Automatic Inspection of Industrial Sheetmetal Parts with Single Non-metric CCD Camera

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Abstract. A novel approach for three-dimensional reconstruction and inspection of industrial parts with image sequence acquired by single non-metric CCD camera is proposed. The purpose of the approach is to reconstruct and thus inspect the producing imprecision (of deformation) of industrial sheetmetal parts. Planar control grid, non-metric image sequence and CAD-designed data are used as information sources. Principles of least squares template matching to extract lines and points from the imagery are presented. Hybrid point-line photogrammetry is adopted to obtain the accurate wire frame model. Circles, connected arcs and lines on the part are reconstructed with direct object space solution. The reconstructed CAD model can be used for inspection or quality control. Experimental results are very satisfying.

1 Introduction

Nowadays, Computer Aided Design (CAD) is widely used in industries. Most industrial parts have their CAD-designed data. Precision evaluating and quality control of parts with reference to CAD data receive attention in industrial communities. Reducing manpower, maintaining high precision and consistency and the time of inspection are the main foci of researchers.

Along with the development of computer vision, automated two-dimensional (2D) visual inspection has been widely used in Printed Circuit Board product lines (Choi 2003). Stereo vision technique with two CCD cameras and two infrared LED lamps is used by (Kosmopoulos 2001) in inspection of gaps on the automobile product line. Precision of 0.1mm within a planar area of 80mm×80mm is obtained. Although automated vision metrology getting more and more mature (c.f. Fraser 1999, Chang 2001), three-dimensional (3D) automatic inspection has been limited due to the complexity of the problem. Precission of about 10 to 20 ppm can be achieved by the V-Stars system (GSI 2003). However, special targets have to be attached onto the surface of the interested object, which makes the system les efficient. Precision of 0.07mm for inspection of industrial parts has been achieved by Zhang (Zhang 2004).

The general purpose of this paper is to inspect the industrial sheetmetal parts automatically and accurately through CAD data and information extracted from the imagery. A planar grid is used to calibrate the CCD camera and provide initial values of camera parameters during reconstruction. World coordinate system is chosen the same as that of the grid. CAD-designed data represents the initial model and the topology of the part. Least-Squares Template Matching (LSTM) is discussed in

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section 2. Afterwards, detailed approaches of how to reconstruct industrial parts are presented. The reconstructed CAD model can be used to inspect the producing imprecision or deformations of the part. Section 4 discusses the experimental results. Conclusions and future work are outlined in section 5.

2 Least Squares Template Matching

2.1 Two-Dimensional Line Template Matching

Image points and lines are the most effective features for 3D reconstruction of objects. If "Minimization of the squared sum of grey-difference" is chosen as the criteria, the image matching equation is $\sum vv = \min$. This is the basic principle of least squares template matching (Schenk 1999). Line template matching is a 2D technique that attempts to match a standard template with a real image patch. The real image patch is rotated into horizontal to facilitate matching. As shown in Fig. 1, the level rectangle represents the standard template, while the dashed rectangle is the image patch to be matched. Two unknowns dy_1 and dy_2 are essential to fit the small rotation angles between the image patch and the template.

The line template matching technique can be used for the extraction of image line features. Grid points are detected as the intersection of two matched lines of each corner, as shown in Fig. 2. The black crosses are the predicted image corners, and the white crosses are the matched ones. The precision of image matching results is higher than 0.05 pixels. Light blue lines in Fig. 3 shows the initial projections of several line segments of the part. Although rust exists on the part and can be seen clearly, the matched image lines are well fitted to the real image features (green lines in Fig. 3). Actually, the matching precision is also higher than 0.05 pixels.

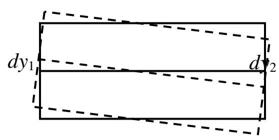

Fig. 1. 2D line template matching

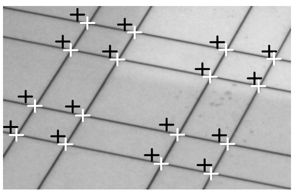

Fig. 2. Matching of points

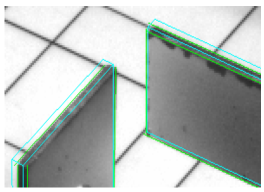

Fig. 3. Matching of lines

2.2 One-Dimensional Point Template Matching

A line can be represented by a group of small colinear segments. If the image window of line template matching is subdivided into small segments, each with a length of 2-5 pixels, named point segment, the rotation angle between standard template and small point segment can be neglected. Matching between the point segment and the template is called point template matching in this paper. As it differs from line template matching, angle is assumed to be not existed, since the length of point segment is usually very short. There is only one unknown *dr* for one-dimensional (1D) point template matching, as shown in Fig. 4.

