GONIOMETER-LIKE LABORATORY METHOD FOR DETERMINING A DIGITAL CAMERA'S INTERIOR ORIENTATION, AS WELL AS RELATIVE ORIENTATION IN MULTIPLE-LENS SYSTEMS

U. Ethrog
Department of Transportation & Geo-Information Eng.
Faculty of Civil & Environmental Eng.
Technion Israel Institute of Technology
Technion City, Haifa 32000, Israel
cvuzi@technion.ac.il

KEY WORDS camera calibration, multiple-lens relative orientation

Abstract.
The increased use of amateur digital cameras for many photogrammetric purposes justifies a simple laboratory calibration method that is suitable for all types of digital cameras. On the other hand, amateur cameras need frequent calibration that sometimes needs be done at remote places, therefore requiring that the equipment for the calibration be portable. This paper suggests a new calibration method based on common geodetic instruments and home equipment which can be utilized and implemented almost anywhere.

1. INTRODUCTION
A multiple-lens system consists of two or more separate cameras joined to a rigid device with their shutters synchronized to obtain simultaneous exposures. Such systems were frequently used in the early days of photogrammetry, almost a century ago, where up to nine narrow angle film cameras were joined together in order to cover a wider field angle (up to 140°). This arrangement again proves useful for air photography taken with narrow angle non-metric digital cameras carried by small or tiny air carriers. The method is particularly useful when digital oblique photographs are required. In many cases the air carrier is equipped also with GPS and IMU systems, so that in theory these photographs can be used also for some photogrammetric measurements without any ground control points. But this requires an accurate determination of both the interior orientations of the cameras as well as the relative orientation of one of the cameras, the main camera, to each of the other cameras. In the case where the multiple-lens system is comprised/consists of amateur cameras, the calibration may need to be done frequently, sometimes far away from any laboratory or test field.
The existing laboratory methods most suitable for film camera calibration and considered to be the most accurate are the goniometer method described by Hakkarainen(1972) and the multicollimator method described by Light(1992). However, the first method is absolutely unsuitable for digital camera calibration. The other is relatively expensive, non-portable, and needs many modifications such as replacing the collimators' diaphragms and changing the space between the collimators. Thus, in practicality this method is also unsuitable for digital cameras.
There are two main field techniques for camera calibration, the first being the test field method described by Krause (1997), Paquette et al. (1990), and many others, the second being the self- calibration method described by Fraser(1997), Fryer(1992), Ghosh ,Rahimi & Shi(1988), and many others. These two methods can be successfully implemented for determining the interior orientation of each individual camera; however, it is very complicated to use these for determining the relative orientation of two cameras, especially if they are focused to infinity and oriented in opposite directions.

2. THE STRUCTURE OF THE PROPOSED DEVICE
The device illustrated in Fig. 1 is based on using common geodetic instruments and home equipment and can be implemented almost anywhere. It consists of a home TV swivel base which is used as a bearing (an almost planar control device with four control points), a theodolite located near the TV swivel base used as a collimator, and an additional theodolite located about two meters from the swivel base which is used to measure the horizontal directions and zenithal angles to the control points.
The collimator is focused to infinity and aimed towards the camera lens to be calibrated. The cross hair of a conventional diaphragm is usually suitable for tele-objective lens and high resolution cameras, but is too thin to be detected by a common digital camera, so there is a need to add a small circle to its diaphragm which is more suitable for digital images (see Fig no. 2). The original cross hair remains and enables the use of the theodolite as usual, but does not appear on the digital photographs.
The camera or the multiple–lens system which is to be calibrated is rigidly mounted to the TV swivel base and is free to rotate together with the control device so their relative orientation remains unchanged
A laser tube that projects a red light focused to infinity as shown in Fig. 3a may be used to replace the collimator. In this case, one theodolite is sufficient for the two purposes, both as the collimator and for measuring directions.
Another alternative is to use a laser eyepiece like the Wild GLO2 and turn the theodolite into a laser beamer (as shown in Fig. 3b). On the other hand, the quality of

