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SYSTEM CALIBRATION OF INTELLIGENT PHOTOGRAMMETRON

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ABSTRACT:

Photogrammetron represents a class of intelligent photogrammetric systems aiming at realizing a number of newly defined functionalities of intelligent photogrammetry that go beyond the traditional photogrammetry and the currently dominant digital one, including real-time photogrammetry in video surveillance, photogrammetry-enabled robots, intelligent multi-camera network for close-range photogrammetry. This paper addresses the geometric calibration of Photogrammetron I - the first type of Photogrammetron which is designed to be a coherent stereo photogrammetric system in which two cameras are mounted on a physical base but driven by an intelligent agent architecture. The system calibration is divided into two parts: the in-lab calibration determines the fixed parameters in advance of system operation, and the in-situ calibration keeps tracking the free parameters in real-time during system operation. In a video surveillance setup, prepared control points are tracked in stereo image sequences, so that the free parameters of the system can be continuously updated through iterative bundle adjustment and Karlman filtering. Two methods of calibration are distinguished: the strong stereo mode where a minimal set of parameters are tracked, and the weak stereo model where each camera is calibrated independently through tracking control points.

1. INTRODUCTION TO PHOTOGRAMMETRON

In order to break through the limitations of the current dominant digital photogrammetric systems, Photogrammetron has been proposed recently [Pan, 2002] as a new class of intelligent photogrammetric systems. It is designed to be an active stereo vision system driven by an intelligent software agent architecture, aiming at realizing a number of newly defined functionalities of intelligent photogrammetry. Some main functionalities that go beyond the traditional photogrammetry and the currently dominant digital one include real-time photogrammetry in video surveillance, photogrammetry-enabled robots, intelligent multi-camera network for close-range photogrammetry. Photogrammetron I as the first type of Photogrammetron is designed to be a coherent stereo photogrammetric system in which two cameras are mounted on a physical base, similar to a head-eye system in robot vision, but the stereo camera baseline length is changeable. This paper addresses the geometric calibration of Photogrammetron I. In the following discussions, we shall simply use the term Photogrammetron while we only confine our scope to Photogrammetron I. For the clarity of the modelling and discussion, we choose to study the video surveillance with photogrammetric functionalities as the underlying application.

The calibration of Photogrammetron is far more complicated than just calibrating the cameras in traditional photogrammetry because Photogrammetron posses a self-contained automatically controlled physical structure driven by an intelligent agent software architecture. Physically, Photogrammetron as shown in Fig.1 is made up of a physical support base called the'shoulder', a pan-tilt unit called the 'head'mounted on the shoulder, a plate mounted on the head called the 'stereo camera plate' or 'stereo plate'simply, the left and right camera with their pan-tilt unit on top of the stereo base. Each pan-tilt unit has two angular freedoms: pan and tilt. In total, there are 9 freedoms: pan and tilt angles for each of the three pan-tilt units, the baseline length between two cameras, the focal length of each of the two cameras. Besides these freedoms, there are still a number of prefixed system parameters such as the geometry between the head and the stereo base, and between the stereo base and each of the camera pan-tilt units, as well as between a camera pan-tilt unit and its supported camera. Therefore, the whole parameter set of the system can be divided between two subsets: the free parameters and the fixed parameters.

The system calibration of Photogrammetron is divided into two parts: the determination of the fixed parameters and of the free parameters. The calibration for the fixed parameters can be done in a laboratory in advance of the system operation, which shall be called the 'in-lab' calibration. The calibration for the free parameters has to be done in real-time during system operation, which shall be called the 'in-situ' calibration.

Since various parts of Photogrammetron such as the head, stereo plate, the left pan-tilt unit and the left camera, the right pan-tilt unit and the right camera, are supposed to be always in motion in the video surveillance setup, the free parameters have to be continuously tracked and updated through continuous image tracking in stereo image sequences. The actual form of image tracking may be uniform optical flow computation or tracking of sparse feature points only.

