DIGITAL TERRESTRIAL PHOTOGRAMMETRY WITH PHOTO TOTAL STATION

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ABSTRACT：

Terrestrial photogrammetry is engaged in measurement, contour delineation or 3D reconstruction with photos captured by a camera located on the ground. Terrestrial photogrammetry has gained wide applications in many fields such as 3D building reconstruction, heritage protection and so on. In this paper, a new instrument named photo total station system has been adopted and meanwhile based on this new instrument, a flexible and efficient digital terrestrial photogrammetry method has been developed. Photo Total Station System (PTSS) is a completely novel surveying system, which installs metric digital camera on total station to compose an integration system together with digital photogrammetry software. PTSS takes full advantages of mature digital photogrammetry techniques and accurate total station survey method and provides the benefits of both systems, while minimizing their shortcomings. The whole process of digital terrestrial photogrammetry includes two stages: field survey and indoor photogrammetric processing. Depends on specific measurement condition and requirement, three measurement modes can be selected to use so that the whole measurement process can be very flexible. After field survey, all measurement data including images are processed by attached photogrammetry software whose unique characteristics are presented in the paper: such as multi images based image matching (short base) are used instead of stereo based one in the conventional photogrammetry; using so called control bars setting near the camera instead of regular control points – a real non-contact measuring method can be implemented so that control points around or on the measured object can be reduced or completely unnecessary. With this technique, DTM and contour generation, volume measurement and 3D modeling all can be completed. The method proposed in this paper has been used in several measurement sessions. The results show its great potential in digital terrestrial photogrammetry.

1 INTRODUCTION

Terrestrial photogrammetry is engaged in measurement, contour delineation or 3D reconstruction with photos captured by a camera located on the ground. During past few years, with the rapid development of digital photogrammetry techniques and the availability of ease-using, focusable and relatively cheap digital cameras, the method and device used in terrestrial photogrammetry also changed greatly. General speaking, digital techniques become mainstream and efficiency has been greatly improved. At same time, terrestrial photogrammetry has gained wide applications in many fields such as 3D building reconstruction, heritage protection and so on.

However in spite of great development of traditional terrestrial photogrammetry over the past years, it is still necessary to set some control points around the objects to be measured[Feng wenhao, 2001]. It is well known that setting control points around the objects is a very time-consuming and labour-intensive job. So in fact photogrammetrists' dream of "non-contact measurement" is still on its way.

On the other hand, although widely accepted as an accurate surveying method, total station survey still suffers from a number of weaknesses: Firstly, total station does not mean total survey. It is impossible to record an absolute survey of all the features within a given area. It would be time-consuming and pointless to record every individual brick in a wall, for example. Secondly, many features such as line segments on the buildings can not been fully used during measurement and however, sometimes they are important to reconstruct the object to be measured.

Based on these considerations above, this paper presents a completely novel surveying system, named Photo Total Station System (PTSS), which installs metric digital camera on the telescope of a total station to compose an integration system together with digital photogrammetry software. In such system, metric digital camera and total station are rigidly connected with a mechanical adapter. During measurement with PTSS, firstly traversing is complemented through total station and total station is also used to measure object coordinates of necessary control points on the control bar (board) near the traversing point, which are mainly used to calibrate the off-set parameters of the camera related to the total station. Meanwhile, at each traverse point photos are taken by metric digital camera. While photographing, camera can rotate with telescope of total station to take scanning photos whose corresponding orientations are observed from total station. Finally measurement data and images are processed by advanced digital photogrammetry software and entire measurement is completed. It can be seen from the process of measurement that PTSS takes full advantages of mature digital photogrammetry techniques and accurate total station survey method and provides the benefits of both systems, while minimizing their shortcomings.

The combination of camera and theodolite or total station can be traced to many years ago. During 1970's, to perform terrestrial photography, terrestrial camera was connected with a theodilite to compose a system named phototheodilite. Different phototheodilites include Zeiss Jena 19/1318 and the Chinese-madeDJS/1318-1, Wild P30, P31, P32, the Zeiss Jena UMK, and the Zeiss(Opton) TMK, etc[Wang Zhizhuo, 1979; Li Deren etc., 1992]. These instruments went to the end as photogrammetry evolved from analogue and analytical stage into digital era.