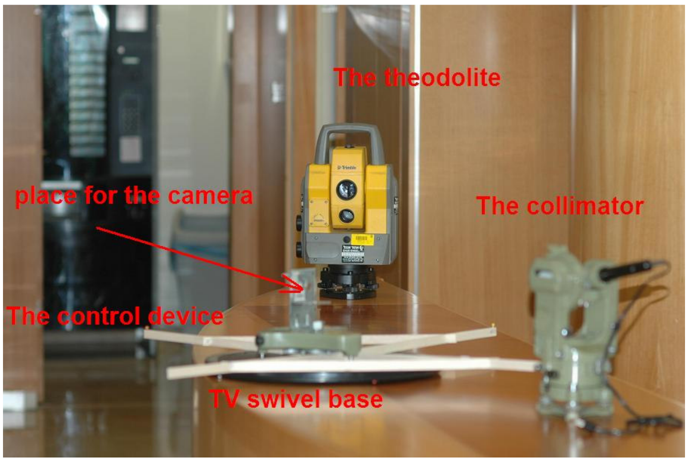

Fig. 1 The device for camera calibration and relative orientation determining

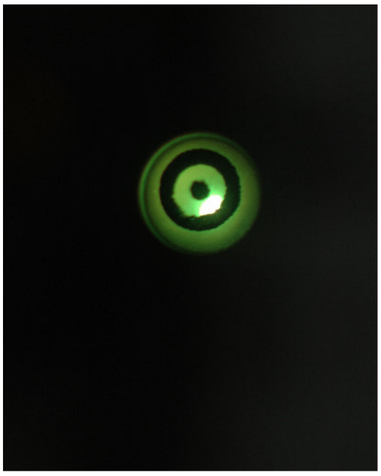

Fig. 2 The image of the collimator diaphragm

Fig. 3a. A laser tube is attached to a theodolite

Fig 3b. A theodolite with Wild GLO2 laser eyepiece

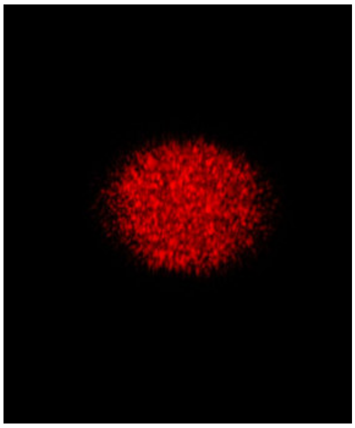

Fig. 3c. The image of a laser beam

the laser light image is not as good as that of a conventional collimator, as shown in Fig 3c.

3. BASIC CONCEPTS UNDERLYING USE OF THE DEVICE

All the methods of camera calibration are based on the equations of collinearity given in Doyle, F. J. et al. (1966):

$$\begin{pmatrix} x - x_0 + \Delta x \\ y - y_0 + \Delta y \\ f \end{pmatrix} = \lambda Q \begin{pmatrix} Vx \\ Vy \\ Vz \end{pmatrix} \qquad (1)$$

Where:

λ is a scale factor,

Q is the transformation matrix, a function of the camera's three tilt angles,

V_X, V_Y, V_Z is a vector in space, oriented towards the camera lens, which in this case is the collimator's collimation line,

x, y are the image coordinates of the collimation line,

x_0, y_0, f are the interior orientation elements, and

$\Delta x, \Delta y$ are the corrections for radial and decentering distortion, given by Brown (1966), (1971).

$$\begin{aligned}
\Delta x &= \bar{x}(K_1 * r^2 + K_2 r^4 + K_3 r^6 + \ldots) \\
&\quad + P_1(r^2 + 2 * \bar{x}^2) + 2 * P_2 * \bar{x} * \bar{y} \\
\Delta y &= \bar{y}(K1 * r^2 + K_2 r^4 + K_3 r^6 + \ldots) \\
&\quad + P_2(r^2 + 2 * \bar{y}^2) + 2 * P_1 * \bar{x} * \bar{y} \\
\bar{x} &= x - x_0 \\
\bar{y} &= y - y_0 \\
r^2 &= \bar{x}^2 + \bar{y}^2
\end{aligned} \qquad (2)$$

Where $K_1, K_2, K_3, \ldots, P_1, P_2$, are unknown constants

4. DETERMINING THE COMPONENTS OF THE UNIT VECTOR (V_X, V_Y, V_Z)

4.1. Measurements, Photography and Photogrammetric measurements

The measurements are made in 7 stages or steps:

Step 1

This step is done once at the beginning of all the measurements:

The collimation lines of the collimator and the theodolite are brought to parallelism by a procedure of collimation. The reading on the theodolite's horizontal circle at this

position is brought to zero while the corresponding reading of the collimator is brought to 180 degrees.
Step 2
The camera is now mounted on the TV swivel base at the proper orientation. This step is done once for all the observations taken for one set of photographs in which the camera's exterior orientation relative to the TV swivel base and the control device remains unchanged.

The following steps are repeated for each observation.
Step 3
The TV swivel base with the control device and the camera are rotated so that the image of the collimator is brought approximately to its desired position.
Step 4.
The collimator is aimed towards the center of the camera's lens. The readings on its horizontal and vertical circles are recorded.
Step 5
An exposure is made. The exposure time and the image number are recorded. The photo coordinates of that image will be determined later.
Step 6
The theodolite is aimed towards the four control points. Each time the readings on its horizontal and vertical circles are recorded.
Step 7
Steps 3 to 6 are repeated for another orientation of the TV swivel base.
Step 8a
For the case of camera calibration, the camera's exterior orientation is changed and steps 2 to 7 are repeated for another set of photographs.
or
Step 8b
For the case of determining the relative orientation of two cameras, steps 3 to 6 are repeated with the other camera while the exterior orientation of the multiple lens system is kept unchanged.

