ORIENTATION OF IMAGES CAPTURED WITH VIDEO-THEODOLITES

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ABSTRACT

Images can be directly oriented without registration of corresponding points or control points if they are taken with a calibrated video-theodolite. The conditions are that the video-theodolite is calibrated for the camera-to-theodolite relationship and appropriate theodolite observation procedures are followed to orient the theodolite. This paper describes the detail of the coordinate relationship between camera, theodolite and the world, calibration requirements, and different methods for theodolite orientation. A new pair of collinearity equations are derived and used in an experiment to relatively orient two video-theodolite stations via image measurement. The new collinearity equations are also applicable to bundle adjustment of data acquired with video-theodolites.

1 INTRODUCTION

Video-theodolites are increasingly used for image data acquisition for measurement and visualisation purposes. They have been used to capture oriented panoramic images for facility management in the oil and gas processing and nuclear generation plants (Chapman et al 1994), to capture oriented image sequences to track moving objects and human motion (Kakiuchi et al. 1999, Anai et al. 1999) and to visualise laser scan surface models with rendered images (Gong et al 1999).

There are many unique advantages of using video-theodolites. These include the capability of acquiring high resolution mosaic panoramic images, the ease of providing accurate direct orientation parameters for the images captured, video-guided theodolite surveying. Because of these advantages, video-theodolites have a great potential for wider application (Huang 1992).

Calibration and orientation are two fundamental problems that need effective solutions for effective application of video-theodolites. Calibration is to determine the camera interior orienation parameters and the six parameters that describe the camera position and attitude with respect to the theodolite. Orientation refers to the process of determining the positions and attitudes of video-theodolite stations relative to each other and to a specified object coordinate system. Some of the author's previous papers have explained and demonstrated an effective method for calibration (Huang et al 1989). This paper is set out to investigate the orientation problem, aimed to provide formulations for practical use and further development.

2 MEASUEREMENT PRINCIPLES OF VIDEO-THEODOLITES

2.1 Definition of Video-Theodolites

The video-theodolite is an instrument which is constructed by attaching or integrating a video (or digital) camera rigidly to the telescope of a theodolite such that the camera and the telescope can rotate together about both the theodolite axes. The camera and the theodolite are optically independent of each other so that the camera can take images and the theodolite can still measure angles as usual, but both are connected to the host computer with image processor mounted.

A video-theodolite can have several working modes. 1) the theodolite mode, where the theodolite is used as the major measuring device, and the video camera is used to provide a visual user interface and/or an artificial eye for target identification. 2) the camera mode, where the video camera is the major measuring device and work on photogrammetric principles, and the theodolite is used to provide precise direct orientation for the camera.

2.2 Definition of Coordinate Systems

2.2.1 Camera Coordinate System O_c-x'y'z': O_c is the perspective centre of the camera. z' is perpendicular to the focal plane of the camera. x' (y') is perpendicular (parallel) to the *scanning line* direction of the image and increases with the number of line (sample). (Note that x and y are usually defined with fiducial marks in metric film cameras)

2.2.2 Image Coordinate System O_i-xy: x and y are parallel to x' and y' respectively. O_i is some convenient reference point, usually, the top-left corner of the images for CCD cameras. For a point in the image plane, the image coordinates and camera coordinates are related by the equation below.
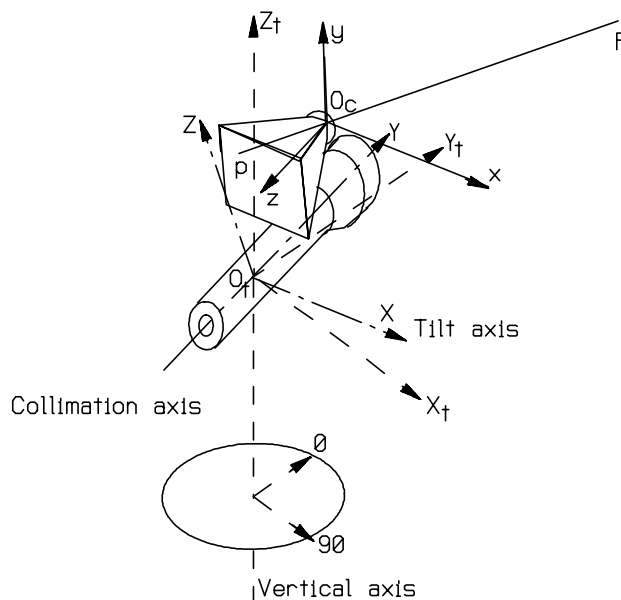
$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} x - x_0 \\ y - y_0 \\ - f \end{pmatrix} \qquad \text{2-1}$$

x_0 and y_0 are the image coordinates of the principal point which is the point in which $O_c z'$ meets the image plane. f is the principal distance of the camera.

