

RE<C: Heliostat Control and Targeting

- Overview
- Heliostat Field Control Strategy
- Individual Heliostat Control
 - Rough Alignment and Targeting
 - Near-Target Capture
 - Precise On-Target Position Control
- Experimental Results
- Disturbance Rejection
 - Imprecise Installation, Foundation Settling, and Thermal Drift
 - Wind
- Conclusions

Overview

Control systems for heliostat fields are designed to accurately direct sunlight at a specific target. They track the sun's movement across the sky while simultaneously correcting for wind, foundation shifting and thermal expansion. In addition, control systems monitor and adjust the amount of thermal power reaching the receiver. The receiver converting solar heat into power needs to operate in a specific temperature range — too little and the power conversion is inefficient, too much and expensive damage could occur. It is the job of the control system to operate the concentrating solar power (CSP) system at this most profitable point of power generation.

Many heliostat systems use open-loop tracking to accomplish these goals. They stay on target by following a preset course given their known positions in the field and the known course of the sun in the sky. This requires heliostats to be placed precisely on level, graded land on a firm foundation.

Google's mechanical design approach led to building lightweight, easily transported heliostat [frames](#) and [reflectors](#), which are installed quickly on non-graded land. This approach required that we develop a closed-loop control system that compensates for low-precision installation.

The precision closed-loop system we developed combines sensing (determining on-target reflected light spot positions) with control (moving the light spots around). We used an on-board 3-axis accelerometer on each heliostat for crude orientation control. Once the light spot was near the target, we shifted to a precise position control system that could independently position reflected light spots with an accuracy of approximately ten centimeters.

Heliostat Field Control Strategy

For any particular CSP system, the number of heliostats pointed at the receiver needs to be adjusted depending on the sun's position in the sky. For example, at noon in the middle of summer fewer heliostats need to be pointed at the receiver than late in the afternoon on a winter's day. A field management system decides which heliostats should be pointed at the receiver and which should be held in reserve.

In our prototype design, we assumed that a field strategy had already decided which heliostats should be on target. We thus focused on developing precision tracking for individual heliostats: aiming them at the target and allowing their solar energy distribution to illuminate the target in a prescribed manner to reduce stress and fatigue and provide optimum heat distribution in the receiver.¹

Individual Heliostat Control

The goal of our prototype system is to demonstrate simultaneous control of the light spots of multiple heliostats on a target. To accomplish this, we developed a closed-loop control system in three parts:

1. Rough orientation control of the heliostat using a reflector-mounted 3-axis accelerometer for alignment within few degrees of accuracy.
2. Capture of the heliostat's light spot by a precise, target-mounted light spot position sensor — in our case a multi-scopic photometry system.
3. Precise, on-target position control using a multi-scopic photometry system to position light spots with an accuracy of 10 centimeters — sufficient to allow some control over heat distribution across a specific target such as a heat exchanger in a receiver.

Rough Alignment and Targeting

Each heliostat utilizes a solid-state 3-axis accelerometer mounted to its reflector to determine its rough orientation. The accelerometer measures mirror orientation with a precision of a few degrees of accuracy, enough to handle the following situations:

- Stowing at night or against inclement weather.
- Transitioning to morning startup orientation.
- Stationing off-target around noon.
- Rough aiming at the target, to allow capture by the precise light spot position sensing system.

Our accelerometer data is made more useful using two unconventional features:

1. **Using pitch and roll articulation:** Rather than using conventional azimuth-elevation control, our heliostats use pitch (from flat to vertical) and roll (about the pitch axis) as the axes of articulation. This allows the accelerometer to resolve orientation in both axes of motion.
2. **Off-vertical angle offset:** The closer the articulated roll axis of the heliostat is to the vertical, the less accurately the 3-axis accelerometer can resolve roll. Mounting the mirror off-vertical from the articulation allows the mirror to be vertical while the roll axis is not — yielding adequate roll resolution throughout commonly used pitch orientations.

