Testing and application of a low-cost photogrammetric recording system suitable for cultural heritage recording

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Testing and application of a low-cost photogrammetric recording system suitable for cultural heritage recording

M.K. Kirchhöfer, J.H. Chandler, R. Wackrow

Department of Civil and Building Engineering, Loughborough University, Loughborough, UK
Email: m.k.kirchhoefer@lboro.ac.uk

Abstract

In the field of conservation, cost effective and easy to use methods are required to record cultural heritage and close-range photogrammetry has proved effective in this area. Off-the-shelf digital cameras can be used to rapidly acquire data at low cost, allowing non-experts to become involved. Exterior orientation of the camera during exposure needs to be known for every image, traditionally requiring known coordinated target points. Establishing these points is time consuming and costly and using targets can be often undesirable. To overcome these problems a recording system is being developed that is capable of deriving the exterior orientation of a camera during exposure directly and cheaply. The system comprises an off-the-shelf digital SLR camera, a small-size 3D orientation sensor and a GPS antenna. All system components were assembled in a compact and rigid frame that allows calibration of the rotational and positional offsets between the components.

The project involves collaboration between English Heritage and Loughborough University and the intention is to test the system at several heritage sites during 2010. It is expected that results from the first heritage site are presented at the conference; allowing assessment of the performance of the recording system, the stability of the calibration and the system's practicability in a heritage recording environment. Intermediate results of the ongoing data analysis indicate that the data recorded by the system can indeed meet the accuracy requirements for heritage recording with either a single or even no control points. As the recording system has been configured with a focus on low-cost and easy-to-use components, it is believed to be suitable for heritage recording by non-specialists. This offers the opportunity for lay people to become more involved in their local heritage, an important aspiration identified by English Heritage.

1 Introduction

The importance of cultural heritage for cultural, national, local or even individual identity is widely acknowledged in the literature (Aldridge, 1989; Uzzell, 1989; Hewison, 1989; Yilmaz *et al*., 2007). In 2000 a survey revealed that the majority of the English population regards heritage as important for education, economy and the cultural life of the country (Power of Place Office and English Heritage, 2000). Laenen (1989) claims that the loss of cultural heritage has an negative impact on the identity of a society.

Despite these benefits, cultural heritage is at a constant risk by neglect and decay, deliberate destruction and damage due to social and economical progress, disasters, and armed conflict (UNESCO, 1972; Power of Place Office and English Heritage, 2000; Palumbo and Ogleby, 2004). This risk, heightened by the global economic crisis, increases the need to record spatially. Comprehensive and accurate documentation can attenuate the risk of losing heritage and in the worst case serve as a basis for reconstruction (Palumbo and Ogleby, 2004). For heritage recording close-range photogrammetry is well suited and the advance of digital

technology improved its use by the availability of cheaper equipment and speeding up data processing. These developments enable non-experts to become involved in cultural heritage recording using consumer-grade digital cameras and off-the-shelf photogrammetric software (Bryan and Chandler, 2008).

Recognising the desirability to record, the costs involved with establishing known coordinated target points for exterior orientation estimation is still time consuming and costly. This problem could be overcome by direct exterior orientation estimation. In recent years small-size and low-cost orientation and position sensors have emerged on the marked. Orientation sensors based on MEMS (Micro Electro Mechanical Systems) technology have already been utilised in connection with mobile mapping projects and photogrammetry (Niu et al, 2006; Guarnieri et al., 2008). Although their accuracy is lower than that of their large-size counterparts, the results look promising. Some research has been done on the accuracy of handheld GPS devices (Schwieger and Gläser, 2005; Wing et al., 2005). Although the results show that currently the accuracy does not meet the requirements for some applications of close-range photogrammetry, Schwieger and Gläser (2005) demonstrated that there is potential for improvements in the future.

