A NOVEL, SPHERICAL SHAPED SUN TRACKER

P. Wajss, M. Filipowicz

AGH University of Science and Technology, Faculty of Fuels and Energy, Kraków, Poland

ABSTRACT

A novel, spherical shaped sun tracker, capable of shifting the centre of gravity, has been built at the Faculty of Energy and Fuels at AGH-UST. First tilting tests were executed and the results of these measurements have been presented herein. To introduce the reader to the authors' concept of sun tracking, a review of the recent literature concerning tracking mechanisms has been conducted and some interesting ideas as well as operating prototypes have been described.

INTORODUCTION

Low-temperature, non-concentrating solar energy systems may be considered a mature technology for the renewable energy sources' sector as they have been rapidly developed over the past two decades, and are currently widely used for a variety of industrial and residential applications.

Consequently, in selected regions, such as southern Europe, the systems are already competitive to fossil fuels in small-to-medium scale applications. This cannot be stated in regards to large scale concentrated solar/thermal power (CSP/CST) and concentrated photovoltaic (CPV) applications. These still do not reach the price breakthrough in comparison with large scale units powered by fossil fuels. After some investments made in the end of the 20th century, their introduction to the market is currently inhibited and the technologies are being revised. The recent publications contain many studies regarding different elements of CSP and CPV technologies with special regards to tracking algorithms, optics, PV cells, thermal absorbers, thermal fluids etc. In comparison to this vast amount of articles, there is very little interest in mechanical construction of sun trackers in CPV and heliostats in CSP technology, although they are considered one of the four main components of the concentrating system (Kurtz, Bett, Hartsoch, 2010), which, in consequence, contributes highly to their costs (Kolb, 2011). The current dominant position of the single central support, with single pole construction of heliostats and trackers, is the result of research conducted in the 70s and the 80s in the USA (Marvis, 1989). Since then there were attempts to improve this type of mechanics but till this moment the goal of ~100USD/m^2 (Kolb, 2007) for heliostats, which would ensure market competitiveness of CSP in relation to fossil fuel based technologies, has not been reached. Within this paper units other than pole mounted tracking devices have been presented. A novel, spherical shaped tracking solution capable of shifting the centre of gravity, has been shown and first results of tilting tests have been plotted.

TECHNOLOGY OVERVIEW

Several articles reviewing different CSP and CPV technologies in detail exist. Some very interesting information may be found in the proceedings of international conferences held world-wide and dealing with these issues as well. As this paper is devoted to a tracking mechanism, only these will be characterized in a more detailed manner.

Basically, the state-of-the-art sun trackers and heliostats are mechanical devices, driven by motors or actuators, which set the payload perpendicularly to the direct solar radiation for the sun trackers or perpendicularly to the bisector of the angle between the sun and the receiver for heliostats.

There are two main approaches to the division of the sun trackers and heliostats, depending on their configuration or the actuating system:

- Single Axis Tracking (SAT) versus Dual Axis Tracking (DAT) and
- Active Solar Tracking (AST) versus Passive Solar Tracking (PST).

The first division concerns the number of degrees of freedom that act as axes of rotation: one and two respectively. The second is in regard to the working principle.

ASTs use motors, actuators and gear trains to set the payload, even purposely miss-tracking, if necessary. They can be categorized as electro-optical sensor based (closed loop); location, date and time based (open loop) or as different combinations of both of the above types.

The principle of operation of the PSTs is the introduction of thermo sensitive materials and/or fluids such as thermal fluids or shape memory alloys. The diversified illumination of sun on the above, causes unbalanced forces, which direct the payload in a manner resulting in the restoration of balance. This type of tracking is not applicable in case of heliostats. This system is much less sophisticated than the AST and, consequently, is less accurate and operational only in selected climates. Due to the working principle these types of trackers must periodically modify their positions by discrete motions which generate series of time-dependent orientation errors. The majority of ASTs use the same discrete motions principle. Consequently, every movement causes a power loss. Taking the mass and the payload's area of the tracker and heliostats into consideration, which may currently reach up to 320 m^2, as introduced by Arizona Pubic Service, their acceleration should be optimized in regards to solar energy yield and friction forces.

