DOI: 10.3901/CJME.2009.03.***, available online at www.cjmenet.com; www.cjmenet.com.cn

3-D Free-form Shape Measuring System Using Unconstrained Range Sensor

REN Tongqun[1,3] *, ZHU Jigui[2], GUO Yingbiao[3], and KE Xiaolong[3]

1 *Key Laboratory for Micro/Nano Technology and System of Liao Ning Province, Dalian University of Technology, Dalian 116023, China*
2 *State Key Laboratory of Precision Measuring Technology and Instruments, Tianjin University, Tianjin 300072, China*
3 *Department of Mechanical and Electrical Engineering, Xiamen University, Xiamen 361005, China*

Received March 10, 2010; revised March 7, 2011; accepted March 10, 2011; published electronically March 18

Abstract: Three-dimensional (3-D) free-form shape measurement, a challenging task pursued by computer vision, is mainly characterized with single view acquisition and multiple view registration. Most of the conventional scanning systems are less flexibility and difficult to realize engineering applications for employing sequential registration tactic. To develop portable scanning system and engineering registration method overcoming problems of error accumulation and propagation is the research direction. In this paper, one 3-D free-form shape measuring system using unconstrained range sensor is designed. A quasi-active stereo binocular visual sensor embedded within a scanning mechanism is used as the range sensor. Error compensation is performed by residual amendment according to camera calibration lattice. Artificial control points are designed and adhered on object and one camera is introduced to shot these control points from different positions and orientations. Then ray bundle adjustment (BA) method is used to calculate the space coordinates of all the control points, so as to set up a global control net work. Registration can be completed by mapping at least 3 control points observed by range sensor in single view acquisition into the global control network. In this system, no calibration for laser plane is required and the motion of range sensor is completely free. The overlapping of neighboring region is unessential for registration. Therefore, the working range of the system can be easily extended. The measuring precision mainly depends on the quality of global control network. The sequential distances of coding control points are observed by electronic theodolites and then compared with those obtained according to BA result. Experimental results show that relative distance error of control points is no more than 0.2%. The proposed measuring system is portable, provides good capacity for global error control, and contributes to the engineering application of 3-D free-form shape measurement.

Key words: shape measurement, multiple view registration, bundle adjustment, global control network

1 Introduction

Three-dimensional free-form shape measurement is always a research focus in computer vision. It is widely used in fields of manufacturing and non-manufacturing applications, e.g. reverse engineering, product inspection, and artifact archiving, etc[1]. Single view acquisition and multiple view registration are two key problems. Up until now, many kinds of methods based on different principles have been proposed[2].

Single view acquisition is to acquire the surface data of object being visible for the range sensor when the sensor is fixed. Camera based range sensors are widely used as they allow non-contact acquisition of dense 3-D coordinate data rapidly. And they are also low cost compared to interferometry and other phase-based measurement systems[3,4]. In case of object surface containing less features, active sensor that projects patterns of light in a systematic way are preferred, e.g. laser-camera range sensor based on triangulation method. The projecting pattern makes the shape information more robust and accurate. Then range data of object surface can be obtained in local measuring coordinate system by acquiring and processing the pattern deformed by the surface state. However, only a single line or profile can be acquired in this way. Generally, outside positioning mechanism is employed to acquire serial profile data, so as to comprise a range view. As a result, the flexibility and working range of measuring system is decreased seriously.

As for complex and/or large scale object surface, it is impossible/or difficult to obtain the whole shape through a single measurement due to the problem of limited measuring range of sensor and/or occluded object surface. At this time, object surface is always divided into multiple sub-regions. These sub-regions are scanned separately by

* Corresponding author. E-mail: ren_tq@dlut.edu.cn
This project is supported by Fujian Provincial Natural Science Foundation for the Youth of China (Grant No. 2009J05136), and Key Program of National Natural Science Foundation of China (Grant No.50735003)

changing the positions of the sensor and/or object. Thus the task of shape measurement is essentially the problem of registering multiple views using an appropriate algorithm. A number of researchers have investigated this topic and got many remarkable achievements[5].The iterative closest point (ICP) algorithm is a dominant method for multiple view registration. It is proposed by BESL and MCKAY[6] and improved by many researchers in succession, e.g. ZHANG, LU and SHARP, et al[7–9]. The availability of ICP-based methods is demonstrated by many applications[10]. However, ICP-based methods often suffer from an inherent shortage of expensive computation cost of searching and refining closest points. Furthermore, these algorithm work well only if a good initial transformation is given. Both these shortages are undesirable in industrial or outdoor applications. Registration method using artificial feature is well-known by both academic and industries. This kind of method is valid and reliable in practical measurement of millimeter level, for its high stability, arbitrary topology, local support and rapid speed. A typical instrument based on artificial features is ATOS optical scanner of GOM company, Germany. ATOS provides both sequential and integral registration scheme and its registration accuracy reaches to 0.1mm/m.

