PC-BASED DIGITAL CLOSE-RANGE PHOTOGRAMMETRIC SYSTEM FOR RAPID 3D DATA INPUT IN CAD SYSTEMS

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ABSTRACT

As long as CAD systems become more powerful and functionally completed they need the effective mean for rapid initial 3D data input. This data must be as possible detailed and as possible precise and ready to be accepted by CAD. The progress in CCD sensors and computers provides the background for integration of photogrammetry as an accurate 3D data source with CAD/CAM.

The paper presents the digital close-range photogrammetric system for spatial coordinate measurements and surface reconstruction for complex industrial 3D objects. The system provides spatial data of high density and high accuracy. It based on Pentium-200/64 PC as central processing unit, two high-resolution CCD cameras, structured light projector and some means for measuring automation such as original coded targets and PC-controlled mechanical devices. The system supports two configurations depending on class of reconstructed object. First configuration is designed for objects every significant point of which can be observed while rotating the object. It includes single CCD and PC-controlled rotating table. The second configuration allows reconstructing objects of more complicated form. It is based on two CCD and PC-controlled structured light projector.

The paper describes the techniques used for non-contact measurements and the methods providing metric characteristics of reconstructed 3D model. Also the results of system application for 3D reconstruction of complex industrial objectsare presented.

1 INTRODUCTION

The progress in technologies of industrial design, rapid prototyping and manufacturing makes a challenge for accurate and productive 3D measurements system for effective input geometry data in CAD system. The existing photogrammetric systems based on workstations and metric high-resolution megapixel CCD cameras (Kochi, N., 1996, Petran, F., 1996) are rather expansive for Russian interior manufacturer market. So now for this purpose in most cases mechanical measuring machines are used, which can not provide required characteristics. The research objective was to develop accurate, productive and low-cost photogrammetric system for rapid 3D reconstruction.

To satisfy these contradictory requirements to the developed system the following approach is chosen. The system is based on PC platform and uses non-metric video cameras, which allows making it not rather expansive. To achieve reasonable productivity the high degree of automation is supported. The main stages of technology are automated by using original coded targets and special structured light for precise and reliable corresponding problem solution. The required precision of measurements is obtained by choosing appropriate scale of acquired images, by generating reference points net and by performing preliminary cameras calibration.

The main stages of technology are camera calibration, cameras exterior and relative orientation, reference points net construction, object scanning using structured light, complete object model generation.

The developed algorithms are supported by original software for Windows 95, which provides all stages of 3D-reconstruction process. The system was tested on various industrial objects, the reasonable precision and performance being shown.

2   SYSTEM CONFIGURATION

The developed digital non-contact measurement photogrammetric system is based on PC as central processing unit. It includes the following components:

Pentium 200/64MB PC
high resolution Panasonic WV-CP410 CCD
2 PCI frame grabbers
PC-controlled rotating table
Structured light projector controlled by PC
Original software for Windows 95

The PC is equipped by two frame grabbers based on Philips and Bt848 chips. Frame grabbers receive composite video signal from two high resolution (about 450000 pixels) CCD cameras and convert it in two 768x576 pixels BMP images, which used for image processing and 3D reconstruction.
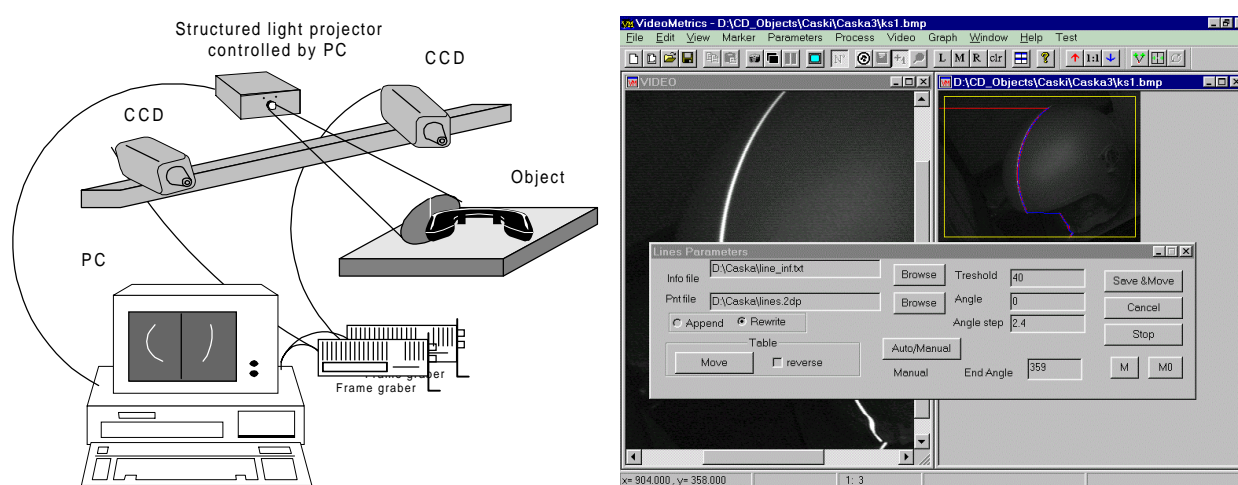