2.2.3 Telescope Coordinate System O_t-XYZ: O_t is the rotational centre of the theodolite. X coincides with the tilting axis of the theodolite. Y coincides with the collimation axis and is positive as it points forward. The transformational relationship between this system and the camera coordinate system is denoted by the rotational matrix $\mathbf{R_c}$ and the translational vector $\mathbf{T_c}$ as below.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \mathbf{R_c} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + \mathbf{T_c} \qquad \text{2-2}$$

$$\mathbf{R_c}^T \equiv \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \quad \mathbf{T_c} \equiv \begin{pmatrix} r_x \\ r_y \\ r_z \end{pmatrix}$$

The rotational matrix is the function of three independent rotation angles. These three angles used in this paper are ω, ϕ, κ as defined as that the reference (now the telescope) coordinate system turns into a system parallel to the camera coordinate system by rotating about its X-axis by ω, then about its current Y-axis by ϕ and finally about its current Z-axis by κ. These three angles are defined as positive if they are counterclockwise when viewed from the positive ends of their respective axes. The expressions of the elements of the rotational matrix as functions of ω, ϕ, κ can be found in most of the photogrammetric text books (Wolf 1983)

2.2.4 Theodolite coordinate system O_t-$X_t Y_t Z_t$: O_t is the rotational centre of the theodolite. Z_t coincides with the vertical axis and points upwards. Y_t is parallel to the zero direction of the horizontal circle of the theodolite. The relationship between this system and the telescope coordinate system is as follows:

$$\begin{pmatrix} X_t \\ Y_t \\ Z_t \end{pmatrix} = \mathbf{R} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} + \mathbf{T} \qquad \text{2-3}$$

where obviously $\mathbf{T} \equiv \mathbf{0}$ and $\mathbf{R}$ is a function of horizontal reading h and the vertical angle v as follows:

$$\mathbf{R}^{\mathrm{T}}(h,v) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos v & \sin v \\ 0 & -\sin v & \cos v \end{pmatrix} \begin{pmatrix} \cos h & -\sin h & 0 \\ \sin h & \cos h & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} \cos h & -\sin h & 0 \\ \cos v \sin h & \cos v \cos h & \sin v \\ -\sin v \sin h & -\sin v \cos h & \cos v \end{pmatrix} \qquad \text{2-4}$$

2.2.5 Object Coordinate System O_w-$X_wY_wZ_w$: defined in accordance with the specification of a particular application. Its transformation with the theodolite coordinate system is denoted as follows:

$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} = \mathbf{R_t} \begin{pmatrix} X_t \\ Y_t \\ Z_t \end{pmatrix} + \mathbf{T_t} \qquad \text{2-5}$$

$$\mathbf{R_t}^{\mathrm{T}} \equiv \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{pmatrix}, \qquad \mathbf{T_t} \equiv \begin{pmatrix} T_x \\ T_y \\ T_z \end{pmatrix} \qquad \text{2-6}$$

2.3 The Principle of Three Dimensional Measurement Using Video-Theodolites

When the camera of the video-theodolite is used as the major measuring device and works on photogrammetric principles, the camera exterior orientation can be determined directly by means of theodolite observations. To explain this, the camera orientation is represented by a rotation matrix $\mathbf{R_{cw}}$ and a translation vector $\mathbf{T_{cw,}}$ and the transformation between the camera coordinate system and the object coordinate system is written in the following equation (see the notation in 2.1.1):

$$\begin{pmatrix} X_w \\ Y_w \\ Z_w \end{pmatrix} = \mathbf{R_{cw}} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} + \mathbf{T_{cw}} \qquad \text{2-7}$$

By substituting Eq.2-7 with Eq.2-5, Eq. 2-5 with Eq.2-3, and Eq.2-3 with Eq.2-2, the following is obtained

$$\mathbf{R_{cw}} = \mathbf{R_t R R_c} \; , \qquad \text{2-8}$$
$$\mathbf{T_{cw}} = \mathbf{R_t R T_c} + \mathbf{T_t} \qquad \text{2-9}$$

It can be seen from the above that the camera orientation can be broken down into three separate steps:
1) **System calibration** to determine $\mathbf{R_c}$ and $\mathbf{T_c}$. These, as defined before, represent the transformation between the camera system and the telescope system. They form part of the constants of the video-theodolite and can be determined together with the camera interior orientation parameters using the camera-on-theodolite calibration method (Huang, 1989);
2) **System orientation** to determine $\mathbf{R_t}$ and $\mathbf{T_t}$. These represent the transformation between the theodolite coordinate system and the object coordinate system. They are constants for each set-up station. Its methods are the subject of section 4.
3) **Theodolite reading** on image capture to determine **R.** This represents the transformation between the telescope system and the theodolite system. It is the function of theodolite the horizontal and vertical angular readings of the theodolite only, as stated in 2-4.

