Regular Digital Camera as a Practical Geodetic Measurement Tool: Issues and Challenges

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Key words: Ground photogrammetry Software, Digital Photogrammetry, Measurements from Ground Photos, Digital Camera Calibration, Image Processing.

SUMMARY

The field of digital photography is undergoing a major technological progress in the last few years. This progress had led to the substantial improvement in the quality of regular digital cameras, and to an order of magnitude increase in their image resolution. This remarkable progress in the quality of digital photography in recent years was coupled with a significant price decline of regular digital cameras. As a result, land surveyors face for the first time an opportunity to adopt regular digital cameras as practical geodetic measurement tools. Using regular digital cameras on a daily basis for geodetic measurements may allow the unprecedented enhancement in the productivity of land surveying field teams. Moreover, it may also allow unparalleled improvement in the ability to control the quality of geodetic measurement projects, and to diminish the need for follow-up measurements in the field. Alas, adopting digital photography as a common tool for geodetic measurements introduces some key geodetic and practical challenges.

This paper overviews some of the theoretical and practical challenges that land surveyors face when embracing digital cameras for geodetic measurements. The paper introduces the geodetic challenge of calibrating a regular digital camera, reviews various methods for camera calibration, and discusses the advantages and drawbacks of each method through quantitative examples. In addition, the paper outlines the mathematical challenge of solving the photogrammetric model from a series of images taken from the ground level, and the anchoring of the model to a local or national geodetic grid in order to extract geodetic measurements from the images. Implementing the solution of the photogrammetric model by software allows turning a computer screen into a high precision theodolite-like tool. After obtaining the coordinates of a certain point in more than two images in which it appears, the software may calculate the point's coordinates in the photogrammetric model. The software may also provide the point's coordinates in any given geodetic grid, if the photogrammetric model is anchored to this geodetic grid through measured control points.

In contrast to aerial photogrammetry in which a small number of images may provide the coverage of a wide region, photography from the ground level is constrained by local obstructions. As a result, short-range photogrammetry usually requires a comparatively large number of images for the coverage of the measurement field. As a result, solving the photogrammetric model requires the sampling a large number of points in numerous images. This increases the complexity of the work, and thus challenges the practicality of using close range digital photogrammetry for the daily work of geodetic measurements. This paper reviews some advanced solutions based on image processing that allow overcoming these challenges, thus turning regular digital cameras into a practical geodetic measurement tool which provides geodetic measurements in a comparatively cheaper manner, and with higher quality compared to traditional land surveying techniques. Finally, this paper presents a practical experiment for creating a high-accuracy topographic map from a series of ground images taken by a regular camera Canon 600D DSLR, and compares the results with geodetic measurements made by a Total Station instrument with a standard geodetic accuracy level for producing 1:250 scale maps.

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1. INTRODUCTION

The field of digital photography is undergoing a major technological progress in the last few years. This progress had led to the substantial improvement in the quality of regular digital cameras, and to an order of magnitude increase in their image resolution. This remarkable progress in the quality of digital photography in recent years was coupled with a significant price decline of regular digital cameras. As a result, land surveyors face for the first time an opportunity to adopt regular digital cameras as practical geodetic measurement tools. Using regular digital cameras on a daily basis for geodetic measurements may allow the unprecedented enhancement in the productivity of land surveying field teams. Moreover, it may also allow unparalleled improvement in the ability to control the quality of geodetic measurement projects, and to diminish the need for follow-up measurements in the field. Alas, adopting digital photography as a common tool for geodetic measurements introduces some key geodetic and practical challenges.

The geodetic challenges may be broadly categorized into several domains. First are the challenges that relate to the fact that the refraction of light rays inside the digital camera and the internal structure of the CCD sensor are not optically perfect and induce various distortions of the image. A camera calibration process is required in order to estimate the image distortion and apply an internal correction to the relative position of the pixels in the CCD sensor. Second are the mathematical challenges from the realm of ground photogrammetry, which will be elaborated in the next section. Moreover, in contrast to aerial photogrammetry in which a small number of images may provide the coverage of a wide region, photography from the ground level is constrained by local obstructions. As a result, short-range photogrammetry usually requires a comparatively large number of images for the complete coverage of the measurement area. This is challenging the land surveyor since every image must be anchored to the other images using tie points, and to a local or national grid using known control points. The more there are images, the more laborious the process becomes. One simple way to address this challenge is to raise the digital camera to a point that is elevated above the photographer's eyes using a mount and a remote control. This may allow significantly reducing the number of images that are required for the coverage of the measurement area. This issue will be further elaborated in subsequent sections. In addition, measuring the coordinates of a point from the images requires the exact digitization of the pixel in at least three images, with the first two images required for the calculation of the coordinates, and the third image required for quality control. However, manually digitizing exactly the same pixel in three different images for every measured point is error-prone, and is especially challenging when the pixel is on a surface with uniform color.
All of these challenges increase the complexity of using ground photogrammetry as a tool for daily work of land surveyors. Fortunately, there are various solutions for these challenges.

1.1 Ground photogrammetry

Ground photogrammetry involves the measurement of coordinates from images made from the ground level. Using appropriate software for ground photogrammetry allows turning a computer screen into a high precision theodolite-like tool. The coordinates of points in the digital images replace the horizontal azimuths and elevation angles. However, in contrast to a theodolite, usually one is not able to determine the exact position of the camera, nor determine in advance its orientation or level it. Moreover, as wide as the camera's field of view is, only a small segment of the space around the camera may appear in the image. Thus determining the exact location and orientation of the camera for every image must be based well-known control points that are well-spread across the measurement area, in a process that employs backward intersection of the lines of sight in space.
Ground photogrammetry exhibits some key advantages. For example, in case of a dispute, photogrammetric measurements and calculations of coordinates may be executed and controlled or inspected by independent teams. Such measurements may be executed even years after the images of the measurement area were taken, which may be crucial for example in case an object with architectural or artistic importance has to be reconstructed.

1.1.1 The geometric model of the image

The first stage of turning coordinates of points on images into coordinates in space requires knowing the internal geometric characteristics of the camera, in order to create a mathematical model of the image. In order to explain the principles of the geometric model of the image, first we need to schematically describe the internal geometry of the digital camera and the paths of light rays inside it. Figure (1a) below depicts a schematic cross section of a camera with four optical elements in its lens. The purpose of these optical elements is to transmit and diffract the light rays in a way that light rays originating from object A in front of the camera will converge to the point a on the CCD sensor. This way, a sharp image of the object A will appear at the point a. The same is true to objects B and C, as well as to the rest of the objects in front of the camera.

