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ON-SUN TRACKING EVALUATION OF A SMALL-SCALE TENSILE GANGED HELIOSTAT PROTOTYPE

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ABSTRACT

Various ganged heliostat concepts have been proposed in the past. The attractive aspect of ganged heliostat concepts is multiple heliostats are grouped so that pedestals, tracking drives, and other components can be shared, thus reducing the number of components. The reduction in the number of components is thought to significantly reduce cost. However, since the drives and tracking mechanisms are shared, accurate on-sun tracking of grouped heliostats becomes challenging because the angular degrees-of-freedom are now limited for the multiple number of combined heliostats. In this paper, the preliminary evaluation of the on-sun tracking of a novel tensile-based cable suspended ganged heliostat concept is provided. In this concept, multiple heliostats are attached to two guide cables. The cables are attached to rotation spreader arms which are anchored to end posts on two ends. The guide cables form a catenary which makes tracking on-sun interesting and challenging. Tracking is performed by rotating the end plates that the two cables are attached to and rotating the individual heliostats in one axis. An additional degree-of-freedom can be added by differentially tensioning the two cables, but this may be challenging to do in practice. Manual on-sun tracking was demonstrated on small-scale prototypes. The rotation arms were coarsely controlled with linear actuators, and the individual heliostats were hand-adjusted in local pitch angle and locked in place with set screws. The coarse angle adjustments showed the tracking accuracy was 3-4 milli-radians. However, with better angle control mechanisms the tracking accuracy can be drastically improved. In this paper, we provide tracking data that was collected for a day, which showed feasibility for automated on-sun tracking. The next steps are to implement better angle control mechanisms and develop tracking algorithms so that the ganged heliostats can automatically track.

Keywords: ganged heliostat, on-sun tracking.

1. INTRODUCTION

Conventional heliostats use large mirrors mounted on a frame that rotates independently in azimuth and elevation angles to track the sun diurnally and yearly [6]. The heliostats reflect and concentrate the sunlight onto a receiver located on a central tower. Each heliostat requires a fixed pedestal, two independent rotational drives for azimuth and elevation tracking, and structures to hold the mirror facets and allow for the angle rotations. Of the collector field cost, the pedestal and rotational drives make up 40-50% of the cost [7]. To address the cost impacts, some ganged heliostat concepts have been proposed [4,10-14]. In ganged heliostat concepts, multiple heliostats are combined such that they share structures and components, particularly the pedestals and rotational drives. The reduced number of pedestals and drives can reduce the overall cost since these make up the majority of the heliostat cost at 40-50%. Several ganged heliostat concepts and designs have been proposed typically utilizing linkages between two actuators and multiple heliostats. Linkages may be flexible steel bard, cables or chains.

The advantage of ganged heliostats is clear in that the cost savings can be realized through the reduction of the components for the same total reflective area. Some of the disadvantages identified are the increased complexity in linkages between actuators and the many heliostats, difficulty in maintaining optical alignment including on-sun tracking (i.e., heliostat normal vectors vary differently but move as a group), and probable operations and maintenance (O&M) cost increases to

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maintain the large number of connection points, which is in reference to the linkage type systems. An aimpoint strategy has also been listed as something difficult to implement with ganged mirrors since the normal vectors for each heliostat is different but move as a group.

Skysun, LLC (Skysun) has developed a unique cable-supported, tensile ganged heliostats concept with the goal to significantly reduce the heliostat cost by reduction in the number of components and amount of structure needed. A preliminary cost analysis showed the concept can meet SunShot cost goal of $75/m^2 [35]. Skysun's design concept eliminates individual supporting posts and dual-axis drive units for each heliostat. In the commercial scale concept, flexible members, or steel cables, support many heliostats from six and up to 16 heliostats (64 m^2 each) on 125-200 m horizontal cable spans depending on the cable tension constraints and blocking/ shading considerations. Flexible member supports are static steel post/foundations. Four single-axis actuators, two at each supporting post manipulate cable tensions and rotational orientation (or roll angle) of the cable pair. Additionally, each heliostat employs one single-axis actuator, rotating the heliostat about its neutral axis (or pitch angle).

