PHOTOGRAMMETRIC METHODS FOR QUALITY CONTROL OF TRENCHLESS CONSTRUCTION PROJECTS

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ABSTRACT: One concern associated with trenchless construction techniques is surface heave or settlement. Surface movements can damage pavements and other structures. Traditional methods of assessing surface damage have involved visual walkovers or total station survey. These techniques require physical access to the area and require time to complete and compile data to determine what has occurred during the monitoring event. While LIDAR can also be utilized to accurately map a surface, it is relatively cost prohibitive to undertake. Photogrammetry is a remote sensing technique in which the geometric properties of objects and surfaces can be determined from photographic images. This process enables accurate three-dimensional measurements of specific points on the ground surface. Measurements are determined utilizing two or more photographs taken from different positions simultaneously at specific time intervals. Photographs from specific time intervals are then complied using photogrammetry software to determine the position of surface points in three-dimensional space within a few minutes. Comparing photographs from different time intervals during the construction process allows the user to monitor surface movements, in almost real time conditions. This technique provides a cost effective, accurate, and timely methodology for inspectors to conduct quality control on trenchless projects and assess surface heave and settlement. This paper outlines the procedure developed to perform quality control measurements utilizing photogrammetric techniques on trenchless projects, discusses calibration procedures, and summaries an exercise in determining the precision of this measurement technique.

1. INTRODUCTION

Ground movements associated with trenchless construction operations can cause significant damage to existing buried and surface infrastructure. This may be the result of soil displacement, slurry or drilling fluid pressurization, over excavation, or settlement. The type of ground movement that occurs is related to the trenchless method utilized, soil conditions, and the contractor’s methodology or actions during the construction operation (Bennett and Ariaratnam 2008). Subsurface soil movements may damage buried utilities, foundations, structures, and depending on the depth of cover, may manifest in surface movements. Surface movements, either settlement or heave, can damage pavements, sidewalks, and on grade foundations (Lueke and Ariaratnam 2005).

It has become common for municipalities and infrastructure owners to specify the monitoring of surface movements in their contracts for trenchless installations beneath roadways or rail lines (Lueke and Ariaratnam 2010). The requirements include documenting the surface elevation prior to the start of construction, then as the construction progresses either daily or at critical junctures in the project. The goal of monitoring ground movements potentially
is different for the owner and contractor. Owners monitor ground movements to determine if movements have occurred, what the magnitude of the movement was, and if there are any potential consequences to their infrastructure. Contractors should monitor ground movements as the installation or replacement progresses to see how their procedure is influencing the development of ground movements, then use this information to modify their methodology to control heave or settlement.

There are several methods utilized to measure ground surface movements. Some of the most common include total station (surveying triangulation), conventional rod and level (geometric leveling), terrestrial photogrammetry, and surveying utilizing global positioning satellite technology. Based on work done by Gili et al. (2000) for the monitoring and measurement of landslides, information pertaining to the precision of the methods applicable to measuring ground movements on trenchless projects is provided in Table 1.

Table 1. Overview of methods used in measuring surface displacements and their precision (Gili et al. 2000)

<table>
<thead>
<tr>
<th>Method</th>
<th>Results</th>
<th>Typical Range</th>
<th>Typical Precision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveying Triangulation</td>
<td>$\Delta X$, $\Delta Y$, $\Delta Z$</td>
<td>$&lt;$300-1000 m</td>
<td>5-10 mm</td>
</tr>
<tr>
<td>Geometric Leveling</td>
<td>$\Delta Z$</td>
<td>Variable</td>
<td>2-5 mm/km</td>
</tr>
<tr>
<td>GPS Survey</td>
<td>$\Delta X$, $\Delta Y$, $\Delta Z$</td>
<td>Variable (usually $&lt;$20 km)</td>
<td>5-10 mm + 1-2 ppm</td>
</tr>
<tr>
<td>Terrestrial Photogrammetry</td>
<td>$\Delta X$, $\Delta Y$, $\Delta Z$</td>
<td>Ideally $&lt;$10 m*</td>
<td>2 mm from 10 m*</td>
</tr>
</tbody>
</table>

* scaled down from 20 mm from 100 m to be applicable to the conditions in this investigation

Traditionally, the measurement of ground movements was accomplished utilizing geometric leveling, or at times triangulation by total station or theodolite. Now GPS has become more common on most construction sites. The major drawback of these methods is that they require direct access by a person to the targets being measured so that the rod or reflector can be positioned for a measurement. Additionally, these methods cannot take simultaneous measurements of all targets at a specific time interval, as time is required between each target measurement to reposition the rod or reflector. These limitations prevent utilization of these methods if access cannot be provided to the area being monitored or if it is not possible or practical to stop the construction process long enough to survey all the targets.