Figure 1: Hardware structure and software interface

For automated corresponding problem solution special structured light projector is used. The structured light is taken in form of narrow contrast line. Depending on system configuration either the object rotate on PC-controlled table or stripe moves along the object surface. PC controls the moving of the contrast stripe.

The developed software provides the complete technology of 3D-model reconstruction. It supports:

image acquiring using 2 frame grabbers configuration
structured light control
image processing of special kind for process automation
system calibration and orientation
3D model reconstruction
3D model visualization

The structure of hardware and the program interface in scanning mode are shown in Fig.1.

3   METHODOLOGY

3.1   Measurement methods

Two non-contact measurement techniques are supported by the digital photogrammetric system. The first one is designed for objects every significant point of which can be observed while item rotating. For 3D reconstruction the technique based on object rotating in contrast stripe structured lighting is used (object rotating technique).

The metric characteristics of generated model are provided:

- firstly by original camera calibration procedure based on using low accuracy test field with further reference coordinates correction
- secondly by projector setup and exterior orientation based on specially developed test field allowing to install structure light strip in required position

For objects, which can not be completely reconstructed by rotating technique, two CCD and movable contrast stripe configuration is developed. Movable contrast stripe structured light is used for automated correspondence problem solution (scanning technique). The required precision of measurement is achieved:

- firstly by transforming images coordinates to undistorted values accounting system calibration results;
- secondly by choosing appropriate scale of acquired images. Then reconstructed surface fragments are combined in uniform model by developed method based on reference points net constructing.

When assembled system is calibrated for cameras interior orientation determination. Calibration is made basing on test field with reference points marked by special targets, targets' coordinates being measured approximately. Then the coordinates of reference points are estimated precisely using bundle adjustment procedure. The calibration procedure has a high degree of automation due to applying coded targets.

Below the more detailed discussion of each technique is given.

3.2 System Calibration

To obtain image scale suitable for accurate 3D reconstruction CCD cameras are equipped with 12-mm focal length lens. Their interior orientation parameters were determined by calibration procedure in laboratory conditions. The plane with 36 contrast targets was used as test field (Fig. 2.), the dimensions of the test field being about 350mm x 320mm. It provides approximately equal targets density in captured images.

The original coded contrast targets were used as reference points for calibration. The developed coded targets (Knyaz, 1998) provide invariance to rotation and scaling, robust recognition of a target number with correction of possible mistakes, exact measurement of a target center, target detection in the image with non-uniform contrast, short processing time. Elliptic approximation is used for high accuracy sub-pixel center of target determination.

For calibration procedure 24 images of test field were captured (12 images for each camera). The average distance between camera and test field was in diapason of 600 mm and 1000 mm. The angle positions of cameras with respect to the test field were: $\alpha \approx 0, \pm 45°$, $\omega \approx 0, \pm 45°$, $\kappa \approx 0, 90, 180°$.