Skysun found the design to be inexpensive but suffered from astigmatism and a non-fixed focus. Earlier research by Skysun (2009 to 2010) showed that a cost-effective concave concentrator could be tensile-based, but substantial optical aberrations would need to be addressed [11]. Chief among the optical aberrations is the resultant astigmatism from obliquely reflected rays. Tensile methods to eliminate astigmatism were then incorporated. Earlier small-scale prototype models demonstrated that aligning six reflectors, increasing later to 12 reflectors, could be improved with additional adjustments. Further research by Skysun with the prototype demonstrated that 24 reflectors, controlled by six actuators including vertical actuation of the end cable anchor points, could be focused to a fixed receiver while eliminating astigmatism. However, Skysun determined that the cost of vertical actuation, requiring two of the six actuators, of the ganged heliostat reflective surface would increase rapidly with increasing scale. Next a method to eliminate the need for vertical actuation was developed. This improvement was demonstrated by the prototype proving that 24 reflectors, controlled by four ganged actuators and one single-axis actuator per reflector, could focus all reflectors to a fixed receiver while eliminating astigmatism. This hybrid style of ganged heliostat implies substantial cost reduction when compared to the current art of heliostats. In addition, the hybrid ganged heliostat can also orient all panels to be simultaneously parallel with each other and all perpendicular to sun position, and maintain this orientation as the sun moves throughout the day. This capability also has applications in photovoltaics (PV), concentrating photovoltaics (CPV) and beam down heliostat field designs.

Accurate tracking, however, becomes challenging where the degrees-of-freedom are now limited for the multiple number of combined heliostats. Tracking is performed by rotating the end plates that the two cables are attached to, which are anchored to the end posts, and rotating the individual heliostats in one axis. An additional degree-of-freedom can be added by differentially tensioning the two cables, but this may be challenging to do in practice. These actuation controls are shown to minimized astigmatism. Manual on-sun tracking was demonstrated on later small-scale prototypes installed at Sandia National Solar Thermal Test Facility (NSTTF). In this paper, the on-sun tracking performance of the small-scale prototypes are evaluated. The tracking control mechanisms were coarse adjustments with linear actuators for rotation arms adjustments and cable tensions, and manual hand adjustments on the mirror pitch angles. With better control mechanisms, the tracking accuracy can easily be improved by 2-3x. A full tracking scheme, including algorithms, was not developed since it was outside the scope of the work, but the initial study performed and the learning developed in this work will provide the foundation for developing tracking algorithms in future work.

2. APPROACH

A small-scale prototype (named Prototype 1) was installed at Sandia NSTTF on March 27-28, 2016 in a north-south orientation. The prototype system was then modified twice (i.e., Prototype 2 and 3). The initial prototype and the changes made to the subsequent systems are described below.

Prototype 1

Majority of the components comprising Prototype 1 (shown in Figure 1) were the same components from the Skysun hybrid style prototype mentioned above evaluated at Lorain County Community College in Ohio. The main difference between the previous prototype and Prototype 1 installed at Sandia was that the first design was supported by posts set into a foundation (4-inch x 4-inch wood posts in foundation 12-inch diameter by 36-inch deep back-filled with concrete), whereas the NSTTF design used a support structure which was above ground and ballasted. The ballasted structure eliminated the need for ground penetration. Approximately 270 kg (600 lbs.) of weight at both ends was used to weigh down the support structure to keep the distance fixed between the support structures, otherwise the structures would get pulled towards each other when the cables were tensioned. Additionally, the support structure rested on casters so the system was mobile. A flat-plate receiver (approximately 14 feet high) was also constructed on site which was installed about 12 m to the southwest of the prototype system set-up (can be seen in Figure 3).

FIGURE 1. Image of small-scale Prototype 1 system. The horizontal distance over the cable span was about 9.1 m. The flat-plate receiver is located about 12 m to the right (not seen in the picture).

On the north end of the heliostat strip, three linear actuators were installed. The linear actuator (mounted vertically) provided the angular rotation adjustments to the cross beam (also referred to as rotation arm) which rotated the cable pair providing rotations on the mirrors in the azimuthal direction (for north-south orientation of the heliostat strip) or roll angle. Two actuators were in line with the cables. These provided tensioning on the cables. On the south end, one linear actuator was installed which provided rotations to the cross beam, similar to the north-end actuator. For cable tensioning, the cables were attached to two ratchet straps, which provided gross cable tensioning. The actuators can be seen in Figure 2.