2 Aims and Objectives

To reduce costs and enable non-experts to get involved in cultural heritage recording projects, an image-based recording system comprising low-cost sensors has been developed. This paper reports on the current status of this ongoing project. The components of the recording system are introduced and the procedures being used to assess the performance and applicability of the recording system. Intermediate results are presented also.

3 Methodology

3.1 Components of recording system

The recording system comprises a calibrated off-the-shelf digital camera (Nikon D80) and a small-size 3D orientation sensor (TCM5, manufactured by PNI) capable of measuring heading, pitch, and roll. The accuracy specifications of the orientation sensor can be found in Table 1. The position of the camera is determined using survey-grade Leica DGPS, because current low-cost receivers do not yet meet the accuracy requirements for close-range photogrammetry. A prism can also be fixed to the recording system and the position can be determined using a Total Station. This option facilitates the utilisation of the recording system when GPS is not available, e.g. inside buildings or under the canopy in forested areas.

Table 1: Accuracy specification of the orientation sensor TCM5.

Name	TCM5
Manufacturer	PNI
Accuracy	
Heading (Tilt < 70º)	0.3º
Heading (Tilt > 70º)	0.5º
Pitch	0.2º
Roll (Pitch < 65º)	0.2º
Roll (Pitch < 80º)	0.5º
Roll (Pitch < 86º)	1.0º

The camera, the orientation sensor and the DGPS antenna or prism have been assembled in a purpose built rigid frame made of aluminium (Figure 1) that prevents the components from moving with respect to each other. Therefore the rotational offset between orientation sensor

and camera as well as the positional offset between DGPS antenna and camera are fixed and can be calibrated. Because the orientation sensor has no internal data storage capability, a laptop is used for storing measurements. The receiver part of the DGPS and the laptop are not attached to the mounting frame but connected to their respective recording system components (orientation sensor and DGPS antenna) via conventional cables (Figure 1b).
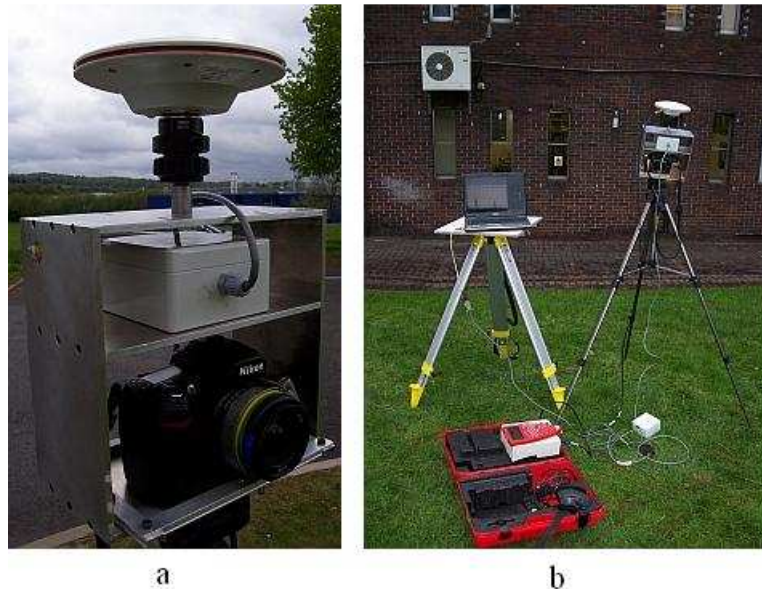

Figure 1: Recording system. (a) Rigid frame with DGPS antenna, orientation sensor, and digital camera (from top to bottom). (b) Completely assembled recording system during data collection.