During 1980's, it seemed likely that motorized theodilites with CCD camera fitted to their telescope would be able to supercede photogrammetric techniques in many industrial situations. They could provide real-time read-outs of coordinates on industrial targets. After a brief period of popularity their bulk, cost and relative slowness compared to digital cameras saw their demise [K.B. Atkinson, 1996].

Nowadays, Total station has been widely used together with digital camera in applications such as accident, archaeological site survey, civil engineering survey as well as 3DGIS, building reconstruction. But in most cases they have been used separately, while total station is just used to achieve the 3D object coordinates of control points for the following photogrammetric process [Masataka Imura, etc., 2001; S. Ikeda etc., 2003]. Carl Gravel presented a CAP (computer assisted photogrammetry) system, which combines a total station with ordinary digital camera and also offers corresponding software for processing the data [Gravel C. etc., 1999]. Unlike his system, in PTSS camera is fixed with telescope of total station instead of total station so that camera can be rotate with the telescope. Field of vision has been extended by rotation photos so that high accuracy has been obtained.

Generally speaking, the technique of integration of total station and digital camera is still under development. So when proposing several problems which should be resolved for further development of geoinformatics in one of his papers, Shunji Murai said "Integration of total station and digital camera for close range measurement: onsite processing for triangulation with ground based control survey has been developed. In future total station with digital camera should be developed."[Shunji Murai, 2002] In this work our contribution aims at providing a further step towards fully development and wide application of this technique.

In the following, section 2 presents the system hardware, photography method, Coordinates System, Collinear Equation, Orientation Offset definition in detail. Then measurement process and mode are introduced in section three. Experimental results as well as accuracy analysis and sample applications are shown in Section four and five respectively.

2 SYSTEM DESCRIPTION

2.1 Hardware

The hardware of PTSS includes metric digital camera, total station and PDA (Personal Digital Assistant). As Fig.1 shows, metric digital camera is rigidly fixed on the telescope of total station with a mechanical adapter and PDA, which is not shown in the figure, is used to store measurement data and image index and also control whole survey process of total station.

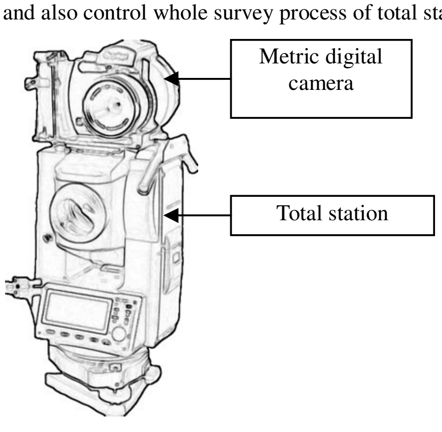


Fig. 1 Hardware of PTSS

2.2 Coordinates System

In PTSS, three coordinate systems have been involved: ground coordinate system(G-XYZ), total station coordinate system (T-XYZ) and image space coordinate system (S-xyz) (see Fig. 2). Ground coordinate system is left-hand system. Total station coordinate system and image space coordinate system are right-hand system, but their orientation of coordinate axis is different. Before calculation, coordinates system should be transformed so that all calculation happens in same coordinate system.

