On-Ground Calibration and Optical Alignment for the Orion Optical Navigation Camera

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Abstract

The Orion Multi-Purpose Crew Vehicle on-board Navigation System will utilize the Optical Navigation measurements of the Moon and Earth during cis-lunar operations. Misalignment or an un-calibrated optical navigation camera may cause large measurement residuals in any on-board attitude determination and navigation system. Therefore, a novel estimation technique to calibrate the internal camera parameters, and a high accuracy optical alignment procedure to estimate the external camera alignment are introduced in this paper.

The intrinsic camera parameters such as the focal length, the principle point offsets, and the camera lens distortion parameters will be estimated and evaluated using images of star fields. This calibration estimation technique can be used either on-ground or in flight.

The proposed technique in this paper is using the discrepancy between imaged star vectors attained from the OpNav camera, and the matched star vectors from the star catalog to determine the changes in internal camera parameters. This gave rise to the two basic types of calibration the attitude dependent and attitude independent methods. The former utilizes the errors in imaged and cataloged vectors themselves, and the latter using the discrepancy in angles between pairs of vectors from the camera and catalog.

The alignment procedure is carried out using Theodolite autocollimator measurements taken off alignment cubes mounted on the Orion frame and also the measurements from the OpNav focal plane. It is assumed that the alignment cubes and OpNav camera are rigidly mounted to the frame so that flexing effects do not significantly alter the orientation of the cubes relative to the OpNav camera.

Introduction

The Orion Multi-Purpose Crew Vehicle (MPCV) is NASA’s next generation crewed vehicle that will take astronauts to exploration destinations beyond low Earth orbit. The Cis-Lunar Extended Kalman Filter is tasked with the estimation of the vehicle position, velocity and attitude during operations away from Earth proximity, typically when GPS measurements are not available.

The optical navigation (OpNav) camera measurement will be used mainly to navigate the vehicle position and velocity when the Moon/Earth is in the camera field of view (FOV). The optical navigation data from the OpNav in the form of Moon/Earth apparent centroids and distance are used to update the estimate of the vehicle state [1].

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The optical navigation camera mis-alignment or not well calibrated internal parameters may cause large measurement residuals in the on-board attitude determination and navigation system. Therefore, on-ground/on-orbit calibration of the camera parameters as well as the camera mis-alignment should be estimated with high precision using geometric calibration and lab test. By geometric calibration, we mean estimation of the calibration parameters that govern where a physical object in the 3D world will appear in a 2D digital image. The parameters estimated in a geometric camera calibration routine can generally be divided into two categories: the camera intrinsic parameters, and the lens distortion parameters.

The camera intrinsic parameters describe image formation under perfect perspective projection and capture the effect of things such as camera focal length, pixel size, and principal point location. The lens distortion parameters describe how optical system imperfections cause the apparent location of a point source to systematically deviate from its ideal location under perspective projection. The camera mis-alignment describes the orientation of the camera relative to some reference (in this case, the alignment of the OpNav camera frame relative to the star tracker frame).

The Orion OpNav camera will be calibrated and aligned to the vehicle optical frame on the ground prior to flight. A variety of factors, however, may cause the in-flight calibration parameters and the alignment matrix to vary from their pre-flight values. These factors include (but are not limited to) vibrations during launch, thermal cycling, and pressure changes. As a result, on-orbit estimation of the calibration parameters as well as mis-alignment states are important to ensure that end-to-end OpNav performance requirements are met.

Ground-based calibration for attitude sensors, including star trackers has been well documented, [2, 3], however ground calibrations cannot adequately simulate working conditions of on-board instruments. In addition, it requires the transmission of a large amount of data between satellites and ground stations. Therefore, the technical benefits of on-orbit calibration include more precise calibration, ability to track parameter variations due to thermal variations, less recorder and telemetry data, minimal interruption of science observations, greater autonomy, and less ground testing [4].