In this paper, a 3-D free-form shape measuring system using unconstrained range sensor is designed. A quasi-active stereo binocular visual sensor embedded within a scanning mechanism is used as the range sensor. In order to improve measuring precision, error compensation is performed by residual amendment according to calibration lattice. Artificial feature-based registration method is adopted. The motion of range sensor is completely free and overlapping of neighboring region is unessential for registration. Therefore, the working range of the system can be easily extended. The system also provides good capacity for global error control.

2 Single View Acquisition

As mentioned in section 1, one standard stereo binocular visual sensor is employed as the range sensor. Coordinate system of major camera, general the left camera, is defined as the measuring coordinate system. Once transformation relation between coordinate systems of major camera and auxiliary camera is given as rotation matrix $\boldsymbol{R}$ and translation vector $\boldsymbol{t}$, space coordinate (x,y,z) of one object point P in measuring coordinate system can be calculated as follows[11]:

$$\begin{cases} x = \dfrac{X_1(f_2 t_y - t_z Y_2)}{Y_2(r_7 X_1 + r_8 Y_1 + r_9 f_1) - f_2(r_4 X_1 + r_5 Y_1 + r_6 f_1)}, \\ y = \dfrac{Y_1(f_2 t_y - t_z Y_2)}{Y_2(r_7 X_1 + r_8 Y_1 + r_9 f_1) - f_2(r_4 X_1 + r_5 Y_1 + r_6 f_1)}, \\ z = \dfrac{f_1(f_2 t_y - t_z Y_2)}{Y_2(r_7 X_1 + r_8 Y_1 + r_9 f_1) - f_2(r_4 X_1 + r_5 Y_1 + r_6 f_1)}, \end{cases} \tag{1}$$

where (X_1,Y_1) and (X_2,Y_2) are image coordinates of P in major camera and auxiliary camera, respectively.

A scanning mechanism is designed and embedded in range sensor to increase flexibility of the measuring system. The mechanism is composed of 5 semiconductor laser devices, a stepping motor and a harmonic speed changer. As shown in Fig. 1, semiconductor laser devices are placed in fan-shaped distribution to generate approximate uniformly-spaced laser lines. The scanning mechanism permits continuous scans to comprise a range view without moving the sensor. And a large scale scanning is permitted via small rotation of stepping motor for each laser scans a small region. Scanning speed and sampling density can be easily changed by adjusting rotational speed and subdivision of the stepping motor. The scanning mechanism increases the flexibility and working efficiency of measuring system. Here, the laser lines are only used as distinct measuring features and no calibration for laser plane is required. Actually, this sensor is a quasi-active visual sensor. The key problem is stereo matching of measuring features. Here, the mass centers of laser lines are selected as measuring features and stereo matching is completed by using epipolar geometry constraint[11].

Since laser contains advantages of high luminance and good directionality, measuring image has good contrast which means easy image process. Theoretically, there are no special requirements for object surface besides of being light reflecting. Therefore, the system suits for most measurement of millimeter level for industrial work piece.

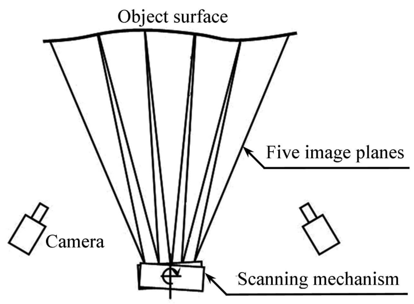


Fig. 1. Schematic diagram of scanning mechanism

An error compensation method is also performed by using residual error amendment in order to increase the measurement precision. As shown in Fig. 2, a calibration point lattice is employed during the camera calibration process. The camera parameters and the data of all the calibration points are obtained simultaneously via calibration model. The data of calibration points are composed of (x_i, y_i, z_i) and $(\Delta x_{di}, \Delta y_{di})$, where (x_i, y_i, z_i) is the 3-D coordinate of the ith calibration point in camera coordinate system and $(\Delta x_{di}, \Delta y_{di})$ is the residual error of its image coordinate.

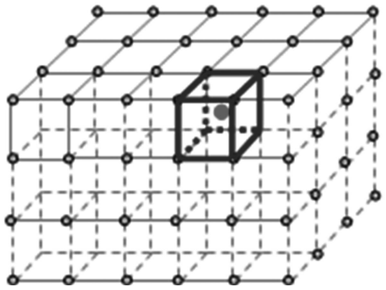


Fig. 2. Index point lattice for residual error amendment

The approximate image coordinate $A_d(x_d, y_d)$ of measuring point is achieved first when measurement starts. Subsequently, its corresponding grid, the bold one in Fig. 2, is located in the whole calibration point lattice. Linear interpolation method is then used to solve (Δx_d, Δy_d), the residual error of the undetermined point. According to the revised image coordinate $A'_d(x_d+\Delta x_d, y_d+\Delta y_d)$, 3-D coordinate of measuring point is recalculated. The validity of this method is demonstrated in Ref. [12].