It can be seen that after system calibration and system orientation have been completed, the orientation parameters of the cameras with respect to the object coordinate system can be found using theodolite readings and Eq. 2-9 and 2-10. It is then possible to use the space intersection algorithm to compute the three dimensional coordinates of unknown object points.

When working in the theodolite mode, the theodolite part of the video-theodolite is used as the measuring device. Three dimensional coordinates of object points are determined by space intersection using angular readings taken from the theodolite rather than image coordinates from the camera. This principle of measurement is familiar to most and well documented. The new features added to this traditional way of measurement by video-theodolites are that the camera provides visual interface for easy field operation and the possibility of development into tele-operation and automation. The camera offers an alternative method for theodolite orientation, which is suitable for automation. This method is explained in Section 4.2.

3   SYSTEM CALIBRATION

The task of system calibration is to determine the camera interior orientation parameters and the camera-to-theodolite orientation parameters. The camera-on-theodolite method proposed previously by the author is most suitable for this calibration. This method involves capturing multiple frames of images of one or two targets set some distances away while rotating the telescope to various directions so that the target images are well spread in the image format. The three dimensional coordinates of the target in the rotating telescope coordinate system are obtainable for each of the target images from the theodolite readings at the moment of capturing that image and the constant target to theodolite distances. The photogrammetric space resection is applied to solve for the camera exterior orientation parameters in reference to the telescope coordinate system and the camera interior orientation parameters. For the detail of the camera-on-theodolite calibration method, see the author's previous papers (Huang and Harley, 1989)

4   SYSTEM ORIENTATION

The task of system orientation is to determine the position and attitude of the theodolite in the video-theodolite system with respect to other video-theodolite stations in the measurement network or with respect to a user specified object coordinate system. The former is termed as relative orientation and the latter absolute orientation. Either orientation can be achieved by means of theodolite observation or via the video camera in the system. One may think of a large variety of different methods based on the adaptation from geodetic surveying methods or from photogrammetry methods by treating the theodolite like a camera. If an EDM or GPS is used, more methods are possible. In the following, we collect a few typical methods based on theodolite observations and contribute with new collinearity equations that can be used for theodolite orientation via the mounted camera.

4.1   System Orientation by Theodolite Observation

Discussion is restricted to the cases with only angular observations using the theodolite. There are classifications in relative and absolute, with leveled or unleveled theodolites.

4.1.1 Space resection with an unleveled theodolite. Three full control points are sighted with the theodolite, both horizontal and vertical angles are recorded. These angles are converted into equivalent pseudo image coordinates and the photogrammetric space resection method is applied to determine the six orientation parameters of the theodolite with respect to the control point system. This is an absolute orientation.

4.1.2 Space resection with a leveled theodolite. As above, but now two angular parameters are set to zero. Only four parameters need to be determined. Thus only two control points are required to be sighted.

4.1.3 Five-point relative orientation for two unleveled theodolites. The horizontal and vertical angular readings of a theodolite can be transferred into their corresponding rectangular coordinates of a pseudo photo if a focal length is assumed. That is the "pseudo-photo" principle of theodolite observations. By this principle we can transplant many methods and algorithms in photogrammetry into use for theodolites. Among these is the analytical relative orientation method for photo-pair, which can be used straightforwardly for the orientation between two theodolites.

The analytical relative orientation method is based on the coplanarity condition that the two rays (or lines of sight) from the two theodolites to a common object point are coplanar with the base line that links the rotational centres of the two theodolites. An equation of coplanarity condition can be formed for each observed object point (Wolf 1983). Observing five points is necessary for the five relative orientation parameters. More points may be needed to observe for a better accuracy and blunder detection. A known distance between any two of those points or a measured base line is necessary for scaling.