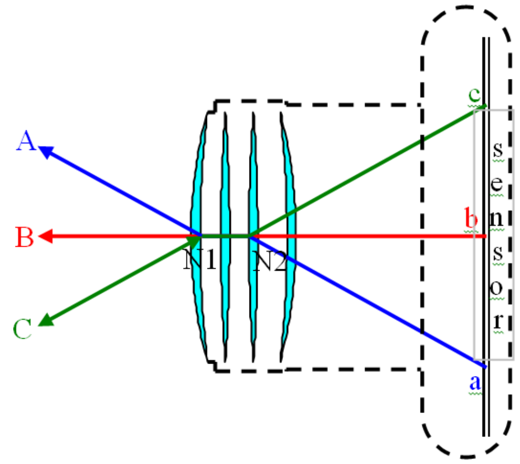

Figure (1b). A schematical cross-section of the paths of equivalent rays through the nodal points

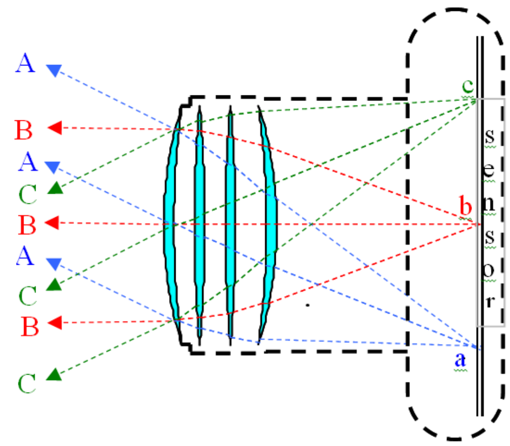

Figure (1a). A schematical cross-section of a digital camera and the path of light rays inside it

In the next step, in Figure (1b) above, we create equivalent light rays by drawing through points a, b, and c lines that are parallel to the light rays originating from A, B, and C, correspondingly. These equivalent light rays intersect at the rear nodal point N2 on the optical axis. Similarly, from the objects A, B, and C we draw lines that are parallel to lines a-N2, b-N2, and c-N2, correspondingly. These lines intersect at the front nodal point N1 on the optical axis. The polyline A-N1-N2-a represents the equivalent of the sum of light rays that emerge from the object A, transmit and diffract through the optical elements, and then intersect at point a on the CCD sensor. The same is true for the polylines B-N1-N2-b and C-N1-N2-c. The front and rear nodal points have the property that a ray aimed at one of them are refracted by the lens such that it appears to have come from the other, and with the same angle with respect to the optical axis.

Finally, as depicted in Figure (1c) below, in order to attain the ideal internal geometric model of the camera, we remove the camera's body and optical elements, and move the left and right parts of the drawing together so that the rear and front nodal points N1 and N2 converge. This turns all 'equivalent light rays', which are represented as polylines in Figure (1b) above, into straight lines in Figure (1c) below. Thus the ideal internal geometrical model of the camera is a central projection. The converged nodal point N1-N2 is the center of projection. The projection of this point on the plane of the CCD sensor is called the principal point of the image, i.e., the principal point is the point on the image plane which is at the base of the perpendicular from the converged nodal point N1-N2.
However, as depicted in Figure (1d) below, real optical elements are not ideal and thus the actual internal geometrical model of the camera diverges from the ideal model. In practice, light rays originating from points A and C pass through the rear nodal point N2 and refract and converge on points a' and c', rather than on points a and c. The distances a-a' and c-c' are denoted radial distortions and their value as a function of their distance from the center of the image is given by:

$$(1) \qquad \Delta r = K_1 r^3 + K_2 r^5 + ...$$

Whereas r is the distance of the point from the center of the image, and K1 and K2 are the radial lens distortion parameters. The radial lens distortion parameters K1 and K2 are specific for a given 'camera system', which includes the camera and the lens. This implies that the radial distortion coefficients K1 and K2 would change whenever a lens is replaced in an interchangeable lens camera.

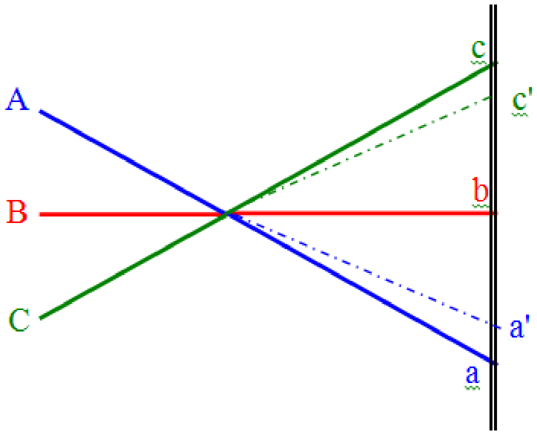

Figure (1d). Schematical cross-section of the camera's realistic internal geometric model due to radial distortions (a central projection + radial distortions).

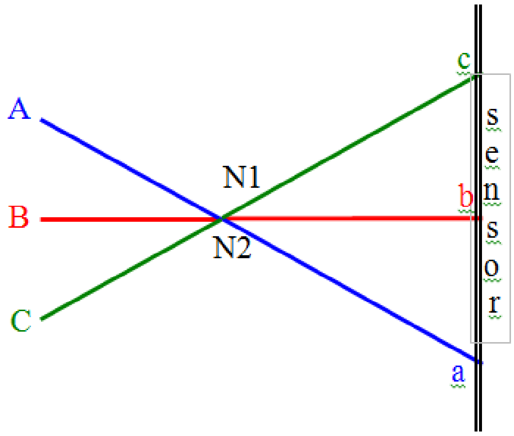

Figure (1c). Schematical cross-section of the ideal internal geometric model of the camera (a central projection).

1.1.2 <u>The relationships of spatial world coordinates and coordinates on the image</u>

In order to understand the relationships between the image and the world system, we'll start with a specific model in which the axes of the image are parallel to the axes of the grid of the spatial coordinates in the world system. Figure (2) below schematically depicts an image taken from the ground level. The principal point of the image is in the pixel at image coordinates (x0, y0) which are measured from the upper left corner of the image, and the focal length is f. Let's position the origin of the coordinate system of the image (x, y, z) in the center of projection point in a way that its z-axis passes through the image's principal point and the center of projection point, and is perpendicular to the image and directed at it. This makes the z-coordinate of each point on the image equal to f. Both x- and y- axes are parallel to the image frame, and are directed to the right and downward, correspondingly. Lines T1, T2, and T3, are the axes of the coordinates of the world system, which converge with the x-, y- and z- axes of the image coordinate system (the only exception is the T3-axis that is oppositely directed to the z-axis).

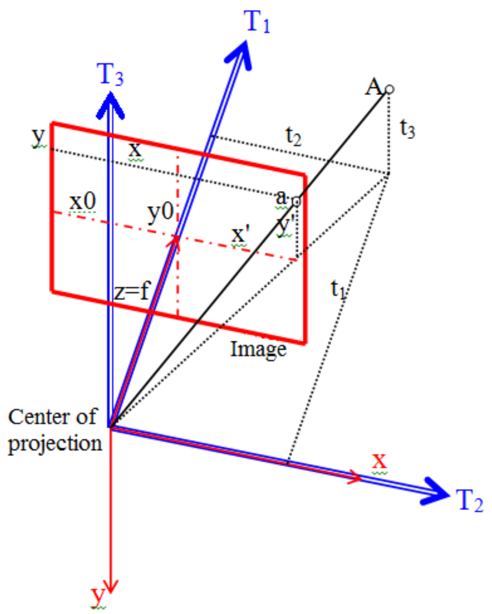

Figure (2). Geometric relationships between a point's spatial coordinates and its coordinates on the image.

