Research on high-precision hole measurement based on robot vision method*

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(Received 26 May 2014; Revised 17 June 2014)

A high-precision vision detection and measurement system using mobile robot is established for the industry field detection of motorcycle frame hole and its diameter measurement. The robot path planning method is researched, and the non-contact measurement method with high precision based on visual digital image edge extraction and hole spatial circle fitting is presented. The Canny operator is used to extract the edge of captured image, the Lagrange interpolation algorithm is utilized to determine the missing image edge points and calculate the centroid, and the least squares fitting method is adopted to fit the image edge points. Experimental results show that the system can be used for the high-precision real-time measurement of hole on motorcycle frame. The absolute standard deviation of the proposed method is 0.026 7 mm. The proposed method can not only improve the measurement speed and precision, but also reduce the measurement error.

Document code: A **Article ID:** 1673-1905(2014)05-0378-5

DOI 10.1007/s11801-014-4091-x

With the rapid development of machine vision technology, the research and application of robot vision systems are getting more attention. Compared with the contact measurement method, the vision detection technology has the advantages of fast speed, non-contact measurement and high degree of automation.

Robot vision method has been widely researched all over the world. Liu et al[1,2] developed an industrial robot flexible coordinate measuring system using real-time online measurement and calibration technology. Zhu et al[3,4] researched the industrial robot positioning error compensation method, and developed a measurement system for flexible electronic checking fixture on robot. Wang et al[5] developed a brake pedal displacement measuring system based on machine vision. Pejman Mehran et al[6] proposed fuzzy machine vision based clip detection. Wu et al[7] proposed the automated solder bump inspection using machine vision techniques. Qiao et al[8] proposed randomized hough transform (RHT) and circle based least (CBL) combined with circular hole detection method with simple clustering analysis, but it removed a little hole edge information. Kazanskiy et al[9] proposed a machine vision system for singularity detection in monitoring the long process. Huang et al[10] proposed a new fast Hough transform circle detection (FHTCD) method. Samuel Shannon et al[11] proposed extracting generalized edge flux intensity functions with the quasidual function method along circular three-dimensional (3D) edges. Bi et al[12] proposed an effective edge extraction method using improved local binary pattern for blurry digital radiography images. He et al[13] proposed a kind of fast image edge detection algorithm based on dynamic threshold value.

In order to get all the centers of holes in the motorcycle frame, a high-precision robot frame hole vision measurement method is proposed based on our previous work[14-16], which combines ABB robot with the binocular vision system. A high-precision vision system for detecting and measuring is established using a mobile robot. Use the Canny operator to extract the captured image edge, employ Lagrange interpolation algorithm to determine the image edge points and obtain the image centroid, and adopt the least square fitting method for the hole spatial circular to fit the image edge point.

The mobile robot vision detection system is based on stereo vision technology for adapting to the new testing environment and meeting the new requirements of detection. With the help of ABB robot, this system is on the basis of the principle of computer vision. Combining

* This work has been supported by the National Natural Science Foundation of China (Nos.60808020 and 61078041), and the Tianjin Research Program of Application Foundation and Advanced Technology (No.10JCYBJC07200).

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robot motion control with machine vision detection and measurement, the non-contact detection is achieved, and the size of the work piece in the system is large, such as a motorcycle and car frame. When the robot receives the start signal, according to the pre-designed optimal path, it drives the binocular vision sensor to detect and measure every motorcycle frame hole in turn. After measuring, the robot returns to the initial state.

The architecture diagram of the high-precision frame hole measurement system with robot vision is shown in Fig.1. The system mainly consists of three parts of the robot system, binocular vision sensor and calibration system[14].

Fig.1 Architecture diagram of the robot vision measurement system

The robot system is composed of an industrial robot with six degrees of freedom developed by ABB motion vector with binocular vision sensor and laser sensor for the detection and measurement of particular objects (take motorcycle frame as an example). By controlling the robot pose transformation in space, the vision sensor can specify the location in turn to collect image information.

In order to realize the simulation of binocular vision detection and measurement, the system adopts the industrial camera and lens with less distortion rate to experiment. Through the framework of binocular vision system and camera calibration, it can be easy to understand the principle of binocular system and construct it, and image acquisition and processing in the next step can be realized.