Attitude Dependent versus Attitude Independent Calibration

The relation between the cataloged and imaged star vectors to each other is important to investigate because this is the key to the calibration procedure. The sets of star vectors determined from the catalog or from the star sensor should be identical if they are represented in the image frame. Additionally, the angle between any pair of corresponding vectors remain constant regardless of the frame of reference. Either of these two pieces of information can be utilized to formulate a calibration algorithm. This gives rise to two distinct methods of on-ground/on-orbit calibration, the attitude dependent (ADC) and independent (AIC) approach [2].

• **Attitude Dependent Calibration**
  In the attitude dependent approach, the inertial vectors from the catalog can be rotated to the star sensor frame using the current estimate of the attitude matrix [5].
  On-orbit calibration of the OpNav camera will be performed using images of star fields. The use of star field images for on-orbit estimation of a camera’s geometric calibration parameters is well established. In fact, our precise knowledge of star line-of-sight directions often makes the quality of these on-orbit calibrations superior to the pre-flight ground calibrations.
  It has been established that if the measurements are ideal, these two sets of vectors should be identical, and any discrepancy in the vectors can be linked to inadequate knowledge of the camera parameters. The advantage of this approach is the smaller amount of computation required in the
estimation process. Each vector determined from the camera counts as one data-point, whereas if pairs of vectors are used, each set of \( m \) vectors mapped by the camera correspond to \( p \) combinations of pairs. Therefore, the attitude dependent approach provides the same information about camera parameters, with a smaller number of equations to solve. The obvious disadvantage in this approach is that the current attitude estimate itself will be erroneous with a poor estimate of camera parameters. Although this method is computationally efficient compared to attitude independent method, the coupled nature of the parameter estimate with the attitude solution renders this method inferior.

• **Attitude Independent Calibration**

Inter-star angles remain invariant to an orthogonal transformation between two frames. This fact is exploited in the attitude independent approach. In this method, the attitude estimate is not needed to estimate camera parameters. This is a major advantage over the attitude dependent approach. Regardless of its relatively lower computational efficiency, the attitude independent approach can provide more reliable and accurate estimates of camera parameters when compared to the attitude dependent method [2, 6].

The method makes use of residuals between measured inter star cosine angles and the inter-star cosine angles between the corresponding cataloged stars to learn the calibration corrections on-orbit, starting from ground-based calibration results. This approach makes use of the truth that inter-star angles are an invariant of rotational transformations, and therefore we do not require knowledge of the generally unknown spacecraft attitude.

**Pinhole Camera Model**

A typical camera consists of an optical system (usually an assembly of lenses) that collects and focuses light onto a planar CCD or CMOS detector array. The most commonly used model, which we will also use in the course, is the so called pinhole camera. The camera has the shape of a box, light from an object enters through a small hole (the pinhole) in the front and produces an image on the back camera detector array as shown in figure (1).
The measured star vector model is given by

\[
\hat{W}_i = \frac{1}{\sqrt{(x_i-x_o)^2+(y_i-y_o)^2+f^2}} \begin{bmatrix} -(x_i - x_o) \\ -(y_i - y_o) \end{bmatrix} \tag{1}
\]

Where, \( x_i \) and \( y_i \) are the centroids of star \( i \)
\( f \) is the camera focal length, \((x_o, y_o)\) are the bore-sight errors and the \( x_i, y_i \) are the centroids of the star \( i \).
So, \( f, xo \) and \( yo \) are the unknowns to be estimated using nonlinear least square optimal estimation. We note that the length unit of \((x, y, f, xo, yo)\) are arbitrary, any convenient choice (mm) or "pixels" can be used; the known focal plane size provide the scale factor needed. Of this scale factor is slightly in error, it will result in compensating converged offsets in \((f, xo, yo)\) and the remaining calibration parameters.
The corresponding inertial cataloged star vector could be calculated using:

\[
\hat{V}_i = \begin{bmatrix} \cos \alpha_i \cos \delta_i \\ \sin \alpha_i \cos \delta_i \\ \sin \delta_i \end{bmatrix} \tag{2}
\]

Where \( \alpha_i \) and \( \delta_i \) are the right ascension and declination for star \( i \) \((i = 1, \ldots, n)\) respectively.