This paper proposes that photogrammetry would be an effective and efficient method of performing quality control on trenchless projects. Photogrammetry is a remote sensing technique in which the geometric properties of objects and surfaces can be determined from photographic images (Mikhail et al. 2001). It essentially allows measurements to be made from photographs. The method used in this research is more appropriately termed stereophotogrammetry, and it is capable of estimating the location of points on objects and surfaces in three dimensions through analysis of two or more photos taken from different positions of the target area.

The photogrammetric process is based on line of sight and analysis of the geometry of the scene or subject. Utilizing a series or set of photos of the subject area, common points of interest, or targets, are identified in each photograph. A line of sight, or ray, is created between each target and the camera for each photograph. Through the triangulation of these rays for each unique target from each photograph, one can solve for the position of the camera and points relative to each other in three-dimensional space. With knowing at least one dimension in the subject scene, typically the distance between two targets, the solution can be scaled. The solution creates a virtual model of the scene, from which accurate measurements can be made of the target positions.

Photogrammetry has many advantages over more traditional methods of monitoring ground movements; some of these are as follows:

1. **Simultaneous measurement of all targets/surface points in the area monitored** – all targets in the camera’s field of view can be measured;
2. **Fast measurements** – each measurement set requires a minimum of 2 pictures (more are preferable), the measurement of all targets is complete in the time required to take the pictures;
3. **Minimal equipment required** – camera and tripod, with a computer to process the photos;
4. **No specialized equipment required** – typically the equipment required to monitor ground movements, a camera, is generally standard issue for a foreman or superintendent;
5. **Minimal training required for operator** – operator must be familiar with operation of camera and how to stage pictures for optimal area coverage;

6. **Quick turn around for results** – after downloading pictures to the computer, software can analyze photos in a matter of minutes and provide Cartesian coordinates for all targets included in the photos; and,

7. **Measurement without access to targets** – measurements can be made without having to access the area where the targets are located.

Table 2 summarizes the four main survey techniques for measuring ground movements and their associated cost of equipment required to take the measurements, time to take the measurements, expertise of the data gatherer, and the speed at which results are available.

<table>
<thead>
<tr>
<th>Method</th>
<th>Cost of Equipment</th>
<th>Time to Take Measurement</th>
<th>Expertise of Data Gatherer</th>
<th>Speed of Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surveying Triangulation</td>
<td>$5-10,000</td>
<td>&lt;60 min</td>
<td>High</td>
<td>Hours</td>
</tr>
<tr>
<td>Geometric Leveling</td>
<td>&lt; $1,500</td>
<td>&lt;30 min</td>
<td>Medium</td>
<td>Minutes</td>
</tr>
<tr>
<td>GPS Survey</td>
<td>$15-25,000</td>
<td>&lt;60 min</td>
<td>High</td>
<td>Minutes</td>
</tr>
<tr>
<td>Terrestrial Photogrammetry</td>
<td>&lt; $2,000</td>
<td>&lt;5 min</td>
<td>Minimal</td>
<td>Minutes</td>
</tr>
</tbody>
</table>

The remainder of this paper discusses the development of a procedure to utilize photogrammetry to perform quality control on a trenchless project. This includes discussion of camera calibration, trial measurements to determine the precision of the technique on targets in a similar configuration to an actual field installation, results from this analysis, and discussion of the results compared to other survey techniques.

