3D POINT LOCATIONS THROUGH THE USE OF NON-METRIC VIDEO CAMERAS AND PHOTOGRAMMETRIC BUNDLE ADJUSTMENT

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ABSTRACT

This paper describes the use of photogrammetric techniques to determine the three-dimensional locations of point-like features imaged by multiple, non-metric video cameras. An exterior orientation program was used to calculate the omega, phi, and kappa orientation angles, as well as the focal length, of a simple camera model used to approximate the actual optics and focal plane of each video camera. The solution to the three orientation angles and the camera constant were found by regressing ground control point information against the collinearity equations through an unweighted, least squares bundle adjustment. The three-dimensional position of each camera was known apriori. Therefore, the x,y,z locations of the exposure centers were kept fixed during the bundle adjustment. Once the exterior orientation and focal length of each camera were known, the three-dimensional location of any other point which was imaged by two cameras could be calculated through the technique of space intersection. This process was performed by using a digital stereoplotter program. Finally, the accuracy of these locations was assessed by using independent check points whose surveyed locations were known. The bundle adjustment residuals and the absolute location accuracies obtained using this process are reported. The 3D location accuracy was better than 10 feet.

INTRODUCTION

Space intersection is a well established technique for determining the three-dimensional (3D) coordinates of a feature imaged by two or more stereoscopic photos (Wolf and Dewitt, 2000, pp. 245-246). Of recent interest in the literature is the use of non-metric cameras to perform photogrammetric analysis (Knyaz and Vizilter, 2001; Carbonneau, Lane, and Bergeron, 2003). Also of continuing interest is the use of the self-calibration form of the collinearity equations to determine the interior orientation of various remote sensing sensors (Wolf and Dewitt, 2000, pp. 255-256; Habib and Morgan, 2003). This research investigated the application of the self-calibration and space intersection techniques to the task of determining 3D locations of features as imaged by commercial-off-the-shelf (COTS) video cameras. The objective was to determine the accuracy which could be obtained if a very simple camera model was used; one which ignored the interior calibration step, and was only loosely based on the actual camera design.

METHODOLOGY

The methodology used in conducting this research was as follows. First, the focal length and attitude of each video camera was determined by using the self-calibration form of the collinearity equations through use of an exterior orientation program. Next, the 3D location of several features was determined by using the space intersection technique through use of a digital stereoplotter program. Finally, the accuracy of these locations was determined by using their surveyed locations. Each of these steps is described in more detail in the sections below.
Study Site

The study site for this research was the PHERMEX hydrodynamics test facility located at the Los Alamos National Laboratory in Los Alamos, New Mexico. The facility consists of a firing site and two buildings containing high energy X-ray machines. The facility was used for high explosives hydrodynamics research, but is currently decommissioned. Video from a previous test was used in this study.

Surrounding the firing site were thirteen utility poles, arranged in a circular pattern (Figure 1). The radial distance of each pole from the firing site was approximately one hundred feet. Each utility pole had a crossbar near the top. The height of the crossbar was between 45 and 75 feet above ground level. The intersection of the crossbars with the vertical poles were the point-like features of interest in this study. Each pole was identified by a single number or letter designation. Five of these poles served as ground control points (GCPs) for determining the exterior orientation of each camera (poles "5", "8", "12", "13", and "C"). The remaining eight poles served as independent check points (ICPs) for determining the accuracy of the space intersection process (poles "1", "2", "3", "6", "7", "9", "10", and "11"). Even though there are more than thirteen poles surrounding the firing site, these particular poles were chosen because they were imaged by each of the video cameras used in this study.

![Figure 1](image-url) Location of the three video cameras, the firing site, and the utility poles. The coordinate system is New Mexico Central State Plane, NAD83. The camera "Phermex West" was not used in this study.

Three video cameras were used for this study. They were named "IJ", "Trailer", and "TA49" (Figure 1). The cameras were positioned several thousand feet away from the PHERMEX firing site. Each camera was pointed toward the firing site, the focus was set to infinity, and the zoom was set such that the field-of-view (FOV) encompassed all the utility poles. Video was recorded from each camera. The video data were post-processed with Adobe Premiere software (Adobe Systems Inc., 2005). A single frame from each video stream was exported as a 480 row by 720 column TIFF formatted image for further analysis (Figure 2).

Camera Model

Video cameras from three different distributors were used in this study; one from Rainbow, one from Sony, and one from Panasonic. The zoom range of these cameras could be varied from a few millimeters to tens of millimeters. The focal plane of these cameras consists of a two-dimensional CCD array containing non-square detectors, each of which are on the order of 5 to 10 microns in size.
Figure 2. Images (frame captures) from the "IJ" (a), "Trailer" (b), and "TA49" (c) video cameras. The utility poles are labeled.

A very simple camera model was used to approximate the actual camera design (Figure 3). The camera (image) coordinate system consisted of a triad of orthogonal camera axes. The focal plane was located perpendicular to the negative z-axis, at a distance equal to the focal length below the camera coordinate system origin (i.e. the focal point). The focal plane consisted of 480 rows by 720 columns of square detectors, each of which was 1.64E-05 feet (1.92E-4 inches, 5 microns) in size. The focal length was considered to be an unknown to be solved through self-
calibration during the exterior orientation process. The principal point was assumed to be located at the center of the focal plane. Radial and tangential lens distortion were ignored.

