3-D MODELLING OF HISTORICAL SITES USING LOW-COST DIGITAL CAMERAS

A. F. Habib [a], M. S. Ghanma [a], R. I. Al-Ruzouq [a], E. M. Kim [a]

[a] Department of Geomatics Engineering, University of Calgary
2500, University Drive NW, Calgary AB T2N 1N4 Canada - (habib, mghanma, al-ruzouq)@geomatics.ucalgary.ca, emkim@ucalgary.ca

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ABSTRACT:

Photogrammetry is the art and science of deriving accurate 3-D metric and descriptive object information from multiple analogue and digital images. Recently, there has been an increasing interest in utilizing imagery in different fields such as archaeology, architecture, mechanical inspection, and surgery. The availability of reasonably priced, off-the-shelf, and high-quality digital cameras is encouraging such interest. Any camera needs to be accurately calibrated and tested before it can be used for accurate derivation of 3-D information. Traditional camera calibration is performed by qualified and trained professionals using a test field with numerous control points (i.e., points with known ground coordinates). To expedite the process of camera calibration, this paper outlines a new approach that is based on linear features within an easy-to-establish test field. Therefore, non-photogrammetrists can utilize the new calibration procedure with the least effort. Moreover, the simplicity of the calibration procedure allows for the evaluation of the camera stability through analyzing the estimated internal characteristics of the implemented camera from repetitive calibration sessions. The proposed technique is considerably more flexible and possesses higher degree of robustness when compared with traditional camera calibration exercises. The introduced calibration methodology allows for the utilization of digital cameras in a vast range of application areas (e.g., three dimensional archiving of models and monuments as well as the capability of generating 3-D perspective views). This paper introduces the calibration procedure, some analysis of the expected accuracy, and the suggested methodology for 3-D modelling of historical sites. Experimental results using real data proved the feasibility and the quality of the outcome from the suggested approach.

1. INTRODUCTION

Photogrammetry is concerned with deriving measurements of the size, shape and position of objects from measurements made on photographs. In its simplest form, a pair of overlapping photographs is used to create a three-dimensional model, which with the use of appropriate instrumentation can yield quantifiable dimensions of the object. Traditionally, these dimensions were represented on maps and plans, either as elevations, facades and/or contours. The use of photogrammetry as a tool to aid in the documentation of cultural heritage has a long history, and is well established as a measurement science. Recent advances in the science make the techniques much more flexible in their application and present new opportunities in the representation of monuments as diverse as aboriginal rock painting shelters, historically significant buildings and structures, and culturally significant precincts or districts.

It is clear that recent advances in digital photogrammetry have accelerated the archiving and analysis of world heritage sites (Chong et al., 2002). However, 3D modelling tools were not completely successful to model the shape of the art works of interest in cultural heritage applications. This is due to the high-cost, and/or inaccurate imaging device and shape complexity associated with artefacts to be modelled. Although, using metric cameras result in accurate measurements, the disadvantage with this class of camera remains to be the high cost. Therefore, there is a desire to utilize cheaper image acquisition tools, particularly amongst non-specialists, such as low-cost digital cameras. Recent developments of digital cameras in terms of high-quality/resolution and reduced costs have had a considerable impact on the applications of photogrammetry and in particular documentation of cultural monuments. Digital cameras, intended to replace conventional film-based mapping cameras, are becoming available along with many smaller format digital cameras capable of precise measurement applications. All such cameras require careful calibration to determine their metric characteristics, which are essential to carry out photogrammetric activities. Metric characteristics of the camera, which are known as Interior Orientation Parameters (IOP), include coordinates of the principle point, camera constant, radial and decentric lens distortion, are usually determined through a camera calibration procedure. Different calibration sessions can be used to check the stability of the implemented camera, (Habib and Morgan; and 2003 Habib et al., 2004).