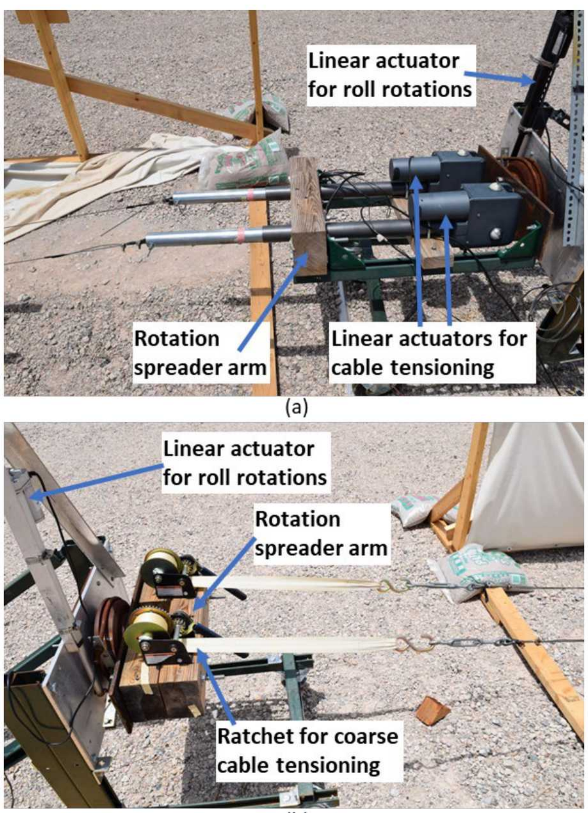


FIGURE 2. Roll angle and cable tensioning mechanisms on the prototypes (a) north end and (b) south end.

The cables used were steel cables 3/8-inch diameter. The mirrors (representing heliostats) were attached to 2-inch PVC pipes with an adhesive which rode over the cables, thus the mirror positions were not fixed to the cables. Twenty-one flat mirrors (12-inch x 12-inch) were installed. Five of the mirrors allowed for independent pitch adjustments. The string of mirrors forms a catenoid when the roll angles at both ends are set horizontally. A relatively shallow catenoid (i.e., with higher cable tensions) approximates a spheroid or paraboloid. At one end of the strip both flexible members terminate to tension actuators. Varying the cable tension in unison changes the focal length or sag of the strip. Varying the tension asymmetrically warps the strip imposing a toric surface contour. The need for vertical displacement of the reflective strip was eliminated with the hybrid design. Cable tensioning adjustment was not necessary while utilizing the hybrid design. However, cable tensioning may be used for improved tracking accuracy, which will be determined in future studies. In this prototype, 5 of the 21 mirrors were instrumented with non-motorized actuators. During experiments, 3 of the 5 were utilized - one at each end of the reflective strip and one located near the middle of the strip. A manually adjusted ball/screw mechanism rotates each mirror (heliostat) about an axis perpendicular to the supporting cables (from coincident with the cables to approximately 60° inclination).

Prototype 2

In Prototype 2 (shown in Figure 3), the 21 mirrors in Prototype 1 were replaced with 13 mirrors by Skysun (on May 16, 2016), each allowing for independent pitch angle adjustment. When the two cables are leveled (i.e., when the rotation arms are at 0° or horizontal), the pitch angles allow the mirrors to move in pure elevation. The pitch angle control consisted of concentric PVC tubes with set screw on the outer tube to lock the angle position. The PVC tubes, which support the mirrors were increased in length to 45.72 cm (18-inches) each increasing the mirror spacing. Individual mirror size was reduced to 15.24 cm × 30.48 cm (6-inch × 12-inch).

FIGURE 3. Image of Prototype 2 set up with a few mirrors put on-sun and the wind fence (covered with canvas tarp) to the west of the heliostat strip.

Prototype 3

In Prototype 3 (shown in Figure 4), the PVC tubes that rode over the cables were cut short, and additional weights were added to the mirrors. In the previous prototypes the PVC tubes were long and butted up against each other. This created the spacing between mirrors. However, two drawbacks were identified with this configuration: 1) the butted-up PVC pipes created a natural dampening effect which impacted the vibration and modal behavior [36], and 2) for large rotation angles of the rotation arms, the PVC tubes chafed at the contact points sometimes changing the pointing angles of the mirrors (particularly for the mirrors at the bottom of the cable sag) which impacted the on-sun tracking accuracy. With the PVC tubes shortened, Prototype 3 better represented the commercial scale concept.