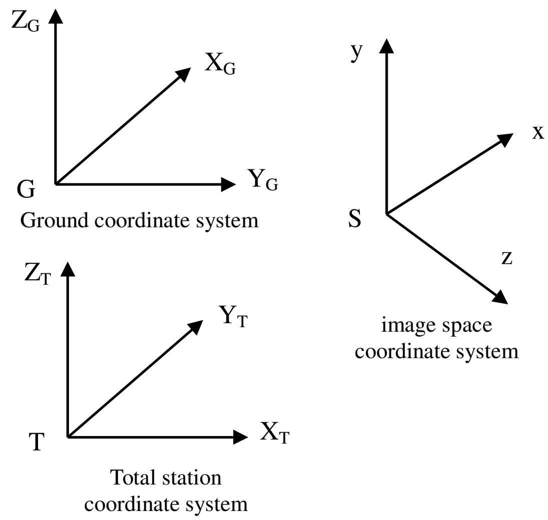


Fig. 2 Coordinate systems

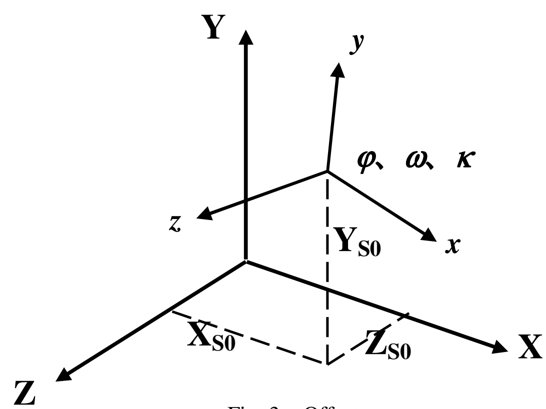


Fig. 3 Offset

2.3 Definition of OFFSET

Image forming process of camera is a central projection defined in image space coordinate system. The location and orientation of central project in total station coordinate system can be uniquely determined in terms of coordinate X_{S0}、Y_{S0}、Z_{S0} of projection center S in total station coordinate system along with the angular orientation elements of its space axis system in the total station axis system (Fig. 3). The elements of angular orientation are commonly represented by three independent angles ($\varphi_0, \omega_0, \kappa_0$), which, along with X_{S0}, Y_{S0}, Z_{S0}, is referred to as Orientation Offset between camera and total station.

2.4 Collinear Equation

In traditional photogrammetry, collinear equation is used to describe the relationship between ground coordinate system and image space coordinate system. But in PTSS a new system, total station coordinate system is added. When an object point in total station coordinate system is projected into an image point (x, y, -f) in image space coordinate system and then transformed into total station coordinate system, we can get following equation:

$$\begin{bmatrix} X_T \\ Y_T \\ Z_T \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} X'_T \\ Y'_T \\ Z'_T \end{bmatrix}$$

$$= \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \left(\begin{bmatrix} X_{S_0} \\ Y_{S_0} \\ Z_{S_0} \end{bmatrix} + \lambda R_{\varphi_0 \omega_0 \kappa_0} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \right) \quad (1)$$

where: X_T, Y_T, Z_T-----coordinates of a object point in total station coordinate system

α, β ----- horizontal angle and vertical angle of total station

$X_{S0}, Y_{S0}, Z_{S0}, \varphi_0, \omega_0, \kappa_0$ ----- Offset between camera and total station

Considering coordinates of object point in ground coordinate system can be represented by the following equation:

$$\begin{bmatrix} X_G \\ Y_G \\ Z_G \end{bmatrix} = \begin{bmatrix} X_T + X_{Gi} \\ Y_T + Y_{Gi} \\ Z_T + Z_{Gi} \end{bmatrix} \quad (2)$$

where X_{Gi}, Y_{Gi}, Z_{Gi} are coordinates of total station in ground coordinate system, we can get**:**

$$\begin{bmatrix} X_G - X_{Gi} \\ Y_G - Y_{Gi} \\ Z_G - Z_{Gi} \end{bmatrix} = \begin{bmatrix} \cos\alpha & 0 & -\sin\alpha \\ 0 & 1 & 0 \\ \sin\alpha & 0 & \cos\alpha \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta \\ 0 & \sin\beta & \cos\beta \end{bmatrix} \left(\begin{bmatrix} X_{S_0} \\ Y_{S_0} \\ Z_{S_0} \end{bmatrix} + \lambda R_{\varphi_0 \omega_0 \kappa_0} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \right)$$

$$= \begin{bmatrix} \cos\alpha & -\sin\alpha \sin\beta & -\sin\alpha\cos\beta \\ 0 & \cos\beta & -\sin\beta \\ \sin\alpha & \cos\alpha\sin\beta & \cos\alpha\cos\beta \end{bmatrix} \left(\begin{bmatrix} X_{S_0} \\ Y_{S_0} \\ Z_{S_0} \end{bmatrix} + \lambda R_{\varphi_0 \omega_0 \kappa_0} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \right)$$

$$= \begin{bmatrix} A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \\ C_1 & C_3 & C_3 \end{bmatrix} \begin{bmatrix} X_{S_0} \\ Y_{S_0} \\ Z_{S_0} \end{bmatrix} + \lambda \begin{bmatrix} A_1 & A_2 & A_3 \\ B_1 & B_2 & B_3 \\ C_1 & C_3 & C_3 \end{bmatrix} \begin{bmatrix} a_1 & a_2 & a_3 \\ b_1 & b_2 & b_3 \\ c_1 & c_2 & c_3 \end{bmatrix} \begin{bmatrix} x \\ y \\ -f \end{bmatrix} \quad (3)$$