2. **CAMERA CALIBRATION**

This research utilized PhotoModeler, a photogrammetry analysis software developed by EoS Systems. Prior to utilizing the software to perform measurements, the cameras to be utilized must be calibrated. Included in the software is a module to calibrate the camera used for taking the images. This software produces highly accurate measurements with “off the shelf” commercially available digital cameras. The calibration involved taking a set of 12 images for a full field calibration. The camera used for this project was a Canon EOS Rebel XSi digital SLR 12.2 megapixel camera CMOS sensor with an EF-S 18-55 mm f/3.5-5.6 IS lens. For this project, the calibration was done both at 18mm and 55 mm focal length. The calibration grid consisted of a total of 100 dots including 4 control target points on a sheet of paper one-meter square. The process of calibration is done such that a total of twelve pictures of the grid were taken. Four pictures from each side of the grid were taken at three different orientations of the camera. The first set of pictures was taken with the camera in the landscape position; the second in portrait; and the third set in inverted portrait position. The camera was mounted on a tripod stand to eliminate shaking while taking the pictures as shown in Figure 1, and a remote trigger utilized to further stabilize the pictures. The objective of this calibration is to determine the characteristics of the camera lens and body. This is accomplished by taking pictures such that as much of the field of view is covered by the calibration grid.

The camera calibration software is able to recognize the position of various points with the help of the control targets by the principle of spectrography. The relative position of all the points is found using the principle of bundle triangulation. Based on the position of the control points, the positions of the other points are found using positional transformations. Hence it is of utmost importance that there is adequate overlapping of points in the photos and at least 80% of the total points are captured in each image. The whole idea behind having good overlap of the images is that, the number of equations possible for the common points outnumbers the points; hence a definite solution is possible. (Aguilar et al, 2004; Luhmann et al, 2007)
At completion of the calibration sequence the software generates a report that summarizes the quality of the calibration, any issues or concerns, and also suggests remedies or methods to improve the calibration. The values of the Standard deviations on all the variables should be as small as possible for a well-calibrated camera. Some of the important parameters to be checked in calibration are ‘Total Error’ (final error) and ‘Point Marking Residuals’ (Overall RMS and Maximum Residual). The point marking residuals are used for identifying if the calibration is properly done and to check for points that have the maximum residual. The final total error value is used to check if the calibration is done properly. For a well-calibrated project, these values should be less than 1. The lesser the error values, the better the calibration. Table 3 summarizes some of the important parameters for the two focal lengths utilized in the study. Calibrations were undertaken at two different focal lengths to account for varying site conditions and constraints that may restrict placement of targets or camera positioning when taking pictures.

<table>
<thead>
<tr>
<th>Parameter\Focal Length</th>
<th>18 mm</th>
<th>55 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Photo point coverage</td>
<td>81%</td>
<td>85%</td>
</tr>
<tr>
<td>Overall Residual RMS</td>
<td>0.320 pixels</td>
<td>0.137 pixels</td>
</tr>
<tr>
<td>Maximum Residual</td>
<td>1.706 pixels</td>
<td>0.531 pixels</td>
</tr>
</tbody>
</table>

The average photo point coverage, given in percentage, denotes how much of the camera lens is calibrated. The field of view must be filled with the maximum number of points possible for proper calibration and the minimum recommended value of this parameter for a good calibration process is 80%. Overall Residual Root Mean Square (RMS) and Maximum Residual values are important parameters to compare the calibration results for different focal lengths of the same lens. These residual values are indicative of the deviation of the processed point to the actual position of the point. In simple words, point residual is the difference between where the algorithm processes the point and where the software algorithm thinks the point should have ideally been. The point locations are obtained using bundle ray adjustment from multiple photographs. The points with largest residuals should ideally have RMS and maximum residual values less than 1 pixel for a well-calibrated project. From table 1 above, we see that 55mm focal length is better calibrated than the others. A single calibration is sufficient if the same camera is used throughout the project as long as the camera parameters are unchanged. However, subsequent calibrations are required each time a new camera is used, or as and when the focal length of the lens is changed. These calibrated cameras can be saved for future use.
3. TRIAL MEASUREMENTS USING PHOTOGRAMMETRY

In preparation for utilizing photogrammetry for measuring ground movements in the field, a series of trial measurements were done under various scenarios. This was done to develop a procedure that considered camera focal length and the number of pictures to be taken to conduct each measurement. The focal length determines the field of view, which in turn determines how close to the subject area the camera has to be in order to take suitable pictures. Higher focal lengths allow the camera to be further away from the subject area. Being able to take pictures at various “zoom” levels is essential on construction sites where access to the subject area may not be optimal.