The additional weight added per mirror was determined from scaling down the 175 m span used in the 10 MW_e power tower model [35]. For the 175 m spans, the weight of one heliostat was estimated to be 1500 kg (3,300 lbs.). This included the weight of the glass, back support, and support frame. This was scaled down to 9.1 m span of the prototype set-up arriving at approximately 4 kg (9 lbs.) on each mirror. Previously, the mirrors alone with the PVC tube weighed about 0.5 kg (1 lb.) each. The objective for the modifications in Prototype 3 was to scale the commercial scale ganged heliostat concept down to the small-scale prototype size. However, the size of the heliostat (64 m^2) was not scaled down, which would have required custom sized mirrors. For the purposes of this study, it was not necessary to scale the mirror size.

After the modifications, it was observed that the mirror strip became more sensitive, although small, to wind perturbations. That is, increased motions across the cables were observed in light winds. This is further discussed in Armijo, et al. [36], where dampening strategies are proposed.

FIGURE 4. Image of Prototype 3 set-up with another wind fence on the east side. The wind fence impacts were studied as part of the mechanical evaluation [36].

3. RESULTS AND DISCUSSION

The development of the tracking algorithm was outside the scope of the work, which would require developing mathematical algorithms and control schemes to perform passive automatic on-sun tracking. However, the evaluation of the on-sun tracking was started. Manual on-sun tracking was demonstrated, first by Skysun and then by Sandia on the different prototype set-ups. Unlike conventional heliostats which each have rotation drives that provide independent azimuth and elevation control, the tracking on the cable-suspended ganged heliostats is nontrivial in terms of angle motions which could be coupled. The rotation actuators at the end-posts provide rotations of the cables in roll to mimic azimuth for heliostat strip aligned north-south; elevation if aligned east-west. For the north-south orientation, the pitch angle rotation on each heliostat provides motion in the elevation direction (see Figure 5). Initial characterization showed the actuators do not provide pure azimuth and elevation motion but are coupled. The azimuth and elevation coupling becomes significant for large roll angles on the cable pair.

The small-scale prototypes helped to develop an understanding of the on-sun tracking control of the system. The prototype system, however, had coarse adjustments. Linear actuators (Figure 6b) were used for rotations of the cable spreader arms. These were manually controlled. The individual mirror pitch rotation was manually adjusted by hand and locked in position using a set screw. The cable tensions were also controlled with linear actuators (Figure 6c). The cable tensioning can compensate for the toroid needed in the reflective strip for accurate on-sun tracking. When both rotation arms were rotated unevenly, a toroid is formed in the reflective strip. It is suggested the shape of the toroid depended on the coupled cable dynamics, which are impacted by the weight load distribution on the guide cables. This hypothesis was not studied because it was outside the scope of the work. In future studies, this will be studied to develop a better understanding. Figure 5 illustrates the angle and tension adjustments.

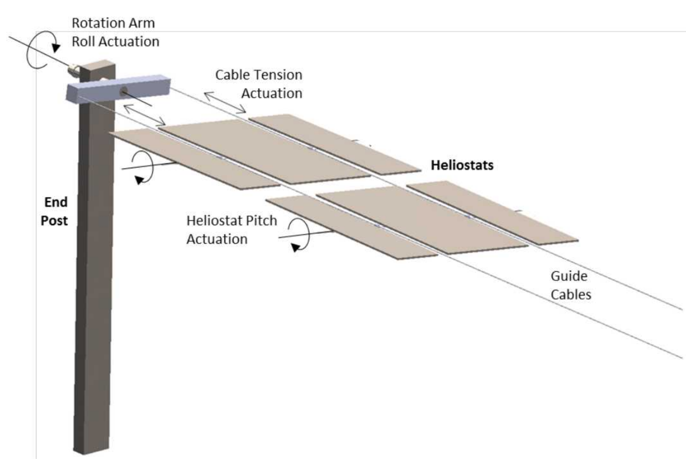
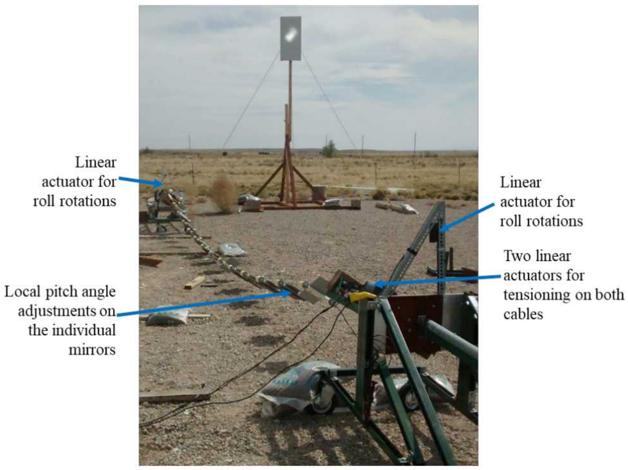


FIGURE 5. Schematic of actuations on the ganged heliostat that provide the degrees-of-freedom for on-sun tracking. The end post at the other end also has roll actuation.

