MACHINE VISION AS A METHOD FOR CHARACTERIZING SOLAR TRACKER PERFORMANCE

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ABSTRACT

This paper describes an approach to measuring the pointing error of solar trackers using a machine vision system. GreenMountain Engineering developed a device that employs this method with a custom embedded system and image processing software. The technical approach of this device (called the "Trac-Stat SL1") is presented here with the results of extended tests on a commercially available tracker. Our conclusion is that using this method of machine vision to characterize solar trackers is useful for tracker and tracker controller research, development, end-user qualification, and other applications where calibrated, accurate information about the performance of tracking systems is needed.

OVERVIEW

Accurate and verifiable sun tracking is a key challenge facing the solar and solar tracker industries, especially in the fields of concentrating photovoltaics (CPV) and concentrating solar power (CSP). The variations in sun elevation, wind loading, and other weather conditions over the course of a year and across different sites makes it difficult to predict the behavior of a tracking system without real-world test data. Even in the development stages of a tracker, control algorithm, system, or site installation, it is difficult to produce quantitative data demonstrating tracking performance.

Array output (power, current, and so on) is not sufficient information to determine tracking accuracy, as there are many conditions that can contribute to changes in overall system performance (including irradiance, ratio of direct to global irradiance, cell temperature, wind speed as it affects convective cooling, deflection across the array itself due to weight or wind loading).

In addition, the lack of existing standards for reporting tracker performance makes it difficult to evaluate and compare tracker manufacturer specifications, and understand how they will translate to real-world operating conditions.

Finally, different solar technologies (HCPV, LCPV, CSP, and dual- and single-axis tracked flat-plate crystalline silicon) each have particular relationships between generated power and tracking error in each axis, leading to different tracking requirements for each technology.

These challenges call for a method for accurately characterizing both absolute and relative tracking accuracy, in the field, under a variety of weather conditions.

In this paper, we present a solution to this problem in the form of the "Trac-Stat SL1", a diagnostic instrument for characterizing solar tracker performance. The Trac-Stat uses principles of machine vision combined with a precise calibration procedure to measure and log high accuracy absolute and relative data on sun position, under a variety of weather conditions. When mounted on a solar tracker it provides both high-resolution and wide field-of-view azimuth and elevation pointing error data. This data is useful for tracker design, algorithm development, and in-field system qualification and monitoring.

Fig. 1. Two Trac-Stat SL1's being tested in parallel.

TECHNICAL APPROACH

We chose a machine vision approach to the problem of locating the position of the sun relative to a tracker's pointing axis because it provides the following advantages:

1. High resolution and accuracy. In general, machine vision algorithms provide the ability to locate objects of known characteristics to within tenths or hundredths of a pixel.
2. Relative insensitivity to noise, dirt on optical windows, and other degradation of image quality
3. Large data sets and robust digital algorithms not available to purely analog devices such as PSDs or quad photodiodes.
    (a) The system can be made insensitive to glare, reflections, cloud-induced distortion, and other effects that lead to a non-ideal sun image.
    (b) The sensor can determine the quality of its own measurements and reject low-quality images instead of reporting inaccurate data.
    (c) The use of machine vision on a large matrix of pixel values provides the ability to use circle-fitting and other algorithms to locate the actual center of a partially-obscured sun (obscured by clouds, shading, or other obstructions), rather than reporting an incorrect "weighted centroid of all bright locations" as a purely analog sensor would.

As a peripheral benefit, using an embedded microprocessor-based system for the machine vision provides an easy platform for integrating various other digital functionalities into the device such as internal datalogging, precision timekeeping, and serial communication.

Sensors

The SL1 utilizes two independent sensing systems: wide-angle and narrow-angle. The narrow-angle sensor is configured with a pinhole to provide high accuracy (+/-0.02 degrees) over a 5-degree field-of-view. For correctly functioning tracking systems, the sun will spend most of its time within this field of view, though we have observed a range of sources of error that will cause an otherwise accurate tracker to drift a few degrees off course. The wide-angle sensor is capable of locating the sun over a 60-degree field-of-view with +/-0.5-degree accuracy. The combination of the two sensors provides a blend of range and accuracy.

Several different types of filters reduce the intensity of incoming sunlight to prevent over-saturation of the imaging sensor, and gain control serves to ensure a consistent image over a range of intensity levels.