As depicted in Figure (2) above, the spatial coordinates of point A are (t1, t2, t3), and it's ideal image is the point a which is the intersection of the image plane with the line that connects point A and the center of projection. The coordinates of point a in the image coordinate system are (x', y', f). Defining dx=x-x0 and dy=y-y0 we get,

$$r^2 = dx^2 + dy^2$$
$$\Delta r = K_1 r^3 + K_2 r^5$$
$$x' = x - x_0 + \frac{x - x_0}{r}\Delta r = x - x_0 + (x - x_0)\left[K_1 r^2 + K_2 r^4\right] \quad (2)$$
$$y' = y_0 - y + \frac{y_0 - y}{r}\Delta r = x_0 - y + (y_0 - y)\left[K_1 r^2 + K_2 r^4\right]$$

From here we get, using similarity of triangles, to the co-linear rule formula which is the basic formula of analytical photogrammetry,

$$\frac{x'}{t_2} = \frac{y'}{t_3} = \frac{f}{t_1} \quad (3)$$

The co-linear rule formula is usually written in the form,

$$x' = \frac{t_2}{t_1} f$$
$$y' = \frac{t_3}{t_1} f \quad (4)$$

In the more general case the axes of the image coordinates do not converge with the axes of coordinates of the world system, and the position of the center of projection point do not coincide with the origin of the X-, Y-, and Z- axes which are the world coordinate system. As depicted in Figure (3) below, T1-, T2- and T3- axes are the local system axes corresponding to the axes of the image coordinate system. Point O is the position of the point of central projection of the image and the origin of the axes of the (T1, T2, T3) coordinate system. The coordinates of point O in the (X, Y, Z) coordinate system are (x0, y0, z0).

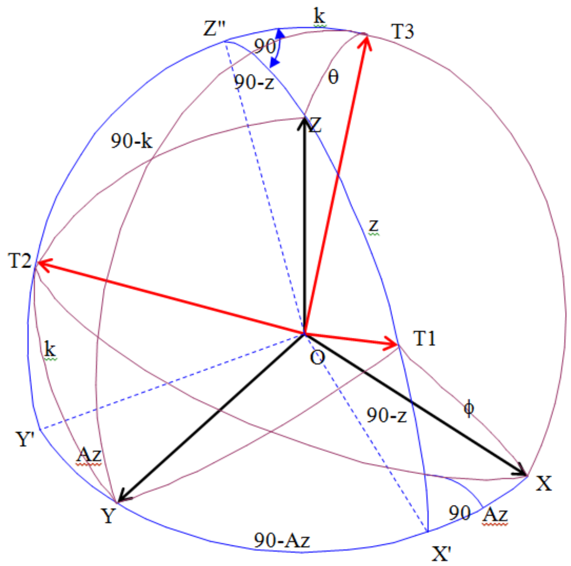

Figure (3). The axes of the local and world coordinate systems and the angles between them.

In order to transform (X, Y, Z) coordinates to (T1, T2, T3) coordinates, one need to employ three steps in the following order,

(a) Rotation at an Az angle around the Z-axis, bringing point X to X' and point Y to Y'.
(b) Rotation at a 90-z angle around the Y'-axis, bringing the X'-axis to T_1 and point Z to Z''.
(c) Rotation at a k angle around the T_1-axis, bringing point Y' to T_2 and point Z'' to T_3.

Thus we may transform from one coordinate system to another using the transformation formula,

$$(5) \quad \begin{pmatrix} T_1 \\ T_2 \\ T_3 \end{pmatrix} = \begin{pmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{pmatrix} \begin{pmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{pmatrix}$$

To calculate in detail the elements qi,j of matrix Q in Equation (5) above, see Salma et al. (1980).

The co-linear rule formulas for the general case may now be written in the form,

(6) $$x' = x - x_0 + (x - x_0)\left[K_1 r^2 + K_2 r^4\right] = \frac{t_2}{t_1} f = \frac{q_{21}(X - X_0) + q_{22}(Y - Y_0) + q_{23}(Z - Z_0)}{q_{11}(X - X_0) + q_{12}(Y - Y_0) + q_{13}(Z - Z_0)} f$$
$$y' = y_0 - y + (y_0 - y)\left[K_1 r^2 + K_2 r^4\right] = \frac{t_3}{t_1} f = \frac{q_{31}(X - X_0) + q_{32}(Y - Y_0) + q_{33}(Z - Z_0)}{q_{11}(X - X_0) + q_{12}(Y - Y_0) + q_{13}(Z - Z_0)} f$$

Whereas,

(X, Y, Z) are the spatial coordinates in the world system of a point in front of the camera that appears on the image.

(x, y) are the coordinates of the point in the digital image coordinate system (line and column numbers).

(x_0, y_0) are the coordinates of the principal point of the image in the digital image coordinate system (line and column numbers).

f *is* the camera's focal length, i.e., the distance between the center of projection point and the principal point of the image.

K_1, K_2 are the polynomial coefficient parameters for the calculation of the radial distortions of the camera system.

(X_0, Y_0, Z_0) are the spatial coordinates in the world system of the camera system during the photography.

$\begin{pmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{pmatrix}$ are the elements of the transformation matrix that is used for the transformation of the world system coordinates to the coordinate system of the image.

K_1, K_2, x_0, y_0, f are the internal orientation parameters which are calculated during the calibration of the camera system.

$\begin{pmatrix} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ q_{31} & q_{32} & q_{33} \end{pmatrix}$ and (X_0, Y_0, Z_0) are the external orientation parameters of the camera during the photography.

Thus, since a point corresponds to one pixel on the image, we may calculate the co-linear line formula of that point, when given that the angles between the axes of the coordinate systems and the camera's position and external orientation are calculated based known control points in the image, we may calculate the elements of the transformation matrix of any image based on (at least) three known control points in that image.

According to the co-linear line formula, every image provides two unknown parameters x and y based on the coordinates of the sampled pixel and the internal camera orientation parameters (K1, K2, x0, y0, f) which compose the set of camera calibration parameters. Thus, one needs to sample the same point in at least two different images in order to calculate its coordinates in the world system. The error ellipse of the point is optimal when the orientation of the two images is near 90°. As the same point is accurately sampled in more images, the accuracy of the measurement of the coordinates of the point will increase. In case of sampling the point in more than two images, one need to employ a least square calculation for all the sampled points using a bundle adjustment method.