![Figure 3. The camera model and camera (image) coordinate system.]

**Exterior Orientation**

The exterior orientation of each video camera was determined by using the self-calibration form of the collinearity equations. This process was implemented as an Interactive Data Language (IDL) code (Research Systems Inc., 2005). The GUI for this process is illustrated in Figure 4. The position of each video camera (i.e. the location of the focal point) was known *apriori* from a differential GPS survey. The focal length and attitude of each camera were considered unknowns. The object coordinate system used in this study was the New Mexico Central State Plane coordinate system with NAD83 as the datum and U.S. Survey Feet as the linear distance unit. Heights were referenced above the WGS84 datum.

The objective of the exterior orientation process was to determine the focal length of the camera model and the orientation of the camera coordinate system relative to the object coordinate system. The location of each of the five GCP poles were manually defined within the image from each camera. This process was performed for each of the camera models associated with the three video cameras. The exterior orientation parameter solutions, and the standard deviations of each adjusted quantity for each of the three video cameras, are listed in Table 1. The positions of each camera were held fixed (i.e. assumed known) during the bundle adjustment, so these values are not listed in Table 1. The attitude angles are body-three x-y-z rotation angles (Wolf and Dewitt, 2000, pp. 551-553).

The bundle adjustment residuals, projected onto the focal plane of each camera model, are listed in Table 2. The nominal ground sample distance (GSD) for each camera was calculated by projecting (ray-casting) the four corners of a detector near the center of the focal plane out to a vertical plane located at the firing site and aligned perpendicular to the camera's z-axis (Table 3). Note that the projected detector sizes are not a function of the distance of the camera to the firing site because the zoom setting was different for each camera. In general, the farther away a camera was from the firing site the higher the zoom setting and the smaller the GSD value.
Figure 4. The exterior orientation interface.
Table 1. Exterior orientation parameters of each video camera.

<table>
<thead>
<tr>
<th>Camera Name</th>
<th>Focal Length [ft]</th>
<th>Omega [deg]</th>
<th>Phi [deg]</th>
<th>Kappa [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJ</td>
<td>0.0182 ± 0.0001</td>
<td>84.88 ± 0.07</td>
<td>148.52 ± 0.06</td>
<td>5.8 ± 0.4</td>
</tr>
<tr>
<td>Trailer</td>
<td>0.0653 ± 0.0006</td>
<td>89.47 ± 0.03</td>
<td>204.97 ± 0.03</td>
<td>2.2 ± 0.5</td>
</tr>
<tr>
<td>TA49</td>
<td>0.0409 ± 0.0003</td>
<td>93.92 ± 0.04</td>
<td>345.78 ± 0.04</td>
<td>1.0 ± 0.4</td>
</tr>
</tbody>
</table>

Table 2. The bundle adjustment residuals as projected onto the focal plane of each camera model.

<table>
<thead>
<tr>
<th>Camera Name</th>
<th>Camera x-axis RMSE [pixels]</th>
<th>Camera y-axis RMSE [pixels]</th>
<th>Total RMSE [pixels]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJ</td>
<td>1.2</td>
<td>2.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Trailer</td>
<td>1.9</td>
<td>4.4</td>
<td>4.8</td>
</tr>
<tr>
<td>TA49</td>
<td>2.3</td>
<td>3.1</td>
<td>3.8</td>
</tr>
</tbody>
</table>

Table 3. Planimetric distance and the nominal "ground sample distance" for each camera.

<table>
<thead>
<tr>
<th>Camera Name</th>
<th>Planimetric Distance to Firing Site [ft]</th>
<th>Bearing from East [deg]</th>
<th>Projected Size of Detector at Firing Site [ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IJ</td>
<td>2,220</td>
<td>61</td>
<td>1.9</td>
</tr>
<tr>
<td>Trailer</td>
<td>4,346</td>
<td>115</td>
<td>1.1</td>
</tr>
<tr>
<td>TA49</td>
<td>3,061</td>
<td>256</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Digital Stereoplotter

Once the exterior orientation of each video camera had been calculated, the space intersection method was used to determine the 3D location of each of the eight poles which served as ICPs. The space intersection process was implemented as an IDL code. The GUI for this process is illustrated in Figure 5. The location of each ICP pole was manually identified for each image from each camera. The location of each ICP was determined three different times by using adjacent pairings of the three video cameras. Each of these pairings created a stereo pair to be used in the space intersection process. The camera used for the left and right image of each stereo pair is listed in Table 4.

Table 4. The left and right cameras for each of the three stereo pairs and the parallactic angle between them.