Simplifying the equations (3), on addition of interior orientation elements x_0,y_0 (the coordinates of the image principal point), we can get collinear equation in PTSS as following：

$$x - x_0 = -f \frac{\begin{matrix} l_1[(X_G - X_{Gi}) - (A_1 X_{S_0} + A_2 Y_{S_0} + A_3 Z_{S_0})] + \\ m_1[(Y_G - Y_{Gi}) - (B_1 X_{S_0} + B_2 Y_{S_0} + B_3 Z_{S_0})] + \\ n_1[(Z_G - Z_{Gi}) - (C_1 X_{S_0} + C_2 Y_{S_0} + C_3 Z_{S_0})] \end{matrix}}{\begin{matrix} l_3[(X_G - X_{Gi}) - (A_1 X_{S_0} + A_2 Y_{S_0} + A_3 Z_{S_0})] + \\ m_3[(Y_G - Y_{Gi}) - (B_1 X_{S_0} + B_2 Y_{S_0} + B_3 Z_{S_0})] + \\ n_3[(Z_G - Z_{Gi}) - (C_1 X_{S_0} + C_2 Y_{S_0} + C_3 Z_{S_0}) \end{matrix}} \quad (4)$$

$$y - y_0 = -f \frac{\begin{matrix} l_2[(X_G - X_{Gi}) - (A_1 X_{S_0} + A_2 Y_{S_0} + A_3 Z_{S_0})] + \\ m_2[(Y_G - Y_{Gi}) - (B_1 X_{S_0} + B_2 Y_{S_0} + B_3 Z_{S_0})] + \\ n_2[(Z_G - Z_{Gi}) - (C_1 X_{S_0} + C_2 Y_{S_0} + C_3 Z_{S_0})] \end{matrix}}{\begin{matrix} l_3[(X_G - X_{Gi}) - (A_1 X_{S_0} + A_2 Y_{S_0} + A_3 Z_{S_0})] + \\ m_3[(Y_G - Y_{Gi}) - (B_1 X_{S_0} + B_2 Y_{S_0} + B_3 Z_{S_0})] + \\ n_3[(Z_G - Z_{Gi}) - (C_1 X_{S_0} + C_2 Y_{S_0} + C_3 Z_{S_0})] \end{matrix}}$$

where: A_i , B_i , C_i , l_i , m_i , n_i (i = 1, 2, 3) are coefficients;

x_0, y_0----position of image principal point.

2.5 Orientation Offset Calibration

As described above, because of the rigid connection between camera and total station, position and pose of camera (exterior orientation parameters) can be derived by the position and orientation of total station and the orientation offset between camera and total station. Position and orientation of total station can be easily calculated with observations of total station in traversing. So at this time, to get the position and pose of camera (exterior orientation parameters), the calibration of orientation offset between camera and total station become necessary, which is normally divided into three steps: (1) Control bar (board) has been putted not far from (less than 5 meters) traverse point and object space coordinates of control points on calibration bar (board) are measured by use of total station. (2) Photos are taken at each traversing point and image coordinates of control points are (semi-) automatically extracted. (3) Calibration is implemented by use of bundle adjustment.

From description above, it can be easily seen that PTSS just uses some “near control” for “far measurement” to avoid locating sufficient control points around or on the surface of measured objects and in this case true non-contact measurement becomes possible. The accuracy of this kind of control method will be described in next section.

When calibrating through bundle adjustment, it is necessary to linearize Equation (4) for practical operation. After linearization of Equation (4), we obtain general form of error equations as following:

$$\begin{aligned} v_x &= a_{11}\Delta X_{S0} + a_{12}\Delta Y_{S0} + a_{13}\Delta Z_{S0} + a_{14}\Delta\varphi_0 + \\ &\quad a_{15}\Delta\omega_0 + a_{16}\Delta\kappa_0 + b_{11}\Delta X_i + b_{12}\Delta Y_i + b_{13}\Delta Z_i - l_x \\ v_y &= a_{21}\Delta X_{S0} + a_{22}\Delta Y_{S0} + a_{23}\Delta Z_{S0} + a_{24}\Delta\varphi_0 + \\ &\quad a_{25}\Delta\omega_0 + a_{26}\Delta\kappa_0 + b_{21}\Delta X_i + b_{22}\Delta Y_i + b_{23}\Delta Z_i - l_y \end{aligned} \quad (5)$$

where $a_{ij}(i=1,2; j=1,2,...,6)$ and $b_{ij}(i=1,2; j=1,2,3)$ are coefficients derived from linearization and the derivation process is omitted here because of the limitation of space for this paper.

