Journal of Theoretical and Applied Information Technology
15 September 2012. Vol. 43 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ON-MACHINE MEASUREMENT OF LARGE-SCALE WORKPIECE BASED ON MACHINE VISION

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ABSTRACT

On-machine measurement(OMM) based on machine vision has been hot research topic in recent years because coordinate measuring machine(CMM) measurement requires significant resources in operating time and cost. This paper aims to develop an OMM method with a manipulator and industry camera. First, an on-machine calibration method of industry camera based on image sequence is studied. A set of monocular stereo system was established on the NC milling machine. A calibration target was designed to meet the requirements of finding enough and accurate correspondence relationship. Calibration method is illustrated involving taking image sequence, detecting the position of the calibration board and the marking points, finding the marking points' correspondence with their projection, determining the camera parameters through optimization algorithm. Accuracy of calibration shows that choosing 10 calibration images is appropriate for on-machine calibration. Second, image mosaic method for on-machine measurement of large-scale workpiece is investigated. Image sequences were acquired by controlling the moving of working table. Image mosaic of large-scale workpiece was realized with high precision. Size measurement result proved the effectiveness and high efficiency of this OMM system.

Keywords: *On-machine Measurement, Camera Calibration, Image Sequence, Image Mosaicing, Large-scale Workpiece*

1. INTRODUCTION

In the automated manufacturing system, such as numerical controlled machine, using online or on-machine inspection technique possess significance and wide prospect for improving efficiency and quality and reducing cost of cutting process[1,2]. Vision measurement uses computer vision to measure accurately and locate for spatial geometric dimension[3]. Because of being effected by camera vision and photographic distances, it is needed to mosaic and fuse sequence images in different times and angles to obtain panoramic image of workpiece when the length of measured workpiece goes beyond camera view field. The objects of image mosaic are sequence images with partly overlapped area in a set of adjacent images. At present, various motion modes of camera are often used for image mosaic to make corresponding cylindrical or spherical projection.

Some studies were carried out on on-machine measurement (OMM) system. The sensors used in OMM are classified into contact, noncontact, and hybrid types. The contact type is a touch probe, in which the cutting tool was replaced by a measurement sensor when the processing was finished[4]. The main factors affecting accuracy of OMM measurement are the sensing system and the machine tool. For the noncontact OMM, laser sensor and charge coupled device (CCD) camera are often employed[5]. While the hybrid type uses both contact and noncontact sensors[6]. Generally, the contact OMM measures objects precisely than noncontact types. But the problems involve compensation of the dimension of a touch probe and the time consuming. On the other hand, the noncontact type is deficient in precision at present. However, it can be applied for soft objects and fast measurement.

In this paper, we present a new method of image mosaicing for on-machine vision measurement of large-scale workpiece. The camera was mounted on the numerical controlled milling machine with no moving in order to keep invariable for calibrated parameters in the camera. The workpiece moves with working table controlled by operating panel and numerical controlled program to acquire sequences images block by block. In fact, the image mosaic process for measurement of large-scale workpiece is different from that of common two

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15 September 2012. Vol. 43 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

images. It associates to camera calibration, elimination of lens distortion and overall configuration relationship of multi-images in order to acquire panoramic image of large-scale workpiece with high precision. It is the base for achieving on-machine vision measurement of two dimensional sizes.

2. ON-MACHINE CALIBRATION WITH IMAGE SEQUENCE

Camera calibration is essential to obtain accurate measurements of objects. Only after the camera calibration, it is possible to correct lens distortions and obtain the object's coordinates in metric units. Much work has been done, in the last 40 years, beginning in the photogrammetry community[7] and, more recently, in computer vision[8-10]. Recent trend is toward convenient and precise calibration methods for vision measurement system in industrial field, which is hence the focus of this paper. This paper intends to introduce a on-field calibration approach on the basis of image sequence, which can not only be used in the lab environment, but also help with the parameter calibration for movable monocular camera of NC machine in the workshop.

2.1 Target Selection

To calibrate a camera, two requirements must be met. First, enough 3D space points in the world coordinate system must be known. Second, the 2D image coordinates of the projection points from these space points must be found. Details about camera models for calibration can refer to [11]. In order to find enough 3D points, objects and signs whose features are easily extracted, such as circular points and marks, are usually positioned at a know location. In general cases, it is enough to measure an object accurately with the position of a reference object relative to the camera known. There is no need to clarify the position of such object in the coordinate system. Therefore, the camera can be calibrated with a movable, previously measured calibration board whose size is known.

