CMOS Star Tracker: Camera Calibration Procedures

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Lasted Updated as of: August 29th, 2016

Based on the thesis work of Andrew Lohmann (MSc), and Patrick Irvin (MSc), Master’s Thesis: “CMOS Imager for Nanosatellite Applications”
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Purpose

The calibration and characterization of a CMOS Star Tracker will be the focus of this report. Emphasis is placed on procedural steps, as well as background information, purpose, and principles of these calibrations. Utilizing calibration methods such as Hotel Pixel Determination, Flat-Field Illumination, and Checkerboard Patterning (the details of these tests are to be discussed later in this report), one is able to characterize the inherent noise (Fixed Pattern Noise, Dark Current, etc.) of the sensor, as well as identify aberrations and distortions that need to be removed to increase imaging quality (yielding greater attitude determination accuracy).

Star Tracker Background

A Star Tracker, also known as a Star Imager or Star Camera, is one of the most accurate attitude determination sensors for Low Earth Orbit (LEO) spacecraft. However, many nanosatellites (a class of satellite defined as being less than 10kg and greater than 1kg) have not used Star Trackers for attitude sensing due to the mass, power, and cost constraints imposed by a miniaturized satellite.

The accuracy of more commonly used sensors is insufficient for many scientific applications, thus the further development of high-accuracy Star Sensors to meet these stringent constraints represents the next step for nanosatellite functionality and scope.

Current research examines the development and characterization of a Star Tracker with emphasis on the use of low-cost electronics, known as Commercial-Off-The-Shelf (COTS) components. This is part of the on-going effort to develop a fully-integrated CMOS (Complementary Metal-Oxide Semiconductor) Star Imager coupled with a Field Programmable Gate Array (FPGA) serving as the processing unit, with software to process the centroiding algorithm for attitude determination.

Pre-Test Calibration Set-Up

Defined below are the materials and procedures required to perform camera calibrations. Note: detailed steps are presented to the reader, however, modified steps/processes may be required if using different hardware, software, setup, etc.
Calibration Requirements

Ensure your PC has the required hardware, software, and USB drivers to run the required programs and perform the tests outlined.

Required (and/or similar) Hardware:

- Altera DE1-SoC FPGA Board
- The Edmund Optics 8.5mm C Series Camera
- Aardvark I2C USB Adapter
- PC/laptop
- Thor Labs SLS201/M collimated light source with Neutral Density Filters for variable intensity.

Required Software tools & drivers:

- Matlab
  - Camera Calibration Toolbox
- PyCharm
- Aardvark I2C driver (not required if using Mac OS X. Driver Installation)

Calibration Set-up

Calibrations are to be performed in near-complete darkness (to simulate the space environment). The CRESS lab (room 425 in the Petrie Building) was used in these tests. A black cage was constructed to perform calibrations, as shown in figures 1 & 2. Set-up is demonstrated in figures below. Ensure the camera has a clear field of view to image the light source (will likely require mounting).

Figure 1: Black-out cage

Figure 2: Set-up inside cage
**Imaging Procedure**

To confirm the proper connection between the FPGA, Aardvark, and PC, run the PyCharm program. Re-run the program in circumstances where power is turned off, hardware/USB has been disconnected, or settings have been changed.

To take an image, a MATLAB script titled ‘fpgatest.m’ is used. Ensure the COM PORT connected to the I2C adapter matches that specified in the script. Run the program. BTN 1 on the FPGA board shall be pressed shortly after (approximately five seconds afterwards for most consistent results) to signal the camera to take an image. A delay of approximately 130 seconds is typical before the image is saved & displayed on the PC.

**Settings Adjustment**

After the image is taken, the camera settings and light source brightness must be changed (through the PyCharm program) one at a time to examine effects on the image (settings to change include analog gain, digital tiled gain, AEC, AGC, etc.). Instructions on settings adjustments are provided by the Camera Board specifications sheet. Imaging process is repeated after each individual change to settings, until optimal imaging settings are achieved (defined by picture clarity, image contrast, best capturing of light, etc.). Document all changes made, and record their effects on image quality.

**Shutter Closed Background**

This calibration is used to determine the Dark Noise & DSNU (Dark Signal Non-Uniformity) of the sensor. Dark Noise (also known as Dark Current) is the small amount of electric current that flows through photosensitive devices (such as this camera), even when no photons are entering the device [1]. DSNU is one of two parameters of Fixed-Pattern Noise (FPN). FPN describes the non-uniformity of pixel read-outs when imaging a uniform scene, and DSNU is the offset from the average across the image array with no external illumination (i.e. a “black” image) [2].

These noises can manifest as pixels that register values well above the average scene value; they are termed as “hot pixels”.

In the case of star imaging, hot pixels must be identified since the rest of the image will typically have a very low signal level, making it is easy for these pixels to be misidentified as stars by the computer algorithm, resulting in inaccurate attitude determination.
**Shutter Closed Procedure**

The camera shutter is fastened onto the lens, so that no light is able to leak into the photo. In this test, the dominant noise varies with exposure time. For a full characterization, images are taken at three exposure times: 0.0243s for 480 rows, 0.0486s for 960 rows, and 0.0729s for 1440 rows.

