ABSTRACT

Increasing resolution and reducing cost of off-the-shelf digital cameras are giving rise to their utilization in traditional and new photogrammetric activities, and allowing amateur users to generate high-quality photogrammetric products. For most, if not all photogrammetric applications, the internal metric characteristics of the implemented camera, customarily known as the Interior Orientation Parameters (IOP), need to be determined and analyzed. The derivation of these parameters is usually achieved by implementing a bundle adjustment with self-calibration procedure.

The stability of the IOP is an issue in digital cameras since they are not built with photogrammetric applications in mind. This thesis introduces four quantitative methods for testing camera stability, where the degree of similarity between reconstructed bundles from two sets of IOP is evaluated. The experiments conducted in this research demonstrate the stability of several digital cameras. In addition, the need for different stability analysis measures for different geo-referencing techniques will be demonstrated. Some potential applications of low-cost digital cameras involving 3-D object space reconstruction will also be discussed.

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DEDICATION

I would like to dedicate this work to my family, especially my parents, and my fiancé. Their support, encouragement, and understanding have been monumental during the course of my education.

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LIST OF SYMBOLS

x_A, y_A	Observed image coordinates of an image point
X_A, Y_A, Z_A	Ground coordinates of an object point
X_0, Y_0, Z_0 ω, φ, κ	Exterior Orientation Parameters (EOP) – X_0, Y_0 and Z_0 represent the position of perspective center with respect to the ground coordinate system, where ω, φ and κ represent the rotation angles between the ground and image coordinate systems
x_p, y_p, c	Calibrated principal point position and principal distance of the camera with respect to the image coordinate system
K_1, K_2	Radial lens distortion parameters
P_1, P_2	De-centric lens distortion parameters
A_1, A_2	Affine deformation parameters
r_{11}, r_{12},…,r_{33}	Elements of a rotation matrix that are a function of ω, φ, κ
σ_o	Square root of the variance component from a least squares adjustment

LIST OF ABBREVIATIONS

2-D	Two Dimensional
3-D	Three Dimensional
CCD	Charge Coupled Device
DEM	Digital Elevation Models
EOP	Exterior Orientation Parameters
GCP	Ground Control Point
GPS	Global Positioning System
INS	Inertial Navigation System
IOP	Interior Orientation Parameters
MIS	MISclosure similarity measure
RMSE	Root Mean Square Error
ROT	ROTation similarity measure
SPR	Single Photo Resection similarity measure
ZROT	Zero ROTation similarity measure

CHAPTER 1

INTRODUCTION

1.1 Background

The fundamental objective of photogrammetry is to generate three-dimensional spatial and descriptive information from two-dimensional imagery. Reliable and accurate recovery of three-dimensional information from imaging systems requires accurate knowledge of the internal characteristics of the involved camera. These characteristics, customarily known as the Interior Orientation Parameters (IOP), include the focal length of the camera, coordinates of the principal point, and distortion parameters. To determine the IOP, a bundle adjustment with self-calibration is the commonly employed technique. The calibration procedure requires control information, which is usually available in the form of a test field. Traditional calibration test fields consist of distinct and specifically marked targets (Fryer, 1996). Alternatively, other techniques have been developed for camera calibration using a test field comprised of linear features. The utilization of linear features for camera calibration provides a means to easily establish the calibration test field, to automatically extract the linear features from digital imagery, and to derive the distortions associated with the implemented camera by observing deviations from straightness in the captured imagery of object space straight lines (Habib and Morgan, 2003).

Since its inception, the use of film/analog metric cameras has been the norm in photogrammetric applications. However, the role of digital cameras in such applications has been rising along with its rapid development, ease of use, and availability. Analog metric cameras, which are solely designed for photogrammetric applications, proved to possess a strong structural relationship between the elements of the lens system and the focal plane. Practical experience with these cameras showed that they maintain the stability of their IOP over an extended period of time. On the other hand, the majority of commercially available digital cameras are not designed with photogrammetric applications in mind. Therefore, the stability of their internal characteristics should be carefully examined prior to their use in photogrammetric applications. This thesis will present four methodologies for comparing two sets of IOP of the same camera that have been derived from two calibration sessions. The objective of the presented methodologies is to decide whether the two IOP sets are equivalent or not. It should be noted that these methodologies are general enough that they are applicable for stability analysis of analog and digital cameras.