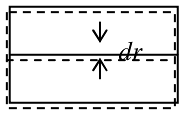

Fig. 4. 1D point template matching

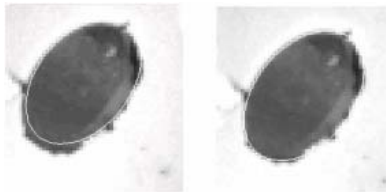

Fig. 5. Matching of circle

Fig. 5 shows the initial projection and matched result of a circle by 1D point template matching. Although rust is evident, the matched circle is well fitted to the image, showing the well potential of 1D point template matching.

3 Reconstruction of Industrial Sheetmetal Parts

The topology of CAD data of sheetmetal part is assumed to be correct since it is designed on computer and often checked many times before the part is produced. But the geometry of the sheetmetal part is usually not identical to the CAD-designed data due to mis-operation during producing. The correct geometric model is reconstructed by two steps, firstly the wire frame model is obtained and then the complex shapes.

3.1 Reconstruction of Wire Frame Model

The world coordinate system is chosen the same as that of the grid. Generally speaking, the coordinate system of the part defined in CAD-designed data will not be identical to the world coordinate system. There are six elements (rotation and translation) to convert the CAD coordinate system into the world coordinate system.

Sheetmetal parts are mostly composed of line segments. This is the reason that we choose line photogrammetry to reconstruct and inspect them. A image line *pq*, space line *PQ* and the projection center *S* should be coplanar (Heuvel 1999, Zhang 2004), while *p* and *P*, *q* and *Q* are not necessarily correspondences, which is the most important advantage of line photogrammetry. Two end points are used to present a line, because it is singularity-free and easy to setup error equations.

The coplanar equation among *p, S, P* and *Q* is:

$$\begin{vmatrix} u_p & v_p & w_p \\ X_P - X_S & Y_P - Y_S & Z_P - Z_S \\ X_Q - X_S & Y_Q - Y_S & Z_Q - Z_S \end{vmatrix} = 0 \tag{1}$$

where (u_p, v_p, w_p) is the model coordinate of image point *p*, (X_S, Y_S, Z_S) the coordinate of camera center *S*, (X_P, Y_P, Z_P) and (X_Q, Y_Q, Z_Q) the coordinates of points *P* and *Q*. The error equation of line photogrammetry can be written as (Zhang 2004):

$$A_1 dx_p + A_2 dy_p + A_3 d\varphi + A_4 d\omega + A_5 d\kappa + A_6 dX_S + A_7 dY_S + A_8 dZ_S + \\ A_9 d\varphi^0 + A_{10} d\omega^0 + A_{11} d\kappa^0 + A_{12} d\Delta X^0 + A_{13} d\Delta Y^0 + A_{14} d\Delta Z^0 + A_{15} dX_P^0 + \\ A_{16} dY_P^0 + A_{17} dZ_P^0 + A_{18} dX_Q^0 + A_{19} dY_Q^0 + A_{20} dZ_Q^0 + F_X = 0 \quad (2)$$

where $A_1 \sim A_{20}$ are the coefficients of unknowns and F_X the constant item. Besides the coplanar equation among *p, S, P* and *Q*, there exits another equation among *q, S, P* and *Q*. The linearized form is similar to that of equation (2).

For parts that are very simple or for those that have a few line segments, grid points should be combined into the adjusmtent model to ensure the reliability of reconstruction. The error equations of grid points are (Schenk 1999):

$$v_x = B_1 d\varphi + B_2 d\omega + B_3 d\kappa + B_4 dX_S + B_5 dY_S + B_6 dZ_S + B_7 dX + B_8 dY + B_9 dZ - l_x \\ v_y = C_1 d\varphi + C_2 d\omega + C_3 d\kappa + C_4 dX_S + C_5 dY_S + C_6 dZ_S + C_7 dX + C_8 dY + C_9 dZ - l_y \quad (3)$$

where l_x, l_y are constant items, $B_1, \ldots, B_9$, $C_1, \ldots, C_9$ coefficients of unknowns. If the coordinates of grid points can be treated as known, terms of (dX, dY, dZ) should be removed. The model of hybrid point-line photogrammetry is composed of equation (2) and (3) and can be used to reconstruct the wire frame model of industrial part.