The pinhole camera model describes a system that is not practically realizable. Real lenses suffer from both optical aberrations as well as manufacturing/assembly defects. The former leads to both radial and decentering distortion; the latter to just decentering distortion.
Radial distortion is the most critical of the five aberrations for precision OPNAV since it alters the apparent location of an object in the image. The perturbation of an object’s observed location away from the ideal pinhole camera model due to radial distortion. The decentering distortion is the non-symmetric distortion due to the misalignment of the lens elements when the camera is assembled. Therefore, the centroids of star calculated and used in Eq. (1) is considered to be the distorted centroid that needs to be adjusted using the lens distortion model.

Brown [7] combined the radial distortion model and the decentering distortion model to create a flexible framework for camera calibration. This approach, now commonly referred to as the Brown distortion model, has become ubiquitous in the computer vision, optics, and photogrammetry communities. Following this convention,
In this case we will consider three radial distortion terms \((k_1, k_2, \text{ and } k_3)\) and two decentering distortion terms \((p_1 \text{ and } p_2)\) — yielding a total of five coefficients to describe the lens distortion effects. Thus, the final model is as follows,

\[
\begin{bmatrix} x_i^u \\ y_i^u \end{bmatrix} = f \left( 1 + k_1 r_i^2 + k_2 r_i^4 + k_3 r_i^6 \right) \begin{bmatrix} x_i \\ y_i \end{bmatrix} + f \begin{bmatrix} 2p_1 x_i y_i + p_2 (r_i^2 + 2x_i^2) \\ p_1 (r_i^2 + 2y_i^2) + 2p_2 x_i y_i \end{bmatrix} \tag{3}
\]

Where \( x_i^u \) and \( y_i^u \) are the un-distorted centroids, and \( x_i, y_i \) values are the distorted centroids and \( r_i^2 \) is calculated from \( r_i^2 = (x_i^2 + y_i^2) \)
The un-distorted centroids are used to re-write Eq. (1) as follows

\[
\hat{W}_i^u = \frac{1}{\sqrt{(x_i^u-x_o)^2+(y_i^u-y_o)^2+f^2}} \begin{bmatrix} -(x_i^u - x_o) \\ -(y_i^u - y_o) \end{bmatrix} \tag{4}
\]
Calibration Procedure

The attitude independent approach will be used to solve for the camera parameters and the lens distortion. Therefore, we can use the fact that the inter-star angles for the perfectly imaged vectors and the cataloged vectors have to be the same, from figure (1) the relation between the undistorted imaged vectors and the cataloged vector could be mathematically written as;

$$\cos \theta_{ij} = \hat{V}_i^T \hat{V}_j = (\hat{W}_i^u)^T \hat{W}_j^u + \text{meas errors}$$ (5)

Now, using equation (2) and use the un-distorted centroids from equation (4) we can show that;

$$\hat{V}_i^T \hat{V}_j = \frac{N}{D_1 D_2} = g_{ij} (x_o, y_o, f, k_1, k_2, k_3, p_1, p_2)$$ (6)

Where;

$$\begin{align*}
N &= (x_i^u - x_o)(x_j^u - x_o) + (y_i^u - y_o)(y_j^u - y_o) + f^2 \\
D_1 &= \sqrt{(x_i^u - x_o)^2 + (y_i^u - y_o)^2 + f^2} \\
D_2 &= \sqrt{(x_j^u - x_o)^2 + (y_j^u - y_o)^2 + f^2}
\end{align*}$$ (7)

The calibration parameters state vector is;

$$\hat{X} = (x_o, y_o, f, k_1, k_2, k_3, p_1, p_2)$$ (8)

By using the linearization about the nominal value $\hat{X}$ we have

$$X = \hat{X} + \Delta X$$

Substitute equation (8) in (6) to get

$$\hat{V}_i^T \hat{V}_j = g_{ij} + \frac{\partial g_{ij}}{\partial \hat{X}} \Delta X$$ (9)

The derivation of the $\frac{\partial g_{ij}}{\partial \hat{X}}$ was derived for each calibration parameters analytically, the details of this derivation is not included in this paper for the sake of briefness.

By using the nonlinear least-squares estimation we can solve for the calibration parameters at every iteration ($\Delta X$) which minimize the residual of equation (9).