In order to fulfill the second requirement, it is necessary to determine the correspondence between the known points in the world coordinate system and their projections in the images which is very difficult. Therefore, in general, the structure of the calibration board should make the process of determining the correspondence as simple as possible. As shown in Figure 1, it is a self-designed planar target with a circular marking point. It is printed by laser printer of high quality and then stick on the back of the plexiglass panel of high flatness. There are following reasons to design this kind of calibration board. Firstly, the black rectangular bounding box around the calibration target can make the central part of the calibration target be extracted easily. Secondly, putting a small direction mark in the corner of the rectangular bounding box can make the camera calibration algorithm work out the only direction of the calibration board. Thirdly, putting circular mark on the surface of the calibration target will help to extract the coordinates of the central point of the circle accurately. Finally, all the circular marking points are ranked as rectangular array, which therefore makes it easier for the camera calibration algorithm to retrieve the pixel coordinates of the corresponding pixel points.

Major design parameters are: a black square with length and width measuring 100mm; a right angled triangle with the length of the right-angle side measuring 12.5mm; two chord peaks located at the line of centers of the horizontally and vertically first marking points; 6.25mm diameter black marking points equally distributed in 7*7 array format with the center distance measuring 12.5mm. These major parameters are compiled as a 'caltab.descr' file which is temperately stored in the work space of the computer for further use.

Several images are used for calibration so that degeneracy, which prevents a unique solution to the camera parameters f, s_x, s_y from appearing through the non-linear optimization, can be better solved.

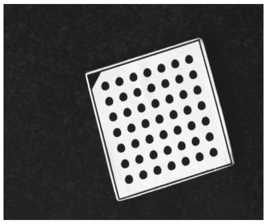

Figure 1: Calibration target with circular marks

2.2 Calibration Method

Let M_i represent the calibration marking points in the world coordinate system, and m_i represent the coordinates in the image cast from the central point. While vector C represents camera

Journal of Theoretical and Applied Information Technology
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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

parameters, with both internal and external parameters of the camera model included.

According to the features of calibrating board, the following procedures are made to accomplish camera calibration:

Step1: Place the calibrating board on the surface of the work table before mounting the workpiece. Figure 2 shows the scene of on-machine measurement system without calibration board. It should be noted that the calibration board can also be placed on the surface of the workpiece. Then, adjust the handwheel of the NC machine hence the work table makes parallel translation in X and Y direction. Take 18 pictures of image sequence (see Figure 3) and store them in the working area of calibration software named “calib_01~calib_10”.

Step2: Detect the position of the calibration board and the marking points. Find out the areas marked with 7*7 circular points. Then extract the edges of all circles by sub-pixel edge extracting and fit them into an ellipse by Steger algorithm[12]. Extract the sub-pixel precision position from the center of the ellipse (see Figure 3).

Step3: Find the marking points’ correspondence with their projection based on the smallest outside quadrangle of the ellipse. In addition, identify the unique direction of the calibration board based on the direction of the black triangle located at corner of the outside quadrangle.

Step4: Determine the camera parameters through the minimization of the distance between m_i , the coordinates of marking midpoints extracted, and $\pi(M_i, C)$ obtained from calculation.

$$d(c) = \sum_{i=1}^{k} \left\| m_i - \pi(M_i, C) \right\|^2 \rightarrow \min \qquad (1)$$

In the equation above, $k = m \times n$ =49, which represents the quantity of the circular points. Due to the complexity of the non-linear optimization, enough right initial values should be provided for the variables. The initial values of the camera’s internal parameters can be found in the image sensor and instruction book for the camera lens, while external parameters can be jointly set by the control panels of the NC machining center and mechanical arm, or obtained from the algorithm above.

