A 25M^2 TARGET-ALIGNED HELIOSTAT WITH CLOSED-LOOP CONTROL

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ABSTRACT

A 25m^2 target-aligned research heliostat with closed-loop control, with a theoretical concentration of 80 suns, has been built at CSIR in South Africa. The heliostat has four degrees of freedom: Azimuth, Elevation, Rotation and Pitch. A control system making use of a solar tracker has been developed and tested on a 1.25m^2 target-aligned mini-heliostat. A tracking accuracy of 3.3 milliradians was obtained. A good focal spot has been obtained with the 25m^2 target-aligned research heliostat.

1. INTRODUCTION

Universal access to electricity is a priority for the South African government. In South Africa (and indeed the rest of Africa), many villages exist that are not connected to the national electricity grid. For many of these it is not economically justifiable to do so, however. The relatively few subscribers who will be supplied thereby do not justify the significant expense of extending the grid to them. For these villages, distributed generation makes more economic sense. The available options are diesel gensets and renewable energy systems (typically photovoltaic cell arrays and wind turbines). Liquid fuel costs, augmented by additional low volume transport costs incurred to deliver to these communities, make the resultant electricity expensive. Renewable energy sources available are intermittent, requiring battery storage and/or backup, both increasing costs and complexity.

Of the available renewable energy resources (solar, wind, biomass, microhydro, geothermal, ocean wave and current), only solar energy is available, in good to excellent quantities, everywhere in South Africa. A single system running on solar energy when available and thermal storage and/or fossil fuel otherwise at low cost would be an ideal solution to the remote rural power question. Solar thermal technologies are cheaper per kilowatt-hour that photovoltaic systems. In 2005, the EU Framework 6 project ECOSTAR published a comparison of experiences with seven different such solar thermal technologies: 2 trough systems & 3 central receiver systems (all steam cycles), a Dish-Stirling & a solar gas turbine [1]. Of the seven technologies, the solar gas turbine gave the lowest levelised electricity costs (LEC) by between 10% & 28% in solar-only operation & by between 47% & 58% in hybrid operation with fossil fuel.

In a solar gas turbine system, a heliostat field concentrates solar radiation to the top of a tower, where it is further concentrated in secondary concentrators. This concentrated heat is absorbed in volumetric receivers by high-pressure air from the gas turbine compressor. This solar heat reduces or even replaces the liquid or gas fuel burnt in the gas turbine combustor.

It is therefore believed that the use of a gas turbine powered by concentrated solar energy would be an ideal system for off-grid South African communities. Gas turbines operate at temperatures above 1100K, so this technology requires higher solar concentration ratios than steam turbine systems, which operate at about 600K.

This paper describes the design, manufacture and initial testing of a 25m^2 target-aligned heliostat at the CSIR in South Africa, using low-cost components and simple systems. This is part of a hybrid solar/fossil fuel gas turbine distributed power research programme with the goal of supplying appropriate technology for electricity supply to off-grid South African and African communities.

2. TARGET-ALIGNED HELIOSTAT BACKGROUND

In order for a heliostat to continuously reflect the rays of the sun to a stationary target, it must be able to rotate in two orthogonal degrees of freedom. The conventional heliostat design used in solar engineering is the "T" design, so called because the two axes used resemble that letter: a vertical mast on top of which a horizontal tube is mounted. The trusses supporting the mirror panels are fixed to the horizontal torque tube which rotates about its own axis (allowing elevation control) and about the axis of the vertical mast (allowing azimuth control). Most heliostat fields make use of this design, examples of which are the concentrating heliostats of solar research facilities (PSA in Almeria, Spain and NSTTF in Alberquerque, New Mexico, and CSIRO in Newcastle, Australia) and solar power stations (Solar 2 in Barstow, California; PS10 in Seville, Spain and SPP5 in the former Soviet Union). T-design plane (non-concentrating) heliostats are used to supply parallel solar radiation to the concentrators of the solar furnaces of Odielle, France; DLR, Germany and PSI, Switzerland.