In the Prototype 3 system, the tracking accuracy was estimated to be about 4 mrad from the multiple on-sun tracking experiments. However, this is with coarse actuations as mentioned. With better control mechanisms the tracking accuracy can easily be improved by 2-3x. A tracking accuracy of 1.65 mrad (~4/2.5) was then assumed for the large scale system. If all other slope errors are kept the same as the baseline case (Table 1), except for the structural stability, the total optical errors for the ganged heliostat case comes out to 2 mrad, which was used in the power tower plant modeling [35]. Figure 6 shows testing of Prototype 3 for on-sun tracking and the linear actuators used.



(a)

Parameter	Specification
Model	LIN-ACT1-12
Stroke length	12"
Power requirements	12 V DC
Max load capacity	225 lbs.
Travel speed	10 mm/sec
Duty cycle	25%
Shaft diameter	20 mm
Material	6061 Aluminum

(b)

Parameter	Specification
Model	HB4500; HB3000
Max lift capacity	4,500 lbs. / 3,000 lbs.
Retracted height	31-3/8"
Vertical travel	18"
Power requirements	12 V DC
Outer tube diameter	2 1/4"
Foot pad diameter	5 ½"

(c)

FIGURE 6. (a) On-sun test of the small-scale prototype, Prototype 3, on 4/10/2017, 3:21 pm MT. Three of 13 mirrors utilized – both ends and middle. (b) Linear actuator for roll rotations. (c) Linear actuator for cable tensioning.

TABLE 1. Optical errors per heliostat tracking axis used in SAM [35].

Optical Errors	SunShot (mrad)	Ganged Heliostats (mrad)
Mirror Slope Error	1.1	1.1
Canting Error	0.25	0.25
Tracking Error	1.04	1.65
Structural Stability	0	0.25
Total (RSS)	1.53	2.0

To collect the mirror angle data, tri-axial accelerometers were mounted on five mirrors. Figure 7 schematically shows an accelerometer mounted on a mirror with its coordinate axes labeled. Figure 8 shows the mirrors with accelerometers attached. The y-axis of the accelerometers monitored mostly the roll angle movement of the mirror, and the x-axis of the accelerometers measured mostly pitch angle movements. However, the accelerometers did not measure pure roll or pitch angles. Due to the motions of the mirrors, roll motions have a coupled x, y movement of the accelerometers. Similarly, pitch angle movement of the mirrors has coupled x, y accelerometer readings. This coupling becomes more significant at large roll angles of the cable pair.

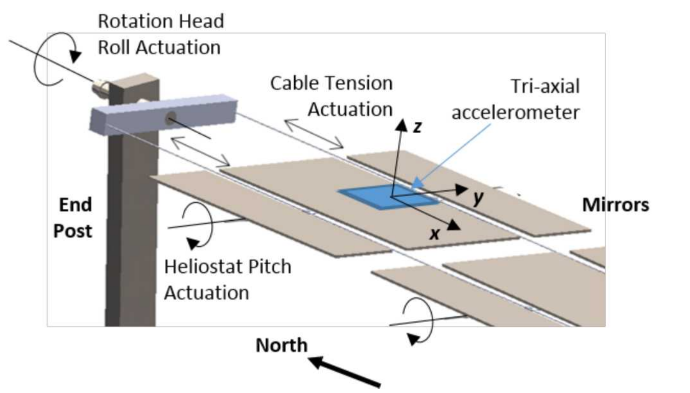


FIGURE 7. Schematic of a tri-axial accelerometer mounted on a mirror and showing its coordinate axes.

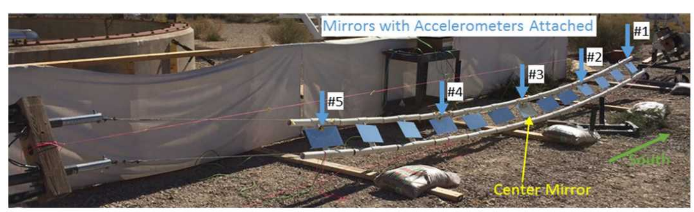


FIGURE 8. Prototype 2 set up with accelerometers attached to the five mirrors. In the Prototype 3 set up the same mirrors had accelerometers attached to them.