Traditional camera calibration through bundle adjustment requires a test field with numerous control points that have to be precisely surveyed prior to the calibration process. Establishing and maintaining such a test field is an expensive procedure that has to be conducted by professionals. This paper introduces a new approach for incorporating straight lines in a bundle adjustment for calibrating off-the-shelf/low cost digital cameras. Utilizing linear features is advantageous for various reasons. First, straight lines can be easily established in the test fields. Also, industrial scenes are rich with straight lines. Moreover, image space linear features can be easily and precisely extracted using image-processing techniques (Kubik, 1991). The most important advantage of straight lines is that they do not have to be precisely measured in the test field. Instead, we can incorporate the knowledge that a straight line in the object space is imaged as a straight line in the image space in the absence of distortion. Therefore, deviations from straightness in the image space can be modelled and attributed to distortion parameters in a near continuous way (limited to the pixel size) along the straight line (Habib et al., 2004).

In summary, utilizing linear features instead of, or in addition to, distinct points in photogrammetry is motivated by the following reasons:

- Linear features are easier to extract than distinct points, especially in a digital environment. Pixels along a linear feature (or edge pixels) have discontinuity in one direction, while a distinct point has discontinuities in all directions.
- In the absence of distortion, straight lines in the object space appear as straight lines in the image space. Therefore any deviation from straightness can be attributed to various distortions that can be modelled using the distortion parameters.
- Linear features can be automatically extracted with sub-pixel accuracy.
- As far as camera calibration is concerned, it is much easier to establish a test field comprised of straight lines rather than establishing a traditional test field with numerous ground control points.

There are a number of approaches for utilizing linear features for camera calibration. Brown (1971) introduced the plumb-line method that uses straight lines to derive radial and decentric lens distortions. The principle behind this method is that straight lines in object space should project through a perfect lens as a straight line image. Any variations from straightness in the image space are attributed to radial and decentric distortions. This method offers a rapid and practical procedure for computing lens distortion parameters. However, the results would be contaminated by uncorrected systematic errors in the comparator and uncompensated film deformations. Moreover, we still need to perform a separate calibration procedure for determining the camera constant and other systematic distortions such as affine deformations.

Heuvel (1999b) proposed another approach for using straight lines to recover the Interior Orientation Parameters (IOP). This method can only be applied whenever we have imagery containing parallel and perpendicular lines. Similar to the plumb-line method, the radial lens distortion is estimated first. Then, the principal point coordinates and the focal length are determined later.

Prior to incorporating straight lines in the bundle adjustment procedure, a decision should be made regarding how they would be represented in the image and object space. Within most existing literature such as the work of (Mulawa and Mikhail, 1988; Tommaselli and Lugnani, 1988; Habib, 1998; Heuvel, 1999a; and Tommaselli and Poz, 1999), a straight line in the object space is defined as an infinite line using minimal representation with four degrees of freedom. Habib (1999) proposed an alternative approach for representing object space straight lines using two points (six-dimensional representation). Uniqueness and singularities are the primary reasons for choosing this representation. Since minimal representations of object space lines as an infinite one have singularities, they would not represent all three-dimensional lines in the object space. In addition, such a representation would require complicated algorithms for the perspective transformation between the object and image space, which would make it difficult to incorporate in existing bundle adjustment programs. In this research, we use two points to represent straight lines in object space, as suggested by Habib (1999). Thus, object space line segments would be well localized. On the other hand, image space lines will be represented as a sequence of 2-D points. This representation would allow us to incorporate various distortions at each point along the line.

As a result, using straight lines in camera calibration can ensure accurate estimation of the IOP. After finishing camera calibration, the 3D-construction process of the object under study can be started. The three-dimensional coordinates of points, which are required to reconstruct the object, are measured in overlapping images and incorporated in a bundle adjustment procedure. The final step is modelling, where the three-dimensional coordinates produced by photogrammetry are launched in a CAD system. In this study, AutoCAD was used to reconstruct the 3D model. Once structural information is provided for the model, AutoCAD can handle geometric, topologic and even semantic information. Moreover, texture and material information can be handled, where rendering and lighting can be used to make the model more representative to the real object under study.