2. USING IMAGE PROCESSING TO ADDRESS GROUND PHOTOGRAMMETRY CHALLENGES

Numerous academic and commercial software packages for ground photogrammetry offer functions for calculating the spatial coordinates of a given pixel in an image based on its sampling in additional images. Most of these software packages are too complex for daily usage, and require a significant effort in order to generate a geodetic-level outcome such as a detailed façade map, a topographic or a-made plan map, a 3-D model of a building, etc. As discussed in the first section above, most usability challenges arise from (a) the fact that multiple images are required for the coverage of the measurement area due to local obstructions; and from (b) the need to sample the same pixel in multiple images, so that the photogrammetric model will be able to generate the spatial position of the point in the local or national grid. In order to appreciate the scale of these practical challenges, one needs to consider that the photogrammetric solution of the system of images is done by either of two methods:

The first method requires the accurate sampling of at least four control points, for which the spatial coordinates are well-known in the local or national grid, in every image. This allows resolving the external orientation of the camera that photographed each image, and thus also the relative orientation of the images.

The second method ties up every image pair by sampling multiple tie points in each image; usually six points are used, but one must assure that these points are well spread in the overlapping area of the images (see Figure (4) below). After tying in this way each image pair so that every image is tied up with at least one image (but preferably more), one can calculate the relative orientation of the images. The sampling of at least four well-known control points in the image system (not necessarily in the same image), one can tie the photogrammetric model with the coordinates of the world system (local or national grid) and calculate the external orientation of all images.

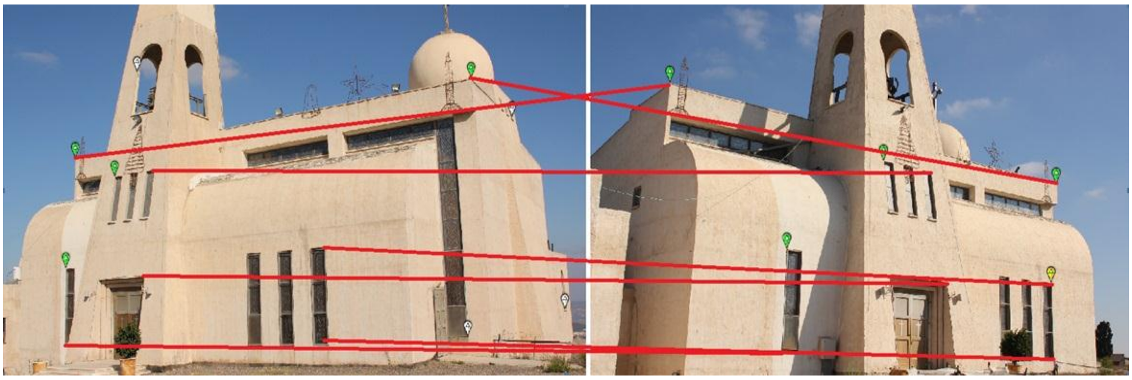

Figure (4). Red lines connect tie points in the image pair; triangles in the point marks indicate these are control points with well-known coordinates in the national grid.

Either one of these methods may be employed for calculating the coordinates of a point in the local or national grid by sampling it in at least two images. Based on geometric principles, one can show that the error ellipse of the point's position will decrease in size as the angle of the intersecting directions of images is closer to 90°, and is a function of $^1/_{\sin\alpha}$ (see Figure (5) below).

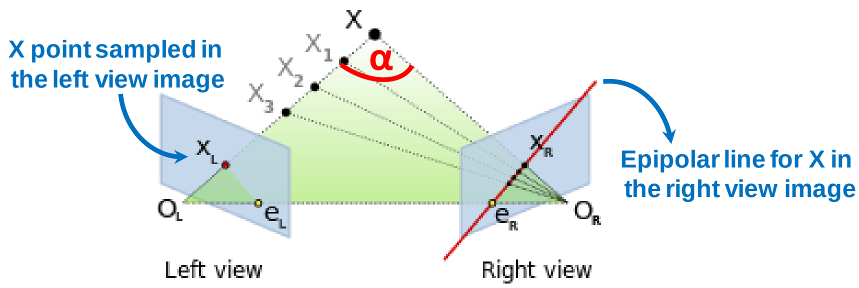

Figure (5). Red lines in the right view image depicts the epipolar line of the point X sampled in the left-view image, for an image pair of known relative orientation.

However, due to the fact that there are many images, in order to photogrammetrically anchor the images together the user must sample at least four well-known control points in each image (method (a) above), or sample at least six tie points in every image pair (method (b) above). Clearly, manually doing that is highly laborious for the land surveyor, and such a process cannot serve as a good substitution for the existing methods of measuring coordinates in the field.

In addition, more work is derived from the need to accurately sample every point in at least three images (the third image is required for quality control). Clearly, it would have been simpler if this process was somewhat shorter. Fortunately, one can calculate the epipolar line of a given point in any other image in an image pair (see Figure (5) above). The epipolar line is generated by a spatial vector intersection between the two points OL and OR when external orientation of the images are known. Once an epipolar line of a sampled point is drawn in a second image, it is sure that the point should reside in the second image on the epipolar line. Drawing the epipolar line may assist the user in finding the point faster on the other image.

An example for such application of the epipolar line is depicted in Figure (6) below. Clearly, even this shorter procedure is still cumbersome, and is not trivial when one needs to employ it to hundreds and thousands of measured points and many images.

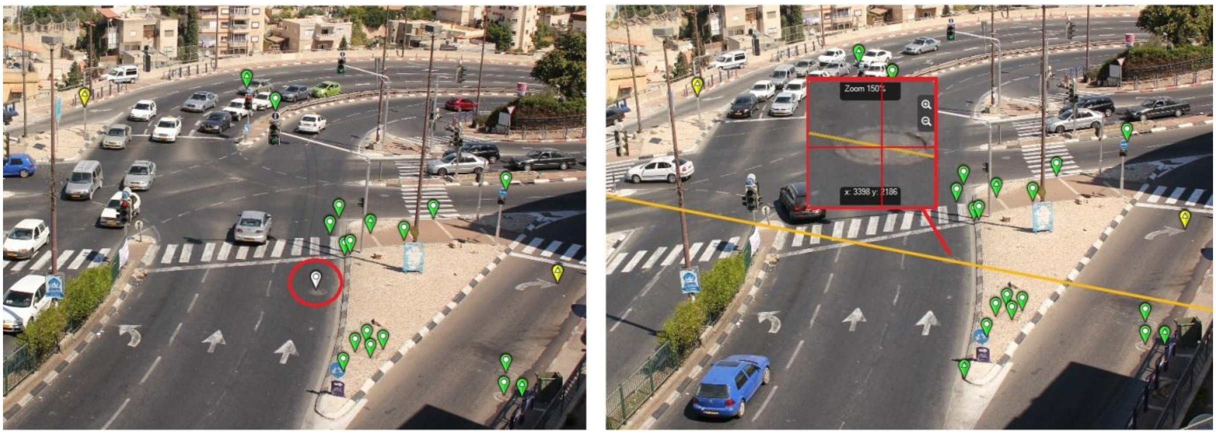

Figure (6). Applying the epipolar line to fain a point in an image pair with known relative orientation. The sampled point in the left image (white mark) generates an epipolar line in the right image (yellow line); the sampled point is on the epipolar line (red cross-hairs).

