Application of Non-Metric Digital 3-D Photogrammetry in Accident Reconstruction

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Abstract The very first step when starting an accident reconstruction project is to collect and measure the information left after the accident. This step, even if it sounds straightforward, can be quite time consuming and can't be repeatable if some information is missed. Photogrammetry is a technique that extracts 2-D or 3-D information through the process of analyzing and interpreting photographs, and is more and more widely used in the accident reconstruction. The purpose of this paper is to give the theory of the non-metric digital 3-D photogrammetry, some precautions when use photogrammetry, and at last an example to evaluate the photogrammetry. The study will show that photogrammetry is indeed a practical and interesting approach to measure the geometry information.

Keywords: Photogrammetry Accident Reconstruction Measurement Vehicle Impact Camera Calibration

1 Introduction

The main purpose of accident reconstruction is to decide the pre-impact velocity based on the information left on the scene after the accident, including tire marks, scrapes, debris, and final resting position of the vehicle(s) [1]. In order to gather these accident artifacts, a major effort is required and the accident scene survey become much time consuming. Furthermore, this geometry information will be non-existent when reconstructors are analyzing the accident. In most cases the only clue to the missing geometry data is contained in the photographs taken by early scene investigators. A reasonably accurate and practical method of extracting geometric data from such photographs would be a very useful tool for reconstrutors.

Photogrammetry began in the late 1800's which was defined by the American Society of Photogrammetry as "the art, science, and technology of obtaining reliable information about physical objects and environment through the process of recording, measuring, and interpreting photographic images" [2].

The cameras used for photogrammetry are defined as metric and non-metric. Metric cameras have stable interior parameters and are used primarily for photogrammetric purposes. Non-metric cameras have less stable interior parameters and should be calibrated (if possible), and generally yield results of lower accuracy than metric cameras [3]. But they are much cheaper and more available.

There are several photogrammetric techniques available to reconstructors. 2-D methods, based on the assumption that desired points lie on a defined plane, are generally used for the placement of markings on a road face. 2-D methods require only one photograph and can provide adequate accuracy for nominally flat surfaces [4] [5]. 3-D methods require one or more photographs and do not require planar surfaces [6]. Because the real road face may be cambered or potholed, 3-D methods become more accurate and all-purpose.

With the development of photography and computer technology, photogrammetry has gone from analytical photogrammetry to digital photogrammetry. Analytical photogrammetry, base on the analytical stereo plotter and physical photographs, can only be used by the experienced and professional operator [7]. Digital photgrammetry, based on the computer programs and digital photographs taken by the digital camera, can be done by the less professional persons [8].

This paper introduces the theory of non-metric digital 3-D photogrammetry, and then gives some guidelines and precautions to increase the accuracy. At last, a typical example is presented to interpret the application of the photogrammetry in the accident reconstruction.

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2 Theory of Photogrammetry

Based on the perspective transformation between actual space coordinate system and image plane coordinate system, 2-D image of the 3-D object can be got by use of digital camera. Based on the two or more pictures in the different directions, 3-D geometry information can be synthesized. Because the Non-metric cameras have less stable internal geometry, it is important to calibrate distortion of the camera to improve the accuracy.

2 Direct Linear Transformation

There exists transformation between the coordinate systems of object space and image plane of camera. This transformation can be explained by the example of two camera positions (see Fig. 1). Where, XYZ is the coordinate system of object space, and xy is coordinate system of image plane of camera. Point A is the 3-D object point, and Point a is the 2-D image point.