In summary, the reconstruction of 3D-historical sites requires a high accuracy measuring device, affordable cost of the imaging device and capable CAD system. According to these requirements, this paper proposes a low-cost 3D modelling procedure and is organized as follows. Review of the role of photogrammetry, and in particular the advent of digital photogrammetry, on the documentation of cultural heritage is described in Section 2. An overview of the suggested mathematical model for incorporating straight lines in a bundle adjustment with self-calibration is described in Section 3. A case study to evaluate the efficiency of the suggested approach is demonstrated in Section 4. Finally, concluding remarks and possible extensions are presented in Section 5.

2. THE ROLE OF PHOTOGRAMMETRY IN PRESERVING CULTURAL HERITAGE

Natural threats to heritage include earthquakes, landslides, flood, storms, fires and avalanches, while cultural threats include war and industrial pollutions. Fire has destroyed more world heritage sites than all other natural threats (Dallas et al., 1995). If cultural sites are to be preserved for future generations, highly detailed records are essential as an insurance against their destruction by natural and cultural catastrophes (Chong et al., 2002).

Photogrammetry has been applied to the planning, recording, reconstruction, and revitalization of world heritage sites. With the advent of digital photogrammetry and image processing technology, photogrammetric recording of world heritage sites has rapidly increased. Working in a digital environment allows flexibility in the choice of computer hardware and software and enables non-photogrammetrists to produce accurate data for recording purposes. Digital object enhancement and 3D-modelling techniques are also possible and usually give clear presentation of heritage sites. They considerably enhance recognition of construction material, shape and area, and their spatial distribution, which is considered as one of the most difficult and time-consuming tasks for architects (Lerma et al., 2000).

In summary, photogrammetry offers a rapid and accurate method of acquiring three-dimensional information regarding cultural monuments. Combining the measurements obtained from the photogrammetric record and 3D CAD models offer the means to recreate historic environments. This facilitates the generation of accurate digital records of historical and archaeological objects, while reducing the overall costs.

Before using photogrammetric techniques for the recording and documentation of cultural heritage, factors that have an impact on recording accuracy and archiving efficiency have to be discussed: namely, metric characteristics of the camera, imaging resolution, and requirements of the bundle adjustment procedure (Chong et al.,2002). The next section will describe a mathematical model that incorporates straight lines in a self-calibration and bundle adjustment procedure for accurate estimation of the interior orientation parameters. This is a necessary prerequisite for accurate and reliable 3D-reconstruction.

3. MATHEMATICAL MODEL

The purpose of camera calibration is to determine numerical estimates of the IOP of the implemented camera. The IOP comprises the focal length (c), location of the principal point (x_p, y_p) and image coordinate corrections that compensate for various deviations from the assumed perspective geometry. The perspective geometry is established by the collinearity condition, which states that the perspective centre, the object point and the corresponding image point must be collinear. A distortion in the image signifies that there is a deviation from collinearity. The collinearity equations, which define the relationship between image and ground coordinates of a point in the image, are:

$$
\begin{aligned}
x_a &= x_p - c\frac{r_{11}(X_A - X_O) + r_{21}(Y_A - Y_O) + r_{31}(Z_A - Z_O)}{r_{13}(X_A - X_O) + r_{23}(Y_A - Y_O) + r_{33}(Z_A - Z_O)} + \Delta x \\
y_a &= y_p - c\frac{r_{12}(X_A - X_O) + r_{22}(Y_A - Y_O) + r_{32}(Z_A - Z_O)}{r_{13}(X_A - X_O) + r_{23}(Y_A - Y_O) + r_{33}(Z_A - Z_O)} + \Delta y
\end{aligned} \tag{1}
$$

where

x_a, y_a:	are the observed image coordinates of image point a
X, Y, Z:	are the ground coordinates of object point A.
x_p, y_p:	are the image coordinates of the principle point
c:	is the camera constant (principle distance)
X_o, Y_o, Z_o:	are the ground coordinates of the perspective centre,
$r_{11,....,}r_{33}$:	are the elements of the rotation matrix that are a function of (ω, ϕ, κ)
$\Delta x, \Delta y$:	are compensations for the deviations from collinearity.

