Closed-loop control for power tower heliostats

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ABSTRACT

In a Power Tower solar thermal power plant, alignment and control of the heliostats constitutes one of the largest costs of both time and money. This is especially the case in systems where individual heliostats are small (~1m²). I describe a closed-loop control system that generates the required feedback by inducing small mechanical vibrations in the heliostat reflector surface using piezoelectric actuators. These vibrations induce time-dependent changes in the reflected wavefront that can be detected by photosensors surrounding the thermal receiver target. Time and frequency encoding of the vibrations allows identification of a misaligned heliostat from among the thousands in the system. Corrections can then be applied to bring the reflected beam onto the receiver target. This technique can, in principle, control thousands of heliostats simultaneously. Outdoor testing of a small-scale model of this system has confirmed that such a system is effective and can achieve milliradian tracking accuracy. If such a system were implemented in a commercial plant, it could relax the accuracy specification required of the heliostats as well as provide an automated alignment and calibration system. This could significantly reduce the installed cost of the heliostat field.

Keywords: Heliostat, Tracking, Alignment, Closed-Loop

1. INTRODUCTION

In central receiver, or “Power Tower” style solar thermal power plants, sunlight is focused using heliostats, which are large mirrors attached to motorized mounts. These must track the sun in two dimensions with a typical accuracy of 1 milliradian. If the pointing accuracy is worse than this, then some of the reflected light will miss the receiver and the plant will lose efficiency. Heliostats form the dominant cost of Power Tower CSP plants and therefore form the most obvious target for cost reduction. A recent report from Sandia National Laboratory[1] performed an analysis of heliostat costs and ways to reduce them. The report states that if the cost of a heliostat could be reduced from $200/m² to $100/m² of mirror area, then the Levelized Cost of Electricity (LCOE) from the plant could be reduced from 8.7 cents/kWh to 5.9 cents/kWh. In other words, the cost would go from being somewhat higher than Natural Gas-fired plants to being wholly competitive with them.

The Sandia report investigates a number of cost reduction methods. Among them is to “study latest closed-loop control options…”. Closed-loop control (CLC) is a technique wherein a feedback signal is produced and used to correct misaligned heliostats. This is useful for a number of reasons. In case of a hardware failure or calibration drift, the closed-loop system could identify and correct the problem. Another benefit of using such a system would be to expedite the alignment procedure that is necessary to bring a Power Tower plant into operation. At the Solar Two plant, which was built in Barstow, CA in the late 90’s, heliostat alignment was a difficult problem that was never fully resolved. It was estimated that 10 to 20% of the reflected sunlight was lost due to poorly aligned heliostats[2]. A more recently built plant, the eSolar plant in Lancaster, CA, was able to use a custom-built open-loop alignment system to achieve excellent tracking resolution[3]. However, the alignment procedure took 20 good weather days for the relatively small 5 MW plant. The costs associated with this due to lost operation time as well as to the need for highly experienced personnel are not disclosed by eSolar. However, it is likely to be equivalent to at least a few percent of the total cost of the plant. CLC may also be used to compensate for less accurate motors or structures, which could be less expensive. Tracking the effects of dynamic wind loads may even be possible.

There have been several proposed methods for generating the feedback signal needed for CLC. One of the most fully developed is described in a paper [4] from the Weizman Institute in Israel. This paper describes a prototype system that
was used to control a single heliostat. In this method, digital cameras are placed around the central receiver. Digital images are taken of the heliostat field and analyzed to determine which heliostats are misaligned. Heliostats that appear bright in the digital images are in need of adjustment. The method encountered problems with saturation and contrast in the digital images, but overall seemed to work well. However, it seems that this feedback system has not been widely adopted. This may be due to cost, or to the difficulty of operating digital cameras in the vicinity of the thermal receiver. Similarly, no other feedback method has been widely adopted.