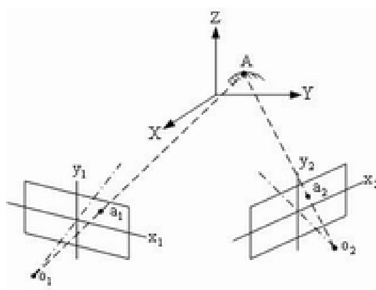

Fig.1 The coordinate systems of object space and image planes of two camera positions

For camera position 1, the transformation between image point coordinate and object point coordinate can be written as:

$$\begin{cases} x_1 = \dfrac{a_1 X + a_2 Y + a_3 Z + a_4}{a_9 X + a_{10} Y + a_{11} Z + 1} \\ y_1 = \dfrac{a_5 X + a_6 Y + a_7 Z + a_8}{a_9 X + a_{10} Y + a_{11} Z + 1} \end{cases} \tag{1}$$

Where the a's are called projection constants which are related to the camera internal parameters and position. This set of equations was given the name Direct Linear Transformation (DLT)[9].

In the same way, for camera postion2, the transformation between image point coordinate and object point coordinate can be written as:

$$\begin{cases} x_2 = \dfrac{b_1 X + b_2 Y + b_3 Z + b_4}{b_9 X + b_{10} Y + b_{11} Z + 1} \\ y_2 = \dfrac{b_5 X + b_6 Y + b_7 Z + b_8}{b_9 X + b_{10} Y + b_{11} Z + 1} \end{cases} \tag{2}$$

Where the b's are also projection constants which are related to the camera internal parameters and position.

Equation set (1) can be transformed as equation (3):

$$\begin{bmatrix} X & Y & Z & 1 & 0 & 0 & 0 & 0 & -x_1 X & -x_1 Y & -x_1 Z \\ 0 & 0 & 0 & 0 & X & Y & Z & 1 & -y_1 X & -y_1 Y & -y_1 Z \end{bmatrix} \times A = \begin{bmatrix} x_1 \\ y_1 \end{bmatrix} \tag{3}$$

Where $A = \left[a_1, a_2, \cdots, a_{11}\right]^T$.

Likewise, Equation set (2) can be transformed as equation (4):

$$\begin{bmatrix} X & Y & Z & 1 & 0 & 0 & 0 & 0 & -x_2X & -x_2Y & -x_2Z \\ 0 & 0 & 0 & 0 & X & Y & Z & 1 & -y_2X & -y_2Y & -y_2Z \end{bmatrix} \times B = \begin{bmatrix} x_2 \\ y_2 \end{bmatrix} \tag{4}$$

Where $B = \left[b_1, b_2, \cdots, b_{11}\right]^T$.

The a's and b's are 22 unknowns altogether. Four linear equations can established by one known object point and two corresponding image points. In order to resolve the 22 unknowns, at least six or more known points will be required. So if six or more points are known, least square method will used to solve the overdetermined set of equations. This is the first step of measuring work.

Next step is to calculate the coordinate of the unknown object point (X, Y, Z) by its corresponding image points (x_i , y_i).

Equation set (1) can also be transformed as equation (5):

$$\begin{bmatrix} (a_1 - a_9x_1) & (a_2 - a_{10}x_1) & (a_3 - a_{11}x_1) \\ (a_3 - a_9y_1) & (a_6 - a_{10}y_1) & (a_7 - a_{11}y_1) \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_1 - a_4 \\ y_1 - a_3 \end{bmatrix} \tag{5}$$

Likewise, Equation set (2) can be transformed as equation (6):

$$\begin{bmatrix} (b_1 - b_9x_1) & (b_2 - b_{10}x_1) & (b_3 - b_{11}x_1) \\ (b_3 - b_9y_1) & (b_6 - b_{10}y_1) & (b_7 - b_{11}y_1) \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} x_2 - b_4 \\ y_2 - b_3 \end{bmatrix} \tag{6}$$

Base on the equations (5) and (6), three unknowns (X, Y, Z) can be easily calculated. With object points calculated one by one, object 3- D profile can be computed.

Due to non-metric digital camera's convenience and low cost, they have been widely used. But the non-metric digital camera neither interior orientation parameters nor exterior orientation parameters are known, so if they are used in the photogrammetry, Direct Linear Transformation is a convenient method which establishes a direct relation between image plane and object space.