Figure 2. Test field for calibration procedure

Targets image coordinates were determined with sub-pixel accuracy with ellipse operator. The additional parameters describing CCD camera model (Beyer H.A., 1992) system in collinearity conditions were taken in form:

$$\Delta x = \Delta x_p + \bar{y}a + \bar{x}r^2 K_1 + \bar{x}r^4 K_2 + \bar{x}r^6 K_3 + (r^2 + 2\bar{x}^2)P_1 + 2\bar{x}\bar{y}P_2$$

$$\Delta y = \Delta y_p + \bar{x}a + \bar{y}r^2 K_1 + \bar{y}r^4 K_2 + \bar{y}r^6 K_3 + 2\bar{x}\bar{y}P_1 + (r^2 + 2\bar{y}^2)P_2$$

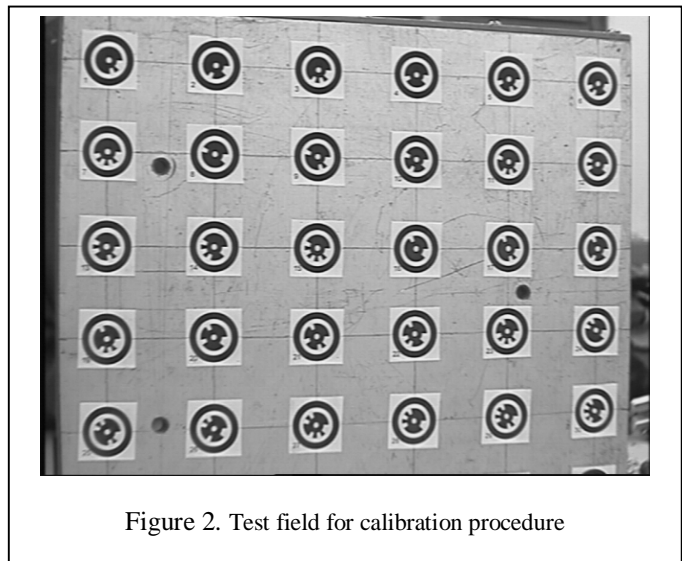$$\bar{x} = m_x(x - x_p); \bar{y} = -m_y(y - y_p); r = \sqrt{\bar{x}^2 + \bar{y}^2}$$

(1)

The parameters of interior orientation: principal point x_p, y_p, scales in x and y directions m_x, m_y, and affinity factor a, the radial symmetric K_1, K_2, K_3 distortion and decentering P_1, P_2 distortion are to be estimated.

Calibration stages include initial values definition, image coordinates determination for reference points, images exterior orientation, test field reference points coordinates and interior orientation parameters being frozen. Unknown parameters vector include:

exterior orientation parameters of all the images
interior orientation parameters of both cameras
coordinates X, Y of all the object reference points excluding the central point (#31) and X coordinate of the point #25, which determine the object space coordinate system. Z coordinates of all points was taken as 0.

While test field reference coordinate were known with low accuracy the reference distances between some of the reference points were measured with higher precision for better system determinability. The original bundle adjustment software developed for Windows 95 performs estimation of unknown parameters.

Precision results (standard deviation) of interior orientation estimation are given in table 3:

spatial reference points coordinates	$\sigma_{xs} = 0.014$ mm
angle exterior orientation parameters	$\sigma_{\alpha\omega\kappa} = 0.062°$
residuals of collinearity conditions	$\sigma_{l0} = 0.066$ mm

Table 3. Precision of interior orientation

The results of calibration show the reasonable accuracy for task of 3D reconstruction.

3.3 Object rotating technique

The method used for 3D reconstruction is based on suggestion that line of rotation of controlled turntable is belong to XOY plane of test field system coordinate. That suggestion requires the precise structured light projector set up. For projector setup the following procedure is perform. The rotating table is moved to initial position. The special test field (Fig. 4.) is established so that rotation line of the table is OY axis of test field. Test field defines the coordinate system for external orientation with the beginning in the reference point #17 marked by coded target. OY axis is up-directed (point #1), OX axis is right-directed (point #16). OZ axis is perpendicular to XOY plane, coordinate system being right.

Structured light projector is positioned so that optical projection center and contrast stripe belongs to XOY plane of test field coordinate system. For controlling this condition one side test field has a special form.