¹ For more information on the receiver used, see the [RE<C: Brayton Project Overview](#).

A command to move the heliostat can either be a desired mirror orientation, or a desired light orientation using a reflection equation. Once the command is sent, the heliostat controller repeats these steps:

1. Retrieving a desired reflector orientation.
2. Determining the approximate current reflector mirror orientation using accelerometer data.
3. Computing the reflector movement path in response to the difference between the desired reflector orientation and measured reflector orientation.
4. Mapping the reflector movement into desired actuator rates.
5. Transmitting the actuator rates to the cable actuators.

Near-Target Capture

When a heliostat's reflected light spot is pointed towards the target, control of the heliostat must transition from rough aiming using accelerometer data to precise, on-target position control. There are two important components of this transition: capture strategy and capture detection.

Capture strategy is lining up the heliostat angle with the target so the on-target position control can sense it and "capture" it. The heliostat accelerometer has an accuracy of a degree, while the on-target position control has a tighter resolution of 1/200 of a radian (about 0.25 degrees). Because of these differences, it's possible that the heliostat could think it's pointed directly at the target, while the target is unable to see it. In our testing, the accuracy of the accelerometer was sufficient most of the time. If it misses, the heliostat could move in a spiral pattern — tight, widening circles — until the light spot is captured.

Capture detection happens when the on-target positioning system detects the location of a light spot from a specific heliostat in its field of view. At this point, the heliostat's control system switches from relying solely on the accelerometer to relying on the on-target spot position sensing system, which has far higher precision and accuracy.

Precise On-Target Position Control

The goal of precise targeting is to position the reflected light spots within 10 centimeters of their optimal location on a target. This resolution — the equivalent of a milliradian or better as seen from the further heliostat reflectors at 100m away — is far beyond the accuracy and resolution of our reflector mounted accelerometer. Since our heliostats are relatively small, it made sense from a cost standpoint to build a central target light spot position sensing system.

We extended the light spot sensing algorithms described by [Kribus et al. in their 2004 paper](#) to provide on-target (x,y) location information for each light spot reflected off a heliostat, and to detect if a light spot was within the greater target area. We built a multi-scopic photometry system, using multiple cameras situated around the target to triangulate and direct incoming light. For each light spot on the target, the system reports an x,y coordinate on a target plane, and if the heliostat is in the system's range of detection.

The high-performance receivers that absorb the heat for CSP power conversion require careful temperature management. Precise distribution of solar flux reflected off the heliostats is required to optimize power generation. This is why we need to carefully measure and position

light spots on target.



The test target with mounted cameras. Although this target has 8 cameras, only 4 were used at a time.

A heliostat starts with a light spot already on or near the target. Given a strategy for determining where we want that light spot to be, our controller moves the heliostat, moving the spot directly to the desired location. The control loop in our precision light spot positioning program performs the following steps:

1. Determines the desired light spot position.
2. Uses the precision sensing system (cameras mounted on the target) to estimate the light spot's position.
3. Determines the heliostat's reflector orientation using its mounted accelerometer.
4. Using a control law, maps the difference between the light spot's actual position and its desired position on the target plane, into a desired spot speed and direction on the target, then maps that into a desired angular velocity for the heliostat, and finally translates that information into heliostat cable actuator speeds.
5. Communicates the desired actuator speeds to the actuators.

Experimental Results

The experimental setup consisted of a collection of heliostats and a vertical target surface surrounded by four cameras. The prototype used a 1m x 1m mirror and could accurately place a light spot 36 meters away (about the full length of the roof we were doing testing on). The shape of the reflection in the image below is in part due to the distortions of the mirror used.