4.1.4 Three-point relative orientation for two levelled theodolites. For levelled theodolites the number of orientation parameters to be determined reduces from five to three. Thus only three points are necessary to be observed. As is seen, there is a trade-off between levelling the theodolites and observing two more points. If possible, the former is preferred

for two reasons. The first is that modern electronic theodolites have precise self-correction device for inclined vertical axes within some range. In these theodolites, the magnitude and the direction of the inclination of the vertical axis are determined and corrections added to each theodolite reading. The accuracy is believed to be higher than that of determination with five-point orientation method. The second reason is that levelling is one of the requirements to ensure a theodolite to work properly.

4.1.5 Theodolite relative orientation with reciprocal pointing. The relative orientation between two unleveled theodolites can be fulfilled by pointing the theodolites at each other's centres and an object point. If the theodolites are levelled, on object point is needed. The scale factor is determined by measuring a distance between one theodolite and the other or the object point. Kyle (1988) has described some reciprocal pointing methods. Reciprocal pointing is generally easier if only horizontal readings are required. In this case, the theodolites need to be leveled and need to point at one object point.

4.2 Theodolite Orientation via the Mounted Video Cameras

All the methods mentioned above use theodolite observation to fulfil orientation among theodolites. For a calibrated video-theodolite system, it is possible to perform orientation for the theodolite via the mounted video camera. There are two different ways of performing this orientation. One involves capturing only a single image from each theodolite station, the other uses multiple images taken from each theodolite station with the camera pointing at different directions.

In the single image method, the camera captures an image on each theodolite station of sufficient control points or tie points. The exterior (absolute or relative) orientation of the image, namely $\mathbf{R_{cw}}$, $\mathbf{T_{cw}}$ in Eq.2-8, Eq.2-9 are determined using the standard photogrammetric algorithms (space resection or relative orientation). The theodolite readings are taken at the moment the image is captured so as to evaluate $\mathbf{R}$. The theodolite orientation $\mathbf{R_t}$ and $\mathbf{T_t}$ can then be solved using the following equations which are derived from equations (2-8,9).

$$\mathbf{R_t} = \mathbf{R_{cw}}\,\mathbf{R_c}^{\mathbf{T}}\,\mathbf{R^T} \quad , \qquad\qquad\qquad\qquad 4\text{-}1$$

$$\mathbf{T_t} = \mathbf{T_{cw}} - \mathbf{R_t}\,\mathbf{RT_c} \qquad\qquad\qquad\qquad 4\text{-}2$$

The shortcoming of this method is that when a narrow angle camera is used, the weak camera orientation will lead to weak theodolite orientation and, in turn, poor orientation for other images taken from that theodolite station.

The multiple image method is possible to avoid this shortcoming of the single image method by capturing multiple images at various theodolite directions to cover wide spread control points or tie points. This method may use the collinearity equations derived below.

5 COLLINEARITY EQUATIONS WITH THEODOLITE ORIENTATION PARAMETERS

Suppose that there is an object point *P* and that its corresponding image point is *p*. According to the collinearity principle the coordinates of these two points and the image projective centre O_c in the theodolite coordinate system have the following relationship (see Section 2 for the notations):

$$\mathbf{X}_{\mathbf{t}(P)} - \mathbf{X}_{\mathbf{t}(O_c)} = s(\mathbf{X}_{\mathbf{t}(p)} - \mathbf{X}_{\mathbf{t}(O_c)}) \qquad\qquad\qquad 5\text{-}1$$

where *s* is a scale factor. Substituting from Eq.2-2 - Eq.2-6 the above equation turns to

$$\mathbf{R_t}^{\mathbf{T}}(\,\mathbf{X_w} - \mathbf{T_t}\,) - \mathbf{R}\,\mathbf{T_c} = s\,\mathbf{R}\,\mathbf{R_c}\,\mathbf{x'} \qquad\qquad\qquad 5\text{-}2$$

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} \equiv \mathbf{R}\,\mathbf{R_c} \begin{pmatrix} x - x_0 \\ y - y_0 \\ -f \end{pmatrix} \qquad\qquad\qquad 5\text{-}3$$

$$\mathbf{C} = (\, C_x \quad C_y \quad C_z \,)^{\mathrm{T}} = \mathbf{R} \, \mathbf{T_c} \qquad \text{5-4}$$

where the subscripts P and p are omitted and $\mathbf{x'}$ are the camera coordinates as stated by Eq.2-1. Now, adopting the following notation

and eliminating s in Eq.4-2, we obtain the collinearity equations below:

$$\frac{u}{w} = \frac{m_{11}(X_w - T_x) + m_{12}(Y_w - T_y) + m_{13}(Z_w - T_z) - C_x}{m_{31}(X_w - T_x) + m_{32}(Y_w - T_y) + m_{33}(Z_w - T_z) - C_z} \qquad \text{5-5a}$$