Thus, in order to address these challenges that arise from the large number of images and sampled points, the ground photogrammetry software should assist the user by automatic image processing algorithms that (a) automatically find homological tie points between any image pair, and find their relative orientation; and (b) automatically find a sampled point in one image in all other images in which it appears. Doing so, the ground photogrammetry software would overcome the key usability challenges that prohibit the usage of ground photogrammetry by land surveyors. Accordingly, there are two issues that are handled by automatic image processing algorithms:

Given an image pair with a shared overlapping area, the algorithm must automatically find at least six tie points that delimit the overlapping area. To do so, the algorithm employs image processing techniques to identify homological tie points in the image pair. Figure (7) below depicts an example for such an automatic function in Datumate's DatuGramTM3D ground photogrammetry software package.

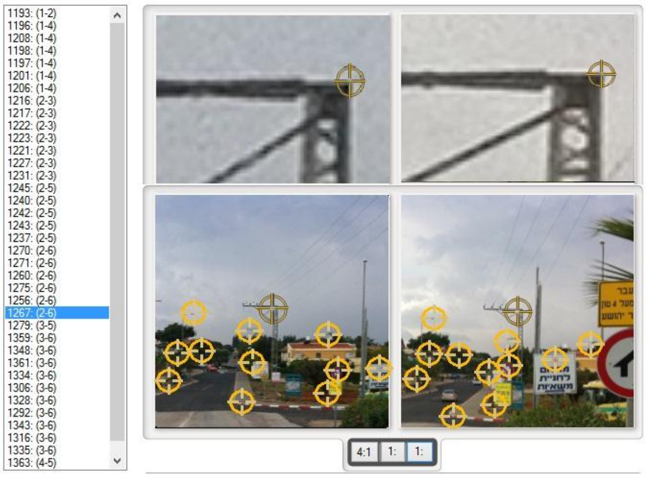

Figure (7). Example for automatically finding homological tie points in an image pair and anchoring the images together; left pane lists all homological tie points automatically found by the algorithm.

Given a number of images that cover a certain area, an algorithm should be able to automatically find a certain points in all the images after it was sampled in only one image. This way, the process of sampling new points on the images is shorten by a factor of at least three, as a point is sampled in only one image. Such an automatic function is for employed for example in Datumate's DatuGramTM3D ground photogrammetry software package.

Overall, after thoroughly implementing and testing numerous algorithms for the two tasks outlined above, one may conclude that the wider is the shared overlapping area in every image pair, and the smaller is the relative external orientation of the images, the higher is the success rate of the algorithms in accurately addressing both these tasks.

3. CALIBRATION METHODS: TUNING A DIGITAL CAMERA INTO A GEODETIC-LEVEL PRECISION MEASUREMENT TOOL

There are various techniques for calibrating a digital camera, i.e., finding the parameters of its internal orientation, and thus turning it into a geodetic-level precision measurement tool. Some of these techniques include the 'Calibration Field' method, the 'Leveling Rod' method, and the 'Checkerboard' method. The first method is the classical approach for camera calibration, which has some practical challenges, inhibiting the frequent usage of this technique by land surveyors. The last two calibration methods are a variation of the classical 'Calibration Field' method, and offer a more practical calibration procedure that may be frequently employed by the land surveyor.

3.1 The Calibration Field method

As depicted in Figure (8) below, the Calibration Field method, which is the classical approach for camera calibration, requires establishing a field of well-spread measurement targets with well-known positions.

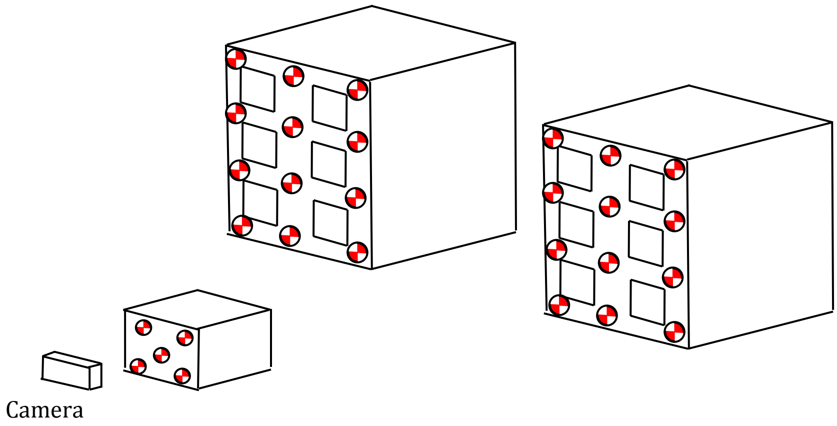

Figure (8). A calibration field using targets on building façades

As depicted in Figure (9) below, the targets in a calibration field should be well-spread across the whole area of the image. Even one image of the calibration field in Figure (9) below is enough for calculating all the parameters of the internal orientation of the camera system, and thus providing the required data for its accurate calibration.

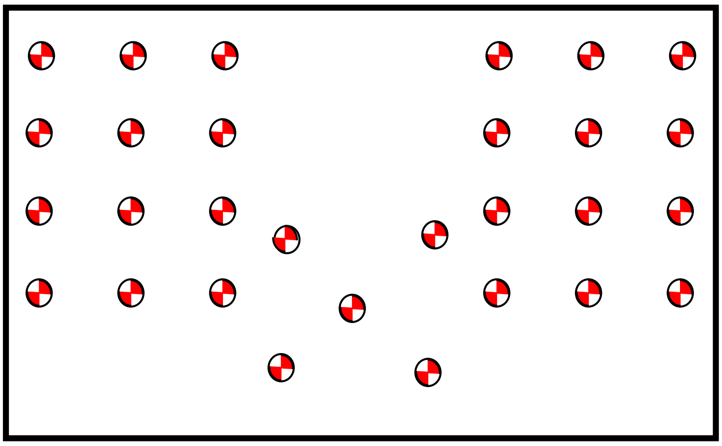

Figure (9). Schematical image of a well-spread calibration field.

After measuring the image coordinates of all the targets in the image of the calibration field, we may use the known coordinates of the targets in the world system to calculate all the hidden parameters of the camera orientation, including the five parameters of the internal orientation of the camera, i.e., (K_1, K_2, x_0, y_0, f).

The key advantages of the Calibration Field method for land surveyors include:

(a) A one-time investment in setting and measuring a robust calibration field may serve us for an extended period of time.
(b) The calibration technique is simple and highly accurate, especially of the targets are spatially well spread.