Chen et al [2] pointed out that the conventional "T" design suffers from strong astigmatic aberration. This is particularly the case with mirror canting approximating spherical curvature. The amount of aberration depends on the incidence angle as measured in the tangential plane: the plane containing the sun, the center of the heliostat, and the target [3]. Ries *et al* [4] introduced the concept, later called the target-aligned heliostat, of aligning one of the degrees of freedom with a line connecting the heliostat centre and the target (In this paper, this will be referred to as the *rotation axis*, while the second degree of freedom will be referred to as the *pitch axis*). This allows the aberration to be corrected by using a non-symmetric heliostat with two different radii of curvature; one in the tangential plane, the other in the plane containing the rotation axis perpendicular to the tangential plane.

Chen *et al* [2] compared two heliostat field systems, the first using conventional azimuth-elevation tracking heliostats with on-axis canted mirror facets, the second using target-aligned heliostats with asymmetric mirror facets canted off-axis. The results showed the target-aligned system performance to be superior, with significant reduction in time variability of the incident flux, and a reduction of receiver spillage loss of between 10 and 30%.

Target-aligned systems have also been researched for some time in the USA by enthusiasts ([5], [6]). These have investigated an as yet unmentioned advantage of target-aligned systems, that of closed-loop control. T-design heliostats are controlled by open-loop systems making use of solar position algorithms, as closed-loop feedback systems using the with heliostat reflected light are cumbersome. Target-aligned systems, on the other hand, require three items to lie in the same (tangential) plane: the sun, the target, and the normal from the plane containing both the rotation and pitch axes. This means that a solar tracker, constrained to rotate about the pitch axis, can control the rotation axis actuation to ensure the sun lies in the tangential plane. If the solar tracker is geared to rotate about the pitch axis at twice the pitch axis rotation speed (making the pitch axis rotate about its own axis at half the speed the sun appears to rotate about the pitch axis), then when the solar tracker follows the sun by controlling the actuators for the rotation and pitch axes, the heliostat focus remains stationary on the target.

A breakdown of heliostat costs are control (14%), tracking (30%), reflector (36%), structure (20%) and pedestal and foundations (10%) [1]. Closed-loop control allows for a distributed power system using autonomous heliostats without computer tracking (as a solar algorithm is not required), placing downward pressure on those 30% tracking costs, which may result in significant cost savings.

3. 25M^2 HELIOSTAT DESIGN AND MANUFACTURE

3.1 Heliostat siting

Figure 1: Rear view of heliostat, showing focal spot on wall above stairwell terminal on roof of northern building and parapet wall on roof of southern building in foreground

The subject of this paper is a heliostat that will be used during the development of the solar gas turbine high temperature receiver. The heliostat location is the roof of the stairwell terminal on the southern building (which runs East-West) of the Aeronautical Systems Competency at the CSIR. Placing it on the stairwell terminal building removed the need to build a heliostat pedestal. Once installed, it was planned to reflect concentrated solar radiation 66 metres to a spot 23° East of North to the stairwell terminal on the roof

of the *northern* building (which also runs East-West). This was decided to prevent unauthorized access to the dangerous focal spot or the heliostat since access is electronically controlled to both buildings, as military aeronautical research is performed there. For development of the high temperature receiver, the choice of focal spot position (above the stairwell terminal on the northern building, see Figure 1) allows researchers to work in the safety of the shadow of the stairwell terminal in the event of a heliostat control malfunction. Once the receiver had been developed, integration with the gas turbine would require the receiver to be placed 85 metres away on top of a tower at a spot 26° degrees West of North. It was therefore desirable that the heliostat be able to point to targets from 27° East of North to 27° West of North.

Calculations during initial scoping indicated that the heliostat would have a mass of between one and two tonnes. The roof and walls of the stairwell terminal could not be guaranteed to take such a load. Fortunately, it was discovered that reinforced concrete columns of a square cross-section ran through the corners of the stairwell terminal right down to the foundations. These columns support the concrete slabs of the floors below, and each column is rated to 20 tonnes compressive load. Any heliostat load should therefore be transferred to these columns.
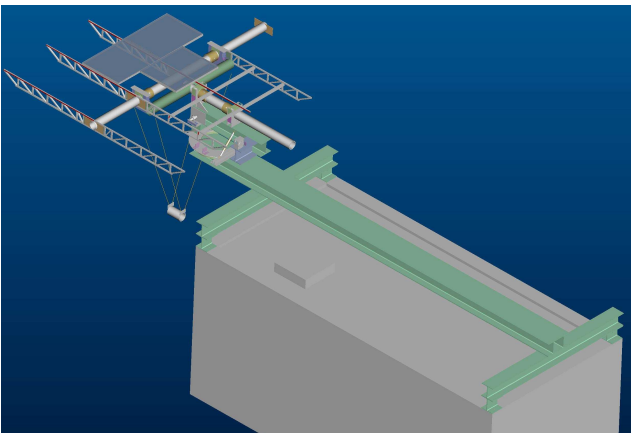

Figure 2: CAD model of the stairwell terminal building and system of I-beams supporting the overhanging heliostat.