As stated above, there is no current research concerning the mechanical construction of sun trackers. An interesting survey of concepts for cost reduction of heliostats has been recently presented (Pfahl, 2014), in which state-of-the-art tracking solutions have been evaluated in order to optimize their costs. Literature review has provided much information about the recent or on-going research dealing with optics and solar cells in private owned companies such as: Amonix, Inc.; Solar Research Corporation, Pty. Ltd; Spectrolab; SunPower Co.; Entech, Inc. as well as at Universities and/or research institutes, i.a.: the Australian National University; the Fraunhofer Institute; the Ioffe Physical-Technical Institute; the Polytechnic University of Madrid; the University of Reading and Zentrum fur Sonnenenergie und Wasserstoff Forschung Baden Wurttenberg (ZSW). The Polytechnic University of Madrid has also developed an innovative frame for one-axis tracking reflective parabolic troughs used in a CSP plant constructed by BP solar. Last but not least, one should mention a wide range of research conducted at the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, both located in the USA.

The main concept of dual-axis sun trackers and heliostats is the same: to follow the sun path and set the proper angle of the payload, perpendicular to solar radiation. The main difference between sun trackers and heliostats is that sun trackers are equipped with an absorber, whereas heliostats are not. Consequently, heliostats are playing just a partial role in the solar-to-energy conversion systems by reflecting direct solar radiation to the central receiver where thermal process occurs. Sun trackers, on the other hand, are not only reflecting (or refracting) solar radiation but at the same time convert it into different kinds of energy such as electricity, heat or less common chemical fuels. As a result, they are responsible for the entire solar-to-energy process. Both, however, are setting the payload depending on the current position of the sun, which allows us to recognize them as similar for further considerations.

As there is much more research on heliostat designs rather than sun trackers in regard to their mechanical construction, we shall focus on the first one and then come back to the latter.

THE HISTORICAL AND STATE-OF-THE-ART HELIOSTATS

Development of heliostats has begun in 1975 in the USA when four industry teams were funded to design their concepts, later named the first-generation (Marvis, 1989). As a result of these studies each contractor proposed up to six heliostat designs. Due to their high production costs, teams have reviewed the concepts and developed second-generation heliostats in late 1977 and 1981. These had been: pedestal mounted, bubble-enclosed membrane, ganged, carousel and rotating field. Selected schemes are presented in fig.1.

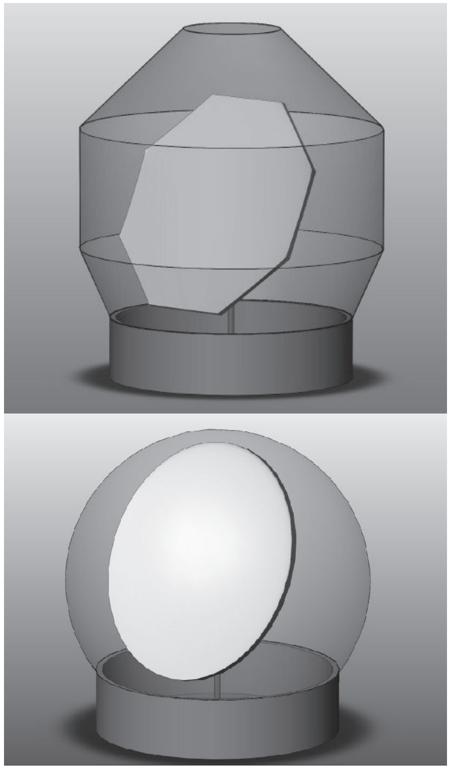


Fig. 1. Bubble-enclosed membrane heliostats developed by Boeing Engineering and General Electric between 1975 and 1982