3.2 Tests on campus

A test field was established on the outside wall of a building located on Loughborough University campus (Figure 2). The field consists of 43 coordinated targets attached to the wall. Ordnance Survey National Grid (OSGB36) coordinates of the targets were obtained using a Total Station set up at two survey stations that had been established using DGPS.
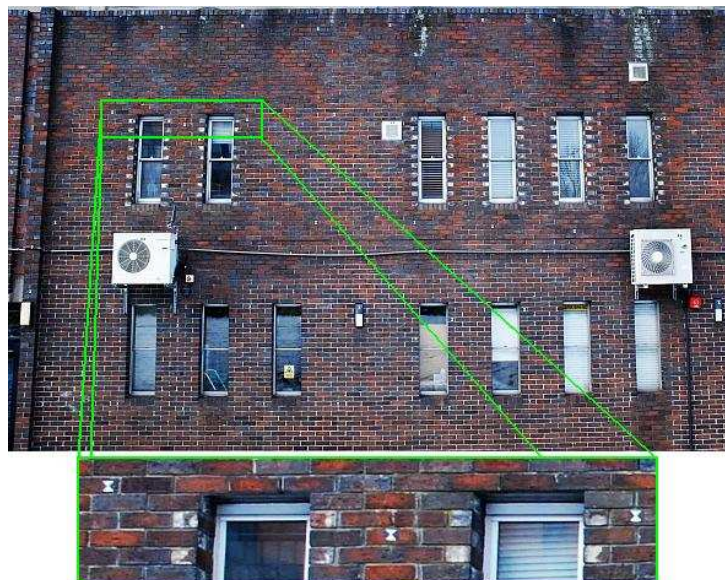

Figure 2: Test field on an outside wall of a building located on Loughborough University campus.

At this test field, data was collected for an intermediate assessment of the stability of the offset calibration and the achievable accuracy. Within three months five data sets were collected on five different days. A data set consists of imagery, the heading, pitch, and roll values from the orientation sensor and 3D position information from either GPS or Total Station. For the most recent data set (Test5) the position was determined using Total Station, for the others DGPS was used. During data collection a wide range of possible orientations were recorded by deliberately introducing high roll and pitch values. For the intervals between recording days the camera was detached from the mounting frame and only reattached for data recording.

3.3 Data analysis

The Leica Photogrammetric Suite (LPS) was used to derive the exterior orientation of the camera for each recorded image in a bundle adjustment. Between 8-17 image frames were included in each block bundle adjustment, with typically 10-20 targeted points measured on each frame. These exterior orientation values are considered true and are used to validate the exterior orientation parameters derived from the orientation sensor and DGPS (or Total Station) measurements.

To assess the accuracy of the orientation sensor omega, phi, and kappa derived in the LPS bundle adjustment were converted into heading, pitch, and roll using a procedure coded in Matlab. The results could directly be compared to the output of the orientation sensor. The stability and reliability of both the required rotational and positional offset calibration was also investigated. The absolute positional offset, i.e. the difference between the measured position using DGPS or Total Station and the position derived in LPS, varies depending on the pitch and roll of the mounting frame. To be able to derive calibration values for Easting, Northing, and Height the positional offsets relative to the mounting frame have to be calculated. For each image frame the vector that represents the absolute positional offset was normalised by rotating it back into the non-rotated camera coordinate system using the rotation angles derived in LPS. These normalised vectors represent the relative positional offset.

Further Matlab software was developed to convert heading, pitch, and roll to omega, phi, kappa and determines calibration values, necessary to correct the directly determined exterior orientation parameters. These corrected values were used to provide initial exterior orientation parameters, constrained by their estimated precision, in a bundle adjustment software known as GAP (Chandler and Clarke, 1992). For each data set this bundle adjustment was run three times. For the first run, three control points were available. In the following run the number of control points was reduced to one. The last bundle adjustment was performed using no control points, relying on the directly determined exterior orientation values only. The coordinates of check points derived in the bundle adjustment were compared to the known coordinates of the points and the RMSE (Root Mean Square Error) was calculated.

3.4 Tests on heritage site

To assess the applicability of the recording system in a cultural heritage environment it has to be tested on real heritage. In May 2010 data was collected at St. Catherine's Oratory on the Isle of Wight, UK. Data analysis for this project is ongoing and therefore the focus is on results of data collected using just the test field.

