the too short pillar, but when moving the prototype by hand, without the actuators the range can be realized without clashes or problems.

PATENTS

The patent issue is still unclear since there is no granted patent that the SKF Twin Tracker is risking to infringe on. There is a patent pending that was filed in 2006 and still has not been granted. It can only be concluded that the claims in the Hispano patent pending is similar to the description of the Twin Tracker, therefore it has to be seen as medium risk of patent infringement.

[3] CDIO: Conceive Design Implement Operate is a University conference about the CDIO framework for producing the next generation of Engineers. The CDIO was originally developed by Chalmers University of Technology in Sweden and Massachusetts Institute of Technology in the US, but has now spread over the world.

RECOMMENDATIONS

After completing the solar tracker product development Master Thesis it is important to understand what more is left in the development process before the product can be industrialized.

The recommended next development steps are:

- Develop the control system for the tracker together with a control system supplier.
- Work with purchasing to find the best suppliers/manufacturers for the mechanical components.
- Start finding a suitable supplier for the frames for PV panels, there is no real point in designing a SKF PV panel frame when there are many functional frames for trackers already on the market.
- Start showing the prototype to the industry and customers to get feedback as soon as possible. It is recommended that this is done already when the prototype is in the US.
- Find a suitable partner/customer company to work with in launching the Twin Tracker to the market.
- Do actual testing of a full scale tracker as soon as the new solar actuators have been developed.
- Develop a Heliostat version of the Twin Tracker that can be leading on the Heliostat market.

DEVELOPING A CONTROL SYSTEM

The solar tracker development project have focused on optimizing the movement range of the tracker and its mechanical components as well as making sure that it can withstand the required loads and wind speed during tracking. Focus has not however been on developing a control system, since this was one of the delimitations for the project. It is suggested that a control system is developed by an external supplier; it is needed to look more into the most suitable suppliers for this purpose. One possible solution can however be to use the Swedish based electronics consultant firm Consat AB, which SKF already has framework agreements with.

BUDGET OFFERING FOR A CONTROL SYSTEM

Consat was contacted during the master thesis, this resulted in a budget offering for developing the control system. The full offering can be found in Appendix A. Consat AB offered to develop the control system for the Solar Tracker product; with controls, programming and GPS for clock and positioning. This can be done to a cost of 10 000 € and the target price for the finished “control box” that will be used to control each solar tracker product will not cost more than 100 €, which is considered a realistic price.

The prototype is controlled through a PC based control and simulation software developed by SKF in the simulation program LabView and this is not, in its current state, sufficient to control the product version of the tracker.

SUPPLIER AND MANUFACTURERS

The SKF dual axis solar tracker is thought to be sold by SKF but the manufacturing and assembly of the component are suggested to be carried out by suppliers. Therefore a project that works with finding the best suitable suppliers for the job needs to be done. The work that the suppliers need to do is: casting, machining, milling, heat treatment, assembly/installation and ground work. Suppliers also need to be found for inverters, monitoring systems and back-up systems that can be connected to the panels. Examples of such suppliers are: SMA Solar Technology AG, Fronius International GmbH or Sputnik Engineering AG, for a full list of possible inverter suppliers see appendix S

Highlighting the prototype

The project has produced a functional prototype with the purpose to highlight the dual actuation product. This has been shown internally but it needs to also be highlighted externally to potential customers and the industry to get feedback. It is important for internal managers to understand that SKF are developing this kind of products, which is a new product category for SKF. Potential customers and other solar industry people also need to see the prototype in order for SKF to acquire feedback of its design. In order to achieve this it is recommended that the prototype is shown on exhibitions, to customers and in different SKF headquarters in the world. It is also recommended that while the prototype is in the US it is shown to customers there and on exhibitions so that lessons can be learned from it.

Design concerns

Since the FEA and calculations that have been done on the tracker have many approximations, it is required to do field testing of a full scale prototype, as soon as the drive units are finished. This field testing should be conducted in order to test that the tracker can move in maximum wind speeds of 20 m/s without failing. Also since one of the limitations of the project was to not conduct any detailed FEA on the tracker this is recommended to be done, by either internal modeling and simulations department or an outside consultant firm. The results from that detailed FEA should serve as a validation of the design and dimensioning of this tracker. Also when conducting the detailed FEA it is also recommended to do a fatigue analysis with approximated load cases and cycles.

Perform testing of full scale Twin Trackers

It is important to perform test of full scale Twin Trackers in order to get accurate data on its performance, load capability and the expected lifetime. This testing should be performed with a possible future customer to get valuable information on design improvements that an accustomed tracker user can provide. To do wind tests there is always the possibility of reserving time in large scale wind tunnels, e.g. in Gothenburg, where a scaled prototype could be put to test in winds up to 40 m/s. Winds can also be tested by mounting the full scale tracker on a truck driving in a booked test race track or the prototype could be tested in natural windy conditions e.g. near the ocean.

Patents

The future development of the patent issue needs to be monitored closely. It is also recomended that the possibilities to kill the Hispano tracker patent application, through proving that their invention has not enough innovation height or that it was already known, needs to be investigated.

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