1.2 Scope of Research

The primary purpose of the research is to establish the practical use of off-the-shelf digital cameras by introducing innovative methodologies for the stability analysis of such cameras, conducting experiments with them, and using them in potential applications.

The following points reveal the central objectives of the research required to fulfill the goals of this thesis work.

Objective 1 – Describe the process of camera calibration:

Calibration is used to model and estimate the IOP of a camera, which is required to generate three-dimensional information. In traditional camera calibration activities, control information takes the form of distinct and specifically marked points/targets. A description of this traditional approach as well as the drawbacks of implementing such control will be presented. As an alternative for representing control, a calibration test field consisting of straight lines is used in this research. Several approaches for the representation and utilization of straight lines that have been proposed in literature will be discussed. A mathematical model that incorporates overlapping images with straight line features in a bundle adjustment with self-calibration process will be described. Furthermore, an explanation of how linear features are incorporated in the calibration process will be provided by describing the process of selecting end and intermediate points along the line, the optimal configuration of the lines, and the linear feature extraction process.

Objective 2 – Present new bundle comparison methodologies for analyzing the stability of cameras:

A point of concern in the camera calibration process is the reliability of the estimated IOP. Professional mapping cameras have been designed and built to assure the utmost stability of their internal characteristics over a long period of time. However, in the case of low-cost digital cameras, their internal characteristics are not given due consideration by the manufacturers. They are designed with amateur applications in mind and hence, the stability of the IOP of these cameras cannot be guaranteed. Therefore, the stability of their internal characteristics needs to be analyzed prior to their use in photogrammetric applications. Since there are no established procedures and standards for evaluating the stability of the IOP, this research focused on developing stability analysis procedures that would be meaningful from a photogrammetric point of view.

Before these proposed measures of stability are described, a basic statistical approach for comparing two sets of IOP derived from two calibration sessions and its drawbacks will be presented. Then the thesis will focus on introducing the four new meaningful, quantitative methods, which are based on evaluating the degree of similarity between two reconstructed bundles that are generated from two sets of IOP. Each method has its own advantages and disadvantages, which will also be explained. The described stability measures are general enough that they can be applied to digital as well as analog cameras.

Objective 3 – Present results of conducted calibration and stability analysis tests:

In this research, a few digital cameras have been calibrated and evaluated for stability over a significant period of time. This thesis will provide these stability results and an analysis of the tested cameras as well as discuss the factors affecting the calibration and stability of their IOP. Additionally, the IOP sets will be compared using three of the four proposed similarity measures. The reason why one measure is not implemented is because it assumes the same principal distance for the two sets of IOP being compared. Furthermore, estimated IOP sets derived from image datasets acquired on the same day will be compared against different calibration conditions. These conditions involve changing certain settings on the camera (like the focusing method), changing the size of the test field, and altering the number of estimated parameters in the calibration procedure. Based on the experiments conducted, some tips and precautions on performing the calibration and stability analysis will also be presented.

Objective 4 – Discuss stability analysis requirements for different geo-referencing techniques:

The use of different stability analysis methods for direct and indirect geo-referencing techniques will be described. Since direct geo-referencing will introduce constraints regarding the position and attitude of the defined bundles in space, a specific stability analysis method will be applicable depending on the constraints. This idea will be confirmed through experiments involving simulations of an image block using a pre-defined object space and one set of IOP; a reconstruction of the object space using the simulated image block and a different set of IOP; and a comparison of the true object space and the reconstructed one. The thesis will essentially test the hypothesis that using a certain IOP set in the reconstruction procedure will yield an object space whose quality is dependent on the degree of similarity between the IOP set used in simulation and the IOP set used in reconstruction.