3.2 Reconstruction of Complex Shapes

For lots of board-like industrial parts especially sheetmetal parts, the reconstruction of complex shapes is also very important but hard to deal with in practice. Up to now, there is few publication or system that can automatically reconstruct circles, connected arcs and lines without attaching any marks on the surface.

Camera parameters, which can be obtained with hybrid point-line photogrammetry, are treated as known. The end points of small line segments are the result of template matching and also functions of circles or lines. Parameters of circles or lines and image features are related by mathematical models. Thus parameters of circles, arcs and lines can be obtained from several images by least squares template matching.

To facilitate the reconstruction, suppose the plane where the circle or arc lies in is known. The camera parameters of the images can be rotated to generate a level plane. So the circle equation in the level plane is very simple:

$$X = X_0 + R \cdot \cos\theta \\ Y = Y_0 + R \cdot \sin\theta \quad (4)$$

where X_0, Y_0 and R are the center and radius of circle or arc, θ varies from 0 degree to 360 degree for circle, and from start angle to end angle for arc. In this paper, circles and arcs are represented by a number of points with different angle θ. The top of Fig. 6 is a space circle, and the bottom is the projected ellipse with known camera parameters. Each point *A* on the space circle defined by θ has its corresponding point *a* in the image. If equation (4) is substituted into collinearity equations, the unknowns are the center and radius of circle or arc. For certain angle θ, the object point is projected onto image and the tangential vector with angle α can be easily determined. The displacement *dr* determined by template matching can be rotated back to the image coordinate system according to α. The error equations of circle or arc reconstruction can be written as:

$$\begin{aligned} v_x &= A_1 \cdot dX_0 + A_2 \cdot dY_0 + A_3 \cdot dR - dx \\ v_y &= B_1 \cdot dX_0 + B_2 \cdot dY_0 + B_3 \cdot dR - dy \end{aligned} \tag{5}$$

where A_1, A_2, A_3, B_1, B_2, B_3 are the coefficients of unknowns, *dx, dy* constant items. Thus the parameters of space circles or arcs can be obtained directly from one or several images. The obtained parameters of circles or arcs should be rotated back to the world coordinate system according to camera parameters.

Arcs in parts are usually connected to lines. As shown in Fig. 7, two arcs c_1, c_2 and three line segments l_1, l_2 and l_3 are connected to each other. For convenience of reconstruction, line segments are also rotated into a level plane:

$$\begin{aligned} X &= X_s + i \cdot \Delta L \cdot \cos\beta \\ Y &= Y_s + i \cdot \Delta L \cdot \sin\beta \end{aligned} \tag{6}$$

where X_s, Y_s is the start point of line segment, β the direction of the line, ΔL the length of small segment approximately equal to the length of point window in circle and arc matching. The error equations of line reconstruction are:

$$\begin{aligned} v_x &= M_1 \cdot dX_s + M_2 \cdot dY_s + M_3 \cdot d\beta - dx \\ v_y &= N_1 \cdot dX_s + N_2 \cdot dY_s + N_3 \cdot d\beta - dy \end{aligned} \tag{7}$$

where M_1, M_2, M_3 and N_1, N_2, N_3 are coefficients of unknowns, *dx, dy* constant items. The circle or arc reconstruction equation (5) can be combined with line reconstruction equation (7) to get solution of connected arcs and lines. To ensure the stability of reconstruction, geometric constrains should be added, such as the center of arc c_1 should lie on the bisector of line $l_1$and l_2, the center of arc c_2 should lie on the bisector of line $l_1$and l_3 and three lines should be tangential to the two arcs, etc.