Potential sources of the deviation from collinearity are the radial lens distortion, decentric lens distortion, atmospheric refraction, affine deformations and out-of-plane deformations. These distortions are represented by explicit mathematical models whose coefficients are called the distortion parameters such as K_1, K_2, K_3 for radial lens distortion; P_1, P_2, P_3 for decentric lens distortion; and A_1, A_2 for affine deformation. The relative magnitude of these distortions is an indication of the condition and quality of the camera.

In order to determine the IOP of the camera, including the distortion parameters, calibration is done with the use of control information in the form of a test field. In a traditional calibration test field, numerous control points are precisely surveyed prior to the calibration process. Image and object coordinate measurements are used in a bundle adjustment with self-calibration procedure to solve for the IOP of the involved camera, EOP of the imagery and object coordinates of the tie points. Establishing a traditional calibration test field is not a trivial task and it requires professional surveyors. Therefore, an alternative approach for camera calibration using an easy-to-establish test field comprised of a group of straight lines as well as some tie points is implemented in this research.

Object space straight lines prove to be the least difficult and most suitable feature to use for calibration. They are easy to establish in a calibration test field. Corresponding lines in the image space can be easily extracted using image-processing techniques such as image resampling and application of edge detection filters. Automation of the extraction process can be a reliable and time-saving approach in camera calibration. Furthermore, linear features, which essentially consist of a set of connected points, increase the system redundancy and consequently enhance the geometric strength and robustness in terms of the ability to detect blunders.

As shown in Figure 1, for a frame camera, a straight line in the object space will be a straight line in the image space in the absence of distortions. A deviation from straightness in the image space is a function of the distortion parameters.

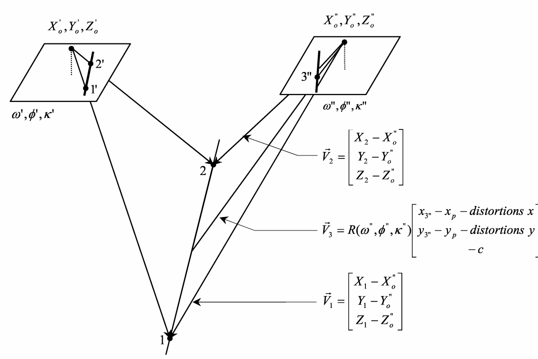

Figure 1. Perspective transformation between image and object space straight lines

Object space straight lines are incorporated in the calibration procedure by representing them with any two points along the line such as points 1 and 2 in Figure 1. These points are monoscopically measured (i.e., there is no need to identify conjugate points in overlapping images) in one or two images within which this line appears. In the image space, the lines are defined by a sequence of intermediate points such as point 3 in Figure 1. Therefore, the distortion at each point along the line can be independently modelled. In order to restrict the points to form a straight line, a mathematical constraint is adopted to establish the perspective relationship between image and object space lines. The underlying principle in this constraint is that the vector from the perspective centre to any intermediate image point along the line lies on the plane defined by the perspective centre of that image and the two points defining the straight line in the object space. This constraint is expressed as follows:

$$(\vec{v}_1 \times \vec{v}_2) \bullet \vec{v}_3 \tag{2}$$

Where

$\vec{v}_1$: is the vector connecting the perspective centre to the first point along the object space line.

$\vec{v}_2$: is the vector connecting the perspective centre to the second point along the object space line.

$\vec{v}_3$: is the vector connecting the perspective centre to any intermediate point along the image line.

Equation 2 incorporates the image coordinates of the intermediate point, the exterior orientation parameters, the interior parameters of the camera (which includes the distortion parameters) as well as the object coordinates of the points defining the object space line. The constraint in Equation 2 can be written for each intermediate point along the line in the imagery. One should note that this constraint will not introduce any new parameters. The number of constraints is equal to the number of measured intermediate points along the image line.