Image Processing

Rather than use a simple centroid-of-bright-pixels method for determining the center of the sun, the on-board microprocessor first identifies the largest region of connected pixels (referred to as a blob), discarding all outliers. Various parameters of this blob are examined and compared against expected values for the sun, allowing errors due to haze or cloud cover to be rejected. Additional processing is then performed to determine the center of the sun.

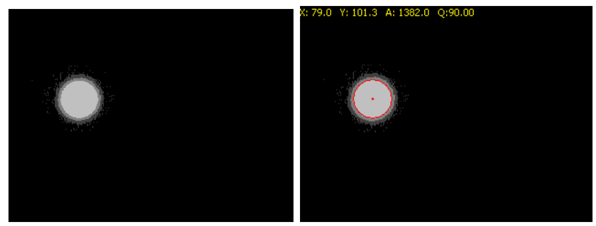

Fig. 2. Image of the sun acquired using pinhole setup, before and after circle-finding.

Fig. 3. Cloud distortion of sun image. *The red circle (center marked with a red dot) illustrates the error that would be associated with a simple centroid calculation of sun position. Simple analog PSD-based measurements would be likely to encounter similar errors.*

Calibration

The performance of the SL1 as a diagnostic instrument depends primarily on accurate and precise calibration. Adjustments (both mechanical and via software scaling and calibration constants) are made to each individual sensor to compensate for small variations in both the components and the assembly process. Both relative and absolute accuracy must be thoroughly tested and verified; estimates based on nominal sensor geometry would necessarily limit either the accuracy or the field of view of the instrument.

However, building a calibration device for an instrument designed to perform at irradiance levels of 1000 W/m^2 presents practical problems of both size and cost.

The SL1's design addresses this issue using adjustable filtration and high-sensitivity photodiode arrays. Each SL1 unit is individually calibrated on a large 3-axis stage using a light source that simulates the area of the sun at lower than one sun intensity, and which can be precisely positioned relative to the sensor to characterize the response.

Additionally, the accuracy of the SL1's calibration has been characterized over a range of temperatures - from below 0C to 70C - indicating a persistent calibration under extreme conditions.

For trackers where it is possible to mount the SL1 parallel to the optical axis of interest, the SL1 can immediately be used to characterize tracking error. An absolute accuracy of +/- 0.05 degrees relative to precision machined case datums allows the sensor to serve as a precise alignment tool, giving useful information about the alignment of structural reference surfaces to the sun's location.

For trackers where no suitably flat or parallel surface exists, the SL1 still provides +/- 0.02-degree relative accuracy, useful for a wide range of tests. To characterize absolute accuracy, the SL1 provides the functionality to perform an addition in-field calibration to compensate for mounting surface inaccuracies. This step effectively re-zeros the instrument based on a user-defined "tracker-on-sun" position, allowing the user more flexibility in mounting the SL1 to the tracking system. The re-zeroing process adds an offset to the in-house absolute calibration values while maintaining the +/- 0.02-degree relative accuracy of the SL1 across its field of view.

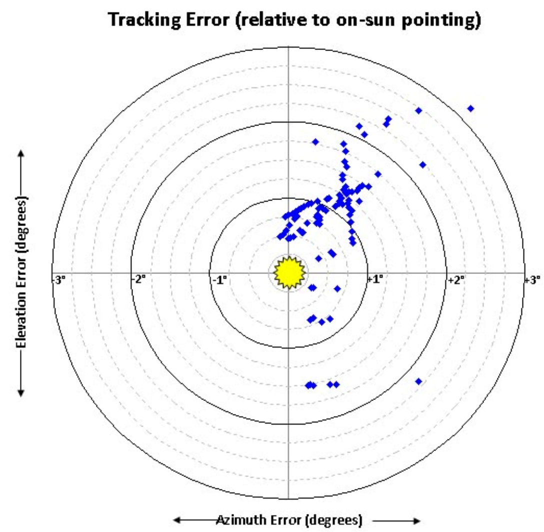

Fig. 4. Polar plot of tracking error.