4.2 Calculations

Three different coordinates systems are involved. The theodolite's and the collimator's coordinate system is the primary one. Its X axis is horizontal and in the direction of the zero of the theodolite's horizontal circle. Its Z axis is vertical and its Y axis is perpendicular to both. The second coordinates system is that of the control points. The third coordinate system is the sensor's own coordinate system determined by its lines and pixels. The vectors from the theodolite to the control points are determined by the measured horizontal directions and zenithal angles . Each such vector determines equations similar to the equations of collinearity from which we obtain the transformation matrix $Q_{k,i}$:

$$\begin{pmatrix} X_j - X_{0,k,i} \\ Y_j - Y_{0,k,i} \\ Z_j - Z_{0,k,i} \end{pmatrix} = \lambda Q_{k,i} \begin{pmatrix} \sin\zeta_{k,i,j} * \cos\alpha_{k,i,j} \\ \sin\zeta_{k,i,j} * \sin\alpha_{k,i,j} \\ \cos\zeta_{k,i,j} \end{pmatrix} \quad (3)$$

Where:

λ is a scale factor,

$Q_{k,i}$ is the transformation matrix, a function of three tilt angles.for image no. i of set no.k,

$\zeta_{k,i,j}, \alpha_{k,i,j}$ are the zenithal angle and the horizontal direction, respectively, to point no. j, at image no. I, of set no. k,

X_j, Y_j, Z_j are the coordinates of control point no. j of the coordinate system, and

$X_{0,k,i}, Y_{0,k,i}, Z_{0,k,i}$ are the coordinates of the theodolite in the second coordinate system corresponding to image no. i of set no. k.

The vector (V_X, V_Y, V_Z) is given by:

$$\begin{pmatrix} V_X \\ V_Y \\ V_Z \end{pmatrix} = Q_{k,i} \begin{pmatrix} \sin Z_{k,i} * \cos A_{k,i} \\ \sin Z_{k,i} * \sin A_{k,i} \\ \cos Z_{k,i} \end{pmatrix} \quad (4)$$

Where:

$Q_{k,i}$ is the transformation matrix, a function of three tilt angles for image no. i of set no. k, and

$Z_{k,i}, A_{k,i}$ are the zenithal angle and the horizontal direction, respectively, of the collimator collimation line of image no. i in set no. k.

5. CAMERA CALIBRATION

The camera is placed so that its lens is located on the continuation of the TV swivel base axis as close as possible to the level of the collimator. In this case, the collimation line remains oriented almost always towards the camera lens. Steps 3 to 6 are repeated about 20 to 30 times over a set of 20 to 30 images, all taken with the same camera orientation relative to the control device. From these observations we obtain 20 to 30 pairs of observation equations like those in eq. 1 and 2. The camera's yaw is change by 90° and another set of 20 to 30 images is taken. It is recommended to take two additional sets of 20 to 30 images, in each of which one diagonal of the camera's sensor is held almost horizontal. All told we obtain 160 to 240 observation equations having eight interior orientation unknowns (x_0, y_0, f and K_1,K_2,K_3,P_1,P_2 in eqs. 1 & 2) plus 4x3 unknown tilt angles. The ratio between the number of observations and the number of unknowns insures a good solution.

6. DETERMINING THE RELATIVE ORIENTATION IN A MULTIPLE-LENS SYSTEM

This is done only after each individual camera has been calibrated according to the procedure in Section 5. The multiple-lens system is laid out so that the two cameras whose relative orientation is determined are at about the same level. In this case, one set of about ten exposures is sufficient, five for each camera.
The image coordinates are corrected for the distortions, and eq. 1 is applied once with the vectors and the

corresponding image coordinates of the first camera to determine the transformation matrix Q_1 and again with the vectors and image coordinates of the second camera to obtain the transformation matrix Q_2.
The relative orientation between the two cameras is:

$$Q_R = Q_2^{-1} Q_1 .$$

7. REFERENCES

Brown, D.C., 1966. Decentering distortion of lenses , photogrammetric Engineering 32(3): 444-462

Brown, D.C. 1971 Close-range camera calibration , Photogrammetric Engineering 37(8): 855-866

Doyle, F. J., et al , Manual of Photogrammetry, 3d ed., American Society of Photogrammetry, Falls Church, Va, pp 469

Fraser, C.S. 1997, Digital Camera Self-Calibration, ISPRS journal of Photogrammetry and Remote Sensing 149-159:(4)52 ,

Fryer, J.G. 1992, Recent Developments in Camera Calibration for Close-Range Applications ,The International Archives of Photogrammetry and Remote Sensing, Washington D.C. USA, Vol XXIX part B5, pp594-599 .

Ghosh, S.K.,Rahimi M.,1988, Calibration of an amateur camera for various object distances, International Archives of Photogrammetry and Remote Sensing, Kyoto, Japan, Vol XXVII,part B5, pp213-222

Hakkarainen, J. 1972, Calibration of aerial cameras with a horizontal gonimeter, Photogrammetric Journal of Finland 6(1)

Krause, K., 1997 , Photogrammetry, vol 2., Advanced Methods and Applications.(4th Ed.). Duemmler Bonn .pp400 .

Light, D.L. 1992 . The New Camera Calibration System at the U,S.Geological Survey. Photogrammetric Engineering and Remote Sensing, 58(2): 185-188

Paquette, L., Stampfler R., Davis W. A., Caelli T. M.,1990. A new camera calibration method for robotic vision. , SPIE Vol. 1395,Close-Range Phogrammetry Meets Machine Vision, PP 656-663