In summary, for a bundle adjustment with self-calibration using straight lines, the end points (points 1 and 2 in the above example) can be selected in any of the images where the straight line appears. These points need not be identifiable or even visible in other images. Four collinearity equations will be written using the measured end points for each line. The intermediate point(s) (e.g., point 3 in Figure 1) can be measured in any one of the overlapping images. These intermediate points need not be conjugate. A constraint is written for each intermediate point according to Equation 2. A schematic drawing to clarify the different scenarios for the end point selection is shown in Figure 2. Figure 2a shows a case where the end points of the straight line are selected in one image (Image 1); while in Figure 2b, they are selected in different images (Images 1 and 4). Intermediate points are shown in the same figure.

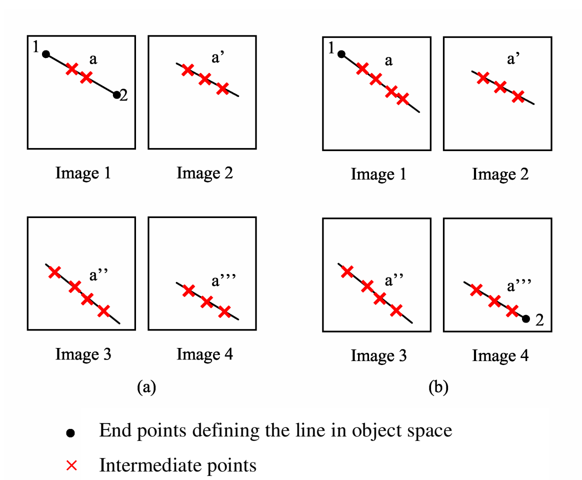

Figure 2. Schematic drawing representing two scenarios for the selection of the end and intermediate points in overlapping images

Once the calibration procedure has been carried out, the IOP of the camera that are derived from two different calibration sessions can be inspected for the purpose of stability analysis. The methodology used in this research is a bundle comparison procedure that quantifies the degree of similarity between reconstructed bundles from two sets of IOP, (Habib et al., 2004).

Afterwards, the calibrated camera is used to capture convergent images for the object to be constructed. Tie points are measured in overlapping images and incorporated in a bundle adjustment procedure. For this purpose, an arbitrary datum is chosen and three-dimensional coordinates are determined with respect to that datum. The datum for the calibration procedure is established by fixing six coordinates of three points as well as a few measured distances

The next section shows in detail a case study for the reconstruction of a historical church. The conducted experiment composed of two main parts. The first part is camera calibration. This includes constructing the test field, capturing convergent images, incorporating straight lines in bundle adjustment procedure and stability analysis of the interior orientation parameters. The second part is the 3D-reconstruction of a historical church. This includes the capture of convergent images, measuring of tie points and estimation of their 3D-coordinates and finally incorporation of these measurements in a CAD model.

4. EXPERIMENTAL RESULTS

4.1 Camera calibration

To perform calibration and stability analysis on a camera, a specific detailed procedure is carried out. A two-dimensional test field consisting of straight lines and points is used for calibration. The lines are thin dark ropes that are stretched between nails on the wall, and the points are in the form of crosses that are signalized targets used as tie points in the calibration procedure, Figure 3.

The datum for the calibration procedure is established by fixing a certain number of points as control points that are distributed in a specific way. To establish a datum, the origin, orientation and scale need to be fixed. The fixed coordinates of three points are shown in Figure 3. By fixing the X, Y and Z coordinates of point E1, the origin is established. By fixing the Y and Z coordinates of points E1 and E7 as well as the Y coordinate of point A4, the orientation is established. Finally, the scale is established by incorporating a distance measurement between any two points.