In this paper, I describe laboratory-scale tests of a new type of feedback system in which photodiodes (PDs) surrounded the central receiver. The PD’s detected light from misaligned heliostats. To identify the source heliostat of the light striking the photodiode, each of the heliostats was caused to vibrate mechanically at its own unique frequency by a small patch of piezoelectric material, called a piezoelectric actuator (PA), attached directly to the heliostat mirror. The vibrations induced on the mirror caused the reflected beam’s spatial intensity distribution to oscillate at the same frequency. The photocurrent from any PD being illuminated by this heliostat was thus modulated in the same way. This modulation frequency was detected with external electronics connected to a computer doing Fourier analysis of the signal. Finding the peaks in the Fourier spectrum identified which of the heliostats was the misaligned one and was used to generate a feedback signal to allow for correction. Although the test system contained only four heliostats, the technique is scalable to a system with thousands.

2. FEEDBACK MECHANISM

A number of different methods could be used to produce the required mirror vibration. The one that has been most extensively tested in this work is to bond a patch of piezoelectric actuator (PA) directly to the back surface of the reflecting material. When the PA is driven with a sinusoidal signal, typically in the audio range of 1-30kHz, vibrations are induced in the reflector surface. Under, the assumption of simply supported boundary conditions, the normal (resonance) frequencies are given by [5]:

\[ \omega_{mn} = \frac{\pi^2}{a^2} \sqrt{\frac{E_g h}{12 \rho}} (m^2 + n^2), \]  

Equation 1

where \( a \) is the square reflector side length, \( E_g \) is the Young’s modulus of the glass, \( h \) is the thickness, \( \rho \) is the density, and \( m \) and \( n \) are the mode numbers. With a number of simplifying assumptions and assuming that the PAs are placed at the anti-nodes, the vibration amplitude of the \( (m,n) \) mode is given by [5]:

\[ W_{mn} = \frac{16 \pi^2 V d_{31} E_p}{\rho a^4 (\omega_{mn}^2 - \omega^2)} \frac{\epsilon \delta}{1 + \frac{6 t E_p}{h E_g}} \]  

Equation 2

where \( V \) is the applied voltage, \( d_{31} \) is the piezoelectric material expansion parameter \((m/V)\), \( E_p \) is the Young’s modulus of the piezoelectric material, \( \omega \) is the driving frequency, \( \epsilon \) and \( \delta \) are the dimensions of the PA. For the measurements described below, I used a square glass mirror, which had a side length of 5.1 cm and a thickness of 0.3 cm. Putting in the appropriate parameters, we find a first resonant frequency of 5.6 kHz and vibration amplitudes in the 1 \( \mu \)m range for a 1 volt excitation and for frequencies near resonance. The power required to drive the PA is much less than one milliwatt.

In initial tests of this system, a diode laser was reflected off of the vibrating mirror and onto a photodiode. This caused the beam to oscillate from side to side at the driving frequency. If the beam spot was located so that it overlapped the edge of the PD, the vibration induced a small modulation of the PD photocurrent at the driving frequency. The PD photocurrent signal was conditioned with a simple op-amp circuit that included a transimpedance stage, a high-pass filter stage (with a knee at 1kHz) and a gain stage. This signal was then digitized with a 100 kHz ADC (National Instruments NI9215) with an acquisition time of 0.1 seconds and the resulting data analyzed with a Fast Fourier Transform (FFT). The FFT amplitude at the driving frequency is thus proportional to the vibration amplitude and exhibits the expected resonant structure. Typically, the photocurrent modulation amplitude was about \( 10^{-7} \) of the DC current. Figure 1 shows the induced photodiode modulation as a function of driving frequency. The boundary conditions of the mirror are not, in practice,
“simply supported”, but rather closer to “completely free”. The expected resonant frequencies for these conditions are calculated in [6] and are shown as blue arrows in Figure 1 after normalizing to the first observed resonance. The good agreement between the predicted and observed resonant frequencies gives confidence that the observed modulation is due to the plate vibrations, which are adequately described by the assumption of “completely free” boundary conditions.