In 3D vision measurement system, the system performance depends on the calibration accuracies of internal parameters in the camera and structure parameters in the sensor. This system adopts the auxiliary plate based on the calibration target as shown in Fig.2. The calibration system can be obtained from our previously published work[14].

The flat plate target is used as intermediary for the calibration of both sensor and camera. The advantage of this method is that the camera calibration is combined with the sensor calibration, which simplifies the calibration process. Its operation becomes simple and convenient, and it has high precision.

The system detects a motorcycle frame hole, it will transmit the signal to the binocular vision sensor, and obtain the high quality digital image of the frame hole in real time. The captured image is transmitted through the USB2.0 interface to the digital image processing system in computer. Due to various factors and random interference, the acquired image has noise, and it needs denoising for edge extraction. Because the Canny operator generates a single pixel edge, and has very good robustness for positioning the hole boundary, we use the Canny operator to extract the image edge.

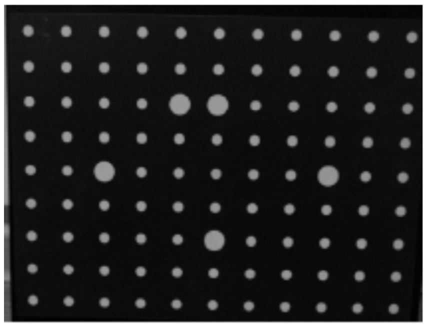


Fig.2 The target for calibration plate

The frame hole image forms a circular curve, so how to locate and extract the center position of circular curve is very important. In 1996, Steger proposed an effective method for extracting center of curve, and Sun et al[17] proposed a rapid extraction algorithm of laser stripe center in rail wear dynamic measurement. According to the consistency of curve method, we remove the error center, and then use the Taylor series expansion to obtain the sub-pixel position of light fringe center in the normal direction for realizing the localization of hole position.

In two-dimensional (2D) plane, it can take the Lagrange interpolation method to realize a pixel location of holes. In the Lagrangian interpolation formula[18], $\varphi_1(x)$ represents a linear combination of two linear functions.

The Lagrange linear interpolation method is used to calculate the hole edge gray values, and after enlarging the obtained images of hole edge, they can be regarded as a series of gray values of g_1 and g_2 connected to the pixel. Taking the calculation of the interpolation point (x', y') between the gray values of g_1 and g_2 as an example, x' and y' are substituted into

$$y' = \varphi_1(x) = y_0 \frac{x' - x_1}{x_0 - x_1} + y_1 \frac{x' - x_0}{x_1 - x_0}, \tag{1}$$

and the gray value of pixel edge can be obtained.

For a continuous 2D gray image, $f(x, y) \geq 0$. The $p+q$ moment m_{pq} and central moment u_{pq} are defined as

$$m_{pq} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x^p y^q f(x,y)\mathrm{d}x\mathrm{d}y, \tag{2}$$

$$u_{pq} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} (x - x_c)^p (y - y_c)^q f(x,y)\mathrm{d}x\mathrm{d}y, \tag{3}$$

where p and q are non-negative integers. For the discrete digital image, Eqs.(2) and (3) are expressed as

$$m_{pq}=\sum_{j=1}^{N}\sum_{i=1}^{N}i^{p}j^{q}f(i,j)\,, \tag{4}$$

$$u_{pq}=\sum_{j=1}^{N}\sum_{i=1}^{N}(i-i_{c})^{p}(j-j_{c})^{q}f(i,j)\,, \tag{5}$$

where (i_c, j_c) is for the centroid coordinates, and $i_c=m_{10}/m_{00}$, $j_c=m_{01}/m_{00}$. Thus the image centroid is the zeroth-order and first-order moments, and the second-order moments are rotation radii.

Through the above calculation, we can get the centroid of hole image, then scribe a certain number of center lines, and ensure that each line and ellipse edge can intersect at two points. According to the epipolar constraint[19] and the sequential consistency principle, we establish a matching relationship for each edge point.