The equation to calculate exposure time for this camera is the following:

\[ t_{\text{int}} = N_{\text{rows}} \times t_{\text{row}} + t_{\text{overhead}} \]

- \( N_{\text{rows}} \) = number of rows being integrated across; this is the value set to change exposure time.
- \( t_{\text{row}} \) = time taken to integrate each row
- \( t_{\text{overhead}} \) = extra time required for the camera to process each image (a property inherent to the specific camera used).

Twenty images are to be taken at each exposure time. Twenty has been selected due to the convergence towards a single, consistent hot pixel value at this image sample size.

A hot pixel is considered to be any pixel which deviates from the average scene value by more than 5\( \sigma \) (five standard deviations from average scene value) in the majority of the test images.

The test is performed once with AEC (Automatic Exposure Control) and AGC (Automatic Gain Control) disabled, then repeated with them enabled. Results are shown in the table below, with automatic settings turned off.

<table>
<thead>
<tr>
<th>Exposure Time (rows)</th>
<th>480</th>
<th>960</th>
<th>1440</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Time (s)</td>
<td>0.0243</td>
<td>0.0486</td>
<td>0.0729</td>
</tr>
<tr>
<td>Number of Hot Pixels</td>
<td>24</td>
<td>149</td>
<td>318</td>
</tr>
<tr>
<td>Average Scene Value (0-1023)</td>
<td>64.5</td>
<td>65.3</td>
<td>66.3</td>
</tr>
</tbody>
</table>
Checkerboard Pattern Background

Camera aberrations can be removed by comparing a known spatial pattern (i.e. a checkerboard) to the distorted images taken of this pattern. A checkerboard pattern is used because of its straight edges and recognizable pattern.

Using the publicly available Matlab Camera Calibration Toolbox, 30 images are taken of the pattern from different angles and distances, with emphasis placed on angle-variation. Clear instructions and examples on how to use the Toolbox are provided on the website.

Thirty images allow sufficient orientations of the pattern to be captured, with several different variations of tilting (high, low, up, down, left, right, etc.).

This calibration is important because it allows us to characterize aberrations of the sensor, and it also produces the pixel error, distortion, and principal point of the camera. By characterizing, then removing distortion from images, we can achieve greater accuracy of star positions.

Checkerboard Pattern Procedure

The Camera Calibration Toolbox offers a default checkerboard pattern image, however, most standard checkerboard images (found online, for example) will suffice (as long as the dimension of each individual checkerboard square is recorded, as it is required during the calibration procedure).

Position the camera such that it has a clear view of the pattern. Both the camera and the pattern may require mounting, as shown in figure 4. The checkerboard pattern is placed at the current focal length of the camera to produce clear images. The positioning of the pattern relative to the camera will likely require trial and error testing.

The lighting in which the characterization is performed in may also have to be experimented with, depending on the light sensitivity of the camera (to prevent over/under saturation of images). An example of a clear image is depicted in figure 5, with a 3D visualization of the 30 orientations shown in figure 6.
After all images have been taken, the Camera Toolbox is used to perform the calibration, with distortions, pixel error, etc. being characterized. A complete distortion model (such as that in figure 7) depicts the distortion pattern of each individual camera pixel. It is recommended that the calibration be iterated several times (correcting for poor corner selection, re-imaging of low-quality pictures, etc.) to improve upon the calibration results.
Flat-Field Illumination Background

The Flat-Field Illumination test is used to determine the PRNU (Photo Response Non-Uniformity) of the sensor, the second parameter of Fixed-Pattern Noise. PRNU describes the ratio between optical power on a pixel versus the electrical signal output [2]. Images are taken of an illuminated white screen with a Lambertian reflectance. A Lambertian surface appears to have the same brightness when viewed from any angle, thus simulating a uniform (flat) field. When imaging this surface, FPN will result in a non-uniform readout of all pixels, as shown in figure 3.

By averaging pixel readout values across a large number of images, the temporal noise sources that cannot be completely eliminated through the technology used to construct the sensor is averaged out of the dataset.

Flat-Field Illumination Procedure

- The test is to be performed at room temperature, twice: once with Automatic Settings turned on, and once with the settings disabled. Twenty images are to be taken under each of these settings conditions.
- The setup of the test is to be similar to that shown below:
- On a clear, flat table, position the Lambertian Surface so that it is approximately perpendicular to the table, as shown on the right of the above image.
- A calibrated light source will be required for this test. The intensity of this light source is recommended to be between 40-70% of the sensor’s full scale so that pixel readout is still high, yet not so large as to oversaturate the image (all pixels readout maximum value) [3][4]. This shall require testing through trial and error.
- Position the light source approximately 1 meter away from the surface, directly facing it, and centred. Ensure that the entire surface is illuminated when the light is to be turned on.
- Place the camera so that it is pointing towards the surface at mid height but slightly off-center so that it is not blocking any of the light. This may require a mounting rod, as shown above. The distance between the surface and camera is approximately 1 ft.
- After all required test images are taken, the average value of each pixel across all the images is taken, as well the average value of all the pixels across all the images.
- The FPN correction is then calculated as follows: $FPN_{i,j} = P_{i,j} - P$, where $P_{i,j}$ is the average value of each pixel, and $P$ is the average value of all pixels.
References


http://info.adimec.com/blogposts/how-to-use-flat-field-correction-in-practice

http://ia.binghamton.edu/publication/FridrichPDF/full_paper_02.pdf