Tests of the vibrating mirror system with sunlight yielded a similarly sized modulation signal that was readily detectable despite very different illumination. In the solar case, the modulation is not due to the beam oscillating from side to side, as it was with the laser. Rather, the beam is being continuously focused and defocused by the deformed mirror as it vibrates at the driving frequency. This causes a similar modulation of the PD current, which is detectable when any part of the beam is striking a PD.

![Figure 1: Induced photodiode modulation amplitude as a function of frequency. Expected resonance positions are shown with blue arrows.](image)

## 3. LABORATORY-SCALE CLOSED-LOOP CONTROL SYSTEM

Once it was proven that the source mirror of a reflected sunbeam could be identified by observing its frequency in the FFT spectrum, the next step was to build a system capable of simultaneously controlling multiple mirrors and performing closed-loop tracking of the sun for each of these mirrors. The necessary components of this system included four mirrors, with attached PAs, that could be moved in altitude and azimuth, a PD array with associated electronics and a control program running on a Windows computer. Figure 2 shows photographs of the components of the system.

The mirror motion was provided by commercial telescope mounts that communicated with the control computer via RS-232. They accepted commands to move in altitude and azimuth at several different speeds and used optical encoders to measure relative angular positions. The PAs were each driven by one output of a four-channel 100kHz signal generator (National Instruments NI9263).

The PD array consisted of four PDs arranged in a diamond pattern. An analog electronic module was constructed to perform the necessary signal conditioning and one channel of a 100kHz ADC (National Instruments NI 9215) was used for each PD.
A control program was written using the National Instruments LabWindows CVI environment. This program could control the four mirrors in either “Manual” or “Sun-Track” mode. Sun-tracking could be done in either “open-loop” or “closed-loop” using the feedback signal from the PDs. For all of the tracking calculations, a set of unit vectors are defined as, e.g.,

\[
\tilde{x} = \left( \sin x_\theta \cos x_\varphi, \sin x_\theta \sin x_\varphi, \cos x_\theta \right)
\]

Equation 3

where \(x_\theta\) and \(x_\varphi\) are the altitude and azimuth angle, respectively. In “open-loop” mode, the required mirror normal unit vector \(\tilde{m}\), was calculated based on the known position of the sun, \(\tilde{s}\), which was calculated using NREL’s “Solar Position Algorithm”, and the direction from the mirror to the target, \(\tilde{t}\), via the vector equation

\[
\tilde{m} = \frac{\tilde{s} - \tilde{t}}{|\tilde{s} - \tilde{t}|}
\]

Equation 4

At the beginning of a run, the target direction, \(\tilde{t}\), was obtained by manually moving the reflected sunbeam onto the target region and inferring the target direction via the vector equation

\[
\tilde{t} = \tilde{s} - 2\tilde{m}(\tilde{s} \cdot \tilde{m})
\]

Equation 5

Every 15 seconds a new mirror position was calculated and the appropriate “Goto” command was sent to the mount. Since the slew time was typically one second, the mount was stationary most of the time. Open-loop tracking performed in this way did not typically track the sun very well. This is because the mount was not typically aligned very well with the earth’s coordinate system. So that, e.g., an azimuthal position of 0 did not really correspond exactly to true north.