After structured light projector set up exterior orientation procedure based on reference points is performed. As a result of exterior orientation the camera coordinates X_0, Y_0, Z_0 and angle position (α, ω, κ) are determined in test field coordinate system. Angles (α, ω, κ) determine transition matrix A.
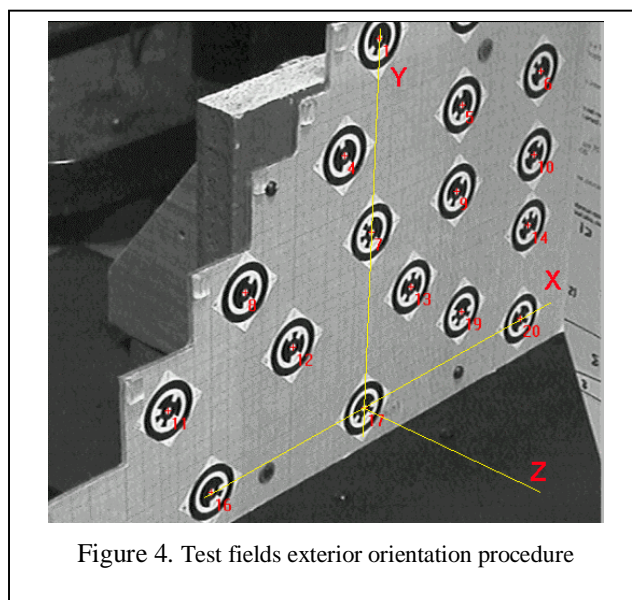

Figure 4. Test fields exterior orientation procedure

Then the procedures of image acquisition in structured light and image preprocessing are performed. These procedures are executed in cycle while given angle position of turntable is reached. On each step stripe is detected with sub-pixel accuracy by weight operator, image coordinates of stripe being recalculate to undistorted values. The results of stripe detecting for each table angle are saved in file.

The object spatial coordinates are calculated basing on condition that every detected image point correspond to object point of Z=0. The collinearity equation for Z=0 are used for X, Y coordinate determination in form:

$$X = -Z_0 \frac{a_1 x + a_2 y - a_3 f}{c_1 x + c_2 y - c_3 f} - \frac{f(b_1 y - b_2 x)}{c_1 x + c_2 y - c_3 f} + X_0$$

$$\text{(2)}$$

$$Y = -Z_0 \frac{b_1 x + b_2 y - b_3 f}{c_1 x + c_2 y - c_3 f} - \frac{f(a_1 x - a_2 y)}{c_1 x + c_2 y - c_3 f} + Y_0$$

where a_i, b_i, c_i, $i=1,2,3$ are elements of A matrix.

Then found coordinates are recalculated to test field coordinate system for each table angle. The original method for uniform surface reconstruction from spatial 3D-point cloud is developed for this class of objects. It is based on finding points projections on reference spatial figure (e.g. sphere) for generating uniform 3D surface by modified Delaunay triangulation procedure. The spatial coordinate cloud and reconstructed surface is exported in CAD formats for further processing.

3.4 Scanning technique

For generating 3D model with required accuracy the following technique is chosen. The model is reconstructed by fragments, which dimensions providing required precision restricted by CCD resolution. To obtain reconstruction precision at the level of 0.1 mm the dimensions are taken about 300 mm x 300 mm. The stereo basis equals 600 mm, convergence equals 38°. The work distance for fragment acquisition is about 800 mm.

Complete model generation from separate fragments is based on reference points net. Special targets mark reference net, targets' coordinates being measured approximately. Then reference points coordinates are estimated by bundle adjustment. After reference points being constructed the fragment reconstruction process begins. Firstly two images of fragment is acquired under common condition for cameras exterior orientation determining. The exterior orientation is performed basing on reference point presenting in the images. Secondly a set of stereo images is acquired in structured light, image processing being performed immediately resulting in two array of image coordinate for left and right images. Then these two arrays are processed for 3D coordinate determination.