The requirement that the heliostat have a 54° azimuth swivel range without striking the corners of the stairwell terminal implied that it would have to overhang the edge of the terminal roof by at least 1.5 metres. This would require a very strong and stiff support system, and the solution chosen was a system of 305mm×305mm I-beams, with top and bottom plate thickness of 15mm and central web thickness of 9mm. Figure 2 shows a CAD model of the stairwell terminal building, the heliostat overhanging the roof, and the composite double I-beam support beam, the

two single I-beams taking the load to the corners of the building and the I-beam "feet" transferring the load from the single I-beams to the corner columns.

The two single I-beams of the composite double I-beam were intermittently welded together along their length (above and below) between the two single support I-beams (see Figure 2), but from the forward support single I-beam to the end were continuously welded together above and below. This was to make the double I-beam rigid in torsion to minimize heliostat movement in wind, and result in the focal spot moving off target.

3.2 Mirror array

A single continuous torque tube was envisaged with no joints to ensure straightness. Since the 191mm OD steel tubing chosen for the torque tube (to which the mirror support trusses are attached) comes in 6-metre lengths from the supplier, a 5m×5m mirror array was decided upon, yielding a 25m^2 mirror reflective area for the heliostat.

Figure 3: Heliostat torque tube with trusses assembled, mirror modules can be seen leaning against the wall.

The mirror arrangement chosen was 5 rows and 4 columns, with each column between a pair of trusses. The middle row only has 3 mirrors panels for two reasons: 1) so that a central mirror panel can be the master mirror, parallel to the rotation and pitch axes when in stow condition and 2) to leave space for the bearing support boxes. The truss design was of 25mm square mild steel tubing, with a 191mm clearance between the top and bottom runner of the truss to snugly clamp the torque tube. 8mm steel pates were welded to the truss roots, which bolt to similar plates welded to the torque tube (see figure 3 and 7), allowing easy assembly and disassembly. The trusses were then galvanized.

3.3 Mirror panels

Each mirror panel is a 1.25m×1m focusing mirror of parabolic (not spherical) curvature with a focal length of 55 metres. (The focal length requirement was later determined

to have to be 66 metres, but the mirrors had already been made). The curvature was obtained by laser-cutting formers of the correct parabolic shape.

The 1.25m×1m mirrors were placed face down onto the formers, and weighted down with weights so that the mirror assumed the correct concave curvature. A commercial epoxy resin, Axson 2022, mixed with a cotton flox, was used to bond three 1.220 metre long stringers, each of 25mm×12.5mm×2.5mm mild steel rectangular tubing, to the back of the mirrors. The stringers were bonded parallel to the long sides, at ¼, ½ and ¾ the short side dimension. A rectangular frame of outer dimensions 1.25m×1m, welded from 25mm×25mm×2.5mm mild steel square tubing, was then bonded to the outer edges of the mirror. When dry, the mirrors were rigid with good parabolic curvature, producing a high quality circular focal spot at 55 metres when the angle between the sun and the target is small (see background of figure 3).

3.4 Wind loading

CFD analysis was performed of the heliostat on the roof of the stairwell terminal on the southern building for wind loads from the 4 directions of the compass at two speeds: 15m/s (max allowable wind speed during operation) with the pitch axis assembly containing the mirror panels in a vertical position, and 43m/s with the pitch axis assembly horizontal (stow position in storm wind). These loads were used to check the roof mount loads of the heliostat. The CFD model included the northern and southern buildings as well as the much bigger Medium Speed Wind Tunnel further to the north (against the wall of which the focal spot is visible in Figure 1).
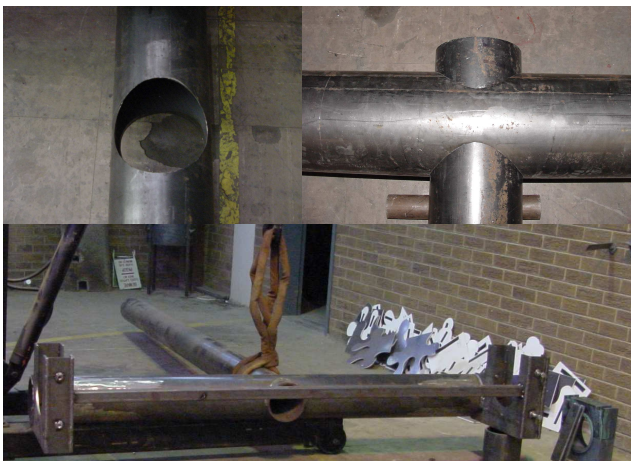
3.4 Heliostat layout