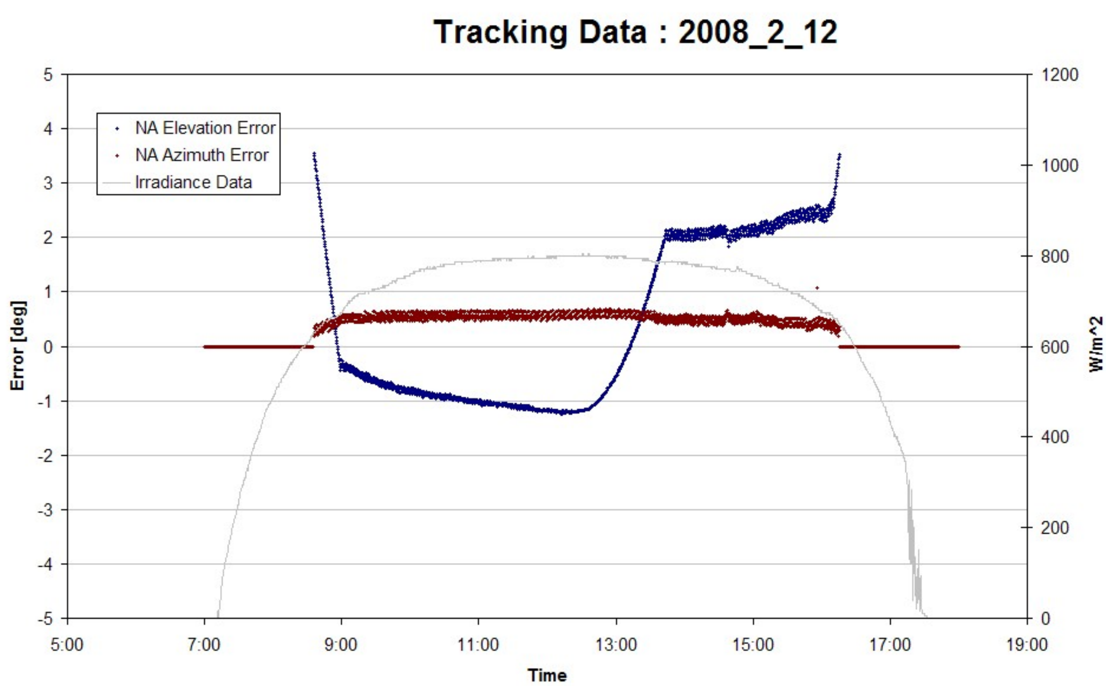

Fig. 5. Tracker performance as measured on a clear day.

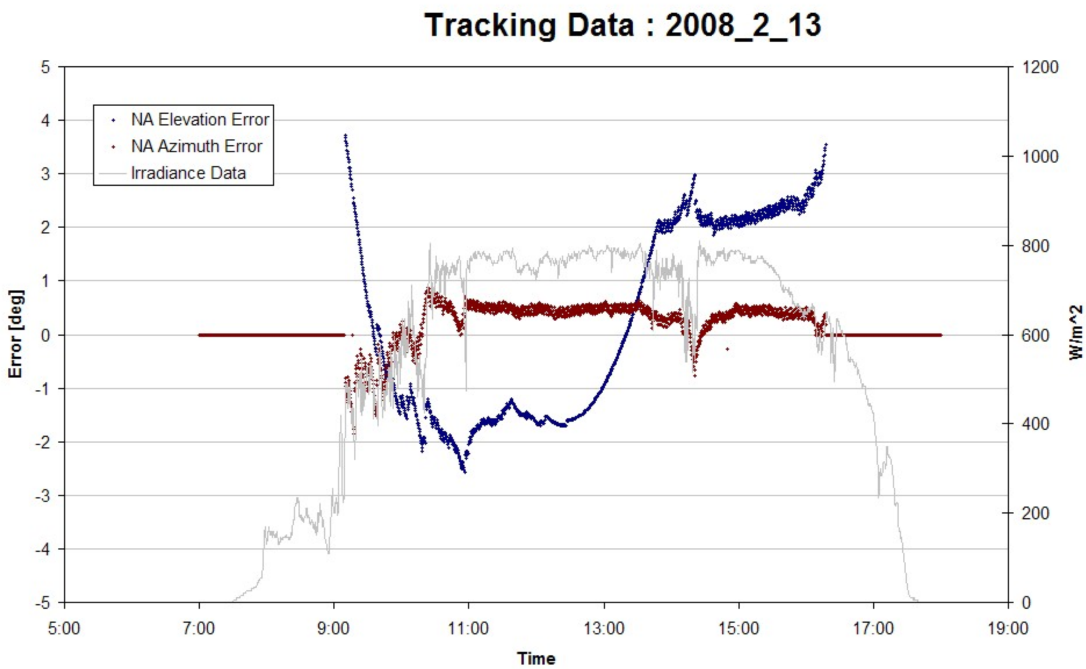

Fig. 6. Tracker performance as measured on a cloudy day.