2.1 Calibration of Distortion

Because non-metric cameras have less stable interior parameters, it is very important to calibrate distortion of camera to improve the accuracy. The distortion includes radial distortion, decentered distortion and affine and shear deformation [10].

Factor distortion can be written as:

$$\begin{cases} \Delta x_r = x(k_1r^2 + k_2r^4 + k_3r^6) \\ \Delta y_r = y(k_1r^2 + k_2r^4 + k_3r^6) \end{cases} \tag{7}$$

It is assumed that origin of the image plane is the intersection of the primary optical axis and the image plane. Where $r=(x^2+y^2)^{1/2}$, which is the distance between image point to optical axis. Where k's are radial distortion factors.

Decentered distortion can be written as:

$$\begin{cases}\Delta x_d = p_1(r^2+2x^2)+2p_2xy \\ \Delta y_d = p_2(r^2+2y^2)+2p_1xy\end{cases} \tag{8}$$

Where p's are decentered distortion factors.

Affine and shear deformation can be written as:

$$\begin{cases}\Delta x_{as} = b_1x+b_2y \\ \Delta y_{as} = b_1y+b_2x\end{cases} \tag{9}$$

Where b's are affine and shear deformation factors.

So the total distortion can be written as:

$$\begin{cases}\Delta x = x(k_1r^2+k_2r^4+k_3r^6)+p_1(r^2+2x^2)+2p_2xy+b_1x+b_2y \\ \Delta y = y(k_1r^2+k_2r^4+k_3r^6)+p_2(r^2+2y^2)+2p_1xy+b_1y+b_2x\end{cases} \tag{10}$$

After compensation, x_i and y_i will be respectively replaced by $x_i+\Delta x_i$ and $y_i+\Delta y_i$. Then input them into equation set (1) and transform equation as:

$$\begin{cases}[x(a_{12}r^2+a_{13}r^4+a_{14}r^6)+a_{15}(r^2+2x^2)+2a_{16}xy+a_{17}x+a_{18}y]\times(a_9X+a_{10}Y+a_{11}Z+1) \\ -(a_1X+a_2Y+a_3Z+a_4)=0 \\ [y(a_{12}r^2+a_{13}r^4+a_{14}r^6)+a_{15}(r^2+2y^2)+2a_{16}xy+a_{17}y+a_{18}x]\times(a_9X+a_{10}Y+a_{11}Z+1) \\ -(a_1X+a_2Y+a_3Z+a_4)=0\end{cases} \tag{11}$$

Where a_{12}, a_{13}, a_{14}, a_{15}, a_{16}, a_{17} and a_{18} are separately equal to k_1, k_2, k_3, p_1, p_2, b_1 and b_2. For one camera position, there are 18 unknown parameters, so at least need 9 unknown points to resolve the question. Often more known points may be needed to increase the accuracy.

Equation set (11) is a very complicated non-linear equation set. The method of least square generalized reverse is used to resolve the non-linear equations [11].

Suppose that non-linear equations can be written as:

$$f_i(x_0,x_1,\cdots,x_{n-1})=0 \qquad i=0,1,\cdots,m-1 \qquad m\ge n \tag{12}$$

Its Jacobian is defined as:

$$
A=\begin{bmatrix}
\frac{\partial f_0}{\partial x_0} & \frac{\partial f_0}{\partial x_1} & \cdots & \frac{\partial f_0}{\partial x_{n-1}} \\
\frac{\partial f_1}{\partial x_0} & \frac{\partial f_1}{\partial x_1} & \cdots & \frac{\partial f_1}{\partial x_{n-1}} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{\partial f_{m-1}}{\partial x_0} & \frac{\partial f_{m-1}}{\partial x_1} & \cdots & \frac{\partial f_{m-1}}{\partial x_{n-1}}
\end{bmatrix} \tag{11}
$$

The iterative formula to compute the equations (11) can be written as:

$$
X^{(k+1)} = X^{(k)} - \alpha^{(k)} Z^{(k)} \tag{12}
$$

Where $Z^{(k)}$ is the least square solution of linear equations:

$$
A^{(k)} Z^{(k)} = F^{(k)} \tag{13}
$$

Where $F^{(k)} = \left(f_0^{(k)}, f_1^{(k)}, \cdots, f_m^{(k)}\right)^T$.