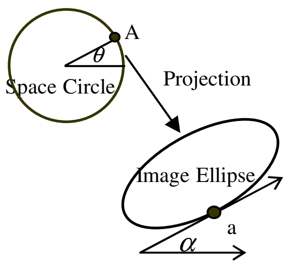

Fig. 6. Projected image point of circle

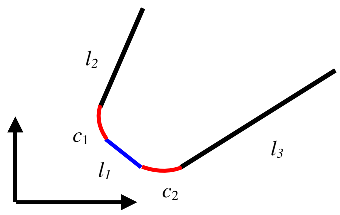

Fig. 7. Connected arcs and lines

4 Experiments

4.1 Overview of the System

To reduce the cost of the inspection system, only one non-metric CCD camera with 1300×1030 pixels resolution is used. Fig. 8 shows the hardware configuration of the system. A planar grid is fixed on the rotation table. The part to be reconstructed is put approximately on the center of the grid. To generate diffused illumination for the grid and the part, four home-used lamps are encapsulated in a semi-transparent plastic box. Image sequence is obtained while the table rotates under computer control.

The developed software runs fully automatically. It can be used to reconstruct and inspect the imprecision of industrial parts mainly composed of lines, circles, connected arcs and lines. The system is composed of 4 steps. Firstly, Image sequence is acquired by CCD camera while the table turns around its center controlled by computer. Image points and lines are obtained by LSTM simultaneous with image acquiring. Then 3D wire frame model of the part is reconstructed. Afterwards, circles, connected arcs and lines are reconstructed by direct object space solution. Finally, inspection can be done automatically or interactively.

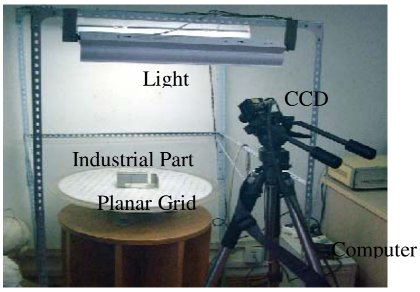

Fig. 8. Hardware of the inspection system

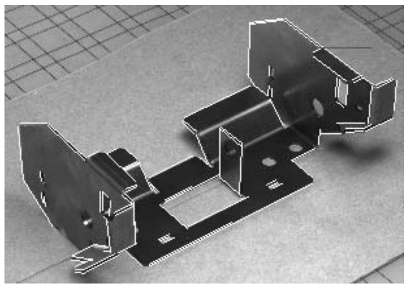

Fig. 9. One image of the part to be inspected

4.2 Real Data Experiments

The inspection system has been tested with real image data of many parts taken by a pre-calibrated CCD camera (Zhang 2003). Experiment of a part with dimension of about 150mm×100mm×80mm will be presented. The part to be reconstructed is put on the center of the planar grid, which is fixed on the turntable. The CCD camera is fixed on a tripod 600mm away from the part. A sequence of 25 images for the part is taken with equal angle intervals while the table turns around, one image is shown in Fig. 9. Image matching is made simultaneous with image acquiring. Grid points are detected as the intersection of two line segments fitted to each corner. Lines are obtained by LSTM with initial values projected by the CAD-designed data.

White lines in Fig. 9 are the matched lines of the part. There is nearly no mismatch for points of planar grid. But for part that are very thin, there maybe some mismatched lines. Most of them can be removed by trifocal tensor (Hartley 2000) computed with camera parameters. The remained mismatches can be eliminated by the iterative least squares adjustment. The system can generate a final CAD model for each industrial part within 3 minutes (includes image acquiring) in a PIV personal computer.

In order to evaluate the precision of the inspection system, 25 distances between lines and planes on the part are measured by calipers and compared with which computed by the reconstructed model. In Fig. 10, “Producing imprecision” means distances between lines, planes or line to plane measured by calipers subtracting the corresponding designed distances. “Computed imprecision” means distances computed with the reconstructed model subtracting the designed distances.

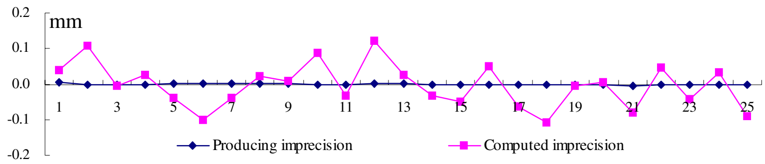

Fig. 10. Inspecting result of the fisrt part

It can be seen from Fig. 10 that the measured distances are very close to that of the CAD data, i.e., the producing imprecision is nearly zero. Deviations of computed imprecision show a well normal distribution. The root mean square (RMS) error of deviation is 0.067mm. The relative precision, which can be calculated as the ratio of RMS against the distance between the camera and the part, is higher than 1/8500 (0.067mm/600mm = 1/8900), which shows the precision of the proposed system when manually measured distances are treated as errorless.