Figure 4: Cross-tube: laser-cut hole, about to be welded to rotation tube, bearing supports (plastic bearing to the left)
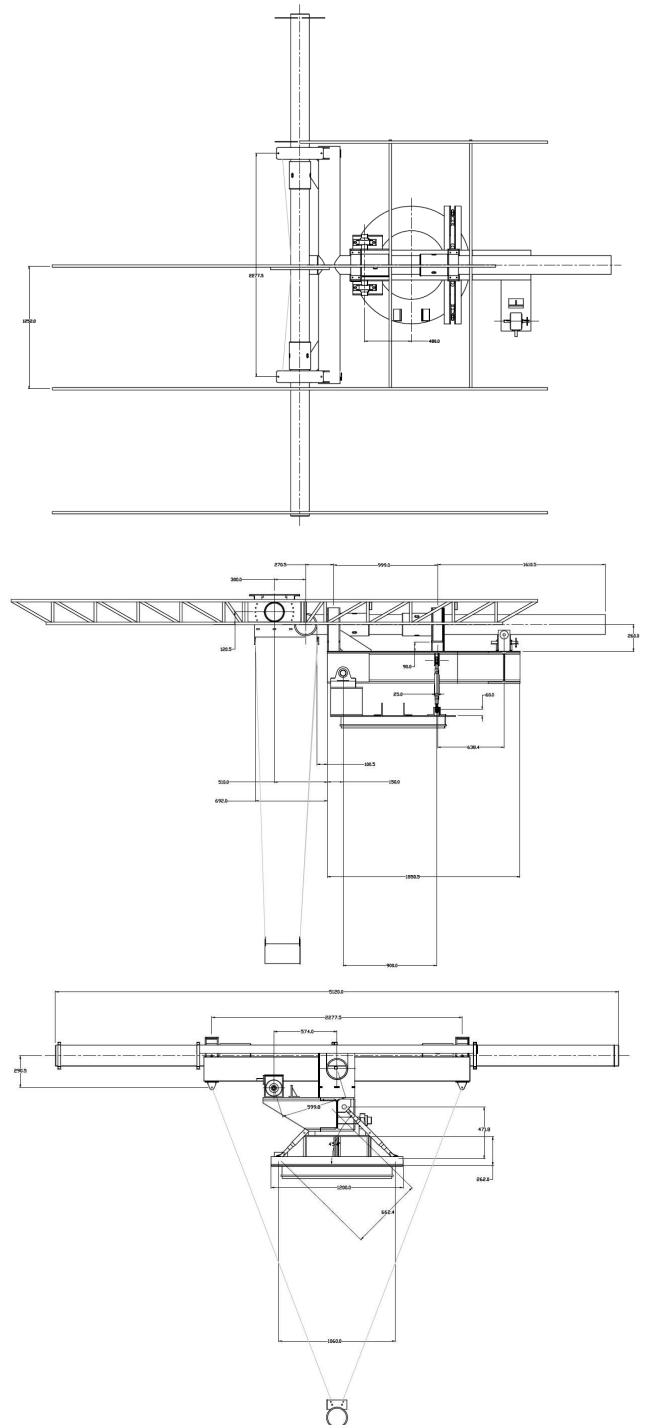

Figure 5: Top, side and rear views of heliostat. Mirror array is in stow condition (turned back parallel to the rotation axis). Some trusses have been omitted from top view

The torque tubes of T-design heliostats are supported at the centre, while in the target-aligned systems of [2], [5] and [6] the torque tube is supported at the ends. To minimise deflections due to sag in the torque tube, it was decided in contrast to support the torque tube for this heliostat with bearings at stations ¼ and ¾ along the torque tube length. To provide this bearing support, the rotation axis tube would have to take on a T-shape, with the bearing boxes at either end of the crosspiece. This was done by the rotation axis shaft being made of 191mm OD steel tubing, and the tube connecting the bearing boxes being 219mm OD steel tubing, both of 10mm wall thickness. A 192mm diameter hole was laser-cut into the 219mm tube. The 191mm tube was introduced and welded into place (see figure 4).