Prototype Heliostat Keeping Light on Target

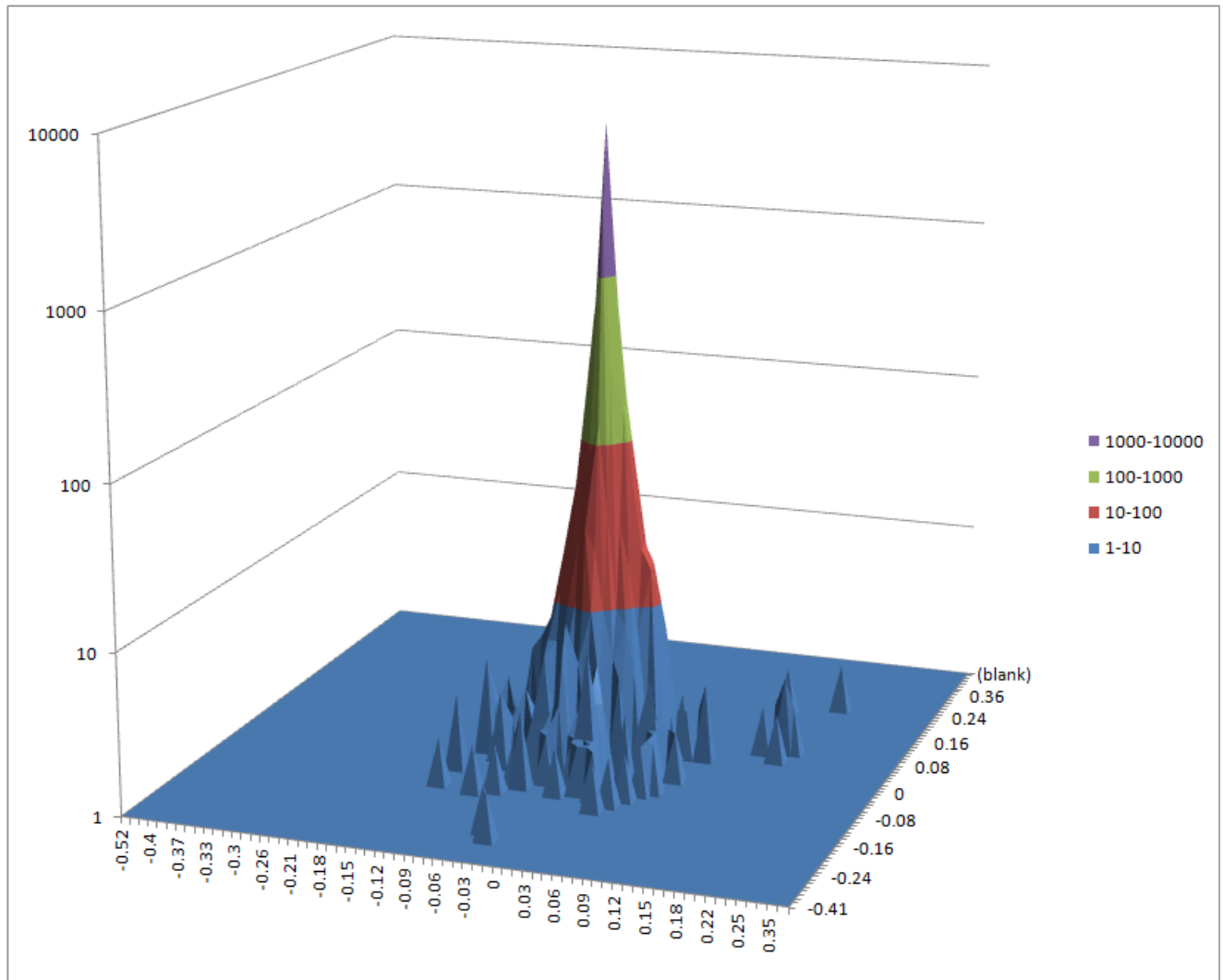
Our prototype heliostat oriented towards the sun in the morning and tracked the sun throughout the day. The following video shows control of a heliostat over a 12-hour period, replete with wind, clouds, sunrise and sunset.