Objective 5 – Discuss potential applications:

In this research, a few applications involving the implementation of low-cost digital cameras for 3-D object space reconstruction have been investigated. These applications necessitate the use of camera calibration and stability analysis measures prior to the recovery of 3-D information and include:

- Generation of 3-D CAD models of a building for archiving
- Measurement of facial features for personal identification
- Photogrammetric measurements used for medical applications like the reconstruction of a human torso for spinal disorders, the measurement of wounds and fixed implant prosthesis

The process of calibration and stability analysis of the implemented cameras is required because the accuracy of the reconstruction is dependent on the accuracy and reliability of the camera's IOP.

1.3 Thesis Outline

The entire thesis is divided into seven chapters. The following list describes the contents of the remaining chapters:

- Chapter 2: Literature Review – A review of some published work related to the thesis topic will be presented, which will include a description of self-calibration distortion models, traditional approaches of calibration, different methods of representation and utilization of straight line features, and a calibration approach where object space straight lines are utilized in a bundle adjustment with self-calibration procedure.

- Chapter 3: Stability Analysis – This chapter will outline the basic methodology for stability analysis using statistical testing, as well as the four proposed methodologies where the degree of similarity is evaluated between reconstructed bundles using two sets of IOP.

- Chapter 4: Experiments and Results – This chapter will provide a description of the test field, the cameras employed in the experiments and the software programs that are used in the calibration and stability analysis process. In addition, an analysis of the experimentation results will also be included.

- Chapter 5: Direct/Indirect Geo-referencing – This chapter will verify the need for different stability analysis measures for different geo-referencing techniques.

- Chapter 6: Applications – This chapter will discuss a few potential applications of low-cost digital cameras involving the calibration and stability analysis of digital cameras.

- Chapter 7: Conclusions and Future Work – A summary of the methodologies and research work will be provided along with some recommendations of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The primary purpose of camera calibration is to determine numerical estimates of the interior orientation parameters of the implemented camera. The interior orientation corresponds to the principal distance (c), location of the principal point (x_p, y_p), and image coordinate corrections that compensate for various deviations from the assumed perspective geometry, which together are known as the IOP of the camera. The image coordinate corrections are modeled as distortion parameters and are described in Section 2.2. The traditional approaches of calibration, which involve the utilization of point targets as a source of control, are then described in Section 2.3. A calibration test field consisting of points is hard to establish and maintain, and requires professional surveyors. For this reason, the calibration test field implemented in this research involves the utilization of linear features. Section 2.4 will look into the advantages of incorporating linear features, various calibration methodologies that utilize straight lines, different methods of representing straight lines, and a mathematical model that incorporates overlapping images with straight line features in a bundle adjustment with self-calibration procedure (Habib et al., 2002-a). The configuration of the lines in the calibration test field is also an important consideration since it affects the accurate recovery of the distortion parameters being estimated. Thus, an optimal configuration of the straight lines for an effective estimation of the distortion parameters will be put forward. Finally, the automated process of extracting linear features from the imagery will be described in complete detail.

2.2 Calibration Distortion Models

As mentioned above, the IOP consists of the focal length, principal point coordinates, 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 center, the object point and the corresponding image point must be collinear (Kraus, 1993). A distortion in the image signifies that there is a deviation from collinearity. Potential sources of the deviation from collinearity are the radial lens distortion, de-centric lens distortion, atmospheric refraction, affine deformations and out-of-plane deformations (Fraser, 1997). All these sources of distortion are represented by explicit mathematical models whose coefficients are called the distortion parameters (e.g., K_1, K_2, K_3… for radial lens distortion, P_1, P_2, P_3 for de-centric lens distortion, and A_1, A_2 for affine deformations).