3.4.1. Reference network construction. For this purpose a set of coded targets are placed on object with density providing about 6-12 targets being visible by stereo system on exterior orientation stage. For car element (rear interior panel) presented as example of system application 80 coded targets were placed on object (Fig. 5.).
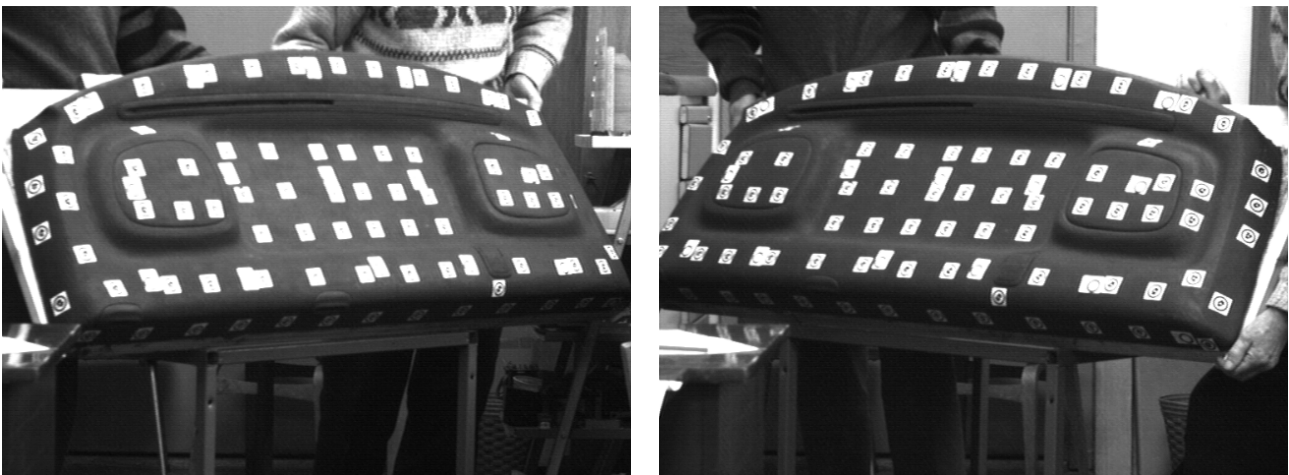

Figure 5. Stereo pair of car element for reference points net construction

Three points are taken for coordinate system determination. The coordinates of the rest points are measured approximately in the given system of coordinates. Then the stereo pair of whole car element with targets are captured (Fig.5.) and image coordinates of reference points are determined.
The image scale does not allow obtaining reasonable accuracy of reference points based on the stereo pair. So to reach required precision the set of stereo pair (49 for presented example) of object's parts is acquired, the scale of images

corresponding to the working condition of system. Then image coordinates of reference points are determined automatically for each image with high sub-pixel accuracy due to using coded target for reference point marking. To construct accurate reference points net the bundle adjustment procedure is performed using original software of developed system. The true spatial coordinates of reference points are to be estimated. Estimated parameters vector includes 6 parameters of exterior orientation for each image (total amount - 90) and 3 spatial coordinates for each reference point (total amount - 80) excluding coordinates of points determining system of coordinate. So for considered object the estimated vector contains 774 unknowns, total number of equation being about 1800.

The resulting reference net has the next accuracy for object of dimension approximately 1600mm x 600 mm x 200 mm:

Standard deviation of spatial reference points coordinates $\sigma_{xs} = 0.090$ mm
Standard deviation of angle exterior orientation parameters $\sigma_{\alpha\omega\kappa} = 0.132°$
Standard deviation of residuals of collinearity conditions $\sigma_{l0} = 0.097$ mm.

3.4.2. Fragments Reconstruction. Firstly the stereo pair of a fragment is acquired under common condition. This stereo pair is used for exterior orientation of cameras. The precise spatial coordinates of reference points are taken from reference net, obtained on the previous stage of object reconstruction.

Then the structured light is placed in initial position on fragment left border and 2D scanning process begins. It repeats the following steps until right border of fragment is reached:

Left image acquiring by first frame grabber
Right image acquiring by second frame grabber
Left image processing resulting in sub-pixel coordinates of structured light pattern in the image
Right image processing resulting in sub-pixel coordinates of structured light pattern in the image
Saving obtained 2D coordinates from left and right images on hard disk
Moving the structured light to the next position with given step
Checking if the right border of fragment is reached