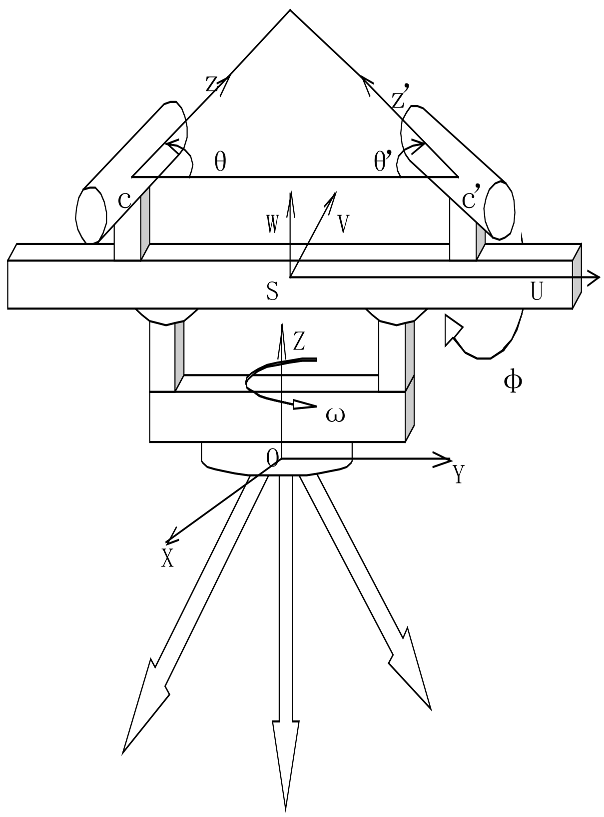

Figure 1. A geometric model of Photogrammetron I

2. A GEOMETRIC MODEL OF PHOTOGRAMMETRON

A basic structure of Photogrammetron consists of 5 hardware parts: the shoulder, the head, the stereo plate, the left camera and its pan-tilt unit and the right camera with its pan-tilt unit. We consider each of them as follows.

2.1 The Shoulder

This refers to the support of the system. It can be a still tripode or a vehicle with wheels or robot with legs. For the time being, we just assume the shoulder stays still relative to the surveillance environment. For this part, a Euclidean reference system $O-XYZ$ is assumed, where the Z axis corresponds to the vertical line pointing from the bottom to the top through the centre of the shoulder.

2.2 The Head

This is a pan-tilt unit mounted on top of the shoulder. Relative to the shoulder, the head can pan an angular freedom ω, around the $O-Z$ axis. It also can tilt an angular freedom ϕ which is orthogonal to the pan angle ω.

2.3 The Stereo Plate

This is a plate to support the two stereo cameras. The stereo plate is fixed on top of the head. On top of the stereo plate the left and right camera pan-tilt units are symmetrically mounted. For simplicity, we shall call the left/right pan-titlt unit supporting the left/right camera the left/right unit. Since the stereo plate is fixed on top of the head, it therefore can tilt an angle ϕ. A reference system $S-UVW$ is assumed for the stereo plate. The origin S is taken to be the apex of the tilt angle ϕ, and it is on the $O-Z$ axis and with a distance h from the origin Z. $S-U$ axis is horizontal pointing from left to right, $S-V$ axis refers to the depth from the system toward the objects, $S-W$ axis is pointing upwards. The transformation from the $S-UVW$ to $O-XYZ$ is defined by

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} + R_\omega R_\phi \begin{pmatrix} U \\ V \\ W \end{pmatrix} \quad (1)$$

where

$$R_\omega = \begin{pmatrix} \cos\omega & -\sin\omega & 0 \\ \sin\omega & \cos\omega & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (2)$$

$$R_\phi = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{pmatrix} \quad (3)$$

and

$$\begin{pmatrix} X_S \\ Y_S \\ Z_S \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ h \end{pmatrix} \quad (4)$$

