Implementation of Solar Tracking Onboard a High-Altitude Balloon Platform

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The HELIOS program is a series of four solar tracking missions with the goal to demonstrate the feasibility of solar tracking on a high altitude balloon platform while maintaining a low mission cost. For this purpose, a tracking system was developed that could be accurate, simple, and cost efficient. This paper documents the tracking system utilized by HELIOS III and IV both physically and algorithmically, with a brief discussion of the performance of the HELIOS III tracking system during the most recent HASP flight.

The marginal mission success experienced by HELIOS III and the early success of the refinements implemented by HELIOS IV strongly suggest that solar observation on a high altitude balloon is feasible. A successful HELIOS IV flight will confirm this and will open up options for high quality solar science to be performed with a low mission cost.

I. Introduction

A. Mission Premise

Currently, solar observations are solely conducted from either ground stations or from orbiting satellites. Observations made from the ground are subjected to extensive atmospheric interference, limiting the quality of any images taken of the sun. Conducting solar observations from satellites such as NASA’s Solar and Heliospheric Observatory (SOHO) produces very high quality images but at a very high cost.

The HELIOS program aims to prove the viability of solar observation on a high altitude balloon platform. High altitude balloon platforms ascend above 99.5% of the Earth’s atmosphere, successfully mitigating any negative atmospheric interference at a fraction of the cost of actually placing the payload into orbit.

HELIOS payloads consist of a static base housing and a dynamic upper housing that contains the cameras and moves along elevation and azimuth in an attempt to track the sun. The HELIOS program began in 2012 with HELIOS I, which used a passive tracking system that consisted of simply rotating the payload and capturing images at a set time interval and succeeded in capturing a single image of the sun. In 2013, HELIOS II used an active tracking system that used photodiodes to determine the location of the sun to orient the payload, but due to reflections of sunlight off of the balloon, they captured only a single partial image of the sun. HELIOS III improved HELIOS II’s design by mitigating the reflections with baffles and flew in 2014, capturing over 75 partial images of the sun.

HELIOS III faced several technical issues before flight and as a result was unable to achieve rotation on the elevation axis, thus severely limiting its tracking time. However, the majority of the images taken during the tracking window contained the sun. Because of a bias in the photodiode readings, the sun was located in the left side of each of the images and was partially cut off.

HELIOS IV plans to launch in September of 2015. The team is currently in the process of improving the HELIOS III design by allowing for movement on the elevation axis as well as the azimuth axis and implementing a real-time photodiode calibration algorithm that will compensate for any bias in the photodiodes.

HELIOS IV has also decided to switch its emphasis from the science mission (capturing hydrogen-alpha images of the sun) to the engineering mission (proving the viability of solar tracking on a high altitude balloon platform). As a result, HELIOS IV will be the first HELIOS payload to fly two cameras with relatively large field of views. This will allow HELIOS to better characterize its tracking performance even in the case that it functions poorly, proving more data that can be used to further improve future HELIOS missions.
B. The HASP Platform

The High Altitude Student Platform is a high altitude balloon vehicle supported by the Louisiana Space Consortium and NASA’s Balloon Program Office. It is launched out of Fort Sumner, New Mexico some time during August and September and achieves float at 36km for up to 20 hours.

HASP can support four large (>20 kg) and eight small (>3 kg) payloads, providing power, serial telemetry, discrete commands and analog output via a standard interface. All of the iterations of HELIOS were large payloads, to which the HASP platform supplied 30 V with a maximum current of 2.5 A and a serial downlink bus running at 4800 baud. A large payload is also required to be less than 38 cm x 30 cm wide and 30 cm tall.

1. The Operating Environment

The environment at float is typical of near-space environments. There is little atmosphere, having a density of 0.007 kg/m$^3$, about 0.57% of the atmosphere at sea level. The lack of atmosphere and constant sunlight makes thermal management for the system quite difficult, as there is negligible atmosphere for convection cooling and a constant source of heat being entering the system. This means the system must be able to handle temperatures ranging from $-40^\circ C$ to $70^\circ C$. Beyond thermal challenges, the environment overall is very ideal for solar tracking missions. The reduced atmosphere increases the luminance of the sun and decreases atmospheric interference compared to observation at sea level.