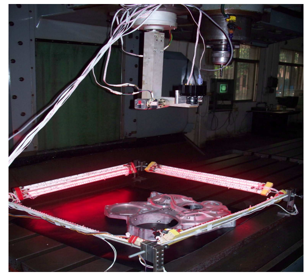

Figure 2: Scene of on-machine measurement system

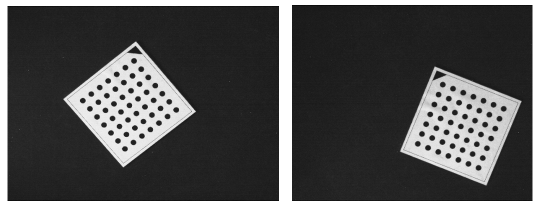

Figure 3: The first and fifth image in the 18 image sequence

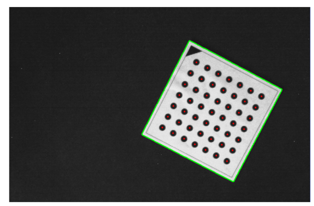

Figure 4: Mark centers detected in the third image

The internal parameters finally marked are listed in Tab. 1. The parameters obtained are stored in a “dat” file automatically for further use of image matching or Stereo reconstruction program (See Figure 4). Here, f is more a camera constant or principal distance than the camera local length. The parameter k represents distortion coefficient. S_x and S_y respectively represent the horizontal and vertical distances between two neighboring sensor elements. C_x and C_y are the values for the x-coordinate and y-coordinate of the principal point is half the image width.

Table I
The internal parameters of camera

f	k	s_x / (m)	s_y / (m)	c_x	c_y
0.0205438	-4426.85	4.19745e-006	4.2e-006	433.475	277.542

For calibration in stereo reconstruction, the movable stereo vision system needs to conduct similar procedures. The camera needs to be translated and rotated at an angle by the manipulator control system in order to obtain stereo images except shooting part by part. The calibration board should be placed on the surface of the work piece. Then, the calibration images are grabbed on the left and right of the row and name them as

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

"calib_cam1_01 ～ calib_cam1_10" and "calib_cam2_01～calib_cam2_10".

2.3 Accuracy Analysis Of Camera Parameters

As mentioned above, several images being used for calibration can better avoid degeneracy, which hinders certain parameters from having a unique solution. But how many images are needed for calibration? In order to figure out the proper number of images, a total of 18 images for calibration are taken, among which l images (l =2,3,…18) of all subsets are used to calibrate the camera. With the parameters got by calculation of each subset, the standard deviation of principal distance f (U: μm), radial distortion coefficient (U: 1/ m^2) and principal point coordinate (C_x, C_y) (U: quantity of pixels) are obtained, which is then analyzed with the relation curve of the number of images used.

As is shown in Figure 5, when less than 6 images are used, the standard deviation of the principal distance f is bigger, less accurate and fluctuates more. As the number of images increases, the accuracy of the principal distance is significantly raised. Similarly, an increase of the number of images is linked to an improvement in accuracy of the radial distortion coefficient as is shown in Figure 6. In addition, the accuracy of C_x and C_y, the coordinates of the principal point, is improved as the images increase (see Figure 7). However, it can be noted that the effect of increased images on C_x is greater than on C_y. When more than 10 images are used, there shows a lower level of accuracy improvement of these parameters. Therefore, the employment of 10 images is proper for calibration given a drop of the calibration speed and even the speed of the whole measurement as the images increase.

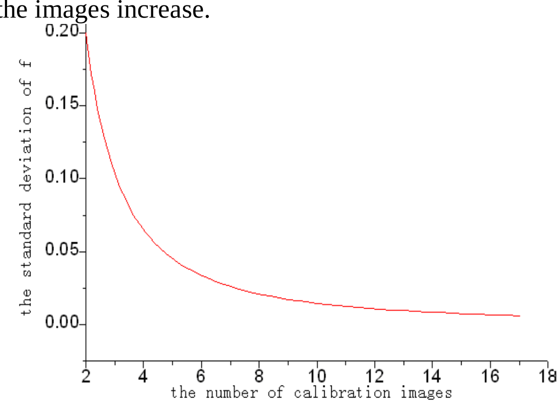


Figure 5: Relation between the standard deviation of f and the number of calibration images

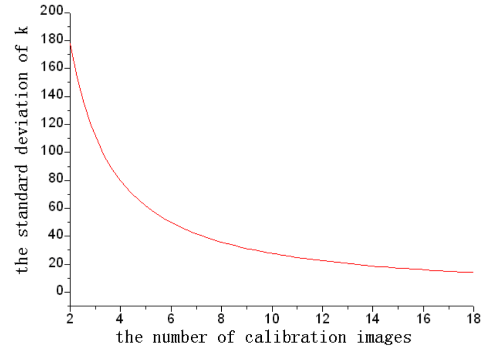


Figure 6: Relation between the standard deviation of k and the number of calibration images

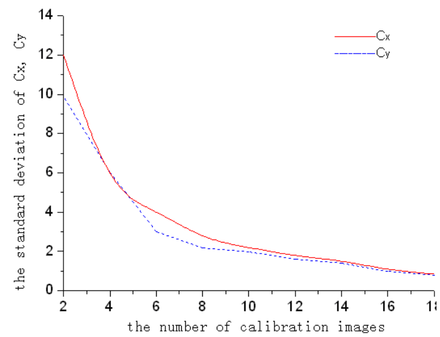


Figure7: Relation between the standard deviation of Cx,Cy and the number of calibration images