The $\alpha^{(k)}$ in the equations (12) is solution to make the 1-D function $\sum_{i=0}^{m-1} f_i^{k+1}$ to the minimal value, and can be calculated by rational extremum method.

Here the initial value of $a_1, a_2, \cdots, a_{11}$ can be calculated by the method provided in Passage 2.1, and the initial value of $a_{12}, a_{13}, a_{14}, a_{15}, a_{16}$ can all be set to 0 because they are some small.

3 Convenience and Accuracy

3.1 Guidelines

As a measurement project, the convenience of the method should be studied. This kind of photogrametric measurement project includes two parts of work. One part is outdoor work, the main task of which is taking photographs. Another part is indoor work, the main task of which is to process to photographs to get the geometry information. If program of photogrametry has been written well or buyed, the task become some easy.

On the face of these two parts of work, we can see that it's more convenient than the traditional methods in the survey of accident reconstruction. However, following practical guidelines should be followed:

1. Try to get the angles between the shots as close to 90°
2. Try to get all important points at least 3 photographs
3. Try to get as much overlap between adjacent photographs
4. Take many photographs of the object but use only 4 at the start until you determine you need others
5. The guideline 1 is the consequence of the following problem (Fig. 2):

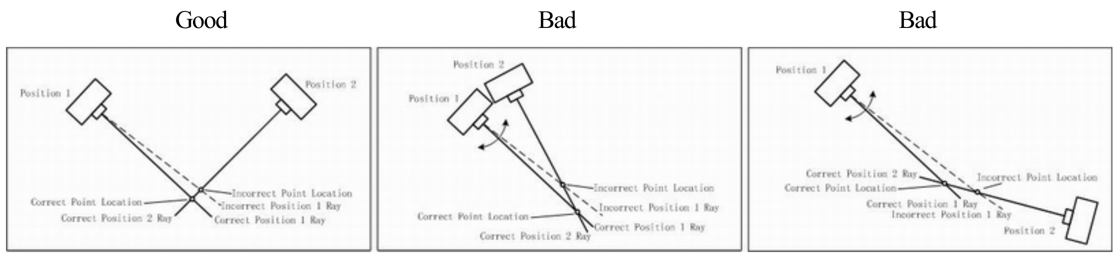

Fig.2 Influence of camera angles

In the all cases, Position 1 has the same position and the same angle error. On the other hand, in the middle figure, Position 2 is close in angle to Position 1. The small error is multiplied and the resulting position of the 3-D point is much farther off the mark. The right figure is the same. The closer the angle between the light rays is to a right angle (90°), the smaller any possible error will be.

Nobody can mark (in order to get the coordinate of an image point) a point perfectly, and occasionally the point you wish to identify is fuzzy or to hard to position exactly in the photograph. If imprecise point locations in the photographs exist, the projected 3-D point will be inaccurate. To reduce this problem, it is important to mark a point in three or more photographs. That way, if the point was positioned incorrectly on one of the photographs, the other photographs could compensate for it. If it is marked on only two photographs, marking errors cannot be found and will cause an inaccurate 3-D point to be created. This is the reason for the guideline 2.

Points need to be marked in two or more photographs. Photographs taken side by side should contain many of the same object features and points. The more references across photographs for each point, the better, but the user wishes to minimize the marking task since it takes time. To balance these two, it is best if the photographs overlap as much as possible. This is the cause for guidelines 3.

If many photographs are used at the start, it will be difficult for the user to mark the points and the user often become confused. This job becomes a hard task. So at first, four photographs are used. Guideline 3 just explains this.