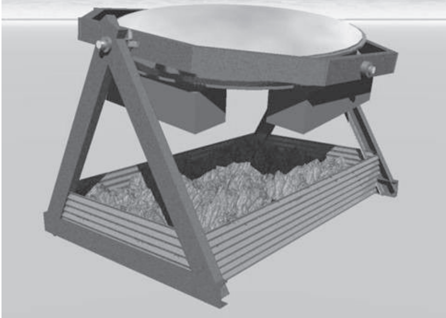
As a result of the tests, the pedestal-mounted heliostat was chosen for further development due to lowest production costs. This type of heliostat is presented in fig. 2. This specific type of a heliostat consists of: mirror assemblies, support structure, pedestal, foundation, tracking control unit and drives. The support structure positions the payload accurately and transmits the weight of the structure and wind loads through the drives to ground. The most common type of ground support for solar concentrators is the poured-in-place tubular pedestal. The drives cause the heliostat to position the payload in two axes: azimuth and elevation. They do not only cause the movement but also transmit the weight of the mirror and any wind loads to the ground through the pedestal and foundation.

Fig. 2 Back structure of a DAT heliostat

Even though the construction of the pedestal-mounted heliostat has been optimized in order to reduce its production and maintenance costs, this technology is still considered too expensive and some research on its further improvement is in progress. Sandia's and NREL's research (Kolb, 2007, Heath, Burkhardt, Turchi, 2012) indicates issues which should be prioritized in order to decrease the costs of heliostat elements emphasizing the role of the reflecting optics and the azimuth drive. As mentioned before, the sun trackers and heliostats are similar, and thus approaches to convert two-axis photovoltaic concentrators into a heliostat by replacing the PV modules with mirrors have been considered. The initiative has been called "mega-heliostat" as the payload of the tracker is bigger than in the current pedestal-mounted heliostats. For this size the use of hydraulic-type azimuth and elevation drives appears to be justified, which is not the case in mechanically driven heliostats.

New approaches

Simultaneously, a very different approach has emerged and has been evaluated at New Mexico Institute of Mining and Technology: the water-ballasted heliostat (Ostergren, 2010). Its schemes are presented in fig. 3. Payload positioning is achieved by pumping water between containers fixed at the back of the mirror. This eliminates the use of costly gear drives. Two different approaches have been investigated: the rolling ball and frame mounted. In the spherical concept, flexure of the ball structure and ground-surface irregularities have led to inaccurate positioning. As a result, a heliostat equipped with A-frame housing, with an inner and outer ring originated.



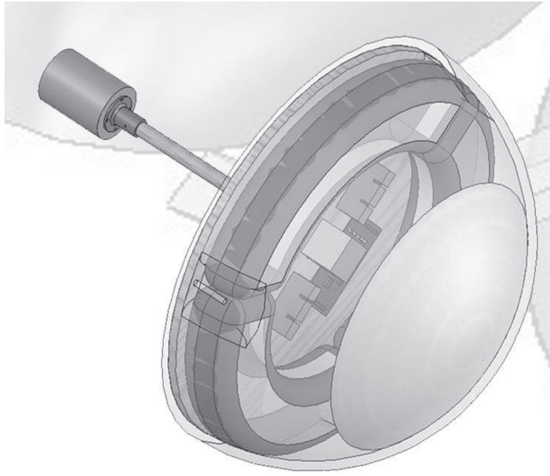


Fig. 3. Concepts of circular shaped (top) and A-frame housing (bottom) water-ballasted heliostats
(Figures published with the permission of Prof. Warren Ostergren)

This technology has been filed for intellectual property protection in 2008. The patent has been published in July 2012. Some concepts similar to the idea of the New Mexico Tech have originated in Germany and the USA: *Arrangement for solar tracking by force and/or mass displacement has masses attached to solar component that can be displaced to shift the center of gravity in controlled manner to track the sun* where the fluid is also pumped from one side to the opposite in order to tilt payload, as shown in fig. 4, and *Passive Solar Tracker for a Solar Concentrator.*