<table>
<thead>
<tr>
<th>Stereo Pair</th>
<th>Left</th>
<th>Right</th>
<th>Parallactic Angle [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IJ</td>
<td>Trailer</td>
<td>54</td>
</tr>
<tr>
<td>2</td>
<td>Trailer</td>
<td>TA49</td>
<td>39</td>
</tr>
<tr>
<td>3</td>
<td>TA49</td>
<td>IJ</td>
<td>15</td>
</tr>
</tbody>
</table>

Accuracy Assessment

For each stereo pair, the error (difference) was calculated between the known and estimated 3D locations of the eight ICPs. The location differences in the x- and y-directions were used to calculate the planimetric RMSE. The location differences in the z-direction were used to calculate the vertical RMSE. The total (radial) error was calculated by using the errors in all three directions. These values are listed in Table 5.

Table 5. Root mean square errors from the space intersection process for the three stereo pairs.

<table>
<thead>
<tr>
<th>Stereo Pair (Left / Right)</th>
<th>RMSE x-direction (Easting) [ft]</th>
<th>RMSE y-direction (Northing) [ft]</th>
<th>Planimetric RMSE [ft]</th>
<th>Vertical RMSE (HAE) [ft]</th>
<th>Total RMSE [ft]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (IJ / Trailer)</td>
<td>2.6</td>
<td>2.4</td>
<td>3.5</td>
<td>5.2</td>
<td>6.2</td>
</tr>
<tr>
<td>2 (Trailer / TA49)</td>
<td>1.9</td>
<td>4.4</td>
<td>4.8</td>
<td>5.4</td>
<td>7.2</td>
</tr>
<tr>
<td>3 (TA49 / IJ)</td>
<td>3.0</td>
<td>7.8</td>
<td>8.4</td>
<td>3.5</td>
<td>9.1</td>
</tr>
</tbody>
</table>
Figure 5. The digital stereoplotoer interface.

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Discussion

The location accuracy in the x-direction (Easting) and in the z-direction (height above ellipsoid) do not appear to vary a great deal with parallactic angle (Figure 6). However, the location accuracy in the y-direction does appear to depend strongly on parallactic angle. This is probably explained by the particular arrangement of the cameras used in this study. For example, the error in the y-direction is greatest for the "TA49 / IJ" stereo pair. The "IJ" camera is located 30 degrees East of North and the "TA49" camera is located 14 degrees West of South. Therefore, these two cameras are mostly separated along the y-direction (North-South). We would expect the error in the y-direction to be large since there is less parallax information contained in the imagery along the North-South line as compared to the East-West line.

![Figure 6. Location error in the x, y, and z directions versus parallactic angle.](image)

The overall (total) location accuracy is a strong function of parallactic angle between the cameras used in each of the three stereo pairs (Figure 7). This is logical since the greatest strength of geometry is expected for a parallactic angle of 90 degrees. The trend line in Figure 7 suggests that if two video cameras were arranged such that the parallactic angle between them was 90 degrees, then the 3D location accuracy would be 3.5 feet.

CONCLUSIONS AND FUTURE WORK

The 3D location accuracy obtained is encouraging. The results suggest that a very simple camera model can be used in both the exterior orientation (self-calibration) and digital stereoplotter (space intersection) processes. The accuracy obtained is better than one part in one-hundred (i.e. better than 10 feet of 3D location accuracy from a distance of greater than 1,000 feet). Use of this simple camera model with the self-calibration process permits the cameras to be fielded without the requirement that the focal length, zoom, and attitude be measured and recorded. The zoom can be changed as needed, and the self-calibration process can determine the focal length and attitude angles which best fit the colinearity equations for each zoom setting. However, this methodology does require that the position of the cameras and several well-defined control points be known apriori. Also, defining the location of point-like features in both the exterior orientation and digital stereoplotter processes is manually intensive.
A different camera arrangement might yield more accurate results. For three cameras, equal parallactic angles would seem to be most efficient (i.e. 120 degrees). However, higher location accuracy might be obtained if four cameras were used and the parallactic angle between adjacent cameras was 90 degrees. Using this configuration, the line-of-sight rays from adjacent cameras would be perpendicular, providing high strength of geometry for each stereo pair. Also, the cameras should be arranged such that the control points are not occluded by trees, buildings, or each other, and the cross bars should not be viewed such that they align with the horizon line or the mountain ridge line in the background. These effects were encountered in this study and made defining some control points quite difficult. This is probably a source of error which propagated through the self-calibration and space intersection processes, ultimately impacting the 3D location accuracy. Mitigating these effects by changing the placement of the video cameras will be challenging, due to the rugged topography of the study site.

Even though the simple camera model used herein has proven useful, several modifications to it should result in higher 3D location accuracy. Non-square detectors should be implemented. Possible evidence of this could be the fact that the focal plane error incurred during the exterior orientation process is consistently higher in the camera y-axis direction than in the camera x-axis direction (Table 2). This effect implies that the actual detector sizes are larger in the y-direction than in the x-direction. The interior orientation parameters (including radial lens distortion) should be determined for each video camera. This could be accomplished by acquiring imagery of a regular grid (or some other arrangement of well distributed control points) and using the self-calibration form of the colinearity equations. Finally, information from all the cameras should be used in a simultaneous space intersection adjustment. This should yield consistent, if not higher, 3D location accuracy.

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REFERENCES