3. ON-MACHINE MOSAICING

3.1 Rule Of Images Taking For Image Mosaic

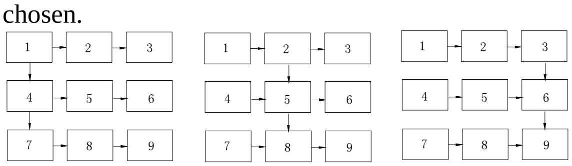
After repeated experiments, we summarized rules of sequence images taking. Firstly, there are overlapped parts in images. Secondly, the overlapping images should be textured in order to make the following automatic image registration identify feature points. The lack of textured overlapped parts of images can e overcome by choosing larger overlapped area. Thirdly, overlapped areas should have approximately the same scale. Generally, the size difference should not exceed than5%-10%. Fourthly, every image should be radiometrically similar. Otherwise, if the brightness differs heavily between neighboring images, it will cause image matching difficulty and clearly visible seams between them. Hence, homogeneous illumination is critical for image mosaicing.

3.2 Definition Of Overlapped Image Pairs

Definition of overlapped image pairs depends on quantity of mosaic images of measured objects. While quantity of mosaic image pairs is up to size

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

of CCD or CMOS, focal length and the distance between the object to camera. We should decrease the number of mosaic image pairs in order to advance matching efficiency, mosaic efficiency and even measuring efficiency. As three by three arrangement of nine images as shown in Figure 8, there are three image pairs matching modes can be chosen.



(a) mode 1 (b) mode 2 (c) mode 3

Figure 8: Configuration modes of nine overlapping images

The image pairs matching configuration mode as shown in Figure 8(b) is the optimal mode because of high precision of image mosaic. For mode 2, No.2, No.5and No.8 in the center array images should be matched after three rows of image pairs matching.

3.3 Feature Point Detection

Generally, many matching feature point pairs in two images need to be detected for mage mosaic. The relationship among feature points determines the location of image mosaic. However, on-machine workpieces are usually smooth and have less feature points. In addition, because of the influence of noise and illumination in factory, it is easy to cause to appear many outliers in image after feature point detection. The method of feature point detection in this paper is Harris feature point detection method[14]. When using Harris method, two things should be considered. Firstly, smooth value of gradient integrals must be optimum. If the smooth value is too large, though the computing speed can be improved, few feature point can be detected resulting in match failure. If the smooth value is too small, there are enough feature points detected, but it will result in slower

calculating speed and even computer corruption.Generally, smooth value of gradient integral should be about 2.0. Secondly, smooth value for computing gradient should be large enough to reduce noise effect for first-order differential in the most extent.

3.4 Projective Transformation Matrix Computation

The key to image mosaic technique is image registration. The projection transformation needs to be calculated according to image consistency in overlapped area. The relationship between two overlapped images can be represented by a 3×3 projective matrix named plane homography matrix. At present, there are three main methods for computing the plane homography matrix: the method based on feature, the method based on gray scale information, and the method based on transform domain[15-17].

In this paper, projective matrix computation is computed by finding corresponding point relation between image pairs. The initial matching methods of finding corresponding points include sum of square differences (SSD), sum of square difference (SAD) and Normalized Cross correlation (NCC). Every method has both advantages and disadvantages. We usually choose the method of NCC. After initial match, we use the method of RANSAC for robust matching. RANSAC algorithm is a method of robust parameter estimation presented by Fischler and Bolles in 1981[18].RANSAC has been widely used in on-machine vision engineering practice for high robustness and efficiency. The way judging whether a point is the correct matching point is to set a threshold value which makes the distance between expected coordinate of the transformation matrix and this point to be less than the threshold value. Therefore, the threshold should be appropriate. In practice, the threshold should be determined by choosing and comparing.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The object of vision measurement is a large-scale automotive die-casting with dimension of about 450mm×450mm under workshop environment as shown in Figure 9 (a).The camera is HV2000FC CMOS, and the industry lens is COMPUTER M1214-MP. CPU of the computer is Intel dual-core E6420 2.13GHz. The memory of the computer is 1G. The system environment was Visual C++6.0. In order to ensure the success rate of feature matching, we paste some paper markers on the work piece. The camera was about 390mm away from the workpiece. The size of image sensor was $7.176mm \times 5.319mm$ .The effective focal length of the lens was 12mm. After computation, the view size of view field is 232.7mm×172.9mm. Because certain overlap region was required between the adjacent two images, we can choose 9 images for image mosaicing. Before image taking, the optical axis of the camera should be adjusted to be perpendicular to worktable. According to field