The proposed circle reconstruction approach is also tested with several real image data. Left of Fig. 11 shows the projection of a circle with CAD designed data and camera parameters obtained from hybrid point-line photogrammetry. As can be seen, the rust is very clear. The reconstructed projection (right of Fig. 11) is well fitted with the image feature. The diameter of reconstructed circle is 9.952mm, very close to 10.00mm that measured by calipers.

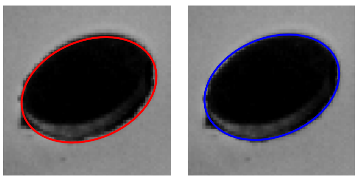

Fig. 11. Reconstruction of circle

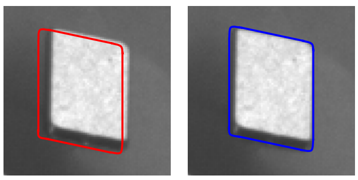

Fig. 12. Reconstruction round rectangle

Left of Fig. 12 shows the initial projection of a round rectangle. The length of the short line segments is only about 12 pixels in the image, and even a few pixels for arcs. They are very difficult to reconstruct with common strategies. But for the proposed technique of object space solution with geometric constraints, they can be reconstructed successfully and stably. The projection of reconstructed model is also well fitted to the image feature (right of Fig. 12).

5 Conclusion

An effective approach for 3D reconstruction and inspection of industrial parts mainly composed of line segments, circles, connected arcs and lines with non-metric image sequence and CAD data is proposed. Wire frame model of industrial part can be reconstructed with hybrid point-line photogrammetry. Circles, connected arcs and lines are reconstructed by point template matching and direct object space solution.

A relative precision of higher than 1/8500 has been obtained. As can be seen, the precision of our system is higher than that of Kosmopoulos (2001), which can achieve a precision of 0.1mm within an planar area of 80mm × 80mm. The proposed technique also has the advantages of low cost of hardware and fully automatic. It shows a promising potential in automatic 3D reconstruction and inspection of industrial parts mainly composed of lines, circles, connected arcs and lines.

However, the proposed system still requires further improvements. Relation between illumination condition and precision of measurement has to be analyzed. Furthermore, the main limitation of the proposed system is that there must be point and/or line features on the surface of the industrial part. Otherwise, artificial patterns have to be projected onto the surface.

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References

1 Chang M., Fuh C., 2001. Fast search algorithms for industrial inspection. International Journal of Pattern Recognition and Artificial Intelligence. Vol. 15, No. 4: 675-690.
2 Choi K. -S., Pyun J. -Y., Kim N. -H., et al, 2003. Real-time inspection system for printed circuit boards. Lecture Notes in Computer Science, Vol. 2781: 458-465.
3 Fraser C., 1999. Automated vision metrology: a mature technology for industrial inspection and engineering surveys. 6th South East Asian Surveyors Congress Fremantle, Western Australia, 1-6 November 1999
4 Hartley R., Zisserman A., 2000. Multiple view geometry in computer vision. Cambridge University Press, UK.
5 Heuvel F. A., 1999. A line-photogrammetry mathematical model for the reconstruction of polyhedral objects, Proceedings of SPIE, Vol. 3641: 60-71.
6 GSI, 2003. V-STARS main brochure. http://www.geodetic.com/vstars.htm.
7 Kosmopoulos D, Varvarigou T., 2001. Automated inspection of gaps on the automobile production line through stereo vision and specular reflection. Computers in Industry, Vol. 46: 49-63
8 Schenk T., 1999. Digital photogrammetry. TerraScience, USA.
9 Zhang Y., Zhang Z., Zhang J., 2003. Camera calibration technique with planar scenes. Proceedings of SPIE. Vol. 5011: 291-296.
10 Zhang Y., Zhang Z., Zhang J., 2004. Deformation visual inspection of industrial sheetmetal part with image sequences. Machine Vision and Applications. Vol. 15, No.3: 115-120.