II. Concept of Operations

HELIOS uses two orthogonal photodiodes to determine the location of the sun relative to the payload and then uses that information to orient the payload toward the sun. Sunlight strikes the diodes at an angle that depends on the location of the sun relative to the payload.

Since the diodes are orthogonal to each other, the angle at which the sun strikes them will be different and thus the light intensity read by each diode will be different. For example, if the sunlight hits one diode at 80° it must hit the other at 10°, and the first diode will read a greater light intensity than the second. The only time at which the diodes read equal occurs when the sunlight strikes each diode at 45°.

The photodiode housings are oriented such that the upper housing is aimed at the sun when the sunlight strikes each diode at 45°. The motors are instructed to move the payload until the orthogonal photodiodes read equal. This simple control logic allows for quick response to changes, but can be imprecise in certain circumstances. Fortunately, the simplicity of the method allows for highly sophisticated control algorithms to be applied with ease.

A functional block diagram of the basic system can be seen in Figure 1.

![Functional Block Diagram of Fundamental ADCS Components](image-url)
III. Physical Implementation

A. Structure

HELIOS is composed of a static base housing and a dynamic upper housing joined by an intermediate structure. The base housing is attached to the platform and contains the azimuth motor, gear, and the primary power board. The upper housing contains two cameras and is able to rotate in elevation and azimuth.

The medium field of view camera has a field of view of 23° by 17°. Images from this camera are used to calibrate the photodiode readings during flight. The second camera is a wide field of view camera with a field of view of 122° by 94°, which is used to characterize the tracking system post-flight.

The two photodiode housings are attached to the side and the bottom of the upper housing, and the elevation motor and gear are attached to the arms of the intermediate structure. Figure 2 illustrates the full HELIOS IV structure.

![Figure 2: HELIOS IV Structure](image)

B. Photodiode Arrays

HELIOS uses photodiodes to determine the location of the sun relative to the payload. The diodes are located inside two photodiode housings, which are 3D printed hollow rectangular blocks with a small opening in the front through which sunlight enters. Each housing contains two primary diodes and two backups. The diodes are set perpendicular to each other inside the housings. In order to prevent any reflections from the balloon or platform interfering with the diode readings, the openings in the front of the housings are small enough to only allow a limited amount of sunlight to reach the diodes, limiting the diodes’ field of view to approximately 30°. This is shown in Figure 3a. Neutral density filters are placed in front of the openings to prevent the diodes from becoming over-saturated, and razor blades are placed at the top and bottom of the openings to prevent reflections from the baffles from interfering with the diode readings.

One diode housing is located on the side of the upper housing and is used to determine the sun’s elevation relative to the payload. The second housing is located on the underside of the upper housing and is used to determine the sun’s azimuth relative to the payload.

1. Electrical Design

The photodiode arrays consist of a 12-bit analog-to-digital converter (ADC) connected to four reverse-biased photodiodes. Reverse-biasing the photodiodes involves connecting the cathode to a voltage source and the anode to ground via a pull-down resistor. This configuration allows for the voltage measured between the diode and the pull-down resistor to be 0 when no light is hitting the diode and equal to the source when the diode is saturated. A basic electrical schematic of this configuration can be seen in Figure 3b on the next page. Reverse biasing the diodes allows the voltage across the diodes to be amplified such that the ADC
Photodiode Housing

(a) Photodiode Housing

(b) Basic Electrical Diagram of Photodiode arrays

Figure 3: Photodiodes

can read the voltage. Otherwise, the voltage would be too low for the ADC to detect, since photodiodes typically output readings on the millivolt scale.

The ADC then measures the voltage differential between the diode on each side of the housing, converts it to a 12-bit integer, and transfers the information to the microprocessor using I²C. The 12-bit unsigned integer is zero when the diodes read equal and increases as the difference in voltage between the two diodes increases.