Figure 9 shows the roll angles measured on both rotation arms (on Prototype 2) for an on-sun tracking experiment on 02/08/2017. The plot only shows the roll angles. To put the reflected beams on the target (as shown in Figure 6a), the pitch angles on the mirrors also need adjustment. With the test setup, pure pitch angles on the mirrors were not measured. This would require encoders mounted directly on the drive mechanism for pitch motions. As seen in the figure, the roll angle motions follow a smooth second order polynomial very well. This example dataset is specific for the position of the heliostat strip relative to the target plate. Heliostat strips in other positions or orientations will have different roll angle dependencies for the same sun movement. The idea is then to build up a database of the roll angles for all spans in the field, and either develop a mathematical model or lookup table, which would be the basis for a passive automatic on-sun tracking for the roll angles on the rotation arms. A similar approach can be developed for the local pitch angle adjustments on the individual heliostats.

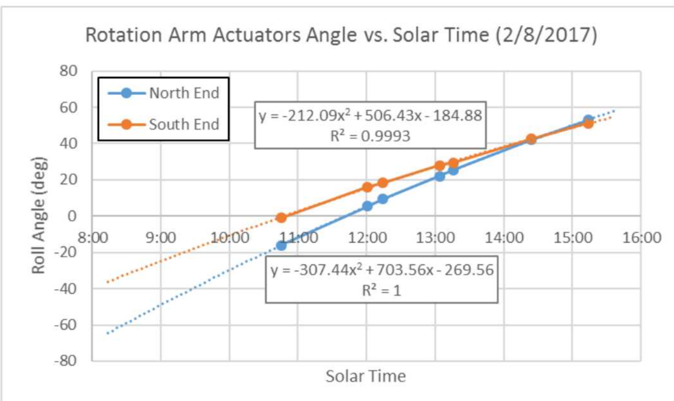
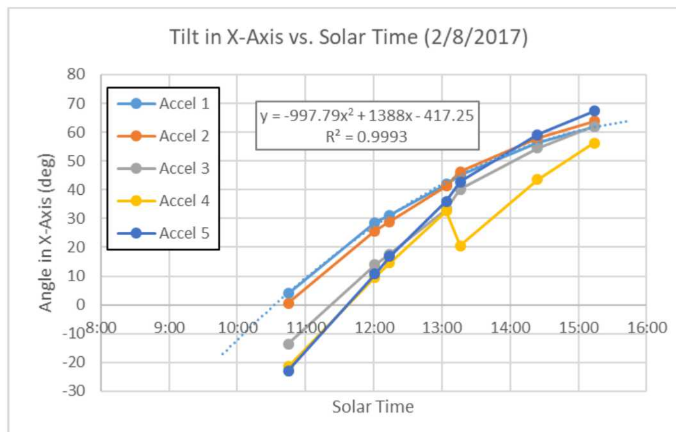


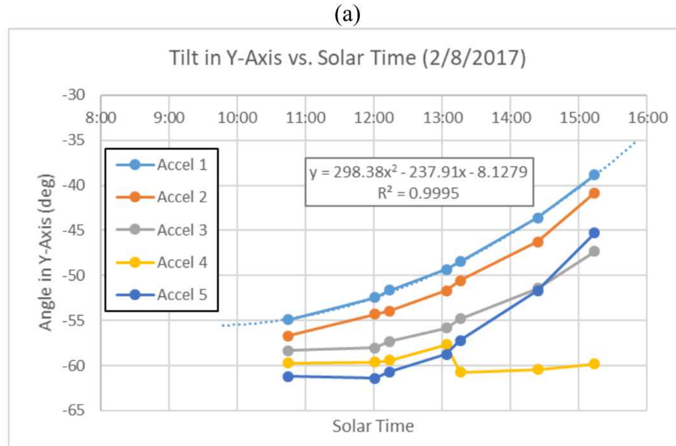
FIGURE 9. Rotation arms (both ends) roll angles measured with an electronic level for on-sun tracking on 02/08/2017. At 0° roll angle (i.e., horizontal position) rotation arms are leveled to gravity.