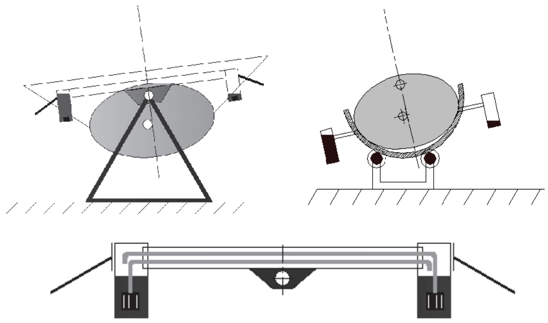
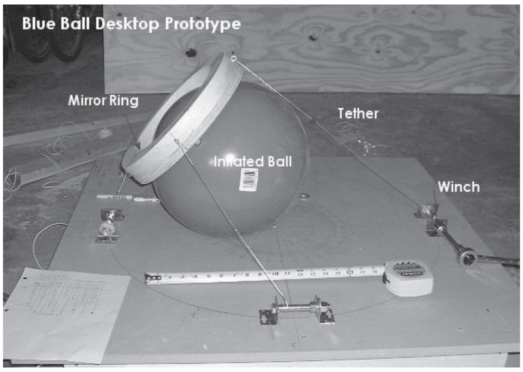


Fig. 4. Concepts of solar tracker assembly (top figures) and its mass displacement (bottom)

Another interesting concept of a spherical shaped heliostat has been proposed by Dr Mithra Sankrithi. Figures 5a-c present three different stages of the project development, the goal of which was to develop a preferred subscale prototype design for a lightweight, low-cost inflatable-structure heliostat. The top picture presents pre-prototype studies with a concept of the inflated ball rolling directly on the ground surface. Insufficient positioning accuracy caused by the base balloon deflections, distortions, and hysteresis effects associated with the roll-to-point paradigm, as well as problems with reaching high tilt angles have been reported. The middle picture presents a following design, where an inflatable structure supports the payload, but wherein the base balloon does not roll over the ground but rather on a ring base with a ring of ball bearings. This solution, however, has not brought satisfactory results. The bottom picture presents the final output of the project: an inflatable heliostat design with a reflective surface inside and a transparent upper surface. Further tests conducted by Dr Sankrithi gave satisfying results. Some interesting conclusions regarding its shape have been stated in the report: *The new configuration also has the advantage of providing a good aerodynamic shape. It has a relatively low drag coefficient, does not generate unwanted lift forces, and has the same aerodynamic properties from all directions*. However, in different paper (Pfahl, 2014) describing this solution, a *big area of wind attack* is mentioned as one of its disadvantages.



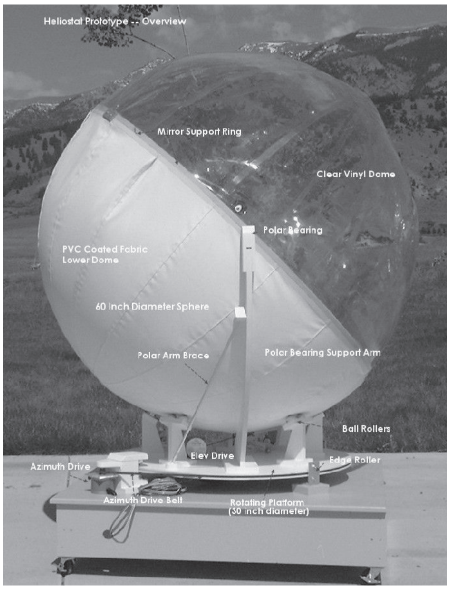


Fig. 5. A lightweight, low-cost inflatable-structure heliostat
(Figures published with the permission of Dr. Mithra Sankrithi)