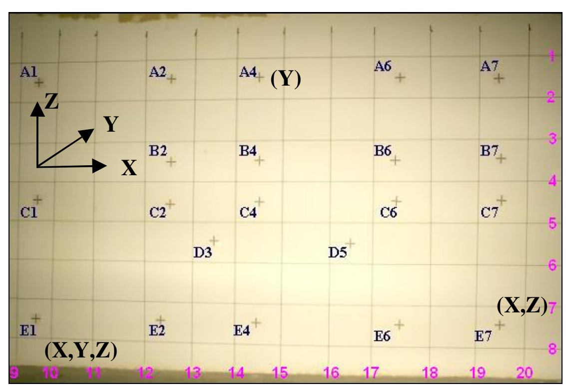

Figure 3. Calibration test field with 20 lines and 21 points

For the conducted camera calibration experiments, a total of seventy two images have been acquired in four different sessions. Each session contains eighteen converging and overlapping images that are captured at six different locations with 90° rotation around the Z-axis at each exposure station, and are roughly four to five meters away from the closest point on the test field. The position and orientation of each captured image are shown in Figure 4.

SONY DSC-F707 digital camera is implemented for calibration and stability analysis. The price of this camera is roughly $700 USD. It is a Single-Lens Reflex (SLR) camera with a Charged-coupled Device (CCD) has a resolution of 2560 x 1920 pixels and 0.004 mm pixel size.

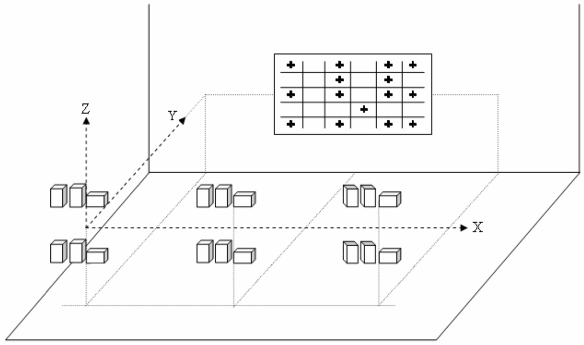

Figure 4. Position and orientation of eighteen images used for calibration

An automatic procedure for measuring the end and intermediate point coordinates along the lines in the involved imagery has been implemented (Habib and Morgan, 2003). For each line in the image space, eighty intermediate points were automatically extracted with sub-pixel accuracy.

Experiments were carried out using line-based self calibration to determine Interior Orientation Parameters of the camera and investigate the stability of these parameters. Derived estimates of camera interior orientation parameters at different times are shown in Table 1.

	July 03	October 03	February 04
σ_0	0.002595	0.0019374	0.002231
x_p (mm)	-0.114675 ± 0.001023	-0.0898 ± 0.000858	-0.090895 ± 0.000902
y_p (mm)	-0.076494 ±0.001063	-0.068292 ± 0.000871	-0.065772 ± 0.000906
c (mm)	11.620700 ± 0.002158	11.6371 ± 0.001897	11.6233 ± 0.002017
K_1	-0.001176 ±1.4730e-6	-0.001225 ± 1.3882e-6	-0.001227 ±1.3614e-6

Table 1. Estimates of the interior orientation parameters

For stability analysis, reconstructed bundles from the three different IOP sets in Table 1 were compared to check the degree of similarity between the reconstructed bundles (Habib et al., 2004). The results proved the stability of the internal characteristics of the camera. Therefore, it can be used for an accurate estimation of three dimensional coordinates as shown in the next section.

4.2 3D-Reconstruction

Architects need different types of data for the derivation of detailed plans in order to precisely reconstruct historical buildings. Generally, views, cross-sections, ground plans or complete 3D CAD models are required. Photogrammetric techniques are used to provide these products.

After estimating the interior orientation parameters of the camera, experiments are conducted based on real data to build a three dimensional model for a historical church in downtown Calgary, Canada, Figure 5. For this purpose, the calibrated SONY DSC-F707 digital camera is used to capture thirty-nine convergent images at three different locations with 90° rotation around the Z-axis at each exposure station. An arbitrary datum is chosen as reference for the object space, where 115 points are selected in the front side of the church. These measurements are introduced into the bundle adjustment in order to estimate their ground coordinates. Selection of the points was performed while considering the following issues:

- Distribution of points. The measured points have to be well distributed and cover the whole object under study.
- Visibility of each point in two or more images. If the same points appear in larger number of images, the geometrical strength as well as the accuracy of three-dimensional coordinates will be improved.
- Adequacy of selected points for the reconstruction of different shapes from an architectural point of view. For example, to draw a circle, at least three points on the circumference have to be located.