3 Multiple View Registration

Multiple view registration is an indispensably step for free-form shape measurement. Here, an integral registration tactic is employed. That is to set up a global coordinate system M_G and then unite all views observed in different local measuring coordinate system M_S to M_G in an integral way. Firstly, artificial control points are designed and adhered to object surface evenly. They are shot by a registration camera from different positions and orientations, and several images of the control points are obtained. The image corresponding points are matched through epipolar geometry constraint. Based on the matching results, BA method is then employed to calculate space coordinates of all the control points in M_G, so as to set up a global control network. For each single view acquisition, at least three control points are observed by range sensor. Registration can be completed by mapping these control points into the global control network.

3.1 Artificial control points

3.1.1 Configuration of control points

It is impractical to design all the control points as coding points that can be identified and located in image uniquely. More coding points mean larger coding density and the identification process will be more difficult as a result. Therefore, both coding and non-coding control points are designed. The coding control points are only used to solve correspondence of non-coding ones collaboratively and they are removed from object surface after BA operation. As shown in Fig. 3, rigid planar support with black background is employed to keep correct identification for coding control points. Annulus coding mode with 10 bits coding capacity is adopted. Besides of zero-code and full-code, the coding values are from 1 to 106. The foreground features, localization circle and coding annulus, are manufactured by retro-reflective target (RRT) that produces quasi-binary image under paraxial ray. While the non-coding control points are just the localization circles. They are adhered to object surface during measurement.

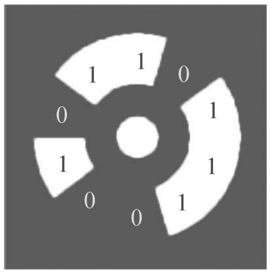


Fig. 3. Configuration of coding control point

The area of localization circle is smallest among all the feature regions of one coding point. In order to guarantee localization accuracy of feature points, every continuous feature region must include at least 10 valid pixels. At the same time, adequate spacing between localization circle and coding annulus is required. Otherwise, the image of localization circle and coding annulus will connect together or appears a transition zone with high grey scale, when the registration camera inclined excessively. Both of these two situations will lead to identification error. Once the registration camera is selected and its operating range and distance are determined, size of coding and non-coding points can be estimated via pin-hole camera model easily. Eventually, diameter of localization circle is designed as 5 mm. The width of coding annulus is 6mm. And the spacing between localization circle and coding annulus is 3.5 mm.

3.1.2 Identification of control point

Given that a continuous feature region in image is composed of pixel points p_i, $i=0, 1,\cdots, n$. This feature region can be located by solving its mass center as follows:

$$x = \sum_{i=1}^{n} x_i \cdot I_i \Big/ \sum_{i=1}^{n} I_i, \quad y = \sum_{i=1}^{n} y_i \cdot I_i \Big/ \sum_{i=1}^{n} I_i, \tag{2}$$

where (x, y) is the image coordinate of mass center of this continuous feature region. (x_i, y_i) and I_i are the image coordinate and gray value of pixel point p_i, respectively.

Actually, the image of feature region is brighter in paraxial area and darker in circumjacent area because of reflection characteristic of RRT. And the spacing between localization circles (coding/ non-coding control points) is much larger than those between localization circle and its corresponding coding annuluses. And hence, the recognition algorithm is designed as follows.

(1) Divide the image into several sub-region and do binary conversion for each sub-region using Otsu's method.

(2) Define all continues white block in binary image as undetermined feature region, and calculate their contrast in original measuring image according to Eq. (3):

$$I = \frac{I_f - I_b}{I_f + I_b}, \tag{3}$$

where I_f and I_b are the average gray values of pixels belonging to this white block region and background region in original measuring image, respectively.Then judge a white block as noise if its contrast in original measuring image is less than a certain preset threshold.

(3) Search all continuous feature regions and compute their mass center according to Eq. (2).

(4) Define a proper distance threshold d and then judge one feature region as a non-coding point if any other feature regions can not be found in its circular neighborhood with center point of its mass center and radius of d, otherwise it is a sub-region of one coding point.

(5) Judge one sub-region as the localization circle if it has the least area among all the sub-regions belonging to one coding point.