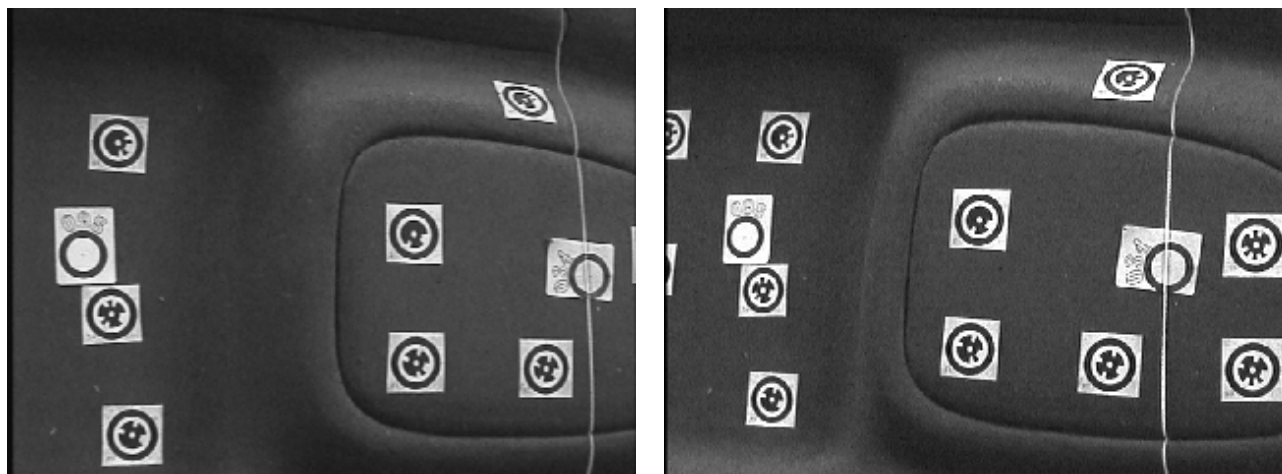The stereo pair of object's fragment acquired in structured light is shown in Fig. 6.

Figure 6. Stereo pair of fragment in structured light

After 2D scanning completing the resulting file of image coordinates is processed for spatial coordinates cloud calculating. On this step image coordinates of structured light pattern recalculate to their transformed to $\Delta\alpha=0$ condition and undistorted values basing on calibration results. Then the corresponding problem is solved with sub-pixel accuracy using epipolar geometry.

For fragment surface reconstruction common Delaunay triangulation procedure is used resulting in triangles surface representation and (if needed) in interpolated DTM form. The whole model's surface is generating by performing triangulation procedure for all points obtained during fragments 3D reconstruction without any smoothing procedure.

4   RESULTS DISCUSSION

The developed system was used for 3D reconstruction of set of objects for purposes of further CAD processing, rapid prototyping and manufacturing. The character dimensions of reconstructed objects vary from 200 mm to 1600 mm.

The result of object reconstruction by rotating technique is shown in Fig. 7. The resulting accuracy was about 0.16 mm. The reconstructed surface is obtained by triangulation on reference sphere. The generated model exported in CAD format then was sent via Internet for rapid prototyping on stereo lithography device.

For complete model generation by scanning technique from 5 to 24 fragments were reconstructed depending on object
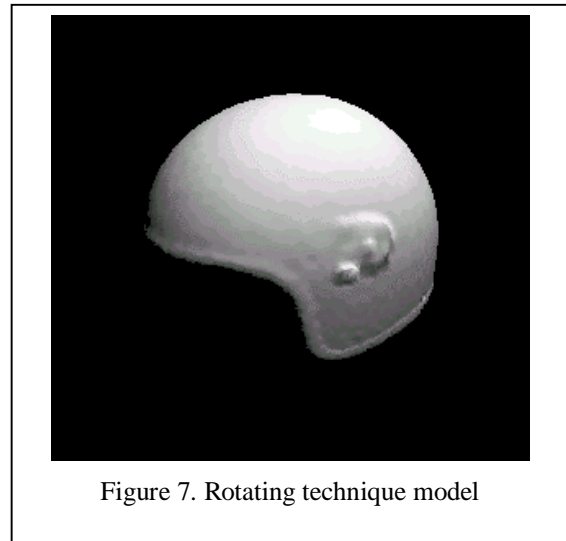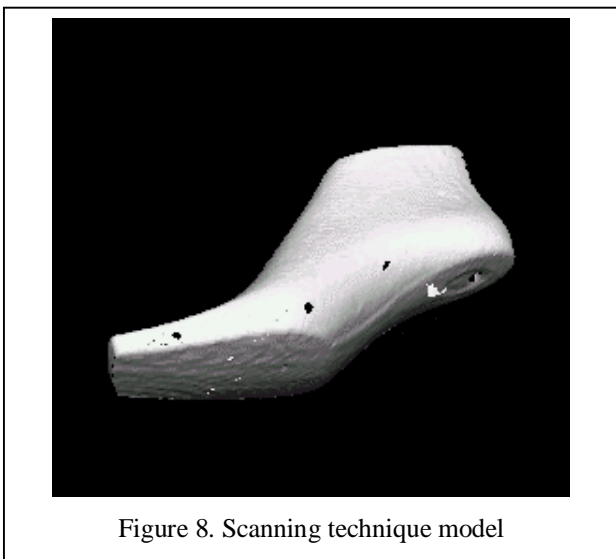