However, the key disadvantage of the Calibration Field method for land surveyors is the fact that it requires and appropriate location for setting the calibration field, and maintaining it without changes over time. This is no minor challenge for the land surveyor.

3.2 The Leveling Rod calibration method

In the Leveling Rod method, the calibration field in use is horizontal rather than vertical, and it consists of two lines of targets, as depicted in Figure (10) below. Practically it is easier to set up the front line of targets using a leveling rod (commonly used by surveyors for leveling works) that is laterally positioned in front of the camera, and thus save time and increase accuracy. In this method, since the image of the measurement targets cover only a narrow strip on the image, one cannot calibrate the camera using a single image only, and needs a minimal set of two to four images, as depicted in Figure (11) below. The solution in this case is according to the formula of the co-linear rule.

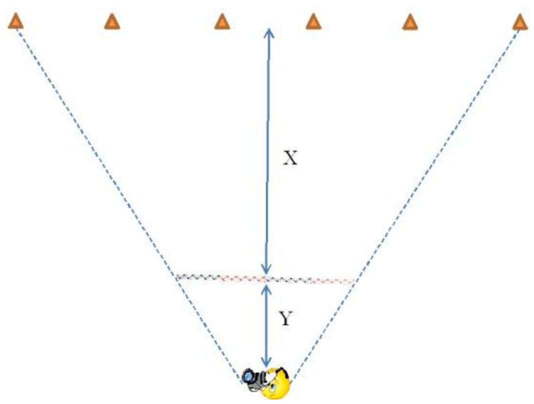

Figure (10). Schematical projection from above of the calibration project using the Leveling Rod method; orange triangles represent the control points in the far-field; Y is the distance to the horizontally positioned leveling rod; X is the distance from the leveling rod to the control points in the far-field.

The calibration process according to the Leveling Rod method includes the following steps:

Step (a). Horizontally position a leveling rod of at least four meters length in front of the camera.

Step (b). As in Figure (10) above, position five to eight measurement targets at a straight line behind the leveling rod. The closer will be the measurement targets to the leveling rod in the image, the more accurate will be the calibration process. However, the larger is the ratio between the distance of the targets from the leveling rod (X in Figure(10) above) to the distance of the leveling rod from the camera (Y in Figure(10) above), the more accurate will be the calibration. The recommended minimal ratio of X/Y is 1/6, i.e., if the measurement rod is positioned five meters from the camera, the measurement targets will be positioned thirty meters from the rod (thirty five meters from the camera). The optimal ratio of X to Y is also dependent upon the distance from which we want to do our geodetic measurements, e.g., if we want to measure a field that is fifty meters from the camera at an accuracy of two centimeters, we must assure that (a) we use a camera resolution that allows an accuracy of a pixel at that range of at least one centimeter; and (b) calibrate the camera system such that the measurement targets will be at the same range, which is fifty meters in this case.

Step (c). Take four images of the leveling rod and targets at the far-field, according to Figures (11a)-(11d) above (see example at Figure (13) below). Assure that the leveling rod is fully imaged, and is at the center of the image.

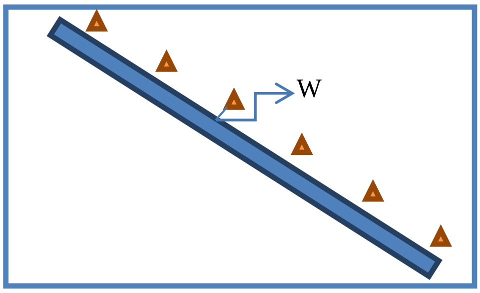

Figure (11b). Left-diagonal image of the leveling rod and far-field control points

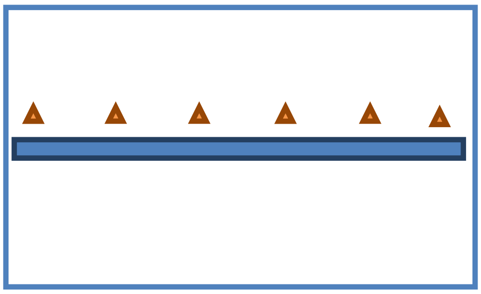

Figure (11a). Horizontal image of the leveling rod and far-field control points

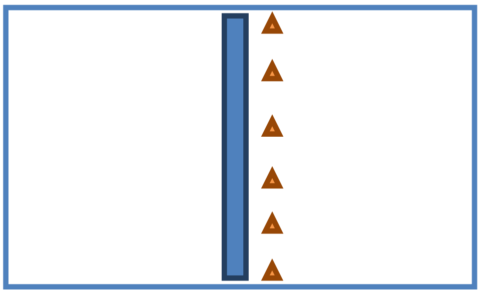

Figure (11d). Vertical image of the leveling rod and far-field control points

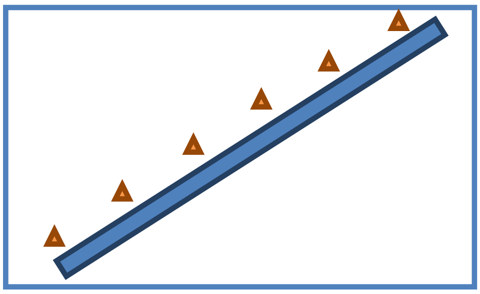

Figure (11c). Right-diagonal image of the leveling rod and far-field control points

Step (d). Measure the position of the measurement targets at the far-field with a Total Station instrument at an accuracy better than one centimeter. The land surveyor should be equipped with an appropriate technology to do so.

Step (e). Measure the position of two points at or near the ends of the leveling rod, which can be accurately located in the images (Figure (12) below). If the leveling rod consists of to several attached sections, to increase calibration accuracy, the position two points near the end of each section should be measured.

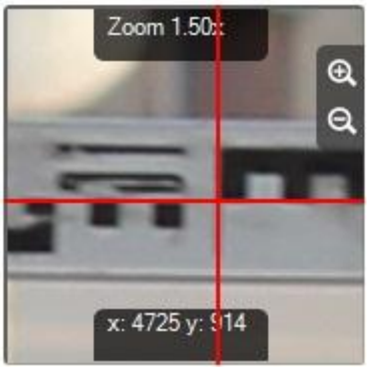

Figure (12). Sampling a well-identified point on the leveling rod which has a well-known position; the rest of the points on the rod may be sampled relative to it without requiring the physical measurement of their position.

Given the appropriate software, one only needs to measure the position of two points per section of the leveling rod, and the software may automatically spread additional measured points across rod's sections.