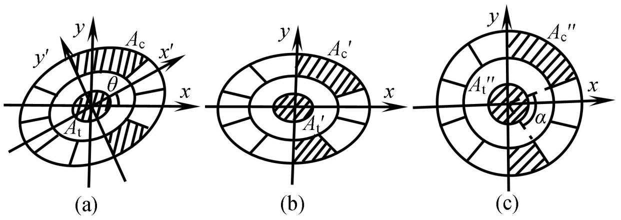


Fig. 4. Decoding process for coding control point

Fig. 4 shows the decoding process for coding control point. As shown in Fig. 4(a), image of coding point must deform to an ellipse. The elliptic equation can be achieved by using least square fitting method based on multiple feature points lying in the external boundary:

$$\frac{\left[(x-x_0)\cos\theta-(y-y_0)\sin\theta\right]^2}{a^2}+\frac{\left[(x-x_0)\sin\theta-(y-y_0)\cos\theta\right]^2}{b^2}=1, \tag{4}$$

where θ is angle between x axis of image coordinate system and the major axis of deformed ellipse. Firstly, the deformed ellipse is turned to make its major axis be coincident with x axis of image coordinate system, as shown in Fig. 4(b). Then it is stretched in y direction to become a standard circle, as shown in Fig. 4(c). Decoding process can be described as a process of solving area ratio. In Fig. 4(c), define A_c'' and A_t'' are areas of a certain continuous "1" coding regions and localization circle, respectively. Then bit size n_{b1} of this "1" coding regions can be computed as follows:

$$n_{b1} = \mathrm{int}\left(10\times\left(A_c''/A_t''\right)/p_s + 0.5\right), \tag{5}$$

where p_s is area ratio of the whole coding annulus to localization circle.

The above decoding method is invalid for "0" coding region because it is unable to perform ellipse fitting. Similarly, the outer straight line boundary of one continuous "0" coding region is solved first using least square fitting method based on multiple feature points lying in straight line boundary of its neighboring "1" coding regions and mass center of location circle, as shown in Fig. 4(c). Thereupon, the angle α between these two boundaries is calculated. The bit size n_{b0} of this "0" coding regions can be computed as follows:

$$n_{b0} = \mathrm{int}\left(\alpha/36 + 0.5\right), \tag{6}$$

3.2 Global control network

3.2.1 Principle of setting up global control network

Briefly, method of bundle adjustment (BA) is a visual reconstruction for producing both optimal structure and viewing parameter estimates simultaneously. The restriction of BA is the collinear equations describing the collinearity of an object point, image point and camera projective center. Combining the pin-hole camera model, the collinear equation can be rewritten as follows:

$$\begin{aligned} x - x_0 + \Delta x &= -f\,\frac{r_1x_d + r_2y_d + r_3z_d + t_x}{r_7x_d + r_8y_d + r_9z_d + t_z}, \\ y - y_0 + \Delta y &= -f\,\frac{r_4x_d + r_5y_d + r_6z_d + t_y}{r_7x_d + r_8y_d + r_9z_d + t_z}, \end{aligned} \tag{7}$$

where (x, y) and (x_d, y_d, y_d) are image coordinates and space coordinates of one object point, respectively. (x_0, y_0) is the image center and (Δx, Δy) is an error term caused by distortion of the lens.

In this case, the registration camera is uncalibrated and the position of control points is undetermined, i.e., all parameters are unknown. The only available restriction is the imaging rays of the same control point intersecting in space. It implies Eq. (7) for each control point in each view. By uniting all the equations, large equation sets for BA are achieved. By solving this equation sets, both cameras' intrinsic/extrinsic parameters and coordinates of all the control points are obtained simultaneously. If the object surface is too large that exceeds the viewing field of registration camera, it is divided into several sub-regions according to distribution of control points and viewing field of the registration camera. At least three common control points should be shared by every two neighboring sub-regions. For each sub-region, BA method is performed to solve the control points belonging to this sub-region. Then all the control points can be unified to a common coordinate system, starting with pair-wise registration of neighboring sub-regions based on their common control points. Only a rough result can be obtained in this way for the reason of error accumulation and propagation. In order to obtain a global optimal result, united BA for all control points is performed subsequently to get coordinates of all the control points in a common coordinate system. And this common coordinate system is defined as the global coordinate system M_G. In fact, M_G can not be absolutely located, because simultaneously solving both the camera position and orientation is an ill-conditioned problem[13]. That is, different initial estimates lead to different results. Yet anyhow, the result of the relative position of control points stays invariant. Fortunately, the absolutely positions of control points are unessential in this work. In another words, only the relative positions of control points are used to set up the global control network.

Actually, it is impossible to compute all the unknown variables directly, because the initial estimate is often too far away from the real solution, and BA equation sets diverges as a result. Therefore, a coarse pair-wise orientation is performed first to produce a better initial estimate[14]. The registration camera is regarded as an ideal camera without distortion during this orientation process.