Figure 7. Rotating technique model

dimensions and configuration. Spatial coordinate cloud of each fragment contains about 50000 points.

For presentation viewing and complete model generation the density of each fragment was reduced in 5 times without any smoothing or interpolation. Spatial coordinates of all fragments were obtained in uniform system of coordinate due to chosen approach. Neither manual correction of any fragments position in complete model, nor local correction of points' coordinates in overlapping regions of neighbor fragments was performed.

The estimated performance in current system configuration is about 10000 points per minute. The accuracy of 3D reconstruction is at designed level of 0.1 mm.

Figure 8. Scanning technique model

One from the reconstructed fragments (a), union of three fragments (b) and the complete model (c) are shown in Fig. 9.
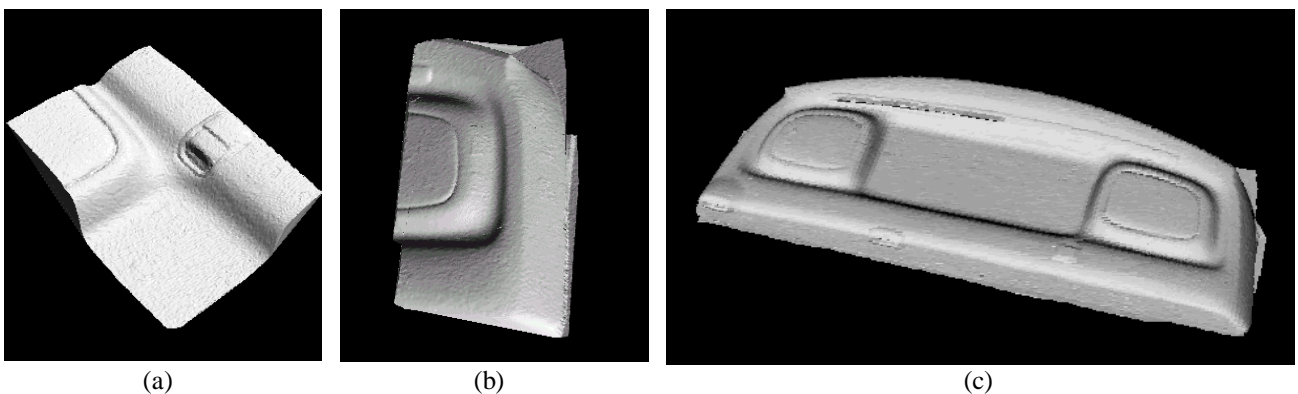

| (a) | (b) | (c) |

Figure 9. Results of car element reconstruction by scanning technique

The results of fragments unionizing show the high precision of reference points net constructing. The errors in points' spatial coordinates in overlapping regions are in the required limits.

5 CONCLUSIONS

PC- based digital photogrammetric system using non-metric CCD cameras as acquisition device is developed. It is designed for rapid 3D reconstruction of industrial object surfaces for further CAD processing.

The system supports two modes of 3D reconstruction: rotating technique for restricted class of objects and scanning technique for free form objects. The proposed approach for complete 3D models generating with required precision approves the designed system characteristics on the set of real objects.

The speed of 3D points measurements is about 10000 points per minute, the accuracy of measurements is at the designed level of 0.1 mm for the described system configuration. The high degree of process automation is provided due to applying original coded targets and additional PC-controlled hardware: rotating table and structured light projector. For rotating technique 3d reconstruction can be performed by "one-button-click".

The results of system application for complex industrial objects 3D reconstruction demonstrate that the developed system provides high density of measured points and reasonable precision and performance. The higher characteristics can be reached by using more powerful processor and applying sensors of higher resolution. The developed digital close-range photogarammetric system has built-in capabilities for full automation and real-time processing.

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