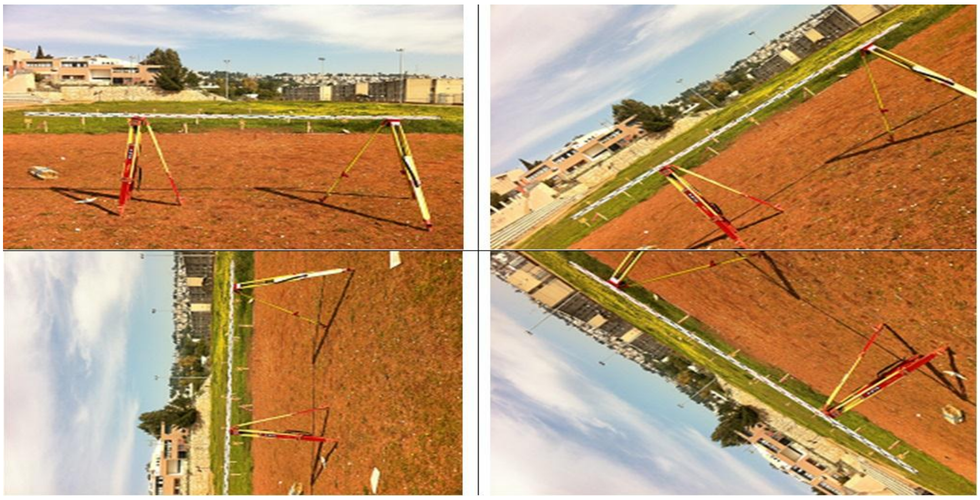

Figure (13). An example of four calibration images employing the Leveling Rod calibration method.

While using a non-prism total station instrument, since the determination of coordinates using this technology is not better than one centimeter, it is recommended to measure the position of the measurement targets at the far-field and the points on the leveling rod in at least two different measurement systems. This is especially true if a high accuracy of the camera calibration is required.

The key advantage of the Leveling Rod calibration method is that any land surveyor may frequently employ it in the field using standard surveying equipment. Moreover, the Leveling Rod calibration procedure may be combined in the photogrammetric measurement work of the measured object, thus attaining 'on-the-job' camera calibration, which is clearly more accurate than any calibration procedure done in the past.

3.3 The Checkerboard calibration method

In the Checkerboard calibration method, a checkerboard target of appropriate size is used as a calibration field. To assure a good solution for the formulas of the co-linear line rule, one must assure that the checkerboard target covers the full area of the images. As depicted in Figure (14) below, two to four images of different angles of the checkerboard target are required for the calibration process.

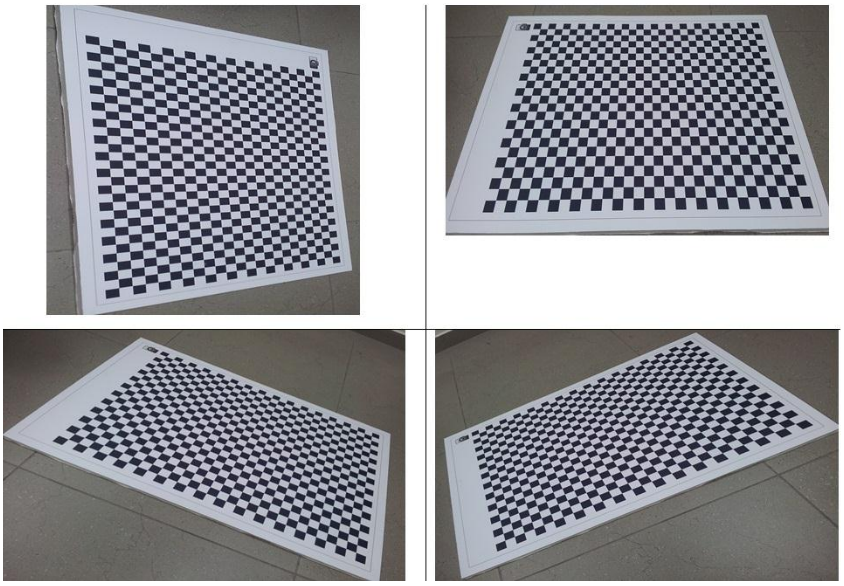

Figure (13). An example of four calibration images employing the Checkerboard calibration method.

The Checkerboard calibration method provides several appealing advantages,

(a) The calibration field is lightweight, portable, and readily available for calibration whenever the surveyor wishes to employ it. The calibration does not require a special space, and may be done in the office.

(b) The size of the target is well-known in advance, so there is no need to make laborious position measurements of targets in the field.

(c) Image processing algorithms may be employed to automatically identify the corners of the rectangles in the checkerboard target, thus allowing for a fully automatic calibration process. The quality of the automatic measurements may be done at sub-pixel accuracy, providing much better accuracy than any manual measurement.

However, while appealing to the land surveyor due to its practical nature, the Checkerboard calibration method has some drawbacks,

(a) There is no guarantee that the checkerboard target is indeed accurately flat, as assumed by the calibration procedure. The checkerboard target should be made of rigid material, assuring it remains flat throughout the calibration procedure.

(b) The parameters of internal orientation of the camera system in close range photographs may differ from the parameters at the range from which photogrammetric measurements will be made in the field. The reason for that is because one must stand relatively close to the checkerboard target in order to assure it covers in full the calibration images. However, a regular 24 mm a focus of infinity is reached from two meters and above, so if the checkerboard target is too small the camera's focus will not be at infinity, and the calibration parameters significantly differ from the parameters of the camera system in the measurement area. To resolve this one must to use a checkerboard target large enough to assure it is both covering the full area of the image while the camera is focused at infinity.

(c) In addition, when making photographs from close range, a too small depth of field may not provide a sharp and focused image of the full checkerboard target in an oblique image.

However, one cannot avoid the fact that the geometry of the checkerboard will make all elements across the main diagonal of the Variance-Covariance matrix of the final solution comparatively large. This means that the standard deviation of the elements of the internal orientation will be comparatively larger than the ones generated by the Leveling Rod calibration method.

Overcoming the challenges mentioned above is feasible by utilizing a checkerboard target as large as possible, making it from a rigid material and assuring it is as close as possible to an

ideal flat surface. To minimize the elements of the matrix of internal orientation parameters of the camera system, it is also recommended to increase the number of rectangles per length unit on the target, as well as use a larger number of calibration images.
Thus it is recommended to print the checkerboard target at a size of A0, attach it to a surface that assures exact flatness, and make a large number of calibration images from different angles (practically ten to twelve images are required). In addition, to minimize the effects of the camera's focus and the change in the focal length, one should use a camera with a lens with a focal length as small as possible (this is also quite useful for the photogrammetry in field, as it allows better coverage of the measurement field). For example, in a 24 mm lens, the light rays arrive from infinity in distance of two meters, while in a 4 mm lens (such as approximately employed in the iPhone and Galaxy smartphones) the infinity is attained already at 0.5 meters.

4. FIELD EXPERIMENTS

Multiple field experiments in different settings were executed in order to test the quality of results and the accuracy of coordinates derived from the photogrammetric model. In the field experiments the positions of objects were measured by a Total Station instrument with 3'' accuracy level in measuring azimuth and 5 mm accuracy level in measuring distances up to 250 meters without prism. This means that one may measure coordinates with this instrument relative to the position of the instrument at accuracy between 5 to 10 mm when measurements are made from a distance of 70-80 meters.