3.2.2 Corresponding point matching

An accurate global control network derives form the correct correspondence of control points. Before BA operation, the intrinsic/extrinsic parameters of registration camera are unknown. The correspondence must be solved by exploiting the only available geometric constraint, namely, the epipolar constraint. The similar work has been engaged on by ZHANG, et al [15], and a little change is done in this work. First of all, fundamental matrix F for each pair of views is estimated based on their common coding points[16]. Fundamental matrix F contains both the intrinsic parameters of cameras and the rigid transformation of one camera related to the other. And all the epipolar geometry is contained in F, summarized as follows:

$$m^{\mathrm{T}} F m' = 0 , \tag{8}$$

where m^{T} and m' are homogeneous image coordinates of one control point in two images, respectively.

Only a rough match result between a given pair can be achieved according to Eq. (8). Since the situation of multiple control points being approximately collinear with one epipolar line is unavoidable, further work to optimize F is insignificant. The match result often undergoes uncertainty of one-to-many states, i.e. more than one matching point might be obtained for one given source point. This problem is solved in an easy way by using epipolar geometry among three views, as shown in Fig. 5. Given one 2-D point m in image 1, its potential corresponding points in image 2 and image 3 can be denoted as $m_{2\mathrm{i}}$ and $m_{3\mathrm{j}}$, respectively. And they must lie inside a narrow searching zone h_2 and h_3 according to Eq. (8). Assume that h_2' is the searching zone for one given point of $m_{3\mathrm{j}}$. Once there is only one point of $m_{2\mathrm{i}}$ lying inside the intersecting region of h_2 and h_2', the unique match m–$m_{2\mathrm{i}}$–$m_{3\mathrm{j}}$ can be determined. Most correct match results are obtained in this way. Then restriction of consistency, uniqueness and continuity are used to ultimately refine the match results.

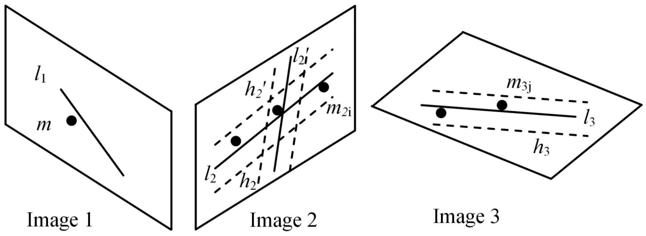


Fig. 5. Epipolar geometry among 3 views

3.3 Registration realization

The control points observed by range sensor are mapped to the global control network and two corresponding points set are achieved. Then the dual quaternion method[17] is used to solve the transformation from M_S to M_G.

Point set mapping is performed based on restriction of the distance invariant under rigid motion. Given a point set S_i in M_S, its minimal bounding ball B_i is computed first. The diameter d of B_i is the longest distance between two points belonging to S_i. Its corresponding point set S_i' in M_G must lies in a ball B_i' with the same size of B_i. All candidate point pairs having distance of d are found out by traversing the global control network. Then all candidate ball B_i' are computed based on these point pairs. For each B_i', all pair-wise distances in it are computed and compared with those in B_i. The measure value D_j with initial value 0 is also set and added by 1 with each equal triangle, i.e., three end to end matching line segments. The unique matching ball can be determined that contains maximal value of D_j. One-to-one correspondence is solved in a similar way. Note that tolerance ε is introduced in the computing process due to error of both the sensor and BA, where ε=±0.2 mm.

4 Experimental Studies And Result

A car's engine covering, about 1.5 m×1.5 m, was detected and the binocular visual sensor composed by measuring cameras of Basler A101f(1300 pixel×1030 pixel, 6.7 μm/pixel×6.7 μm/pixel) was employed, as shown in Fig. 6. The first step was to define a suitable scanning range for the range sensor. The choice should be a tradeoff between resolution and the size of object surface. In this case, the main goal was to test the capacity for global error control of the registration method mentioned above. Therefore, a small scanning range was intentionally selected for range sensor and the number of sub-regions was increased as a result. In this work, the scanning range of the sensor was defined as about 300 mm×200 mm at operating distance of 700 mm. And hence resolution of 0.27 mm/pixel could be considered. The object surface was divided into 23 sub-regions ultimately.

(a) Measuring scene

(b) Registration camera and control points

Fig. 6. Experiment for proposed system

In camera calibration, one laser point source was fixed on the measuring rod of CMM(Brown&Sharp ZOO3/1077, 3+4L/1000, μm) and one 4×4×4 calibration point lattice was obtained through 3-D motion of CMM. The camera was fixed during calibration. The laser point source was shot at its each new position. In order to get accurate calibration result, the calibration point lattice should fill up both the viewing field and the depth of field of the measuring camera. Furthermore, the stability of laser point source was also an important factor that influenced the calibration accuracy. A stability experiment of laser point source was done before calibration. That was to keep the camera and laser point source fixed with a certain relative position. The laser point source was shot every two minutes and located in the image by its mass center. We took Y coordinates of the laser point source to evaluate its stability. As shown in Fig. 7, the laser point source tended to be stable after preheating time about half 1h and the drift error is no more than 0.05 pixel.