C. Motors

HELIOS uses two stepper motors to orient the upper housing toward the sun. The first motor controls the movement in azimuth and lies horizontally inside the base housing. It is attached to the intermediate structure, and through it the camera housing, with a 4:1 gear ratio. By increasing the gear ratio and thus decreasing the step size, the payload is able to turn in azimuth with four times the precision and increases the torque output by the motors.

The second motor controls the movement in elevation and stands vertically attached to the arm of the intermediate structure. It is attached to the camera housing through a 1:1 gear ratio. A higher gear ratio would allow for greater precision but would decrease the effective torque. Since movement on elevation must counteract the effect of gravity, the full torque is necessary.

The motor drivers are able to decrease the size of each step that the motor takes by implementing microstepping. By driving the three step select pins on the drivers high or low, the motors can achieve steps that are 1/2, 1/4, 1/8, and 1/16 the size of the original steps. A smaller steps size allows for greater precision, but reduces the speed and strength of the motor. Table 1 on the following page shows the step size, angle, and rotation speed for all of the microstep settings.

1. Electrical Design

The motors are commanded via motor driver by the microcontroller and powered via motor driver by the power board. Four wires run from each motor to the primary power board, through which they are connected to the drivers. The board supplies power to both the motors and the drivers and connects the drivers to the microcontroller. By driving the step and direction pins on the driver high and low, the microcontroller instructs the motors to take steps in a specified direction.
Table 1: Step size, angle, and speed for each axis of rotation

(a) Elevation

<table>
<thead>
<tr>
<th>Step Size</th>
<th>Step Angle (°)</th>
<th>Rotation Speed (°/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.8</td>
<td>750</td>
</tr>
<tr>
<td>1/2</td>
<td>0.9</td>
<td>375</td>
</tr>
<tr>
<td>1/4</td>
<td>0.45</td>
<td>187.5</td>
</tr>
<tr>
<td>1/8</td>
<td>0.225</td>
<td>93.75</td>
</tr>
<tr>
<td>1/16</td>
<td>0.1125</td>
<td>46.875</td>
</tr>
</tbody>
</table>

(b) Azimuth

<table>
<thead>
<tr>
<th>Step Size</th>
<th>Step Angle (°)</th>
<th>Rotation Speed (°/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>187.5</td>
</tr>
<tr>
<td>1/2</td>
<td>0.225</td>
<td>98.75</td>
</tr>
<tr>
<td>1/4</td>
<td>0.1125</td>
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<tr>
<td>1/8</td>
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<tr>
<td>1/16</td>
<td>0.028125</td>
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</tr>
</tbody>
</table>

IV. Algorithmic Implementation

A. Photodiode Calibration

A problem noted during HELIOS II was a constantly shifting voltage bias in the photodiodes. To combat this, a real-time photodiode calibration system has been developed utilizing image analysis to dynamically generate a photodiode calibration during flight. This system was being actively developed during the HELIOS III project but was not completed before launch. The system is now complete and undergoing testing for HELIOS IV.

To calibrate the diodes, images from a medium field of view camera (23° by 17°) are analyzed during flight, and the center of the sun is found. Then, the angular distance of the sun from the center of the image is computed for both axes using the angular pixel size of the image. This angle is then associated with the voltage difference read by the corresponding photodiode array at that time. Using a collection of these points, a best fit line can be constructed that takes the following form:

$$\Theta = mV + b$$

where $V$ is the voltage difference measured by the photodiode array, $m$ is a conversion factor between voltage and angle, $b$ is a calibration factor that represents the inherent voltage bias in the diodes, and $\Theta$ is the angle to be rotated. A graphical representation of the data acquired and best fit line can be seen in Figure 4 on the next page.

This function is then actively updated throughout flight and used by the ADCS algorithm to convert photodiode array readings to rotation angles. Since this model is dynamically generated throughout flight, the tracking system can react to changes in the electrical properties of the photodiodes and consistent sources of stray light.