After the image acquisition and image edge extraction, we can obtain some 3D data space on boundary of hole. After the optimal fitting of the holes, the position of hole can be detected. The 3D coordinates of central hole of spatial circle are $O(x_0, y_0, z_0)$, the radius is R, the coordinates of any point in circle are $X(x_i, y_i, z_i)$, and the hole spatial circle exists in the only circular plane. The equation of circular plane is

$$\left(x-x_{0}\right)^{2}+\left(y-y_{0}\right)^{2}+\left(z-z_{0}\right)^{2}=R^{2}\,. \tag{6}$$

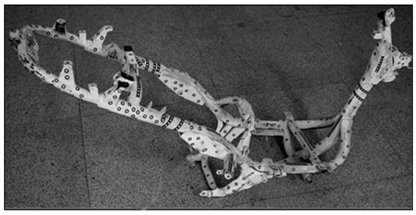
Suppose that $d_{ci}(X)$ is the Euclidean distance from any point of a circle X_i to the center, and $d_{pi}(X)$ is that to the circular plane. Establish the optimization objective function as

$$f(X,r)=\sum[d_{pi}^{2}+(d_{ci}^{2}-r)^{2}]\,, \tag{7}$$

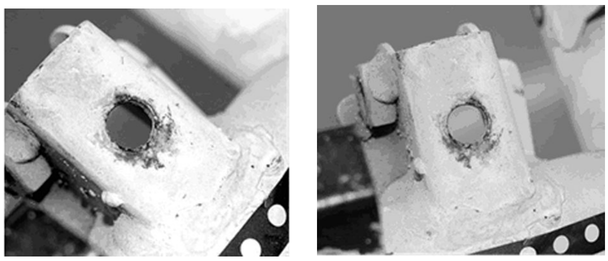
where r is the radius of fitting circle.

The geometric parameters of hole position can be obtained by the Levenberg-Marquardt nonlinear least squares fitting method. The key problem of nonlinear optimization is the selection of the initial value, and the method of choice for the center coordinates of circle is shown as follows. The center of spatial circle is the center of all edge points and the radius of the circle is the average distance from the center to the edge. The normal vector of circular plane is obtained by least squares plane fitting on all the edge points. Experimental results show that the initial value selection method is reasonable, and it can guarantee the calculation speed and convergence in the process of optimization. Using stereo vision to calculate the coordinates of the points on spatial edge, we can measure the geometrical parameters of circle by optimal fitting method in spatial circle.

In order to verify feasibility and accuracy of the experimental method, we use an ABB robot and two charge coupled device (CCD) cameras to set up a high-precision vision measuring system based on industry robot to detect and measure the hole position in motorcycle frame. Before the ABB robot measurement, we need to demarcate the robot and the binocular vision sensor. Taking account of the position error caused by elevated temperature in the robot measurement, we set the reference target in the robot based on Denavit-Hartenberg (D-H) model to establish the temperature error compensation model based on coordinate vector deviation. The binocular vision detection system is carried by the ABB robot. The robot follows the optimal path to detect all the holes on the motorcycle frame in turn, and collects the image information of special holes. The images of a frame hole are shown in Fig.3. Using the Canny operator to extract the image edge of hole position, we get the image as shown in Fig.4.

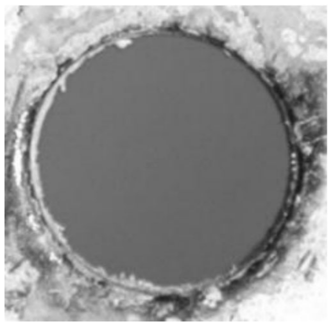


(a)

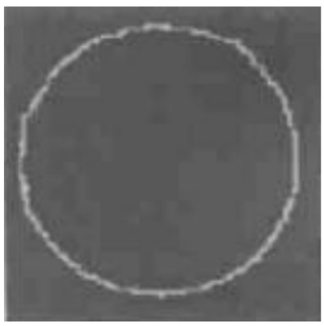


(b) (c)

Fig.3 (a) Image of motorcycle frame; (b) Frame hole image from left camera; (c) Frame hole image from right camera



(a)



(b)