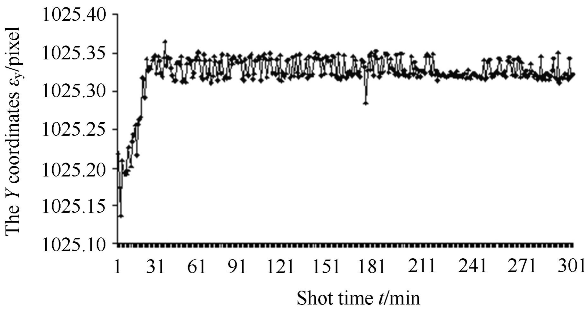
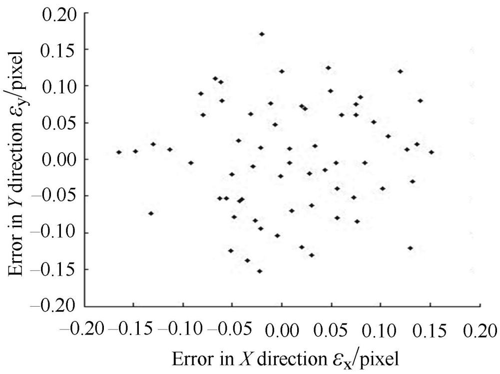
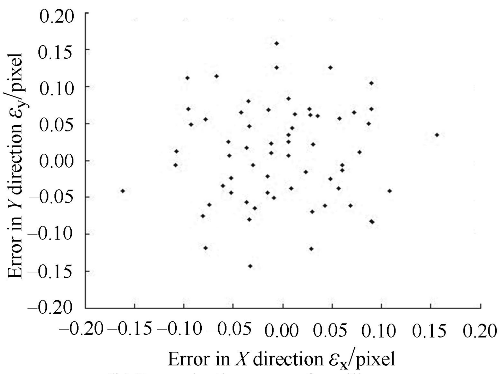


Fig. 7. Result of stability test of laser point source

The calibration point was re-projected to the image plane according to calibration result. As shown in Fig. 8, the coordinate difference between real image coordinate and re-projection coordinate, defined as re-projection error, was no more than 0.18 pixel in both x and y direction.



(a) Re-projection error of major camera



(b) Re-projection error of auxiliary camera

Fig. 8. Result of re-projection error of camera calibration

The sequential pair-wise distances of adjacent calibration points given by CMM were compared with those solved by range sensor according to calibration result. The absolute distance error was summarized in Fig. 9. The maximal absolute error is no more than 0.05mm. Higher accuracy can be expected for real measurement after error compensation.

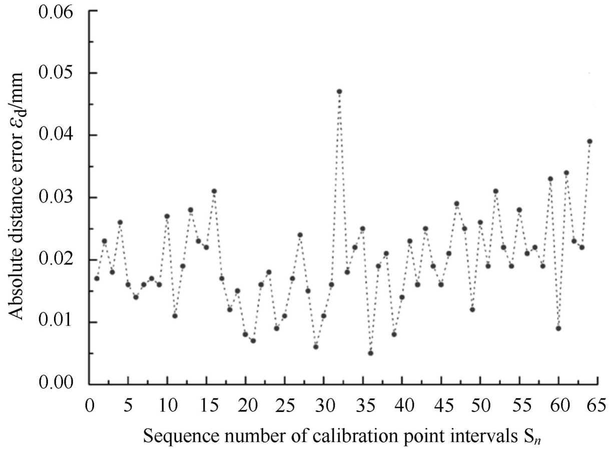


Fig. 9. Calibration accuracy of camera/range sensor

Note that this calibration method needs large auxiliary equipment and includes complex process. And hence it is unsuitable for field calibration. XUE Ting proposed a novel calibration method based on planar target with arbitrary poses[18]. It advanced 3D computer vision one more step from laboratory environments to real world use.

According to Eq. (7), one control point must be visible for at least two views simultaneously if it can be reconstructed by BA method. Furthermore, the restriction of imaging rays intersection becomes stronger if one control point is visible for more views simultaneously. It means more constraint equations and contributes to improve reconstruction accuracy. A simple way to guarantee this condition is to increase shooting positions and get more images. However, it also means more difficulty of solving correspondence of control points. At the same time, every increased shooting position increases the number of unknown variables, i.e., a set of intrinsic/extrinsic parameters of registration camera. It is possible to leads to more control points being required conversely, which will influence the implementation of the registration method. By comprehensive consideration on above situation, four shooting positions were selected to get four images for each sub-region. And the spacing between two adjacent shooting positions was selected as large as possible to achieve adequate common viewing field. At the same time, intrinsic parameters of registration camera were remained unchanged. Totally, 21 coding control points and 72 non-coding control points are used in this experiment.