For closed-loop tracking, the photodiode signals were used to generate tracking corrections. The procedure for a single mirror is described by the flowchart shown in Figure 3. The first step is to manually move the beamspot onto the target. It does not need to be accurately positioned in the center of the PD array. It just needs to be illuminating at least one of the photodiodes. From the initial mirror position, \(\tilde{m}\), and the current sun position, \(\tilde{s}\), it is possible to infer an effective target direction, \(\tilde{t}\). Then, the program enters the “Sun Track” Loop. In the loop, the first step is to calculate a new mirror position, \(\tilde{m}'\), which is based on the open-loop calculation, with corrections applied to azimuth and altitude, \(\Delta\varphi\) and \(\Delta\theta\), respectively. On the first pass through the loop, these will both be zero, so no correction will be applied. The next step is to check if any of the photodiodes are being illuminated by the mirror by checking the FFT spectrum for each PD for signals at the mirror’s frequency. If the \(i\)th PD is being illuminated by the mirror, \(a_i\) will be set to one, otherwise it is zero. The target direction correction needed to bring a beam illuminating the \(i\)th PD toward the center of the target is \(p_i\). So, the total correction needed at the target plane is

\[
\tilde{d} = \sum_{i=1}^{4} a_i \tilde{p}_i
\]

If, for example, both horizontal diodes or both vertical diodes are illuminated, no correction is applied in the respective direction. The next step is to calculate an “effective target”, \(\tilde{t}'\), which is where the target would be given \(\tilde{s}\) and \(\tilde{m}'\). Then, a new target vector \(\tilde{t}'' = \frac{\tilde{t}' + \tilde{d}}{|\tilde{t}' + \tilde{d}|}\) and a
new corresponding mirror vector, $\overrightarrow{m''}$, are calculated. The altitude ($\Delta \theta$) and azimuth ($\Delta \varphi$) mirror position corrections are then incremented by the difference between $\overrightarrow{m''}$ and $\overrightarrow{m'}$. The program waits for 15 seconds and goes back to the beginning of the loop, where the $\Delta \theta$ and $\Delta \varphi$ corrections are applied to the “open-loop” mirror positions and then moves to this newly calculated position.

Since the light from each mirror is individually identifiable, each mirror is controlled independently of the others. “Open-loop with corrections” may be a better name for this system than “closed-loop”, because it is able to track even in the absence of feedback. For example, if the sun goes behind a cloud, the system will still track in an “open-loop” way until the sun returns. Also, if the initial alignment is sufficiently good, the system will operate largely without feedback with only occasional corrections being applied. It is expected that this would be the mode of operation for a mature system that has been running for some time.

Outdoor testing of the system proved that the system could simultaneously control the four vibrating mirrors and keep their reflected beams in the target region formed by an array of four photodiodes. Figure 4 shows a Fourier spectrum for a photodiode that is being simultaneously illuminated by sun reflecting from four mirrors each vibrating at its own frequency. The four peaks are clearly separated from each other and well above background. Figure 4 also shows a photograph of the four reflected sunbeams being held within the target region formed by four photodiodes. Once the CLC was turned on, the system was capable of keeping the beams in this region indefinitely despite poor initial alignment. The operation of this system is demonstrated in a video that can be viewed at: http://www.youtube.com/watch?v=yyyLeP-Fo9s.

Figure 3: Flow chart for closed-loop tracking algorithm.

Figure 4: Fourier spectrum of a photodiode being simultaneously illuminated by four vibrating mirrors (left). Photograph of four reflected sunbeams being kept within the target region (right).
4. OFFLINE CALIBRATION

As the CLC operates, it generates a time series of $\Delta \theta$ and $\Delta \phi$ corrections for each mirror that are necessary to keep the reflected sunbeam from that mirror within the target region. These required corrections can be used to perform an offline calibration of the heliostats alignment parameters. Four parameters were used: the altitude and azimuth of the target and the altitude and azimuth offsets of the heliostat coordinate system from true vertical and true north. For each value of these parameters the expected values of $\Delta \theta$ and $\Delta \phi$ as a function of time may be calculated and compared to the measured ones. An optimization algorithm then finds the “best-fit” values of the four parameters.