Now since the rotation axis must point to the target, it is important that there be an unobstructed view of the target through the rotation axis tube to allow adjustment (when the mirror array is in stow condition as shown in the side view in figure 5). This is not possible unless the pitch axis tube is raised by half its own diameter and the height of the truss 25mm square tubing, allowing the user to look past the pitch tube at the target along the bottom of the truss (see figure 6). The imbalance caused by raising the pitch axis tube (which with trusses and mirrors weighs 908kg) by 134.5mm is eliminated by placing a 35kg counterweight at a distance of 3.5 metres from the rotation axis centreline. This counterweight can be seen in figures 2and 5 as the short cylinder suspended below.
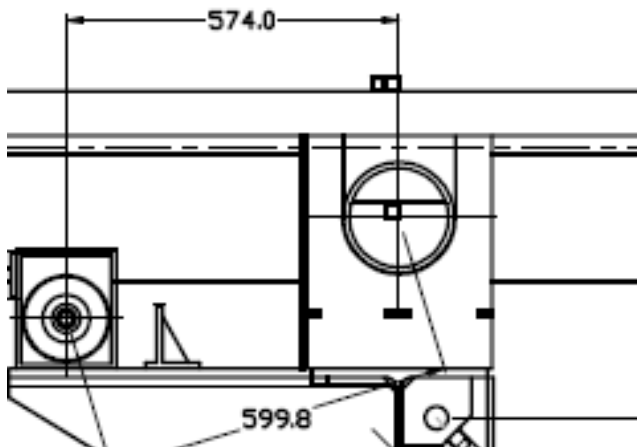

Figure 6: Close-up of rear views of heliostat, showing view along rotation axis. Note square tubing of truss in "cross hairs", with pitch axis tube obscuring view above square tubing.

3.5 Bearing manufacture

Bearings were needed for the 191mm OD steel tubes of the rotation and pitch axes. While the tubes need support in rotation they also need anti-slide thrust bearing-type support when either tube is not horizontal, which is most of the time. Four such thrust bearing rings were manufactured from 320mm lengths of 219mm OD (199mm ID) tube. On a lathe four 10mm grooves were cut and a bearing surface turned at one end. They were then split lengthways, and 5mm was removed from the split surfaces. The 199mm ID was then reduced to the required 191mm by clamping in a hydraulic press around a 191mm OD off-cut. The half-rings were then hose-clamped around the 191mm OD steel tubes of the rotation and pitch axes (figure 7) and welded into place (figure 8). The use of the hose-clamps ensured that the two halves of the thrust bearing surface were properly aligned.
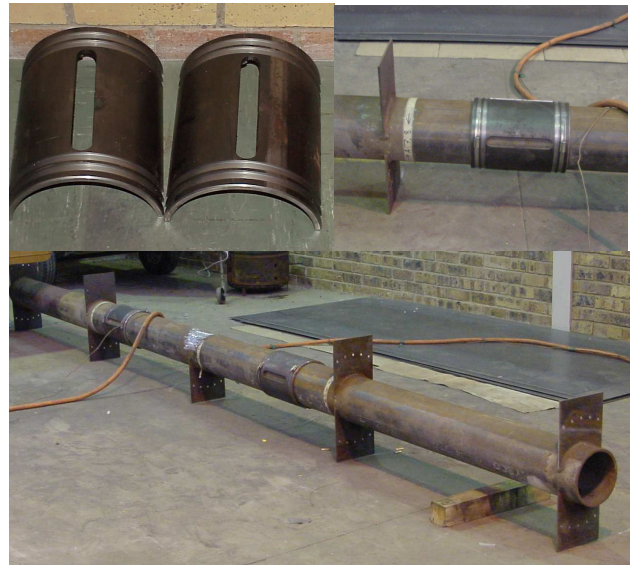

Figure 7: Anti-slide thrust bearing rings: halves, one and both sets hose-clamped

Figure 8: Thrust bearing rings on the pitch axis torque tube, up against the bearings

Four bearings were cast and then machined from an engineering plastic bearing material, as 100mm thick 320mm squares containing a 191mm ID hole, and cut into halves (see figure 4).