Camera of Kodak Dcspro14n is selected as the registration camera (4500 pixel×3000 pixel, 8 μm/pixel×8 μm/pixel). In fact, it is a color camera unprofessional for measuring situation that will decrease the measuring accuracy in some extent. According to Eq. (2), the control point is located in image by extracted its mass center using its location information and gray value. Therefore, the color image taken by Kodak Dcspro14n was converted into gray-scale image, which caused accuracy loss inevitably. To evaluate the result of BA, all the coding control points are observed by electronic theodolites(Leica T-1800, angular resolution of 2"). Similarly, sequential distances of coding control points are calculated and compare with those obtained according to BA result. The distance error of coding control points is summarized in Fig. 10, where the maximal absolute error is 0.2114 mm and the relative error is no more than 0.2%.

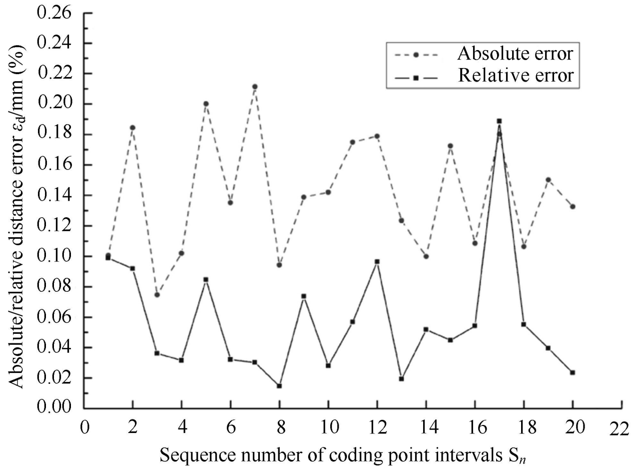
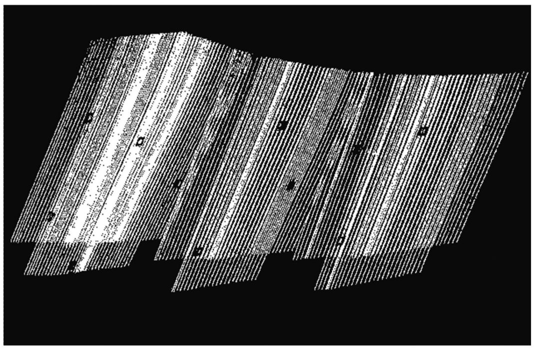
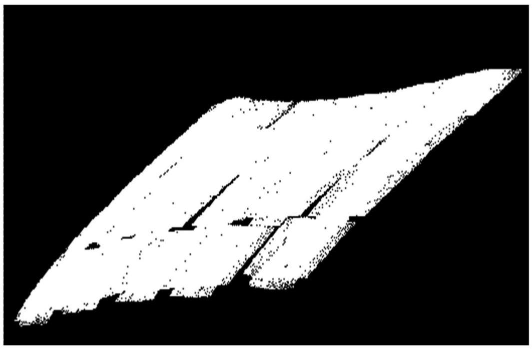


Fig. 10. Result of global control network



(a) Partial registration result of the engine coving



(b) Integral registration result of the engine coving

Fig. 11. Ultimate measuring results

According to Fig. 9 and Fig. 10, the measuring accuracy of range sensor is much higher that of the global control network. Therefore, it can be said that the ultimate measuring precision of the system is influenced mainly by the quality of the global control network. And the influence on ultimate measuring precision caused by range sensor can be ignored. The integrated measuring result after registration was shown as Fig. 11. Note that there are gaps at joint of adjacent views dues to sub-range division rather than registration error. Actually, there are no sample points in that position at all.

5 Conclusions

(1) An embedded scanning mechanism is designed to permit continuous scans comprising a range view without moving range sensor. The flexibility of the measuring system is increased. Residual amendment method is employed to do error compensation which can improve measuring accuracy of range sensor distinctly.

(2) A sort of simple and reliable coding control point is designed and corresponding localization / identification algorithm are developed.

(3) Epipolar geometry among 3 views is used to solve correspondences of control points in uncalibrated views. BA method is employed to compute relative positions of control points to set up global control network. Finally, registration is completed by mapping at least 3 control points observed by range sensor during single view acquisition into the global control network.

(4) A feasible measuring system for 3D Free-form shape measurement is presented. Range sensor is permitted continuous free motion which provides greater flexibility and expandability in measurement. The registration method contains simple process and presents good capacity for global error control. The system is suitable for practical measurement of millimeter level.

(5) It should be considered that non-coding control points are adhered to object surface which destroy original object surface in some extent. So some compensation measures should be employed for object surface covered by control points.

References

[1] KOFMAN J, KNOPF G K. Surface-geometry measurement using an untracked range-sensor head[C]// *Proceedings of SPIE's Optomechatronic Systems,* Boston, MA, USA, November 5–6, 2000: 102–114.