The Photomodeler software develops a three-dimensional virtual model of the subject area, based on the analysis of a set of photos. A photo set is composed of some number of photos, of the same subject area, at the same or similar instance in time, which captures all the survey targets of interest. The number of photos in a set influences the ability of software to develop a solution for each target in three-dimensional space. Minimally a set of 2 photos is required to develop a solution, however better solutions can be achieved utilizing more photos. In developing a measurement procedure for the field, a mock monitoring scenario was conducted to understand the influence of focal length and number of pictures in each measurement set.

This trial was conducted to gain familiarity with the actual project scenario, to gain comfort levels before going for the actual site location, and mainly to check the precision of Photomodeler software. This trial experiment involved the following steps: 1) setting up the targets; 2) taking pictures of the targets; and 3) analysis in Photomodeler. The images were taken for focal lengths of 18mm and 55mm in 20 sets of 3 pictures, 4 pictures and 5 pictures, resulting in a total of 480 pictures taken. We did not anticipate drastic change in results for the number of pictures in a set; however, all the cases were tested nonetheless for comparison purpose and for repeatability.

Setting Targets
The targets discussed in this section were as shown in Figure 2. Each target was square in shape of size 2.75” × 2.75” and consisted of a white circular region within the black entirety. A cross hair was provided within the target that would be taken as the reference of the target while marking them in the software. The marking of the point of intersection of the cross hair would represent the location of that particular target. A total of 22 identical targets were set up on the ground for this experiment. The targets were set up in two rows of 11 each and placed at a distance of 1 foot between each target in the line. The distance between the two rows was also 1 foot (Figure 3). The distances were measured using a standard steel measuring tape. All the targets were fastened in all the directions to the ground using a tape so that they could not move by the blowing wind or any other disturbance causing elements. Even a slight movement in any of the targets would hamper the actual result and as a precaution, we opted to affix them to the ground. Since this experiment was conducted in an open parking lot, signs were placed to warn people of the ongoing experiment and people were cooperative not to disturb the experimental setup.

Figure 2: Sample target (actual size 2.75” by 2.75”)

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Taking Pictures
After setting the targets on the ground, we started taking the pictures. We started with 55mm focal length with 5 pictures sets, 4 pictures sets and 3 pictures sets respectively in that order. The same was repeated for 18mm focal length. Care was taken that the focal length of the camera did not change at any instant of time during the experiment, and so, a piece of tape was fastened at the end of the lens to curtail the rotation of the lens. In order to achieve higher accuracy, we tried to maintain an angle greater than 45° between any two consecutive photos (Photomodeler v6.0). Also, effort was made to take the pictures 360° of the targets, covering all the sides for proper perspective from all the directions. The photos were taken so as to capture all the targets within the lens calibrated region. In other words, the efforts were to capture all the targets in the center of the lens. The camera was mounted on a tripod and pictures were taken with a remote wireless trigger to minimize camera body movement as pictures were taken.

Analysis in Photomodeler
Once all the pictures were taken for 55mm and 18mm focal length, the pictures were loaded in the laptop for analysis in Photomodeler software. All the pictures were categorized into their respective sets before analysis. Having done this, each set was individually worked upon in the software. In each set, all the targets were first sub-pixel marked on the first picture. These were then referenced with the targets in remaining pictures and the software was able to establish all the point coordinates. It is important to have at least two photos in which a particular target is clearly recognizable. After referencing all the points, the pictures were processed. On successful processing of these pictures, the coordinates of all the 22 points were copied into an excel sheet. Photomodeler indicates any problems encountered during the processing and also provides suggestions for those problems. Similarly, the coordinates of the points from all the sets are copied in to the excel sheet.