Based on these error equations, normal equations can be formed through conventional methods. The solution of normal equations would give the elements of orientation offset between camera and total station. And subsequently exterior orientation parameters of each image can be determined.

Once the offset (X_{S0}、 Y_{S0}、 Z_{S0}、 φ_0、 ω_0、 κ_0) is calibrated, according to our test, it is normally unchanged during the whole measurement session.

3 MEASUREMENT PROCESS AND MODE

The whole process of digital terrestrial photogrammetry includes two stages: field survey and indoor photogrammetric processing. Field survey mainly focuses on data acquisition. Firstly, traversing is complemented through total station and object coordinates of necessary control points are measured and photos are taken by metric digital camera. For specific measurement mission, three different measurement modes can be used depending upon the measurement condition and requirement: (1) Photos are captured completely by PTSS; (2) Photos are captured partly by handheld camera and partly by

PTSS and in this case the photos captured by PTSS, named control photos, server as control in whole calculation process; (3) All photos are captured by handheld camera and total station is just used to obtain object coordinates of control or check points. Thus the measurement process can be very flexible.

After field survey, all measurement data including images are processed by attached photogrammetry software. In this software, multi images based image matching (short base) is used instead of stereo based one in the conventional photogrammetry. Because geometry distortion in close-range photography is relatively large, traditional single-stereo matching which uses only two images is very difficult to meet the demand of matching in reliability and accuracy. Multi images based image matching use uses multi images and combines with short baseline and multi-photo perfectly solves the image matching and intersection accuracy problem at same time. This method has following characters: on one hand because the baseline between the neighbouring photos is relatively short, the geometry distortion of images is relatively little, thus help automatic matching; on the other hand, because baseline is short and multi photos are used, overlap between the neighbouring photos is normally very large, we can calculate 3D coordinate with multi image intersection to achieve high intersection accuracy. Another feature of our terrestrial photogrammetry method is that control bars (shown in Fig. 4) located near the camera are used, which are mainly used to calibrate the Offset and can replace regular control points around or on the object to be measured. Therefore, a real non-contact measuring method can be implemented so that control points around or on the measured object can be reduced or completely avoided. With this technique, DTM and contour generation, volume measurement and 3D modeling all can be completed. The measurement accuracy with control bar will be described in next section in detail.

Fig. 4 Control bar

4 ACCURACY TEST AND ANALYSIS

In this section, several sets of data have been used to test the measurement accuracy of PTSS in different situations.

4.1 Measurement accuracy with OFFSET self-calibration

This part aims at testing measurement accuracy when using OFFSET self-calibration. OFFSET self-calibration is completed during the process of measurement and two control bars with different size are used for calibration. As described in section 3.4, bundle adjustment has been used during the process of calibration. In this test, a hill was measured. Six traversing points is arranged and the interval between neighbor traversing points is about 8m. 13 check points is set on the hill. Two kinds of test condition are used as following:

(1) All control points and check points spread around the object to be measured, which is a hill here. All their coordinates are measured with total station. During adjustment, the coordinates of check points are deemed unknown. In the end, adjustment results are compared with observation of total station to check the accuracy and results are shown in Table 1.

(2) Compared with condition 1, the only difference is that control points is on control bar not far from traversing point instead of around the object to be measured. Test results are shown in Table 2. Two control bars with different size are putted in front of each traversing point.

From the test results, conclusion can be drawn that although the accuracy when control bar is used is not as high as that when control point around the measured object is used, it is still up to 1/1500, high enough to meet ordinary measurement requirements. More important thing is that there is no need to put control points around of on the surface of the object to be measured and so photogrammetrists' dream of "true non-contact measurement" becomes reality.