The Ground-Calibration Algorithm Results

In order to run the calibration program, the image processing algorithm is applied for each of the OpNav star Night Sky Images (NSI). The OpNav camera has a focal plane size of about 2592 x 2048 pixels and a focal length of about 35 mm. The field of view of the camera is about 16x20 deg. Accurately finding the locations of observed stars in an image is carried out using an image processing algorithm that starts with the dark frame removal. The dark frame describes random intensity bias for each pixel that occurs when no photons are striking the focal plane. Due to a variety of factors, the light from a single star (which is very nearly a point source) will spread out over multiple pixels, with a shape described by the Point Spread Function (PSF). For the Orion OpNav camera, the shape and size of the PSF is expected to be dominated by a small amount of intentional defocusing near the center of the field of view and off-axis lens aberrations near the outer regions of the field of view.
The method of calculating the center of intensity (COI), around each PSF of a star, is used for computing star centroids, including convolution, and model fitting via non-linear least squares. An example of a typical OpNav NSI is shown in figure (2) with its associated star coordinates \((x_i, y_i)\). The lost in space star identification is used to identify the stars and find the associated cataloged vector for each centroided star in order to have the inertial position vector of all the imaged stars for the initial image. The centroids of the observed objects (stars) are shown in the green circles and the identified stars are shown in the yellow stars in figure (2). It can be seen from figure (2) that the number of centroided objects (15) is greater than the number of identified stars (10). This is because either the centroided object is not a star or a star that is not included within the on-board star catalog [8].

![22hr37min58sec611ms1Cam725002246.tif](image)

Figure (2), a NSI with the centroids and Star IDs.

Figure (3) shows the results of the calibrated bore-sight position \((x_o, y_o)\) and the focal length \((f)\) versus the number of iterations for the NSI depicted in figure (3). It can be shown that the values of intrinsic camera parameters are converged after 2 or 3 iterations. Similarly, the calibrated values for the lens distortion coefficients are shown in figure (4). The computed residuals in this case are independent of the attitude errors because the inter-star angle approach does not rely on the estimated attitude. The main error source of this calibration technique arises from the error of the centroiding algorithm.
Figure (3), the Estimation of the Offsets and the Focal Length

Figure (4), the Estimation of the Lens Distortion Parameters.
The ground calibration test is executed using several hundred night sky images (about 800). The following table summarizes the results of the camera intrinsic parameters as well as the lens distortion. The principle point offsets are not stable across most of the images. The mean and standard deviation values of the calibration parameters are given in Table (1).

Although it is useful to calibrate all the intrinsic camera parameters, as well as the lens distortion parameters as shown above, the focal length and the $k_1$ lens distortion factors are the most important two parameters to utilize the end-to-end image processing for any star/moon image. These two parameters are consistent and remain stable across most of the test images. The other lens distortion parameters ($k_2$, $k_3$, $p_1$ and $p_2$) are considered higher order terms and the principle point offsets parameters are not fully observable through all the images.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>34.976 (mm)</td>
<td>0.094503</td>
</tr>
<tr>
<td>$x_0$</td>
<td>0.07925 (mm)</td>
<td>0.00062</td>
</tr>
<tr>
<td>$y_0$</td>
<td>0.03032 (mm)</td>
<td>9.0885e^{-05}</td>
</tr>
<tr>
<td>$k_1$</td>
<td>0.11439</td>
<td>0.0012914</td>
</tr>
<tr>
<td>$k_2$</td>
<td>-0.45091</td>
<td>0.00319</td>
</tr>
<tr>
<td>$k_3$</td>
<td>0.063278</td>
<td>0.001308</td>
</tr>
<tr>
<td>$p_1$</td>
<td>0.000885</td>
<td>0.00434</td>
</tr>
<tr>
<td>$p_2$</td>
<td>-0.000125</td>
<td>-0.0343</td>
</tr>
</tbody>
</table>

Table (1), the Calibration Results using Several NSI

Alignment Test/Procedure

The lab alignment test procedure for aligning the OpNav camera to the Orion optical base and star tracker (ST) have been achieved using the Theodolite (TH) measurements taken off alignment cubes mounted on both the Orion optical base and the Star tracker as shown in figure (5). The Orion optical base, along with its attached star tracker and OpNav camera, was mounted on the lab’s optical table for this set of alignment measurements.