[Video: Time Lapse of heliostat operation](#)

The control software we developed for the prototype was written in C++. Matlab code that uses a similar control algorithm was also developed for simulation. The Matlab code simulates the control of a field of heliostats, using simulated position error sensing and 3-axis accelerometer sensing. We've published the Matlab code as [open source code available for download](#).

To measure our accuracy, we plotted the location of the light spot placed by the tracking system for one heliostat under clear skies. From our plot, 96% of the observations falls within a 5 cm radius, 88% within 2 cm.²



Targeting System Accuracy

We added two more heliostats to the control system to prove that we could control several heliostats simultaneously. Video recordings show the light spots of three heliostats being simultaneously controlled in three separate but coordinated paths. Since the actuators are designed to only move the heliostat slowly: the video is sped-up in time by a factor of 5 so motion is obvious.

² The horizontal plane represents the target, and the Z-axis represents the number of times the positioning system reported the center of the reflection to be within a centimeter of the target.



[Video: Demonstrating single and multiple heliostat control](#)

Disturbance Rejection

Many factors can contribute to light spot inaccuracy. We thus developed procedures to address errors resulting from imprecise installation, foundation settling, thermal drift, and wind.

Imprecise Installation, Foundation Settling, and Thermal Drift

The cumulative error introduced by these factors can add up to several degrees of orientation error. All of these contribute to errors during rough pointing, and if significant enough, could make light spot capture for precise, on-target positioning difficult. These factors only introduced problems when we had grossly miscalculated the location of the heliostat relative to the target, or when it was misoriented by more than a few degrees. A one-time calibration after installation addressed these issues, and this calibration process could be fully automated in a production setting.

During precise on-target positioning, these sources of error do not affect the positioning of the heliostat due to the closed-loop nature of the control system. We tested this by tilting and moving heliostats as they were actively tracking. The precise pointing control system automatically compensated for these disturbances and realigned the light spot with the target.

Wind

Wind is a slightly trickier technical challenge. Wind can move and shake the reflector, causing the light to go off-target. The reflector element is stiff enough to not deform significantly in the wind. However, our choice to go with a lighter-weight heliostat frame led to the heliostat's structure and actuator flexing in response to large wind loads.

When examined in the frequency domain, orientation changes of the reflector due to wind can be classified into three frequency bands, each with its own characteristics:

Frequency Band	Example	Compensation
Low-frequency: (less than 1 cycle/minute)	Steady wind from a fixed direction.	Feedback control system compensates directly for steady wind-induced spot position error.
Mid-frequency: (1/10 to 10 cycles/second)	Wind gusts, shifts in wind direction., and vortex shedding	Reflector motion could be dampened using passive viscous damping devices such as dashpots .
High-frequency: (more than 10 cycles/second)	Turbulence and wind mixing.	The mass and inertia of the heliostat reflector dampens wind induced oscillation increasingly effectively with higher frequency.

Using a control system running at 1 sample per second, we addressed the ultra-low and low-frequency wind disturbances. A discussion of the mid-frequency and high-frequency wind effects is covered in the heliostat wind mitigation document.

Conclusions

By adopting a closed-loop control system that combined rough orientation sensing using 3-axis accelerometers with precision camera-based light spot position sensing technology, we were able to create a controller that achieved the following design goals:

- Orienting the mirror in the morning to be ready for sun-up.
- Roughly placing the light spot close enough to the target to be “captured” by the precision control system.
- Keeping the light spot positioned precisely throughout the day.
- Keeping a light spot positioned precisely when (manually) tilting the frame of the heliostat by several degrees.
- Independently positioning the light spots from three heliostats simultaneously on target.
- Redressing some of the potential errors from imprecise installation, foundation settling, thermal drift and wind disturbance.

We continue to believe that the cost savings of moving away from strong structural members and precision heliostat installation significantly outweighs the cost of the sensors and control system software, since computation continues to become cheaper every year, unlike raw materials.