Fig.4 (a) Captured image of hole; (b) Image after edge extraction using the Canny operator

According to the edge matching points in stereo vision and the 3D measurement model of points, we calculate the 3D coordinate fitting spatial circle based on the edge points. From the fitting spatial circle, we calculate the geometric center, radius and normal vector of the circular plane. The coordinate distribution of the matching points at hole edge is shown in Fig.5, and the 3D space coordinate distribution of hole edge is shown in Fig.6. Matching pixels on the image edge of the hole spatial circle are shown in Tab.1. The measured parameters of the hole are as follows: the center coordinates are (412.175 mm, 325.426 mm, 603.578 mm), the normal vector of the circular plane is (1.126, 1.345, 3.789), and the radius of the circle is R=9.663 mm. In order to verify the accuracy, the radius of hole is measured for several times by venire caliper, which is 9.699 mm in average. After calculation, the absolute standard deviation of the proposed method is 0.0267, which is smaller than that of the manual measurement results.

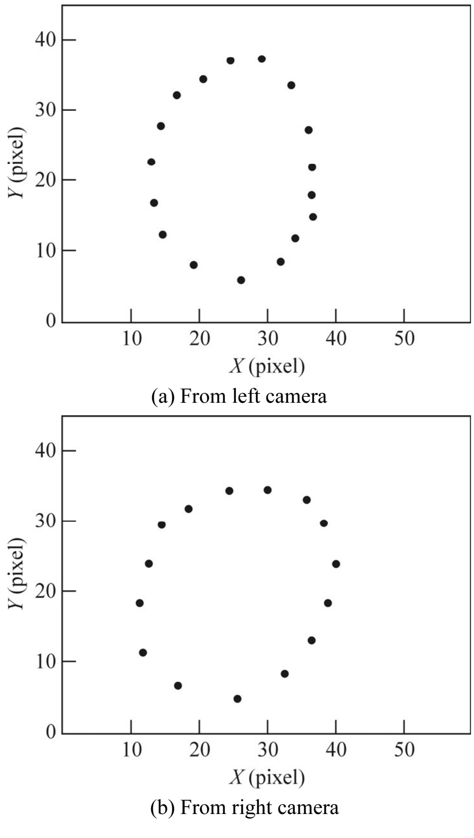


Fig.5 Coordinate distributions of matching points at hole edge

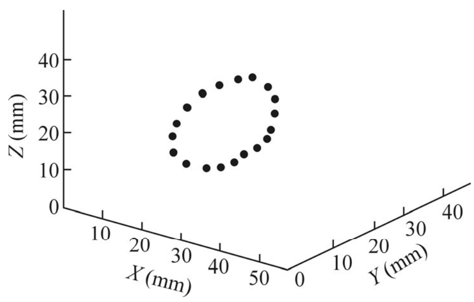


Fig.6 3D space coordinate distribution of hole edge

Tab.1 Matching pixels on the image edge of the hole spatial circle (Unit: pixel)

From left camera	From right camera
(12, 18)	(11, 20)
(16, 20)	(17, 21)
(20, 22)	(22, 24)
(25, 31)	(26, 30)
(27, 35)	(28, 36)
(26, 34)	(25, 33)
(23, 30)	(22, 29)
(19, 25)	(18, 24)
(15, 23)	(17, 22)

The robot vision inspection system is proposed based on the principle of the robot motion control and machine vision detection technology. Use the Canny operator to extract the captured image edge, employ Lagrange interpolation algorithm to determine the image edge points and obtain the image centroid, and adopt the least square fitting method of hole spatial circle to fit the image edge points. The error does not exceed 0.05 mm. The method reduces the error in the measurement of spatial circle shape distortion caused by perspective projection, improves the precision of measuring circle geometric parameters based on machine vision, and shortens the visual detection and location measurement time. So the system is of robustness, as well as high-precision for the hole measurement in the industry field.

Acknowledgement

Thanks for the support from National Natural Science Foundation Committee and Tianjin Research Program of Application Foundation and Advanced Technology. This research is also supported by the Tianjin Key Laboratory of Advanced Electrical Engineering and Energy Technology.

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