Radial lens distortion (RLD):

The radial lens distortion occurs when the path of a light ray is altered as it passes through the perspective center of the lens. It is caused by large off-axial angles and lens manufacturing flaws, and takes place along a radial direction from the principal point. The correction for the radial distortion of the measured point is modeled by the polynomial series in the following equations (Kraus, 1997):

$$
\begin{aligned}
\Delta x_{RLD} &= K_1(r^2-1)x + K_2(r^4-1)x + K_3(r^6-1)x + \ldots \\
\Delta y_{RLD} &= K_1(r^2-1)y + K_2(r^4-1)y + K_3(r^6-1)y + \ldots
\end{aligned}
\qquad (2.1)
$$

Where: $r=\sqrt{(x-x_p)^2+(y-y_p)^2}$, K_1, K_2 and K_3 are the radial lens distortion parameters, x_p and y_p are the image coordinates of the principal point, and x and y are the image coordinates of the measured point. The K_1 term alone will usually suffice in medium accuracy applications and for cameras with a narrow angular field of view. The inclusion of K_2 and K_3 terms might be required for higher accuracy and wide-angle lenses. The decision as to whether incorporate one, two, or three radial distortion terms can be based on statistical tests of significance (Habib et al., 2002-b). Another reason why estimating only K_1 would be preferable is that estimating more than the required amount of distortion parameters could increase the correlation between unknown parameters and this will likely affect the IOP estimates.

De-centric lens distortion (DLD):

The de-centric lens distortion is caused by inadequate centering of the lens elements of the camera along the optical axis. The misalignment of the lens components causes both radial and tangential distortions, which can be modeled by the following correction equations (Brown, 1966):

$$\Delta x_{DLD} = P_1(r^2 + 2x^2) + 2P_2xy$$
$$\Delta y_{DLD} = P_2(r^2 + 2y^2) + 2P_1xy \qquad (2.2)$$

Where: P_1 and P_2 are the de-centric lens distortion parameters.

Atmospheric refraction (AR):

Atmospheric refraction occurs when a light ray from the object point to the perspective center passes through atmospheric layers that vary in temperature, pressure and humidity. To remove the effect of atmospheric refraction, standard correction formulas are applied to the image measurements prior to the adjustment. If there are any remaining atmospheric refraction effects in the measurements, it can be compensated for by the radial lens distortion coefficients in view of the fact that both distortions occur along the radial direction.

Affine deformations (AD):

Affine deformations are deformations that occur in the focal plane and usually originate from non-uniform scaling along the x and y directions, and sometimes from non-orthogonality between the x-y axes. They could be caused by non-square pixels, which will lead to scale differences if considered square, and by the non-orthogonality of the rows and columns in the CCD array. The correction equations for affine deformations are:

$$\Delta x_{AD} = -A_1x + A_2y$$
$$\Delta y_{AD} = A_1y \qquad (2.3)$$

Where: A_1 corresponds to half of the scale difference along the x and y axes, and A_2 represents the non-orthogonality angle.

The relative magnitude of the distortions listed above is an indication of the condition and quality of the camera. The mathematical model equations that represent the combination of the distortions are:

$$\begin{aligned} \Delta x &= \Delta x_{RLD} + \Delta x_{DLD} + \Delta x_{AR} + \Delta x_{AD} + \ldots \\ \Delta y &= \Delta y_{RLD} + \Delta y_{DLD} + \Delta y_{AR} + \Delta y_{AD} + \ldots \end{aligned} \quad (2.4)$$

Where: Δx and Δy are the total compensations for the various distortions. During experimentation, different combinations of distortion parameters are included in the calibration. The number of included parameters will depend on the type of camera implemented and the accuracy required for the intended application.

2.3 Traditional Calibration Approach

Camera calibration requires control information, which is usually available in the form of a test field. Traditional calibration test fields consist of distinct and specifically marked points or targets (Fryer, 1996), Figure 2.1. These targets are established and precisely measured in a test field using surveying techniques. The number and distribution of the targets are vital for the recovery of the IOP of the implemented camera.