[2] FOREST J, SALVI J. A review of laser scanning three-dimensional digitizers[C]// *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems,* Lausanne, Switzerland, September 30–October 4, 2002: 73–78.

[3] CHEN F, BROWN G M, SONG Mumin. Overview of three-dimensional shape measurement using optical methods[J]. *Optical Engineering,* 2000, 39(1): 10–22.

[4] YAMAQUCHI I, YAMAMOTO A, YANO M. Surface topography by wavelength scanning interferometry[C]// *Proceedings of SPIE's Laser Interferometry IX: Applications,* San Diego, CA, USA, July 22, 1998: 24–33.

[5] WILLIAMS J A, BENNAMOUN M, LATHAM S. Multiple View 3D Registration: A Review and a New Technique[C]// *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics,* Tokyo, Japan, October 12–15, 1999: III-497 – III-502.

[6] BESL P J, MCKAY N D. A method for registration of 3-D shapes[J]. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 1992, 14(2): 239–256.

[7] ZHANG Zhengyou. Iterative point matching for registration of free-form curves and surfaces[J]. *International Journal of Computer Vision,* 1994, 13(2): 119–152.

[8] LU Feng, MILIOS E. Globally consistent range scan alignment for environment mapping[J]. *Autonomous Robots,* 1997, 4(4): 333–349.

[9] SHARP G C, LEE S W, WEHE D K. ICP registration using invariant features[J]. *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 2002, 24(1): 90–102.

[10] GUIDI G, BERALDIN J A, ATZENI C. High-Accuracy 3-D Modeling of Cultural Heritage: The Digitizing of Donatello's "Maddalena"[J]. *IEEE Transactions on Image Processing*, 2004, 13(3): 370–380.

[11] ZHU Jigui, WANG Hao, REN Tongqun, et al. Portable Laser Scanning System for 3D Contour Measure[J]. *Chinese Journal of Mechanical Engineering,* 2005, 41(2): 166–169. (in Chinese)

[12] REN Tongqun, ZHU Jigui, GUO Yinbiao. Study on Portable Optical 3D Coordinate Measuring System[C]//*Proceedings of SPIE's 4th International Symposium on Advanced Optical Manufacturing and Testing Technologies: Optical Test and Measurement Technology and Equipment*, Chengdu, China, November 19–21, 2008: 1–8.

[13] FERMÜLLER C, ALOIMONOS Y. Observability of 3D Motion[J]. *International Journal of Computer Vision,* 2000, 37(1): 43–63.

[14] REN Tongqun, ZHU Jigui, Li Yanjun, et al. Key Technology on Stereo Image Mosaic of Shape Measurement[J]. *Chinese Journal of Mechanical Engineering,* 2008, 44(5): 137–141. (in Chinese)

[15] ZHANG Zhengyou, DERICHE R, FAUGERAS O, et al. Robust technique for matching two uncalibrated images through the recovery of the unknown epipolar geometry[J]. *Artificial Intelligence,* 1995, 78(1–2): 87–119.

[16] ARMANQUÉ X, SALVI J. Overall view regarding fundamental matrix estimation[J]. *Image and Vision Computing,* 2003, 21(2): 205–220.

[17] WALKER M W, SHAO Lejun, VOLZ R A. Estimating 3-D location parameters using dual number quaternions[J]. *Computer Vision and Graph Image Process: Image Understanding,* 1991, 54(3): 358–367.

[18] XUE Ting, WU Bin, ZHU Jigui, et al. Complete calibration of a structure-uniform stereovision sensor with free-position planar pattern[J]. *Sensors and Actuators A: Physical,* 2007, 135(1): 185–191.

Biographical notes

REN Tongqun, born in 1980, is currently a lecturer at *College of Mechanical Engineering, Dalian University of technology, China.* He received his PhD degree on precision measuring technology and instruments from *Tianjin University, China,* in 2008. He was a postdoctoral researcher of *Xiamen University, China,* from 2008 to 2010. His research interests include computer vision, optical precision measurements and instruments.
Tel: +86-411-84707949; E-mail: ren_tq@dlut.edu.cn

ZHU Jigui, born in 1970, is currently a professor at *College of Precision Instrument and Opto-electronics Engineering, Tianjin University, China*. His research interests include computer vision, photoelectric test technology.
E-mail: jiguizhu@tju.edu.cn

GUO Yinbiao, born in 1962, is currently a professor at *Department of Mechanical and Electrical Engineering, Xiamen University, China*. His research interests include ultra-precision machining, light mechanical and electrical integration technique, and MEMS technology.
Tel: +86-592-2187283; E-mail: guoyb@xmu.edu.cn

KE Xiaolong, born in 1981, is currently a PhD candidate at *Department of Mechanical and Electrical Engineering, Xiamen University, China.*
Tel: +86-592-2187283; E-mail:xlong_19@163.com