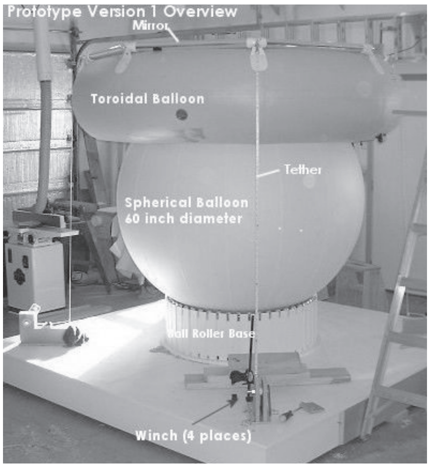


Fig. 5. A lightweight, low-cost inflatable-structure heliostat
(Figures published with the permission of Dr. Mithra Sankrithi.)

A spherical shaped sun tracker capable of shifting the centre of gravity

Within this paper the first prototype of a two-axis, spherical shaped sun tracker shifting the centre of gravity, constructed at AGH is described. The principle of work is similar to that used in liquid-ballast heliostats developed at New Mexico Tech. The fluid displacement is causing shifts of the centre of gravity and consequently the tilting of the sun tracker. The difference lays in the avoidance of water pump(s) or other devices, which are directly causing the flow of fluid. The system consists of at least one pair of containers partially filled with fluid and gas, fixed to two opposing sides of the axis of rotation. Each of the pair has been joined pneumatically and by fluid, by means of tubes and valves. Within the containers gas and liquid are separated by an airtight, elastic membrane. The differential gas pressure is determining the filling ratio of the proper tank with water. That means that due to control of the pressure within two or more tanks combined in one hydraulic system we may influence the flow of water or other fluid. It may be highly corrosive as it has no contact with any metallic part. Moreover, the tracker's payload may be set in any position from horizontal to vertical as the containers' fluid inlets and outlets are not position sensitive. Energy to run the tracker is provided from outside the system in the form of electricity, which powers an on-board compressor but it may be as well provided directly in the form of pressurised air and disseminated among proper tanks using two-way pneumatic valves. External control unit is currently controlling the flow of water in the function of tilting angle obtained from the accelerometers. Fig. 6 presents the scheme of the system used for patent registration and 3dCAD drawings of external and internal views of the first prototype.

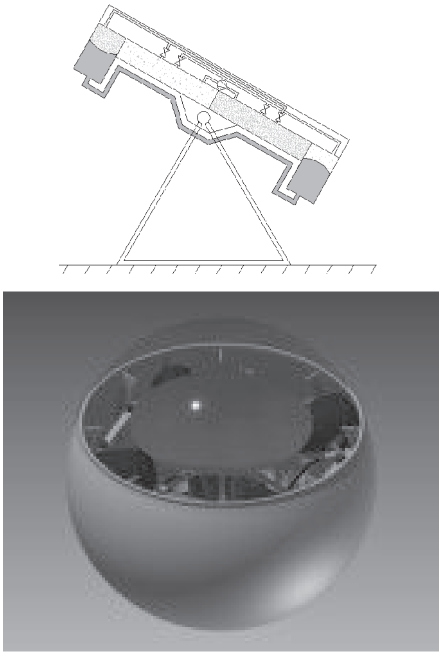


Fig. 6. Scheme of concept and 3dCAD drawing of first prototype of the sun tracking system developed at AGH

Spherical shape has been chosen to evaluate possibility and accuracy of tilting in two-axis. At present stage, the tracker is floating on water surface to exclude the influence of ground tension and other problems observed by the New Mexico Tech team and avoid friction of roller bearings. The latter have been used for positioning the sphere in one place. As it has been shown, the entire aperture has been installed inside the sphere to protect it from environmental conditions and enhance design.

RESULTS AND DISCUSSION

The first spherical shaped prototype of the tracker has been constructed and tested. It has a diameter of 2 m and is equipped with 4 air/water containers, compressor, pneumatic valves, flow and pressure sensors as well as electronics to control the tracker tilting process. It is also equipped with accelerometers to measure angle of tilting. No algorithms for setting payload have been introduced at the present stage of the project. To validate the technical feasibility of tilting the tracker in a controlled manner, first tests of the prototype have been conducted.