4 Results

4.1 Calibration stability and reliability

The average rotational offset (Figure 3a) is calculated by averaging the differences between heading, pitch, and roll measured by the orientation sensor and the equivalent values calculated from the output of the LPS bundle adjustment (omega, phi, kappa) using Matlab. It represents the calibration value that is used to correct the orientation sensor data for the rotational offset between sensor and camera. Ideally the average offset has the same magnitude for each data set, thus once determined being valid for every subsequent dataset. Here the average offsets for the three angles vary significantly. The variations are especially high for the heading values, where they exceed 4 degrees (Figure 3a). This is caused by detaching the camera after data recording and reattaching it before new data is collected. If the camera is fixed to the system permanently it can be expected that the average offset is more stable. The standard deviation of the average rotational offsets (Figure 3b) is significant to the calibration reliability. It should be no higher than the accuracy specifications of the orientation sensor. A high standard deviation indicates variation of rotational offsets during data collection, i.e. the camera and the orientation sensor are moving with respect to each other.
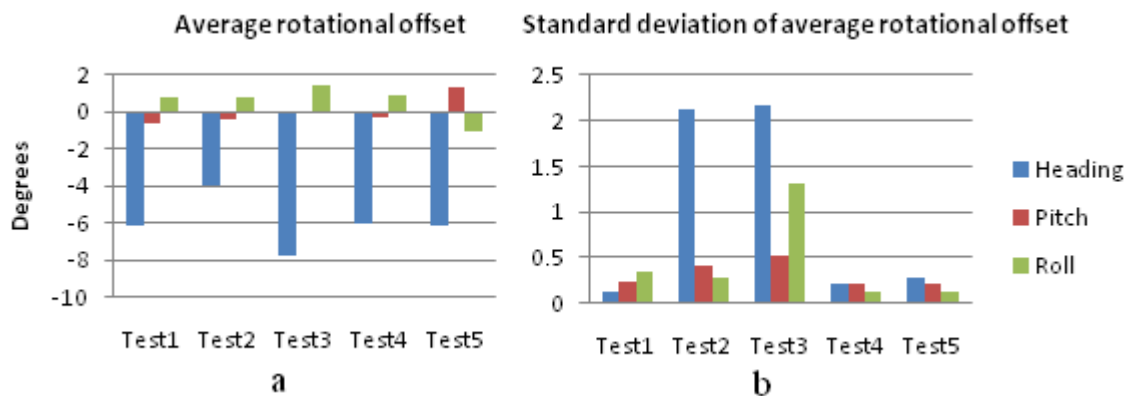

Figure 3: Average rotational offset (a) and standard deviation of the average rotational offset (b) calculated for each test data set separately.

The increase in the standard deviation from Test1 to Test3 is noticeable and again reaches the highest value for the heading difference with about 2°. An investigation of the data for each image frame separately revealed that changes in the rotational offset always occurred when the measured roll angle was large (>30°). Some smaller changes also occurred when the pitch angle was larger than 20º. In Test4 where no large roll or pitch angles occur the standard deviation is below 0.25°. The source of the problem could be identified as a weakness of the fixture of the camera to the mounting frame. The fixture loosened during use and allowed the camera to rotate with respect to the orientation sensor. Test5 was recorded after the camera fixture was modified to prevent these rotations. Even with large roll and pitch angles in Test5 the standard deviation, 0.27° for heading, 0.21° for pitch, and 0.12° for roll, meets the orientation sensor specifications (Table 1).