2.4 The Left Camera and Its Pan-Tilt Unit

On top of the stereo plate, the left and right pan-tilt unit are placed along the $S-U$ axis, and they are symmetrically placed about the centre - the $S-W$ axis. Let C denote the perspective center of the left camera, and f the focal length. A reference system $C-xyz$ is assumed for the left camera, $C-z$ axis is the principal axis of the camera pointing through the perspective center C towards the scene. The image plane is on back side of C . An image point is positioned with coordinates $(x, y, -f)$. The principal point is located at $(x_c, y_c, -f)$. For the left unit supporting the left camera, there is a geometric centre T , the pan angle α and the tilt angle β . We must be aware that the perspective centre C and the unit centre do not coincide. And due to the discrepancy between the two centres, the perspective centre C is a function of the pan and tilt angles α and β as well as the focal length f , which may be expressed generally as

$$C = C(T, \alpha, \beta, f) \tag{5}$$

A simple form of this function in the stereo plate reference system $S - UVW$ is

$$\begin{pmatrix} U_C \\ V_C \\ W_C \end{pmatrix} = \begin{pmatrix} U_T \\ V_T \\ W_T \end{pmatrix} + dR_0 R_\alpha R_\beta \begin{pmatrix} a \\ b \\ f+c \end{pmatrix} \tag{6}$$

where a, b, c, d are constants and fixed once the camera is fixed on the unit, and R_α, R_β are two two-dimensional rotation matrices

$$R_\alpha = \begin{pmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{pmatrix} \tag{7}$$

$$R_\beta = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{pmatrix} \tag{8}$$

and

$$R_0 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \tag{9}$$

Note that the image coordinate system generally has a rotation about the principal axis, which we denote here by γ . The transformation from the image coordinates to the stereo plate reference system is defined by

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = \begin{pmatrix} U_C \\ V_C \\ W_C \end{pmatrix} + R_0 R_\alpha R_\phi R_\gamma \begin{pmatrix} x - x_c \\ y - y_c \\ -f \end{pmatrix} \tag{10}$$

where

$$R_\gamma = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{11}$$

2.5 The Right Camera and Its Pan-Tilt Unit

Similarly we have everything for the right camera and its pan-tilt unit. Any element on the right camera or pan-tilt unit is denoted by x' corresponding to its counter part x on the left camera or unit. Therefore for the right camera we have the perspective center C', the reference system $C' - x'y'z'$, the focal length f', and the principal point $(x'_c, y'_c, -f')$. For the right pan-tilt unit, we have the unit centre T', pan angle α' and the title angle β' as well as the angle γ'.

The left and right pan-tilt units can translate but only symmetrically left-right about the central axis $S - W$ along the $S - U$ axis in accordance with the requirement on the stereo baseline length change due to different photogrammetric precision requirement. In general, we require the system to maintain

$$U_T = -U_{T'} = s \text{ , } V_T = V_{T'} \text{ , } W_T = W_{T'} \tag{12}$$

where s is a symbol denoting the distance from the left or right unit centre to the centre of the stereo plate, which is about the half of the baseline length. Note that a primary difference of Photogrammetron from general robots is that the baseline length is changeable and is controlled by the system.

Although each of the left and right camera pan-tilt units has two angular freedoms, we distinguish between two general system modes: strong stereo mode versus weak stereo mode. On the strong stereo mode, two principal axes $C - z$ and $C' - z'$ must be maintained coplanar， and that plane is called the principle epipolar plane. The two principal axes $C - z$ and $C' - z'$ form two angles θ and θ' respectively with the baseline CC'. In the weak stereo mode, we do not require the two principal axes be strictly coplanar, but the left and right camera should maintain overlapping views. We shall discuss the calibration for the two modes respectively.

3. IN-LAB CALIBRATION OF FIXED PARAMETERS

In the geometric model described above, there are fixed relations as follows:

1) the stereo plate is fixed on top of the head, so the distance parameter h is a constant;
2) the left and right units can only translate in one dimension, so the other two distance parameters V_T, W_T and $V_{T'}, W_{T'}$ are constants;
3) the left camera is fixed on top of the left unit, so the translations and scaling a, b, c, d as expressed in equation (6) are constant, which mediate the influence of the pan and tilt angles of the unit to the perspective centre.