B. Motor Control

After photodiode readings have been calibrated and converted into an angle to rotate, they will be translated into the number of steps to turn the camera housing in a given direction. Based off of the number of required steps, the step size is set according to the data found in Table 1, such that the largest step is taken that does not overshoot the goal.

Another consideration that is made during motor control is wires connecting the camera housing to the base structure. The motor control algorithm has an implemented safe guard from applying too much torsion to those wires and thus causing damage to the electrical components in the payload. A step count is implemented to determine how far from a code specified 0° the camera housing is rotated. When the camera housing has taken the net equivalent of 360° in steps in one direction, the housing will automatically rotate back to 0° in the opposite direction.

C. Special Circumstances

Due to the varying environment the balloon platform experiences during flight, the tracking system must be robust enough to recover from unexpected events. These include shadows or reflections from other objects
1. Shadows and Stray Light

Shadows or reflections cast on the diodes will produce sharp jumps or dips in the diode data. To compensate, the baffles on the diode housings reduce the diodes’ sensitivity to shadows by limiting the diodes’ field of view. The diode readings are then filtered through a moving average that ensures no single outlier reading will cause the payload to act erratically. Finally, since the platform is rotating constantly, the payload should pass out of the shadow relatively quickly, at which point it will continue tracking normally.

When the sun is at its highest point in the sky it will lie behind the balloon. During this time no direct sunlight should be able to enter the diode housings, so the diodes should read near equal and the motors will move very little. Once the sun begins to sink and the payload can once again see sunlight, it will continue its normal tracking.

2. Manual Intervention

The baffles on the diode housings prevent stray light sources from interfering with tracking, however, they severely limit the diodes’ field of view. As a result, if the payload is pointed more than 30° away from the sun, no sunlight will be able to enter the diode housings and give information about the payload’s location. To compensate, the ground team will be constantly observing the payload through the live stream camera that is mounted on the HASP platform. If the payload appears to not be tracking the sun, the ground team will send “nudge commands” to turn the payload on either elevation or azimuth a certain number of steps until the payload appears to have locked on to the sun and is tracking again.
V. Performance Analysis

The motivation for a fourth iteration of the HELIOS program comes from the near success of the tracking system in HELIOS III. HELIOS III succeeded in locking onto and tracking the sun with enough accuracy to obtain over 75 partial images of the sun. Figure 5 illustrates a time lapse of images taken during the HELIOS III flight and shows that the tracking system was slightly biased such that the sun lies too far left in the images. Furthermore, HELIOS III’s tracking window was severely limited due to the fact that it only had movement along a single axis.

![Figure 5: Time Lapse of Images](image)

A solution was sought to compensate for the bias and increase the accuracy of the tracking system. The idea of aiding the tracking system with image analysis originated from HELIOS II and has been in consideration since, but was never implemented. HELIOS IV has implemented this procedure and is currently preparing to test it. Furthermore, HELIOS IV has focused extensively on finding better motor drivers, adjusting the voltage to the motors, and meshing the gears better such that the payload is able to move on both axes.

In order to further ensure that the engineering aspect of this mission would succeed, the design of the payload was not focused on the science of the system but instead the tracking became the primary goal. To accomplish this the science camera was removed and replaced with a wide-angle camera. This complements the medium angle camera used for calibration and allows for better characterization of the tracking system.

VI. Conclusion

The HELIOS mission aims to prove the viability of solar tracking on a high altitude balloon platform. Tracking is achieved with photodiodes that determine the location and orientation of the payload relative to the sun and motors that turn the payload toward the sun. The diodes are calibrated automatically during flight through an image analysis algorithm. Cameras take images at regular time intervals to measure the accuracy and precision of the tracking system.

HELIOS IV is unique in that it focuses solely on its engineering mission by putting its emphasis on creating a reliable tracking system and not on capturing high quality images in different wavelengths. This is done with the hope that future iterations of the project will be able to add more sophisticated instruments to HELIOS IV’s robust and well-tested tacking system to conduct more scientifically-geared missions.

References


2 Louisiana State University; Department of Physics & Astronomy and NASA Balloon Program Office. Call for Payloads 2015. Oct 2014.