3.6 Design of actuation and degrees of freedom

The rotation and pitch axes need electronic actuation to follow the sun. The rotation axis is driven by a 24V DC windscreen wiper motor using 300:1 gearing: first with a 50:1 worm gearbox and finally a 6:1 sprocket drive. The pitch axis is driven by a 36" stroke satellite dish actuator.

A heliostat field of autonomous target-aligned heliostats, just like T-design heliostats, requires the ability for the focal point of individual heliostats to be changed for testing and mirror canting adjustment. This requires the orientation of the rotation axis to be adjustable, introducing azimuth and elevation as another two degrees of freedom.

The pitch axis assembly, as mentioned, has a mass of 908kg. The rotation axis T-assembly has a mass of 350kg, bringing a total of 1.25 tonnes. Accurately adjusting the angle of all this would require some careful planning. A 908mm diameter ball bearing turntable was used as the azimuth adjustment bearing, upon which the entire assembly was bolted.

Elevation adjustment first required a structure to support the rotation axis bearings and the rotation axis drive mechanism. As significant lengths of 305mm square I-beam were to be purchased for stairway terminal building support system, it made sense to make use of the same in the elevation axis support structure. The forward rotation axis bearing had to be in line with the edge of the azimuth bearing turntable disc to allow rotation clearance for the rotation axis T-tube. The rear rotation axis bearing had to be sufficiently far from the forward bearing to provide good angular support without excessive loads to achieve the same moments, but not so far that the sprockets are significantly far from the azimuth bearing turntable centre. A distance of 1 metre was chosen. The resultant support I-beam can be seen in figures 2 and 5.

Elevation angle control was achieved by hinging the I-beam at the forward end around a pair of 60mm self-aligning ball bearings with matching shaft. Two 10mm mild steel plates, rather than the central web, transfer the load from the I-beam to the shaft. This was done to reduce the shaft moment arm to the bearings and also the resultant bending stress in the shaft. The bearings, shaft and I-beam side plates can be seen in figure 8. The bearings were raised from the azimuth ball bearing turntable by a "footstool" made of two I-beam off-cuts on end (see figure 8).

As the azimuth and elevation degrees of freedom will not be reset often in the life of the heliostat, manual adjustment rather than electronic actuation was chosen. For both axes this is achieved using inexpensive agricultural tractor top-links, as they have left- and right-handed threaded rods at each end, allowing extension or contraction by twisting the connecting tube (See figures 5 and 8). As the centre of gravity of the mirror array is not in line with the centre of the azimuth ball bearing turntable (problem also encountered by [7]), use had to be made of a rotation axis counterweight. 219mm OD tubing was slid over the rear of the rotation axis tube (white tube in Figure 1).

4. SOLAR TRACKER DESIGN AND TESTING

As mentioned in the Introduction, a solar tracker geared to rotate about the pitch axis at twice the pitch axis pitch rotation speed, can control the pitch and rotation axis actuation to ensure the heliostat focus remains stationary on the target. This may result in significant cost savings.

4.1 1.25 m2 heliostat

To develop the heliostat control system, a mini-heliostat was built using a single planar $1.25m^2$ mirror panel. Only the rotation and pitch degrees of freedom were incorporated: elevation control was eliminated by fixing the rotation axis in the horizontal plane. Azimuth control was achieved by placing castor wheels on the mini-heliostat. The same motor and worm gearbox drives the rotation axis as in the large heliostat, but using a 3:1 sprocket drive instead. The pitch axis is driven using a 300mm stroke hospital bed actuator.

4.2 Solar tracker

Figure 9: Close-up of solar tracker, geared 2:1 to the pitch axis

The solar tracker controls both motor and actuator, and points the tracker at the sun. The solar tracker (Figure 9) comprises a 160mm length of Bosch Rexroth square aluminium extrusion, 40mm wide, with a 10mm slot in each of the four sides, bolted at one end to an aluminium disc of 80mm diameter, and capped at the other end by a square 40mm wide. Four photo-transistors are attached to the disc using LED holders, with a photo-transistor located in the middle of each of the four slots in the extrusion. When the extrusion points at the sun, the shadow cast by the square cap causes each of the four photo-transistors to lie not in shadow or sunlight but in the penumbra, allowing very fine positional control. Using this controller, the mini-heliostat achieved a focal spot targeting accuracy of 3.3 milliradians (see figure 10).