In practice, it is not required to follow these guidelines strictly, but the closer the requirements are met, the easier the measurement process will be and the more accurate the measurements. Angle, distance and height should be change as much as possible when taking photographs.

3.2 Accuracy

The accuracy of a measurement project is dependent on [12]:

- the quality of the calibration of the camera
- the resolution of the camera
- the geometry of the camera positions
- the precision with which the user marks the features as they appear in images

If the user takes the following precautions, the errors will be minimized and measurement accuracy maximized:

- Ensure that a well-calibrated digital camera is used for the project
- Maximize the number of photographs that each point is marked on

- Ensure that all points appear on three or more photographs
- Minimize the number of points that appear on only two photographs
- Ensure that the angle between the camera positions is as close to 90 degrees as possible
- Ensure all point markings on the images are precise
- Do not guess at a point position when it's fuzzy to identify

4 Application to a Typical Traffic Accident

4.1 Photogrammetric Analysis of the accident scene

There was an accident happened to one car in Hai Nan province, China in December 2001 as shown in Fig.3.

Fig.3 A typical accident scene

I have made the photogrammetric analysis to this accident scene with the method described above, see Fig.4.

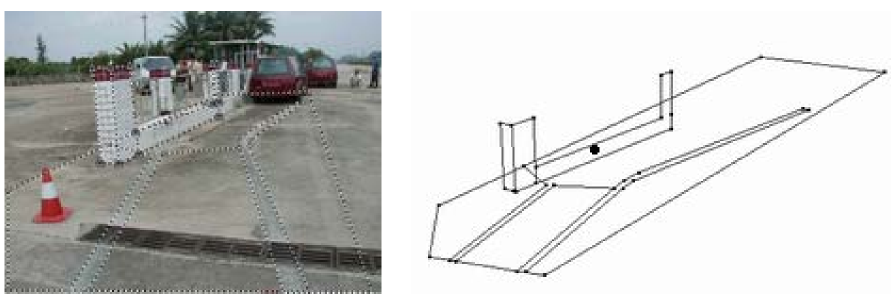

Fig.4 Photogrammetric analysis of the accident scene

In this example, I have used 3 photographs of accident scene (but only show 1 photograph here). These photographs are taken by digital camera OLYMPUS C900Z. By photogrammetric analysis, I have got the 3-D model of the tire marks on the road and the crash center on the wall.

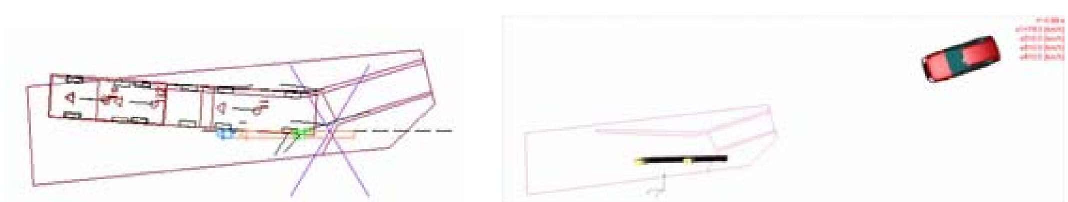

Fig.5 Accident reconstruction in PC-Crash

4.2 Additional Accident Analysis with the Software PC-Crash

In order to validate practicability of the phtotogrammetry's application in the accident reconstruction additionally, the model computed in the above passage is imported into the PC-CRASH, one of the famous accident reconstruction softwares, and I calculate the pre-impact velocity, 51.3km/h (See Fig.5).

5 Conclusion

In this paper, the theory of non-metric digital 3-D photogrammetry is discussed at length. And then, some guidelines and precautions are given to increase the accuracy. In the end, I give an example to explain the application of phtogrammetry in accident reconstruction. From this, we can see that, photogrammetry is a very practical and convenient method to measure the geometry information left after the accident. The main benefits are the increased accuracy compared to manual measurements, short immobilization time, simplicity, enhanced visualization and low cost.

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