Figure 4a shows the average positional offset, which represents the calibration value for the position. Test5 is the only data set where Total Station was used for positioning. Although the positional offset cannot be compared to the results of the other data sets it is included in the graph for completeness. The variation of the values of Test1 to Test4 was expected as both the camera and DGPS antenna had to be reattached to the mounting frame every time new

data was collected. As with the rotational offsets the standard deviation (Figure 4b) is significant to the calibration reliability. For data sets Test1 to Test4 the standard deviations range from 1cm up to 6cm. These standard deviations do not meet the theoretical accuracy for DGPS, which should be 5-10mm in plan and 10-25mm in height. The standard deviations in Test5 are significantly smaller (< 1cm). This can be explained by the higher positional accuracy of the Total Station compared to DGPS. It can partly be a result of the modifications to the camera fixture also.
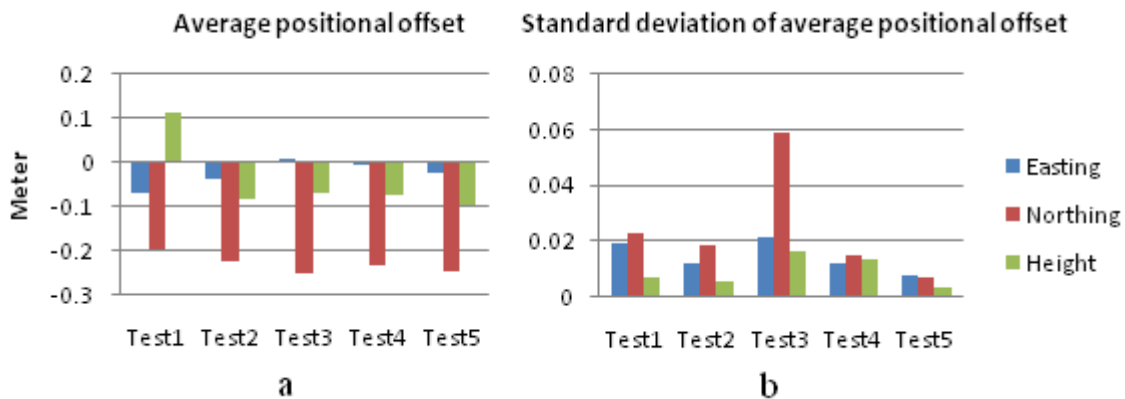

Figure 4: Average positional offset (a) and standard deviation of the average positional offset (b) calculated for each test data set separately.

4.2 Recording system performance

The overall performance of the recording system during testing on campus was assessed by comparing the coordinates of check points derived in a bundle adjustment using the directly determined exterior orientation with the known coordinates of the check points. The results are shown in Figure 5.
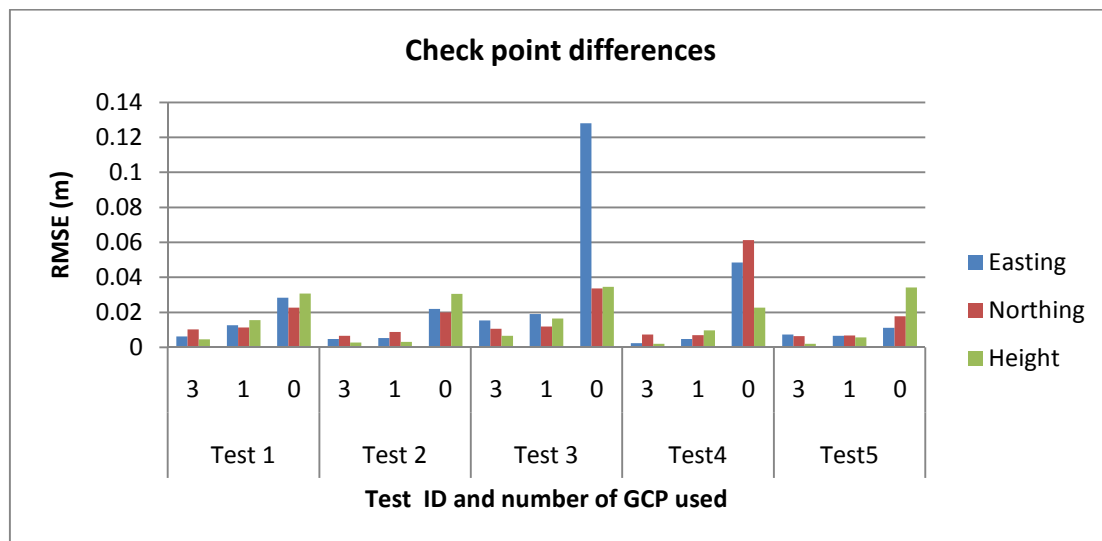

Figure 5: Results of bundle adjustments using directly determined exterior orientation data. For each data set bundle adjustment was done three times varying the number of control points (3, 1, and 0 control points).