The set of constant parameters is therefore defined as

$$(h, V_T, W_T, V_{T'}, W_{T'}, a, b, c, d) \quad (13)$$

The constant parameters $h, V_T, W_T, V_{T'}, W_{T'}$ can be measured through pure mechanical procedures, which we shall not elaborate here. The constants a, b, c, d are determinants of the perspective centre of the camera relative to the pan-tilt unit, which have to be determined using control information such as control points in a laboratory setup. However, the actual procedures for determining these constants can be the bundle adjustment using the perspective equations which is well established in the photogrammetry literature.

In the following discussions, we assume these 9 constant parameters are known as precalibrated in laboratory before any actual application of Photogrammetron.

4. IN-SITU CALIBRATION FOR THE STRONG STEREO MODE

In the strong stereo mode, for the simplicity of the geometry, we freeze the tilt freedom of the left and right camera units to absolute zero, so the two principal axes are coplanar with the $S-UV$ plane. The remaining pan angle of the left or right unit is now denoted by θ and θ' respectively as shown in Fig.1, i.e.

$$\theta = \alpha, \quad \theta' = \pi - \alpha', \quad \beta = \beta' = 0 \quad (14)$$

With the reference systems and geometric elements defined above, we can establish the stereo imaging equations. Take $O-XYZ$ as the global reference system. At any time t, an object point $P(X, Y, Z, t)$ is projected through the two cameras onto the left and right image points $p(x, y, f, t), p'(x', y', f', t)$ on the left and right images I, I', the corresponding image values are $I(x, y, t), I'(x', y', t)$. The projective equation between P and p can be expressed as

$$P = \overrightarrow{OP} = \overrightarrow{OS} + \overrightarrow{SC} + \lambda \overrightarrow{Cp} \quad (15)$$

where λ is a scalar.
Written in analytical form, we have

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ h \end{pmatrix} + R_\omega R_\phi \left(\begin{pmatrix} U_C \\ V_C \\ W_C \end{pmatrix} + \lambda R_0 R_\theta R_\gamma \begin{pmatrix} x - x_c \\ y - y_c \\ -f \end{pmatrix} \right) \quad (16)$$

where R_θ has the form of R_α as defined in (7) with α replaced by θ, and R_0 is a commuting matrix as defined in (9).

Similarly we can derive the projective equation between P and p' for the right camera as

$$P = \overrightarrow{OP} = \overrightarrow{OS} + \overrightarrow{SC'} + \lambda' \overrightarrow{C'p'} \quad (17)$$

or in analytical form as

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ h \end{pmatrix} + R_\omega R_\phi \left(\begin{pmatrix} U_{C'} \\ V_{C'} \\ W_{C'} \end{pmatrix} + \lambda' R_0 R_{\theta'} R_{\gamma'} \begin{pmatrix} x' - x'_c \\ y' - y'_c \\ -f' \end{pmatrix} \right) \quad (18)$$

where λ' is a scalar and R_θ has the form of R_α as defined in (7) with α replaced by $\pi - \theta'$.

Let

$$R = R_\omega R_\phi R_0 R_\theta R_\gamma = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \quad (19)$$

$$R' = R_\omega R_\phi R_0 R_{\theta'} R_{r'} = \begin{pmatrix} r'_{11} & r'_{12} & r'_{13} \\ r'_{21} & r'_{22} & r'_{23} \\ r'_{31} & r'_{32} & r'_{33} \end{pmatrix} \quad (20)$$

$$\begin{pmatrix} u \\ v \\ w \end{pmatrix} = R \begin{pmatrix} x - x_c \\ y - y_c \\ f \end{pmatrix} \quad (21)$$

$$\begin{pmatrix} u' \\ v' \\ w' \end{pmatrix} = R' \begin{pmatrix} x'-x'_c \\ y-y'_c \\ f' \end{pmatrix} \tag{22}$$

we have

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ h \end{pmatrix} + R_\omega R_\phi \begin{pmatrix} U_C \\ V_C \\ W_C \end{pmatrix} \tag{23}$$

$$\begin{pmatrix} X_{C'} \\ Y_{C'} \\ Z_{C'} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ h \end{pmatrix} R_\omega R_\phi \begin{pmatrix} U_{C'} \\ V_{C'} \\ W_{C'} \end{pmatrix} \tag{24}$$