Figure 5 shows the results of this procedure for one day of data on one mirror. The required $\Delta \theta$ and $\Delta \phi$ corrections are shown as red dots in the two left hand plots and were quite large due to an initially poor calibration. The blue curve in the left column plots shows the expected required corrections for the best-fit values of the four parameters. The fit is quite good and yields precise values of the parameters. The middle column shows the fit residuals, i.e. the difference between the expected and observed corrections with the best fit parameters. Typical residuals are in the range of 0.1 degrees.

As a test of these fitted parameters, they were used to calculate the open-loop mirror positions (map of Figure 3) during a subsequent day’s run. One would expect that the required corrections ($\Delta \theta$ and $\Delta \phi$) would then be much smaller. As shown in Figure 6, this was indeed the case, with the typical correction being less than 0.1 degree. The typical tracking resolution was 1.5 milliradian. Despite the much improved tracking, there are still clearly some systematic effects in the corrections that could be improved with further work. Adding more parameters, such as ones describing an overall “pedestal tilt” of the heliostat could improve the resolution. A detailed description of the beampot shape may also improve the resolution. Both of these issues are potential topics of future study. With the large amount of alignment data

![Figure 5: Performance of the CLC system for a single mirror during a one day run for altitude (top row) and azimuth (bottom row). X-axis is the time since the beginning of the run. Left column plots show the required corrections in red dots, and the best fit expectations as a blue curve. Middle column plots show residuals. Right hand plots show the commanded mirror positions.](image-url)
produced by the CLC system, very complex fitting models can be developed to correct for many different types of heliostat inaccuracy. Furthermore, the time required for this alignment may be as short as one day for an entire system of heliostats.

Figure 6: Performance for the CLC system for a subsequent day’s run incorporating the alignment constants calculated from the data of Figure 5. Plot definitions are the same as Figure 5.

5. LARGE-SCALE COMPONENT TESTS

Using a CLC system in a commercial-scale system would involve larger mirrors and higher intensities and temperatures at the target. Addressing these two issues is necessary before attempting to scale up this system. Some simple tests have been performed to test whether the system would function under these conditions.

In the first such test, a large-scale 1 m² mirror was driven with a PA attached. A laser and sunlight were used to confirm that the PD modulation signal was produced. Due to the larger mirror size, the resonant frequencies are much closer together than with the small mirror. Nonetheless, the modulation signal was still measurable with a PD and it appears that the scheme of producing mirror vibration with an attached PA is viable with commercial-scale mirrors.

In the second such test, a new type of sensor was developed to replace the simple PDs used in the laboratory-scale system. This was necessary because simple photodiodes would not function properly in the high solar intensity environment in the vicinity of a commercial receiver. The new sensor must be capable of functioning at high intensity and temperature and must have sufficient bandwidth (>10kHz) to preserve the audio frequency modulation signals. The latter requirement rules out most thermal sensors. The most promising concept that has been explored so far is to use a silica optical fiber to sample the light distribution near the receiver and transport it some distance away. There, the light could be detected by a PD after being allowed to diverge so that it is below the PD damage threshold. The audio frequency modulations should be
preserved by this technique. Silica optical fibers with diameters in the millimeter range are commercially available. The melting temperature of the silica optical fiber itself is certainly much higher than 500°C.

Some simple tests of this type of sensor have been performed that confirmed that the fiber sensor preserves the audio frequency signals and that the modulation signal is detectable even in the presence of a high intensity background. This work confirms that such a sensor can work in principle. However, more work would be necessary to produce a truly viable fiber sensor.

6. CONCLUSION

The laboratory-scale model of the CLC system performed very well. The mirror vibration technique was found to produce detectable modulations in the photo-diode signal. These modulations could be used to identify the source mirror of light that is illuminating it. This information could be used to correct mirror misalignments and keep beams on target despite initially poor alignment. The time-series of corrections generated by the system could be used to calculate alignment constants that greatly improved open-loop tracking accuracy. Some simple tests of components that would be needed for scale-up to a commercial-scale system have been tested and found to work well.

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REFERENCES