Another thing to note is if the heliostat span was directly north of the target stand, at solar noon (12:00) the roll angle on the rotation arms should be zero when the sun is reflected onto the target plate. However, the heliostat strip was positioned north and slightly to the east (by about 3 m). This can be seen in Figure 9 where the roll angles cross 0° before solar noon.

Figure 10 shows the accelerometer mirror angle measurements on the same Prototype 2 set up. As mentioned above, the accelerometers angle measurements are coupled between the mirror pitch and roll angles. It is nontrivial to decouple the mirror pitch and roll angles from the accelerometer measurements. This study on angle coupling is left for future work. It is only when both rotation arms are at 0° that the accelerometers x-axis will measure pure mirror pitch angles, which would be the equivalent of elevation angle motion in a conventional heliostat with independent azimuth and elevation angle drives. For increasing rotation arms roll angles, the coupling becomes stronger between the pitch and roll angles. When the rotation arms both reach 90°, then the mirror pitch angles are more equivalent to azimuth angle motion on a conventional heliostat. However, due to the cable dynamics under weight loads, pure azimuth motions may not be achieved. Although these measurements couple the mirror pitch and roll angles, the trends in both axes appear to follow smooth curves. As an example, a second-order polynomial fit to the Accelerometer #1 data shows a good fit with R^2 equal to 0.9993 in the x-axis and 0.9995 in the y-axis. This informs us the actual mirror pitch and roll angles will also follow smooth curve trends, and mathematical models or lookup tables can be developed for automatic on-sun tracking. Only Accelerometer #4 is showing a non-smooth curve. Around 1:00 pm solar time, the angles shift in both x- and y-axes. Recall the phenomena of PVC pipes chaffing in Prototype 2 mentioned above. This is the cause of the angles shift. The PVC pipes that support the mirrors are butted up against each other to provide the spacing between mirrors. Through friction, the butted pipes can stick to each other. As the rotation arms are rotated, the PVC pipes in contact can slip causing a change in mirror angle. This is what happened to the mirror with Accelerometer #4, and this was one reason for development of Prototype 3 where the PVC were cut short and they were no longer in contact.



(a)



(b)

FIGURE 10. Accelerometer mirror angle measurements on Prototype 2 during on-sun tracking experiments on 2/8/2017. (a) Accelerometer x-axis tilt, and (b) y-axis tilt.

Due to time and budget constraints, on-sun tracking experiments were limited on the Prototype 3 set up, and the collected data were not analyzed.

4. CONCLUSIONS

The tensile-based ganged heliostat is a novel concept and has potential to reduce collector cost. However, as with any ganged heliostat, developing an accurate tracking scheme is challenging. In this work, manual on-sun tracking was demonstrated on the tensile small-scale ganged heliostat prototype setups. The degrees-of-freedom for the mirror angle motions were described. Since the degrees-of-freedom for the angle motions on a group of heliostats are limited, the on-sun tracking becomes non-trivial. This means a single drive mechanism when adjusted will move all the mirrors at once but at varying angle rates on the mirrors. Tracking algorithms for such tensile ganged heliostats do not exist. The manual tracking was developed from trial and error. The available angle adjustments were varied to get a “feel” for the response on the reflected beams. Each angle adjustment provided a coupled vertical and horizontal response on the reflected beam motion. After developing an understanding of the adjustments, a set of mirrors were put on-sun in an iterative process (i.e., the reflected sunlight from the set of mirrors were directed to a point on the flat target plate). The successful manual on-sun tracking informed us this can be done automatically with appropriate controls. In future work, developing the mathematical algorithms that will be used for automatic passive on-sun tracking will be addressed. This function is critical for future development of the tensile-based ganged heliostat.

5. FUTURE WORK

Although manual on-sun tracking was demonstrated, demonstration of automatic on-sun tracking is a critical piece in the development of the tensile-based ganged heliostat concept. The development of the tracking algorithms was outside the scope of this work, but the initial work performed here is a start and lays the foundation for future work. In future work, further understanding will be developed for heliostat roll and pitch angle motions. Test setups will include installing encoders on the rotation arms and each heliostat for measuring the angles. The angle data can then be used to develop mathematical models or lookup tables, so the measured angles can provide feedback to the control system for passive automatic on-sun tracking. In addition, drive mechanism must be improved. The current prototypes used linear actuators and hand adjustments for coarse mirror angle adjustments. In the next prototype, better drive mechanisms will provide finer control and improvement on the tracking accuracy.

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