Tilt angle measurement assumptions:

0 deg. – vertical; perpendicular to the ground; east direction

90 deg. – horizontal, parallel to the ground

180 deg. – vertical; perpendicular to the ground; west direction

Two different measurement methods have been employed:

1) “down” measurements: at the starting position the payload has been set parallel to the ground which corresponds to 0 deg. elevation angle. Opposite vessels have the same volume of water; 15 dm^3 each. In subsequent steps, water has been transferred from one vessel to the opposite using the difference in pressure. Maximum tilting angle of 50 deg. has been achieved. In the emptied vessel 6 dm^3 of water was left and the filled vessel contained 24 dm^3 of water. Further tilting has been limited by the supporting structure.

2) “up” measurements: one vessel has been emptied and the second has been filled with water. In subsequent steps, water has been transferred between them gradually to set payload horizontally.

The results of the first prototype tilting in one axis are shown in fig. 7 and fig. 8.

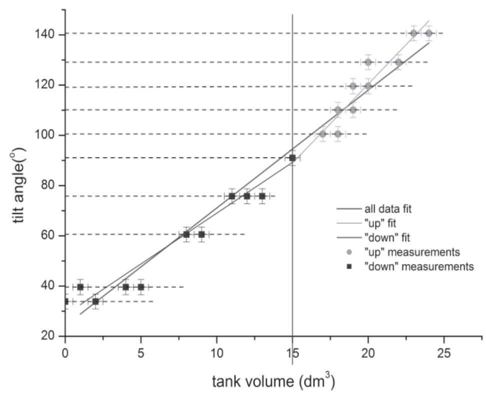


Fig. 7. Tilting measurements in the function of water fill in the tanks. Dashed lines represent measurement points of the tilting angle

Fig. 8. Spherical shaped tracker tilting process. Starting from the left: 32 deg., 76 deg., 89 deg

A linear regression equation describing the data from both measurements is as follows:

$$\alpha = a \cdot V + b$$

where α – tilting angle, V – volume of vessel, a & b – fitting parameters.

Estimation of parameters for different ranges:

5. “down” measurements:
   $a = 6.3 \pm 0.4$ deg./dm^3, $b = -5.5 \pm 7.0$ dm^3
6. “up” measurements:
   $a = 4.0 \pm 0.7$ deg./dm^3, $b = 28.5 \pm 6.7$ dm^3
7. “all” measurements:
   $a = 4.7 \pm 0.3$ deg./dm^3, $b = 24.2 \pm 3.6$ dm^3

As it may be concluded, the linear function may fit properly to the evaluated data but the a parameter is varying depending on the selected measurement method: from 4.0 deg./dm^3 for “up” measurements to 6.3 deg./dm^3 for “down” measurements.

Such difference in the results could be caused by position and shape changes of the air-tight membrane and – in consequence - minor but not negligible movement of gravity mass center within the containers. It should however be mentioned that basic measurement tools have been used at this stage of the project and their measurement errors and inaccuracies may have had a significant influence on the data obtained.

Currently, a CFD model of such a container is created and will be soon evaluated. A second spherical shaped prototype made of glass is under construction. It is planned to use more accurate measuring tools to confirm or reject their influence on the collected data.

Future work

Further tests with the existing prototype will be carried out. In the authors' opinion it is crucial to develop new concepts of support structures, understood rather as foundations than holders of the payload. CFD modeling of spherical shaped trackers shall be performed. Influence of strong wind on tracker's accuracy of positioning will be examined.

ACKNOWLEDGEMENTS

This research is co-funded by EIT as a part of KIC InnoEnergy Project "*Bio-Eco-Matic*". Pawel Wajss is a participant of the "Doctus - Malopolska scholarship fund for PhD candidates"co-funded by the European Union under the European Social Fund. The authors would like to thank for this financial support.

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