Equations (16) and (18) now can be rewritten as

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} + \lambda \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{25}$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_C' \\ Y_{C'} \\ Z_C' \end{pmatrix} + \lambda' \begin{pmatrix} u' \\ v' \\ w' \end{pmatrix} \tag{26}$$

Eliminating the scalar λ and λ' from above equations results in the collinearity equations

$$x = x_c - f \frac{\begin{pmatrix} r_{11} & r_{12} & r_{13} \end{pmatrix} \begin{pmatrix} X-X_C \\ Y-Y_C \\ Z-Z_C \end{pmatrix}}{\begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} X-X_C \\ Y-Y_C \\ Z-Z_C \end{pmatrix}} \tag{27}$$

$$y = y_c - f \frac{\begin{pmatrix} r_{21} & r_{22} & r_{23} \end{pmatrix} \begin{pmatrix} X-X_C \\ Y-Y_C \\ Z-Z_C \end{pmatrix}}{\begin{pmatrix} r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} X-X_C \\ Y-Y_C \\ Z-Z_C \end{pmatrix}} \tag{28}$$

and

$$x' = x'_c - f' \frac{\begin{pmatrix} r'_{11} & r'_{12} & r'_{13} \end{pmatrix} \begin{pmatrix} X-X_{C'} \\ Y-Y_{C'} \\ Z-Z_C' \end{pmatrix}}{\begin{pmatrix} r'_{31} & r'_{32} & r'_{33} \end{pmatrix} \begin{pmatrix} X-X_{C'} \\ Y-Y_{C'} \\ Z-Z_{C'} \end{pmatrix}} \tag{29}$$

$$y' = y'_c - f' \frac{\begin{pmatrix} r'_{21} & r'_{22} & r'_{23} \end{pmatrix} \begin{pmatrix} X-X_{C'} \\ Y-Y_{C'} \\ Z-Z_{C'} \end{pmatrix}}{\begin{pmatrix} r'_{31} & r'_{32} & r'_{33} \end{pmatrix} \begin{pmatrix} X-X_{C'} \\ Y-Y_{C'} \\ Z-Z_{C'} \end{pmatrix}} \tag{30}$$

For each object point we have 4 collinearity equations at time t. Note that there are only 7 free parameters which are controlled by the system:

$$\mathbf{x} = (\omega \quad \phi \quad \theta \quad \theta' \quad s \quad f \quad f')^\tau \tag{31}$$

where $\mathbf{x}^\tau$ means the transpose of vector $\mathbf{x}$.

Applying equations (6), (7), (8), (9), (11), (19), (20), (23), (24) into equations (27)-(30), we obtain the functional form of x, y, x', y':

$$x = F(\omega, \phi, \theta, \theta', s, f; X, Y, Z) \tag{32}$$
$$y = G(\omega, \phi, \theta, \theta', s, f; X, Y, Z) \tag{33}$$
$$x' = F'(\omega, \phi, \theta, \theta', s, f'; X, Y, Z) \tag{34}$$
$$y' = G'(\omega, \phi, \theta, \theta', s, f'; X, Y, Z) \tag{35}$$

For target tracking, we must assume that the object points are also moving and every free parameter is also changing with time, so the collinearity equations should be written as

$$x(t) = F(\omega, \phi, \theta, \theta', s, f; X(t), Y(t), Z(t); t) \tag{36}$$
$$y(t) = G(\omega, \phi, \theta, \theta', s, f; X(t), Y(t), Z(t); t) \tag{37}$$
$$x'(t) = F'(\omega, \phi, \theta, \theta', s, f'; X(t), Y(t), Z(t); t) \tag{38}$$
$$y'(t) = G'(\omega, \phi, \theta, \theta', s, f'; X(t), Y(t), Z(t); t) \tag{39}$$