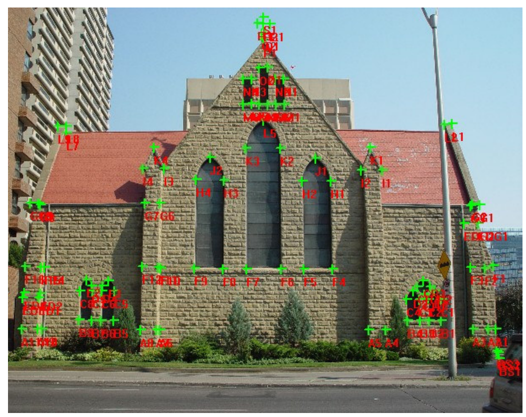

Figure 5. Historical church in downtown Calgary, Canada

As shown in Figure 6, the three dimensional coordinates resulting from the adjustment procedure are introduced into a CAD model.

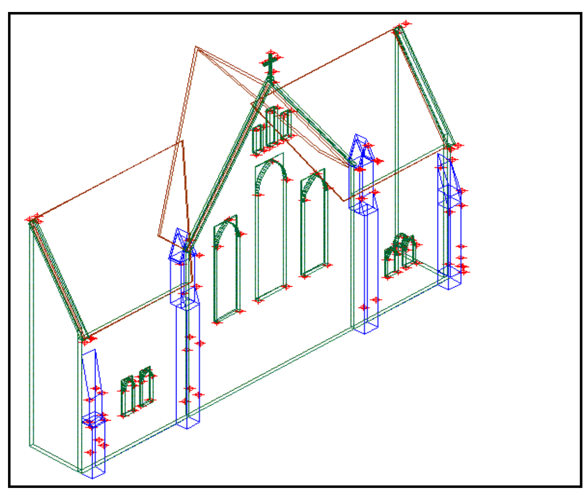

Figure 6. AutoCAD wire frame representation of the historical church

Surface rendering, which involves the generation of a 3D model with real world surface texture, is constructed, Figure 7. That is, surface textures are added to the 3D model surfaces to give a real world appearance to the displayed model. 3D surface rendering is very important for the presentation of ruined heritage sites where architects and renovation experts must have a realist view of the ruin for further inspiration (Ogleby 1999). Moreover, the 3D model can be digitally rotated to give a whole range of perspective views.

Figure 7. 3D model of the church with surface rendering

5. CONCLUSION AND RECOMMENDATION

In this study, we have presented an operational approach for the reconstruction of historical buildings. The output is in standard (AutoCAD) format, which directly supports the visualization of the reconstructed scene. The method is fast, reliable, and flexible with respect to the level of detail. The approach requires accurately measured 3-D points and the ability of the operator to interpret the scene and to subdivide complex structures into manageable sub-units.

In order to guarantee the accuracy and stability of IOP, straight lines constraints are incorporated in a bundle adjustment with self calibration. The lines are defined by a sequence of intermediate points along the line. Those points are monoscopically measured (there is no need to identify conjugate points in overlapping images). The suggested approach for camera calibration has the following advantages:

- Automation of the intermediate point measurements along the linear features improves the efficiency of the suggested approach.
- Non-photogrammetric users of off-the-shelf digital cameras can carry out the calibration procedure. This is important since it will allow such users to generate high quality photogrammetric products from regular digital cameras.

Our main goal, while developing this approach, was to show the feasibility of 3D reconstruction from a low-cost camera. Future work will focus on building a complete system that allows the user to perform three-dimensional measurements of the objects of interest (i.e., if those objects can be incorporated in the calibration test field, then the measurements and calibration can be done simultaneously).

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