In general better results can be expected when control points are available. But even with no control points used the RMSE is no worse than 3.1cm in object space for the data sets of Test1 and Test2. This is different for Test3 and Test4 where the RMSE is as high as 12.8cm.

The RMSE decreases in Test5 with the highest value being 3.4cm. It appears that as long as at least one control point is available, the RMSE is never higher than 2cm.

5 Discussion

The high standard deviations for the average rotational offset (Figure 3b) were traced back to a weakness in the fixture of the camera. Because consumer-grade cameras are designed to be comfortable when hand held, it is difficult to attach them to a system in a way that prevents rotations with respect to the mounting frame. For a reliable and stable offset calibration it is crucial to solve this problem. To be able to verify the stability of the modified camera fixture more data is needed, as Test5 is the only test data set recorded with the enhanced system. The standard deviation in Test5 (Figure 3a) indicates an improvement of the rotational calibration reliability due to the modification of the camera fixture. The problem with the camera fixture might have also affected the position calibration. This is indicated by the fact that the standard deviation of the average positional offset for Test1 to Test4 is higher than the theoretical accuracy for DGPS. Whether the modification of the camera fixture improved the positional calibration reliability can only be verified with new data sets where DGPS was used for position determination. Currently the average offset difference for both rotation and position is calculated using the measured and calculated exterior orientation values of all image frames. Therefore the calibration still relies on a high number of control points and processing in photogrammetric software. At the same time it was shown that the calibration currently is not stable enough to be valid for all data sets recorded with this recording system. To solve this it is planned to find different approaches that relies on a smaller number of control points (1-3) in one image frame only.

The results of the recording system performance investigation indicate that if one control point is available, the recording system could be applied in cultural heritage recording projects where a positional accuracy in object space of 2cm is acceptable. It appears that even if individual orientation frame estimates are unreliable, the combination within an appropriately constrained block bundle adjustment generates an acceptable coordinate system definition.

A sixth test data set has been recorded recently using a non-planar object on a campus. That led to a different range of orientation values which during data analysis revealed a small error in the approach used to convert heading, pitch, and roll measurements of the orientation sensor into omega, phi, and kappa. These values are used for offset calibration and subsequently utilisation in a bundle adjustment. Currently the transformation algorithm is being revised and it is expected that the utilisation of the new algorithm will improve further the quality of the rotational offset calibration and the result of bundle adjustments using directly determined exterior orientation parameters.

A further source for inaccuracies that might affect the calibration and therefore the recording system performance is the initialisation of the orientation sensor. The orientation sensor has to be initialised to calibrate for magnetic distortions that might affect the built-in compass used to determine heading. The initialisation is performed using a program provided by the manufacturer of the orientation sensor (TCM Studio). The investigation of the reliability of the initialisation process is ongoing also.

6 Conclusion

In this paper it is suggested that direct exterior orientation determination for close-range photogrammetry using a consumer-grade digital camera, a low-cost orientation sensor and DGPS can reduce costs in cultural heritage recording projects. Although it still has to be

tested fully, if the new camera fixture to the mounting frame is stable enough to allow for a reliable offset calibration, intermediate test results indicate potential for cost reduction by reducing the number of control points needed. The ultimate objective is to remove the need for any control points and thus further enable non-experts to use close-range photogrammetry in cultural heritage recording.

7 Acknowledgements

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