OUTPUT DATA

The Trac-Stat SL1 has been running in the field on an off-the-shelf tracker since late 2007. Data from selected days during this testing period at a GreenMountain test site is shown above in Figures 4-6 in graphical form, which allows for quick qualitative assessments of tracker performance. Figure 4 shows the azimuth and elevation pointing error as measured at regular intervals, relative to perfect on-sun tracking, represented by the sun icon at the center of the plot.

Data collected under a range of irradiance and weather conditions shows that the SL1's performance is robust, even under less than ideal solar conditions.

Figure 5 shows the tracker's performance on a cloudless day. This data reveals information about the tracker being tested that could be applied to tracker improvements. In particular, the change in elevation tracking error between noon and 2 pm indicates tracker controller hysteresis as the sun passes through its apex.

However, as seen in Figure 6, on a partly cloudy day the tracker drifts off course during the morning hours, tracks more accurately (at least in azimuth) around noon, and drifts again after 2 pm. Note that in this case the SL1 is still able to locate the sun during periods where the tracker's built-in closed-loop sensor does not. Irradiance data captured using a separate pyranometer shows that this occurs between about 500 and 700 W/m2.

Repeatability

Figure 7 shows the performance of a tracker as measured by two SL1s running simultaneously on the same tracker over a period of several hours. Differences in absolute calibration have been subtracted out, and the close alignment of the results from each sensor indicates a repeatability within 0.01 degrees. The calibration process described earlier has also been used to characterize the sensor field of view and verify the rated accuracy.

CONCLUSIONS

Based on the functionality and robustness of the approach outlined above, the machine vision approach to tracker performance measurement employed by the SL1 can be successfully utilized in any of the following applications:

- Characterizing tracker, controller, and algorithm error under real-world conditions
- Calibrating and aligning trackers on initial setup
- Qualifying tracker performance in new installations
- Monitoring tracker accuracy over time
- Aligning outdoor test fixtures and DNI sensors to the sun
- Verifying tracker performance in preparation for IEC 62108 and similar testing