Table 1 Accuracy when control points around the object to be measured

Focus (mm)	Planar relative accuracy	Z coordinate relative accuracy	Photo Number
10	1/3413	1/7687	24
30	1/4406	1/14603	105
10&30	1/4515	1/18514	129

Table 2 Accuracy when control points on the control bar not far from traversing point

Focus (mm)	Planar relative accuracy	Z coordinate relative accuracy	Photo Number
10	1/1638	1/2093	24
30	1/2296	1/5419	105
10&30	1/2131	1/4647	129

In above test, two control bars with different size are used in front of each traversing point. When the number of control bars is reduced to one, the accuracy is shown in Table 3.

Table 3 Accuracy when number of control bars is reduce to one

focus	Planar relative accuracy	Z coordinate relative accuracy
10mm	1/1365	1/1331
30mm	1/1435	1/7876

At this time the accuracy falls down, but still higher than 1/1300. Reducing the number of control bar can greatly save labor force and work time, so it can be used when the accuracy requirement is not very high.

5 APPLICATION

The usability of PTSS has been tested with two different cases.

5.1 Case 1

In first case, PTSS has been used to measure a stone pile in a concrete manufacturer where such measurement task is necessary and often used. The result is shown in Fig. 5.

5.2 Case 2

In this case, PTSS has been used to measure a building to create its 3D model. Because of the limitation of time, only part of this building is measured and reconstructed. The result is shown in Fig. 6. These results show that the 3D model reconstructed by PTSS can be very detailed.
Such two application experiments described above show the usability and application potential of PTSS in terrestrial photogrammetry, cyber city modeling and so on.

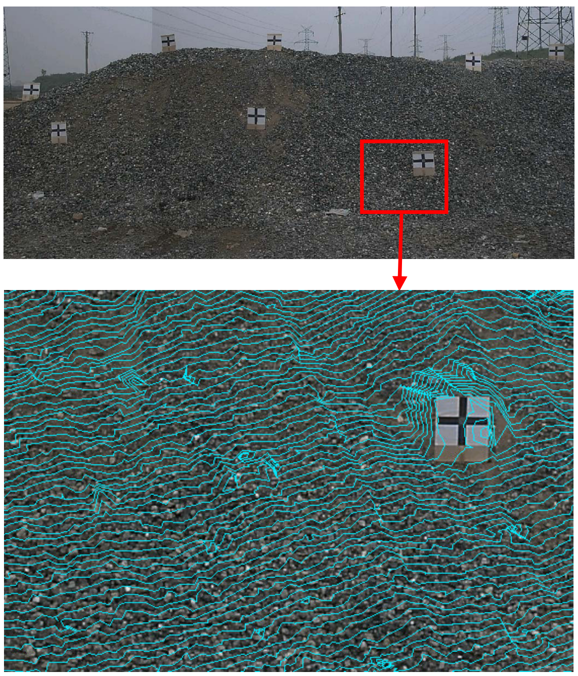
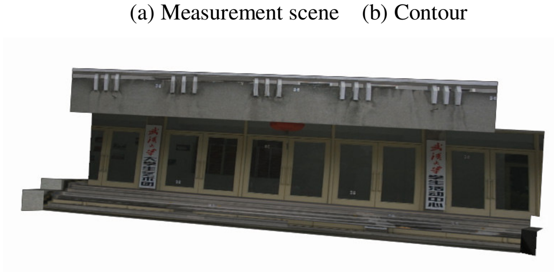


Fig. 5 PTSS has been used to measure stone pile.
(a) Measurement scene (b) Contour



(a)

(b)

Fig. 6 PTSS has been used to measure and reconstruct buildings.

6 CONCLUSION

In this paper, we presented a completely novel surveying system, photo total station system (PTSS), which is an integration of mature digital photogrammetry technique and high accurate engineering surveying equipment (total station). Compared with traditional terrestrial photogrammetry, control points around or on the measured object are not needed in this system. Compared with traditional engineering survey, which mainly involves field survey, PTSS is much more laborsaving, efficient and automatic.
To conduct experiments, metric digital camera D30 produced by Rollei company, Germany and total station SET 500 produce by Sokkia company, Japan are currently used in PTSS. Test results show that PTSS can implement true non-contact measurement and its measurement accuracy is high enough to meet the need of normal close-range measurement, it not only can complete ordinary engineering survey and large-scale topography survey, but also shows great potential in special survey, like the measurement of dams, coal mines, ore piles, Buddha, buildings and so on. Its accuracy, reliability and efficiency have been show in application examples.

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