Figure 10: Mini-heliostat with additional mirror tiles and solar tracker, target of A4 paper obscured by focal spot at 120 metres.

5. 25M^2 HELIOSTAT INSTALLATION AND FOCAL SPOT

Figure 11: Close-up of solar tracker on 25^{2}m heliostat torque tube.

After the solar tracker had been successfully tested on the mini-heliostat, it was fitted to the 25^{2}m heliostat torque tube. Instead of a 2:1 timing belt drive as in the mini-heliostat (see figure 10), a timing belt and wheel with a pitch diameter of 194.04 mm was chosen. A shaft and bearings were attached to the torque tube. A thin strip of stainless

steel was riveted around the torque tube. This provided sufficient filler such that the timing belt, after passing around the timing wheel, slides over the torque tube at the same pitch diameter. A garage door torsion spring keeps the timing belt under tension. Figure 11 shows the shaft with torsional spring protruding over the mirror to the left, and the timing wheel can be seen between the two bearings in the centre and the solar tracker is clamped to the shaft on the right. The solar tracker now rotates around the pitch axis at twice the speed the torque tube does.

The heliostat was assembled on the stairwell terminal roof and can be seen in figure 12. Individual mirrors were adjusted until a mostly coherent focal spot was obtained. As can be seen in Figure 13, two more mirrors need further adjustment to obtain a circular focal spot.
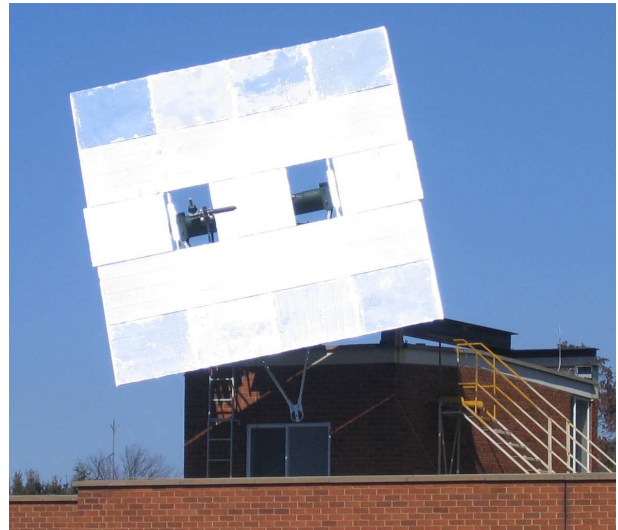
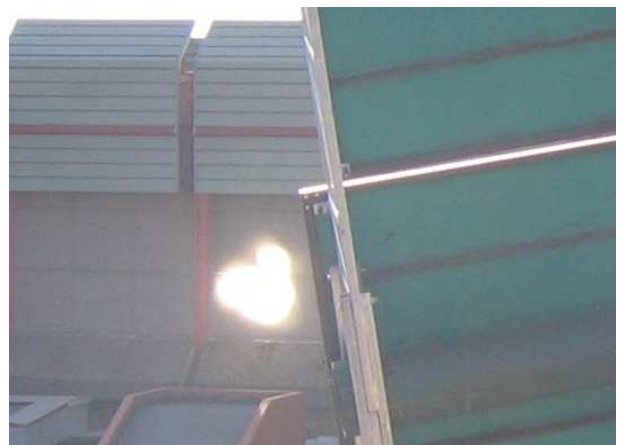

Figure 12: Heliostat mounted on stairwell terminal roof

Figure 13: Close-up of focal spot

5. CONCLUSIONS

A 25^2m target-aligned research heliostat with closed-loop control, with a theoretical concentration of 80 suns, has been developed at CSIR in South Africa. The closed-loop control system has been tested on a 1.25^2m target-aligned mini-heliostat, and produced a tracking accuracy of 3.3 milliradians. A good focal spot has been obtained with the 25^2m target-aligned research heliostat. Future work involves testing the control system on the 25^2m target-aligned heliostat, tightening up the focal spot and characterizing it, before progressing to the high temperature receiver development.

6. ACKNOWLEDGMENTS

7. REFERENCES

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