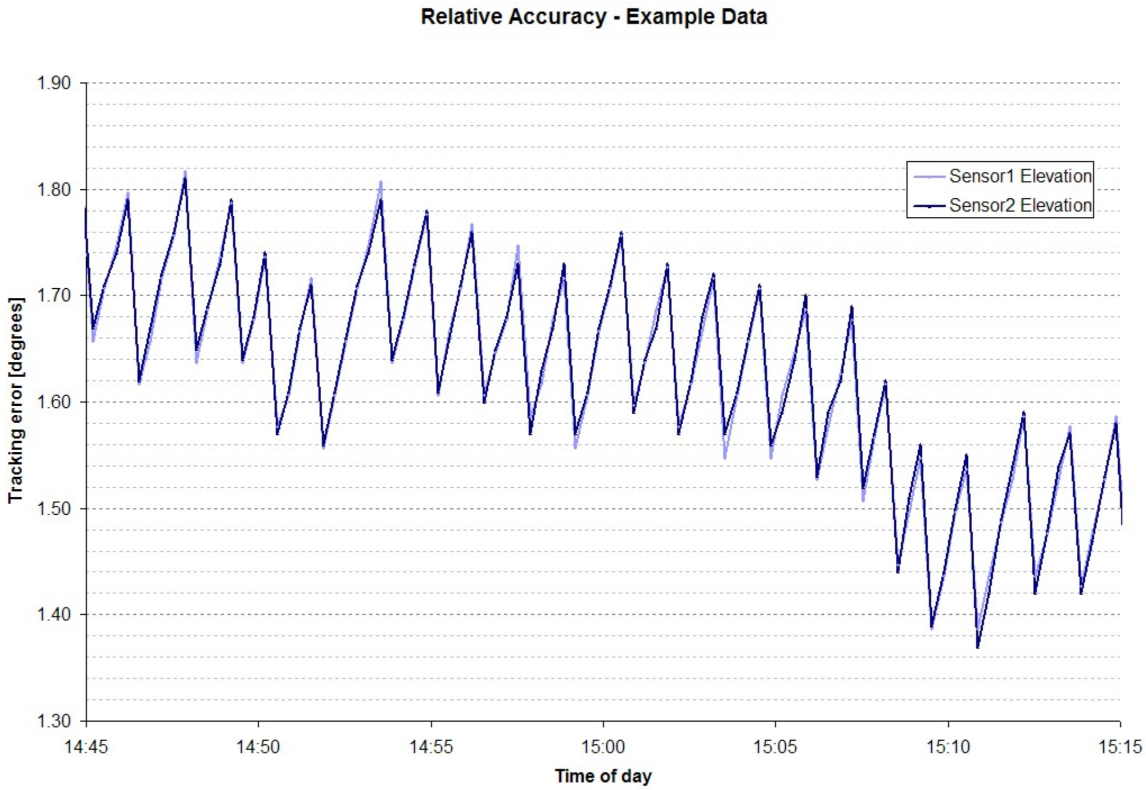

Fig. 7. Repeatability of two sensors

AREAS FOR FURTHER INVESTIGATION

Production-Optimized Low-Cost Version of the Technology

While we have been selling the Trac-Stat SL1 to various customers worldwide, we have also been exploring a production-oriented low-cost version of the SL1. In order to meet the cost required for mass deployment, a different set of design tradeoffs must be made (in both the design of the sensor itself, and in the implementation of the calibration procedure).

Potential Use as a Proxy For DNI

Testing data as shown in Figure 8 suggests a strong correlation between sun image area, as measured on the SL1, with independently-measured irradiance values. Further investigation is needed, but there is potential to calibrate the SL1 as a low-resolution DNI (direct normal irradiance) sensor in addition to a sun position sensor.

This functionality could be especially useful in an “SL2” low-cost production version of the SL1, to allow production trackers to integrate DNI information needed for auto-correcting tracker control algorithms.

Improved Algorithms

The implementation of an imaging-based machine vision platform provides many areas for improvement in gain control, filtration, sampling, and algorithms, to locate the sun with greater accuracy, over a wider range of weather conditions, and with a lower-resolution lower-cost imaging sensor.

Using selected portions of the visible or non-visible spectrums to improve performance under different weather conditions is also an area of exploration.

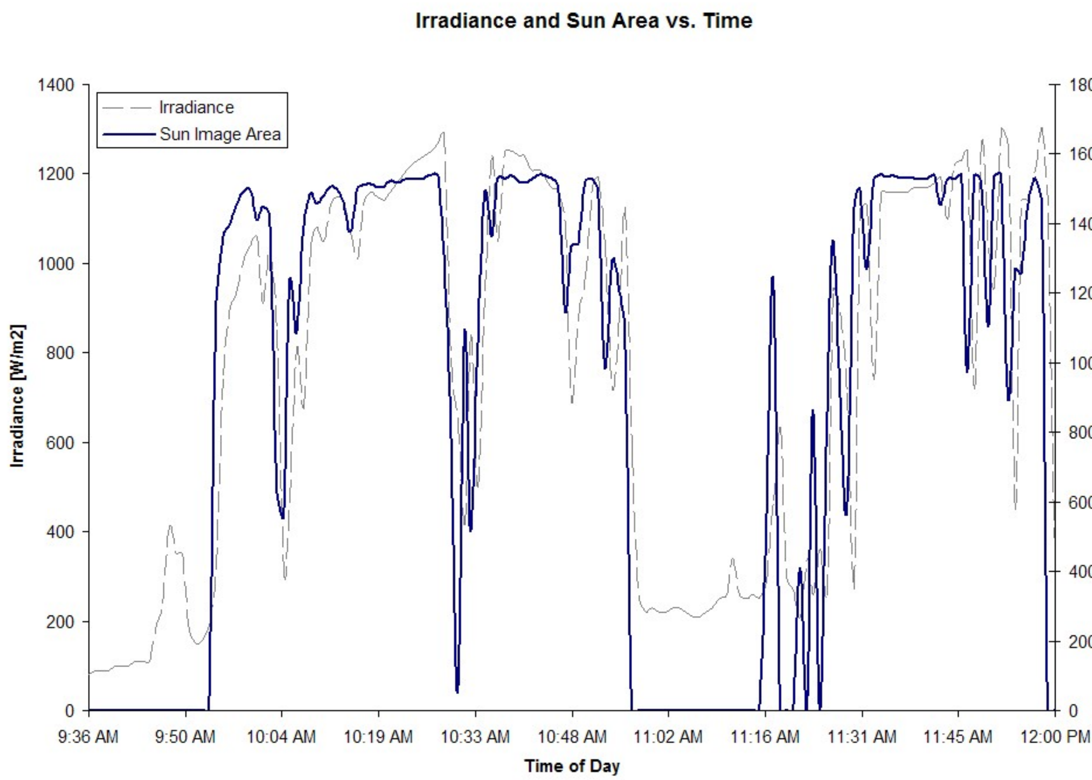

Fig. 8. Correlation of sun image size with independently measured global irradiance.