However for system calibration, we assume a number of control points exist in the surveillance area, and they are either man-made or extracted feature points, but they all fixed still. For each such control points, we have 4 collinearity equations, being continuous in time t :

$$x(t) = F(\omega,\phi,\theta,\theta',s,f;X,Y,Z;t) \quad (40)$$

$$y(t) = G(\omega,\phi,\theta,\theta',s,f;X,Y,Z;t) \quad (41)$$

$$x'(t) = F'(\omega,\phi,\theta,\theta',s,f';X,Y,Z;t) \quad (42)$$

$$y'(t) = G'(\omega,\phi,\theta,\theta',s,f';X,Y,Z;t) \quad (43)$$

There are basically two approaches for solving these equations for determining the 7 free parameters which themselves may change continuously in time.

The first approach uses $n > 2$ control points to form $4n$ collinearity equations of the form (40)-(43), and then solves for the 7 free parameters at any time point t . The actual procedure is similar to the bundle adjustment in analytical photogrammetry [Wang, 1990], but with the particular parameter set of (31). We shall not delve into the details of this approach as the bundle adjustment is well established in photogrammetry, and this particular bundle adjustment can be developed in a similar way.

The second approach builds on top of the first approach, but also takes into account the continuity of the parameter variables and system dynamics as welll as also take the system reading of these parameters as observations to the parameters themselves. The state transition equations and the observation equations of the Kalman filtering [Kalman, 1960] are written as

$$\mathbf{x}(t_k) = \Phi(t_k,t_{k-1})\mathbf{x}(t_{k-1}) + \Gamma(t_{k-1})\mathbf{w}(t_{k-1}) \quad (44)$$

$$\mathbf{z}(t_k) = \Psi(t_k)\mathbf{x}(t_k) + \mathbf{v}(t_k) \qquad (k \geq 1) \quad (45)$$

or using simplified notations as

$$\mathbf{x}_k = \Phi_{k,k-1}\mathbf{x}_{k-1} + \Gamma_{k-1}\mathbf{w}_{k-1} \quad (46)$$

$$\mathbf{z}_k = \Psi_k\mathbf{x}_k + \mathbf{v}_k \qquad (k \geq 1) \quad (47)$$

where $\mathbf{x}(t)$ is the 7-dimensional parameter vector as defined by (31) at time t, also called the state vector of the system; k is the integer index of time, and satisfying

$$-\infty < \ldots < t_{k-1} < t_k < t_{k+1} < \ldots < \infty \quad (48)$$

$\mathbf{w}(t)$ is *m*-dimensional dynamic noise vector; $\mathbf{z}(t)$ is *l*-dimensional observation vector, $l \leq 7 + 4n$, which includes system readings of the free parameters and image coordinates (x, y, x', y') of visible control points; $\mathbf{v}(t)$ is *l*-dimensional observation noise vector. Note that not every free parameter or every control point is visible, so the observation vector can be incomplete data. $\Phi(t,\tau)$ is a 7×7 non-singular matrix, called the state transition matrix of the system; $\Gamma(t)$ is a $7\times m$ matrix, called the dynamic noise matrix; $\Psi(t)$ is a 7×7 matrix, called the observation matrix. $\Phi(t,\tau)$ has the following properties:

(1) $\Phi(t,t) = I$ (where I is an identity matrix) (49)

(2) $\Phi^{-1}(t_k,t_{k-1}) = \Phi(t_{k-1},t_k)$ (50)

(3) $\Phi(t_{k,},t_{k-2}) = \Phi(t_k,t_{k-1})\Phi(t_{k-1},t_{k-2})$ (51)

The observation equations (45) include the linearized version of the collinearity equations (40)-(43) as well as the additional observation equations of the system readings for the parameters $\mathbf{x}(t)$. We shall not delve into the detailed form of the state transition equations (44) and the observation equations (45).