$$\frac{v}{w} = \frac{m_{21}(X_w - T_x) + m_{22}(Y_w - T_y) + m_{23}(Z_w - T_z) - C_y}{m_{31}(X_w - T_x) + m_{32}(Y_w - T_y) + m_{33}(Z_w - T_z) - C_z} \qquad \text{5-5b.}$$
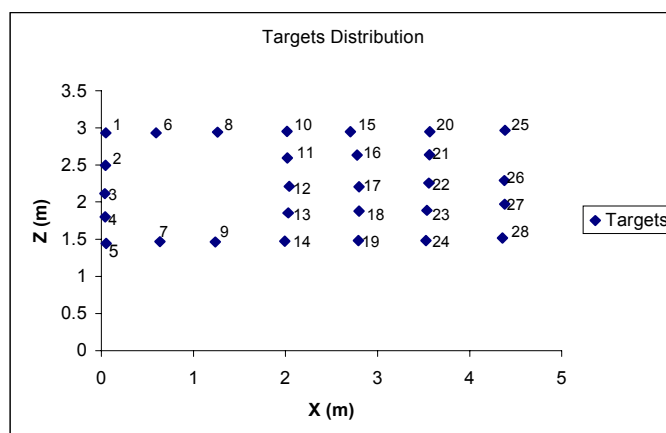
It can be seen that by using these equations, it is possible to solve for the theodolite orientation parameters $\mathbf{R}_t$ and $\mathbf{T}_t$ in a similar way to the analytical space resection or relative orientation when the theodolite readings at the time of image exposure are used as well as the image coordinates of the measured points. An experiment on using these equations for theodolite relative orientation is detailed in Section 6. These equations can also be applied to a multiple stations bundle adjustment.

6   EXPERIMENTS

An experiment has been carried out to test the validity of the new collinearity equations for video-theodolite orientation. A calibrated video-theodolite was used at two stations to capture multiple images of 28 targets (Fig.1). Theodolite readings were recorded on capture of each image. The target images were measured to 0.3 pixel accuracy. Six of the targets were used to determine relative orientation between the two stations using the new collinearity equations. Space intersection was then performed for the rest targets using the same collinearity equations. The root mean squares of residual image position errors from space intersection were computed to assess the overall accuracy of the whole operation.

The camera used is a zoom CCD camera set and calibrated at 65mm. With a 1/3 inch chip and 576*480 digitization resolution, it gives a pixel angle of about 30" of arc. The target images were measured manually to 0.3 pixel which is equivalent to 10" in angle. Compared with this, the Geodimeter theodolite has an 3" arc angular precision and thus can be treated as error free in this experiment.

Calibration was performed using the camera-on-theodolite method and achieved higher than 0.1 and 0.3 pixel in the line and sample direction respectively. This accuracy is poorer than average previously achieved due probably to the heavey linejitter encountered recently

Targets Distribution

with the camera and frame grabber. The repeatability was assessed to be about 0.3-0.4 pixel using the method described in (Huang 1999). The calibrated values were used as known constants in orientation and space intersection.

Both theodolite stations were levelled and dual axial compensation was on. Relative orientations with three parameter (κ, By, Bz) and five parameters (ω, φ, κ, By, Bz) were performed respectively using the new collinearity equations with 6 widely spread points captured on 6 different frames of image at different theodolite pointings from each station. The 6 points used were No. 1,5,10,19,25,28. Space intersection was then carried out using the new collinearity equations again to determine 3D coordinates of all target points.

The root mean squares image position residual errors from space intersection were 0.35 and 0.51 pixel for the 3-parameter and 5-parameter relative orientations respectively. These accuracies are consistent and believed to improve with the calibration accuracy. A similar experiment to this but with simulated data has also been carried out. That has validated the correctness of the algorithm and computation.

7 CONCLUSIONS

It has been shown in the paper that the orientation of images captured with a calibrated video-theodolite can be determined directly by theodolite observation. There are a variety of methods for choice in practice. Given the high precision of modern theodolites, using video-theodolite is probably the most accurate means for providing direct orientation for cameras.

It has been shown that theodolite orientation for a video-theodolite can be achieved using the camera in the video-theodolite. For this purpose, new collinearity equations have been derived to incorporate theodolite orientation parameters. They have successfully been used to orient two video-theodolite stations relative to each other using image observations. They are believed to be applicable to bundle adjustment of multiple video-theodolite stations; experiments on this are recommendable.

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