4. PRECISION ANALYSIS
To determine the effectiveness and practicality of utilizing photogrammetry as a means to provide quality control or monitor surface movements in the field, it is essential to determine the accuracy and precision of the technique. The accuracy of a measurement system is defined as the closeness of the measurement to the actual value, while precision is defined as repeatability or tightness of the measurement. The precision of a measurement is its standard deviation when the physical quantity (point being measured) remains constant. The information presented in this paper focuses only on an analysis to determine the precision of measurements determined by our methodology utilizing the PhotoModeler software.

In this analysis a total of 480 pictures were taken, composed of 20 measurements of the 22 surface targets taken in sets of 3, 4, and 5 pictures at 18 and 55 mm focal lengths. Each set of pictures was analyzed in PhotoModeler, solving the three dimensional Cartesian coordinates (x,y,z) of each target. Coordinates for this analysis were determined by assigning a specific target as the origin, and then determining the scalar value of each coordinate based on the position of the origin. For application in the field, one target would be tied into the survey datum on site so that the measurements are pertinent to the project.
All pictures taken for this analysis were completed over a 4-hour time period utilizing the same procedure, with the targets left in the same place for all measurements. While the actual position of the targets was not determined, the precision analysis could still be undertaken as it only determined the repeatability of the measurement. Table 3 summarizes the results of the analysis and provides the average standard deviation achieved for each axis, for the different focal lengths and number of pictures taken for each measurement. Each average standard deviation value shown is the average of 20 measurements of 22 targets.

Table 4. Average standard deviation by number of pictures and focal length

<table>
<thead>
<tr>
<th>Focal Length</th>
<th>Pictures in Set</th>
<th>Average Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>18 mm</td>
<td>3</td>
<td>11.06</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>3.20</td>
</tr>
<tr>
<td>55 mm</td>
<td>3</td>
<td>9.43</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.92</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.93</td>
</tr>
</tbody>
</table>

For the measurements taken with the camera set with an 18 mm focal length (wide angle thus closer to the targets) the standard deviation of the coordinates decreases with increasing the numbers of pictures included in a measurement. As additional photos are added to the model Photomodeler creates, the solution for the coordinates for each target strengthens thus “focusing” the modeled target location. Similar improvements to the standard deviation of measurements taken with a focal length of 55 mm (telephoto thus camera further from targets) are observed as the number of photos taken with each measurement set increases. It should be noted that there were some abnormalities in the processing of a few of the photo sets taken at 55 mm focal length and 4 pictures in the measurement set resulting in slightly higher standard deviations than expected.

This analysis determined that the typical standard deviation on the Z axis was less than 1 mm – for photo sets consisting of more than 3 photos. This means that the precision of this technique is less than 1 mm. This is significantly better than conventional leveling, triangulation, and surveys utilizing GPS.

5. FUTURE WORK

Accuracy determination will be conducted on an auger bore installation in Glendale, AZ. The project involves the installation of a 1,372 mm (54 inch) steel casing pipe beneath Grand Avenue, a rail line, and a block wall fence. The installation is approximately 125 m (410 ft) in length, and designed with approximately 5 m (16.4 ft) of cover beneath the Grand Avenue and 7 m (23 ft) of cover beneath the rail line. The city and rail road company were very concerned with any ground movements that might occur during the installation process, and outlined specific means to monitor ground movements as part of the construction contract. In the construction specifications for this project, the City requires the contractor to install settlement points consisting of a 150 mm (5.9 in) diameter concrete pile to a depth of 1,200 mm (3.9 ft) into which a leveling hub is to be set. Elevations of the hub are to be taken at regular time intervals to monitor the settlement or heave that might occur.

To determine the accuracy of the photogrammetric process, the contractor will be monitoring the settlement points with conventional rod and level as well as GPS. We will be monitoring the same points utilizing photogrammetry and comparing the measured values. By comparing the measured elevations and differences in settlement point elevations, we should be able to determine the accuracy of the method.

6. CONCLUSIONS

Based on the results of this analysis, it has been determined that the precision of this photogrammetric technique to measure surface have is generally better than 1 mm. This value is based on a total of 120 individual measurements of 22 surface targets. This level of precision is better than conventional survey techniques, and has several
advantages in terms of speed of data gathering, lower costs, and minimal training required to conduct the measurements. These results support the premise that this technique could see application in the monitoring and quality control of trenchless construction projects.

7. REFERENCES