Let $\hat{\mathbf{x}}_k$ denote the estimate of $\mathbf{x}(t)$ at time t_k , and $\tilde{\mathbf{x}}_k = \mathbf{x}_k - \hat{\mathbf{x}}_k$ denote the error of estimation. Assume the estimate $\hat{\mathbf{x}}_k$ is a linear function of the observation $\mathbf{z}$, the linear least square estimation is achieved under the following criterion

$$\min E[(\mathbf{x}_k - \hat{\mathbf{x}}_k)(\mathbf{x}_k - \hat{\mathbf{x}}_k)^\tau] = E[\tilde{\mathbf{x}}_k\tilde{\mathbf{x}}_k{}^\tau] \quad (52)$$

Suppose we have made k observations $\mathbf{z}_1, \mathbf{z}_2, \ldots, \mathbf{z}_k$ to the 7-dimensional linear dynamic system of (44) through the *l*-dimensional linear observation system of (45) from time *1* to time *k.* According to these k observation data, we can estimate the system state $\hat{\mathbf{x}}_k$ at time *k,* and the actual estimation procedure has a particular form of Kalman filtering,

$$\hat{\mathbf{x}}_k = \Phi_{k,k-1}\hat{\mathbf{x}}_{k-1} + K_k(\mathbf{z}_k - \Psi_k\Phi_{k,k-1}\hat{\mathbf{x}}_{k-1}) \quad (53)$$

where K_k is called the weight matrix or gain matrix and is defined by the coefficient matrices of the state transition equations (44) and the observation equations (45) as well as the stochastic properties of the noises $\{w_k\},\{v_k\}$. We shall not delve into the detailed form of K_k and further details of the estimation procedure due to the space limitation.

5. IN-SITU CALIBRATION FOR THE WEAK STEREO MODE

In the weak stereo mode, each of the left or right pan-tilt unit has two angular freedoms α,β (or α',β' for the right camera) and the principal axis of the left camera and the right one are not required to be coplanar. In this mode, the free parameter vector consists of 9 free parameters which may change in time:

$$\mathbf{x} = (\omega \quad \phi \quad \alpha \quad \beta \quad \alpha' \quad \beta' \quad s \quad f \quad f)^{\tau} \tag{54}$$

There are two approaches for calibration in such a weak stereo mode: the first approach is a joint solution for estimating all the 9 parameters simultaneously through a particular form of Kalman filtering as described in the previous section; the second approach is to estimate the absolute orientation and interior orientation for each camera independently using control points. Still in the second approach, the continuity and dynamics of the system state parameters can be exploited through a Kalman filtering mechanism.

6. CONCLUSIONS

In this paper, a theory of geometric calibration of intelligent Photogrammetron is proposed upon a geometric model of Photogrammetron. Two system operating modes are distinguished: the strong stereo mode versus the weak stereo mode. In the strong stereo mode, the free parameter vector is made up of 7 parameters, while in the weak stereo mode each of the left or right pan-tilt unit has its own pan and tilt angular freedoms. A pure photogrammetris solution is a particular bundle adjustment using fixed control points. However the general solution is a particular Kalman filtering which builds on top of the bundle adjustment but extends to exploiting the continuity and dynamics of system motion. The theory proposed here is quite general, but any actual implementation has to take into account the actual physical structure and control mechanisms of the Photogrammetron system.

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REFERENCES

Kalman, R.E., 1960. A new approach to linear filtering and prediction problems. *Transactions of the ASME, Journal of Basic Engineering,* (March 1960),pp.35-46.

Pan, H.P., 2002. Concepts and initial design of intelligent stereo Photogrammetron. *Journal of Surveying and Mapping*, accepted to appear, Beijing, in Chinese with English abstract.

Wang, Z.Z., 1990. *Principles of Photogrammetry (with Remote Sensing)*. Publishing House of Surveying and Mapping, Beijing.