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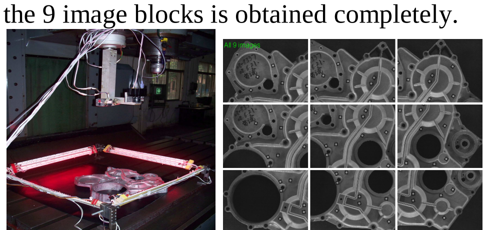
ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

of view size at this time and the required overlap size of adjacent two images', moving distance of the worktable before and after two adjacent images taking is determined. Then, the camera and the lens are adjusted manually till high quality images can be taken. We place the calibration board on the workpiece for camera calibration. Finally, we take the images of the workpiece from the upper left corner to the lower right of the workpiece. The images were named Part_01～Part_09. According to the method described previously, image mosaic of the 9 image blocks is obtained completely.



(a) On-machine scene (b) Original 9 images

Figure 9: On-machine vision measurement

Figure 9.（b）shows the arrangement of the original 9 image blocks of a large-scale aluminum alloy casting. Using the above idea of mosaic, we carry out distortion elimination, we implement the steps of camera calibration, feature extraction, initial image matching, robust image matching, projective matrix calculation, projective mosaicing to obtain quite good mosaic effect. Figure 10 shows the matching result with robust RANSAC algorithm. The green points are feature points extracted by Harris detector. The blue lines are the epipolar lines of correct matching points between the two adjacent images after robust matching. Figure 11 shows the final mosaic result. As we can see, the mosaic effect is perfect with almost no distortion. The course of mosaic takes 25.4 seconds.

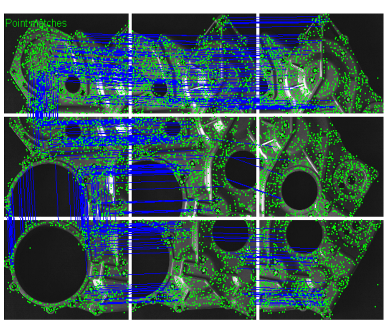


Figure 10: Robust matching result with RANSAC algorithm

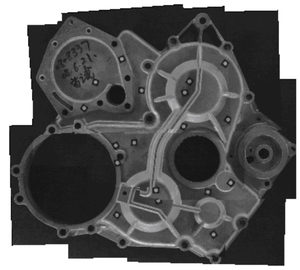


Figure 11: Mosaic result

Threshold segmentation and subpixel edge extraction are carried out to obtain the precise edge localization. The centers of the measured holes are determined using the subpixel detection algorithms of ellipse center, and marked with the red "+".

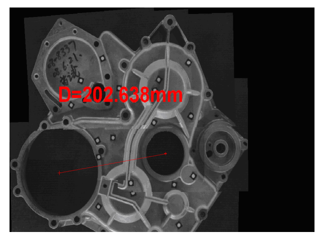


Figure 12: Measuring result of the distance between two large holes

The distance between two big holes center is obtained, and the display result of mosaic image is returned as shown in Figure 12. The difference between the measured result and the measured value (202.6033 mm) with three-coordinate measuring machine is less than a pixel which further verifies the property of high precision of image mosaic.

5. CONCLUSION

In this research, an OMM system was developed for measuring the large-scale workpiece on the machine tool. An on-machine camera calibration method based on image sequence was presented. The problem of degeneracy in calculating the camera parameters accounts for using calibration image sequence. Furthermore, the number of calibration images is the

main factor influencing the accuracy of camera calibration. The accuracy of calibration parameters is markedly improved as the number of calibration image increases. Since the accuracy of calibration become stable after the number of calibration image increases to 10. Consequently, choosing 10 calibration images is appropriate for on-machine calibration. On the other hand, an on-machine image mosaic method was developed. Image pair configuration, feature extraction and the projection

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

matrix calculation methods of image were analyzed and utilized. With the aid of the feed movement of numerical control machine, we can realize image mosaic and on-machine vision measurement of large-scale workpiece with high precision and high efficiency under proper illumination.

ACKNOWLEDGMENT

This work was supported by Hubei province science and technology research project through grant number Q20112609, P.R.C and Hubei Natural Science Funds through grant number 2009CDB390.

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