Figures (14) and (15) below depict two of these field experiments. In both filed experiments, the Total Station instrument was used to measure the position of control points to anchor the images by, as well as the position of points that were used to compare and verify the accuracy of the photogrammetric measurements. Both projects were processed by Datumate's DatuGram™3D high-precision photogrammetric software package.

The coordinates of the points that were measured by the Total Station instrument were compared to the coordinates measured photogrammetrically by Datumate's DatuGram™3D software package. The results of the experiments indicate a the difference of no more than 10-25 mm in the points' position and only 3-15 mm in the points' elevation. This makes a good case for utilizing ground photogrammetry for daily usage in geodetic measurement projects.

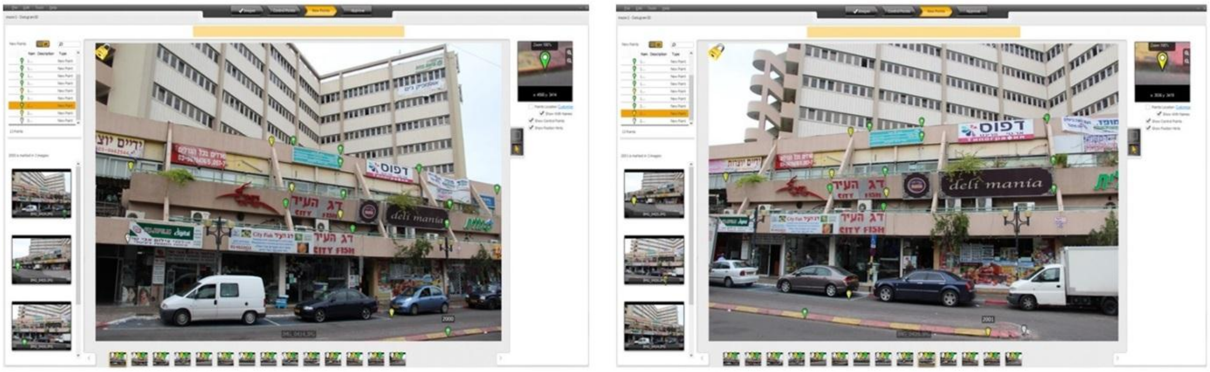

Figure (14). An example of a measurement project of a geodetic mapping of a building façade, which was used to test the photogrammetric model.

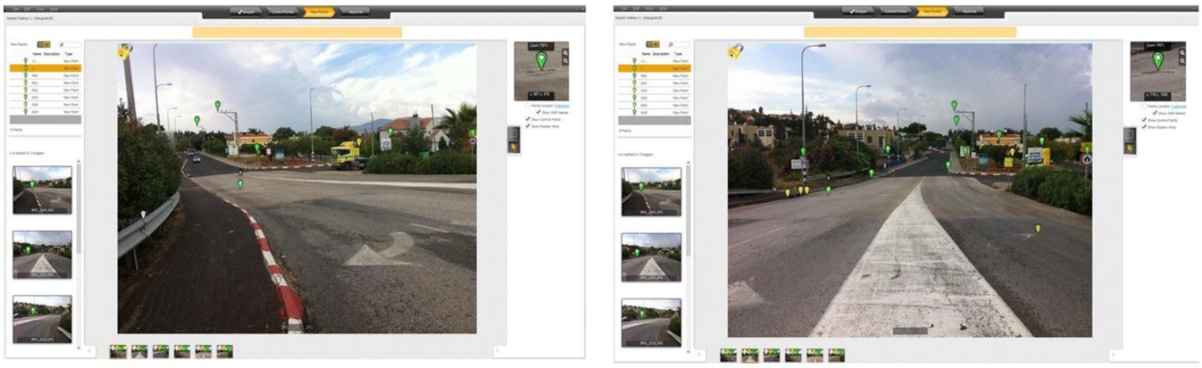

Figure (15). An example of a measurement project of geodetic mapping of a road, which was used to test the photogrammetric model.

5. CONCLUSION

There are many potential advantages for land surveyors from employing ground photogrammetry, including,

(a) As much as three-fold increase of productivity of field teams.
(b) No need for a complex sketch of the field area, as measurements are made in the images.
(c) Unparalleled quality control measures on the measurements: see what was measured, and correct if required.
(d) Ability to make follow-up measurements without returning to the field.
(e) A perfect geodetic-level way to document the measurement, allowing future measurement or quality control by other teams.

This paper outlined some of the practical challenges of employing ground photogrammetry in the daily work of land surveyors, explained the mathematical principles of ground photogrammetry, and demonstrated the ability to calculate the spatial coordinates of points from images at a geodetic accuracy comparable to Total Station instruments by using calibrated digital camera.

The paper reviewed three common methods for camera calibration, including their key advantages and disadvantages. Te paper also discussed some of the key automatic image processing algorithms that are required in order to allow land surveyors to make daily use of ground photogrammetry, replacing classical field measurement methods.

In the end of the paper two real-life examples of land surveying project were presented, the geodetic mapping of building façade and the geodetic mapping of a road, utilizing Datumate's DatuGram^{TM}3D ground photogrammetry software (www.datumate.com).

To conclude, in the opinion of the authors, when automatic image processing algorithms will be able to automatically identify the position of most pixels in a given image in all other images of the area, taken by a high-resolution camera with a known internal orientation, the ground photogrammetry technology will replace LIDAR technology at a an accuracy level of 2 cm in 3D. Such technological evolution is expected already in the near future.

In any case, ground photogrammetry technology may be immediately employed by land surveyors on a daily basis in common geodetic measurement projects. This requires the land surveyor to allocate the required technical and managerial resources for assimilating the technology, starting from using it for quality control purposes, through using it for the completion of geodetic measurements, and up to utilizing it as the main position measurement technology in geodetic mapping projects.

REFERENCES

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BIOGRAPHICAL NOTES

Dr. Jad Jarroush was born in Nazareth in 1977. Jad earned a B.Sc. in Geodetic Engineering with honors in 2000, a B.Sc. with honors in Civil Engineering and M.Sc. in Geodetic Engineering in 2002, and a PhD in Mapping and Geo-Information Engineering in 2009 - all from the Technion, Israel's Institute of Technology. In 2010 Jad founded Geo-Point, in partnership with Ofek Arial Photography, one of the largest companies in the Middle East in this field. Geo-point specializes in geo-Information, cadastre, real-estate and civil engineering, especially in building information management (BIM). Jad is currently the CEO of Datumate, a vendor of geomatic expert systems. Jad is active in the academy at the Faculty of Environmental and Civil Engineering in Israel's Technion. Jad is also a professional consultant in the cadastre field to the Survey of Israel (SOI). Jad's main fields of interest include cadastre, 3D cadastre, dynamic cadastre, legal digital cadastre, GPS RTK, VRS GPS, VRS RTK GPS,3D infrastructure presentation models and ground photogrammetry.

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