It is assumed that the OpNav camera and star tracker are rigidly mounted to the Orion frame so that flexing effects do not significantly alter the orientation of the payloads relative to the star tracker during flight.

Figure (5), the OpNav and ST configuration.
The Orion optical base and the ST each have an alignment cube mounted on their local frames. Theodolite autocollimator measurements can be taken from two of each cube’s reflective surface to establish its orientation relative to a local vertical local horizontal (LVLH) reference frame. The direct orientation relationships between the various cubes can be derived from the included TH LVLH reference frame measurements. Three Theodolites are used to perform these, one is the reference TH and the LVLH frame is defined with respect to it. The other two THs are repositioned for each measurement and oriented around the test bench to face the alignment cubes and both OpNav, Star tracker focal planes. The measurement in terms of the vertical and horizontal angles of each TH is collected when facing the cube faces or the camera(s) FOV as shown in figure (6).

![Theodolites moving around test bench](image)

Figure (6), the Theodolites are moving around the test bench.

Some assumptions are made during the test procedure:

- An alignment cube (AC) frame is generically defined by the three pair of nearly orthogonal faces (planes) of a given cube.
- The OpNav and ST reference frames are defined such that the Z-axis of the camera is toward the focal axis. The X and Y axes are in the focal plane as shown in figure (5).
- Both OpNav and the ST are calibrated prior to the test and the calibration parameters are used to get the measured vectors from the centroiding.
- The undistorted images are used for image processing.
- The TH2 and TH3 angles are optional as long as they are within the FOV of the OpNav and Star tracker and the cross shape is full and centered (symmetric).
- The measured angles in the FOVs are used to calculate the inertial vectors similar to the one given in equation (2).

The final alignment rotation matrix (quaternion) that rotates a vector from the ST reference frame to the OpNav reference frame is achieved through sequences of rotations:

1- The rotation matrix that rotates the vector in AC frame to the OpNav frame
\[ T_{\text{OpNav}}^{AC} = T_{\text{LV}LH}^{AC} \ast T_{\text{OpNav}}^{LVLH} \]  

(10)

2- The rotation matrix that rotates the vector in AC frame to the ST frame

\[ T_{ST}^{AC} = T_{ST}^{LVLH} \ast T_{ST}^{AC} \]  

(11)

3- Finally the rotation matrix that rotates the vector in ST frame to the OpNav frame

\[ T_{\text{OpNav}}^{ST} = T_{AC}^{ST} \ast T_{\text{OpNav}}^{AC} \]  

(12)

The end-to-end alignment test is repeated with different ST/OpNav Centroiding measurements from both theodolites while they are in the bore-sight(s) FOV. The residuals between the estimated and measured centroids after each alignment test are calculated to find the best alignment setup and use that as the reference (final) rotation matrix.

A night sky test with the alignment setup/configuration shown in figure (5) was also accomplished to verify the alignment matrix obtained from the lab optical bench. The body to inertial attitude quaternion from both the ST and OpNav are acquired, in real time, and the calculated alignment matrix (quaternion) is verified to be within a few arc-sec from the lab results.

**Conclusion**

This paper presents how to solve for the estimation of the OpNav camera focal plane parameters and the lens distortion using the standard nonlinear least-squares estimation. Also, the alignment procedure for aligning the OpNav camera to the Orion optical base and star tracker have been summarized. Using attitude independent focal plane distortion, the computed residual is free of attitude errors. This is a major advantage for this method; however, numerical simulation has shown that numerical stability is highly dependent on the choice of basis function. This result is likely due to the fact that residual error components are coupled into the scalar residual, the cosine of the inter-star angle. The results are provided using real star field images to prove the proposed approach. It is also worth noting that if a single image contains 6 or more stars, then more residuals are available in the attitude independent approach due to the formation of star pair residuals. The alignment between the OpNav frame and both the Orion frame and the star tracker frame are carried out using theodolite autocollimator measurements taken off alignment cubes mounted on the Orion frame and also the measurements from the OpNav/ST focal planes.
References


