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Design and implementation of automatic assembly software system based on machine vision

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Abstract. At present, relative technology and research of high precision measurement and automatic assembly have attracted extensive attention. In this paper, optical measurement theory, image processing technology and visual positioning technology were used, and a precise part measuring and assembling system was set up. Then the image preprocessing algorithm was analyzed and compared, and a mixed distortion model considering radial distortion and centrifugal distortion was proposed. The camera calibration method was adopted, and the camera was calibrated, and thus the effect of camera lens distortion on measurement accuracy was reduced. In addition, an improved Canny algorithm combined with elliptic curve fitting algorithm was adopted, and the sub-pixel precision edges of the parts were extracted. And the accuracy of measurement and positioning were further improved, thus providing the basis for automatic assembly of parts. The experimental results prove that the system can meet the industrial requirements.

Key words. Machine vision, automatic assembly, distortion model.

1. Introduction

With the quickening pace of human life, mobile, portable, micro machinery and electronic equipment have become the mainstream. Most of these devices are made of tiny, precision parts, usually of micron size. At present, the measurement and assembly of most micro precision parts require manual micrometer or microscope, which greatly reduces the detection efficiency, and may damage parts, and is also very easy to cause eye fatigue, low efficiency. In addition, assembly personnel should have a certain professional knowledge, which increases the cost of product production, and assembly consistency is poor, and stability is low. Therefore, high precision micro size measurement and precise assembly method are required, so as to further improve the detection efficiency, and have important significance to the actual production. In recent years, machine vision has made great progress in quality inspection, size measurement, and object recognition and so on. Machine vision is a

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multidisciplinary field, and requires the support of related fields such as biology, digital vision processing, and communication and so on. With the increase of computer processing speed, the research and development of algorithms, and the deepening of theoretical research, high speed and stable image processing and control system has been developed more and more, thus widening the applicable areas of machine vision.

2. State of the art

Machine vision technology abroad has developed earlier and has been widely studied and applied. Moreover, it has been heading for a higher rate of development, higher accuracy, unknown detection environment and diversified testing objects [1]. Machine vision technology was first used in the manufacturing industry in the United States. Through the analysis of the development of machine vision to all the applications now, in the world, there are: printed circuit board inspection field, automobile parts inspection field, parts defect field and agricultural products detection [2]. In China, the research and application of machine vision have been developing rapidly. Yue Xiaofeng and others have developed the automatic detection system of engine cylinder bore by using digital image processing algorithm and theory, and have achieved higher detection accuracy; Chen Yongguang and others have realized the defect edge morphology according to the gray morphological characteristics of wood and using threshold segmentation algorithm; Liu Xuefang has analyzed and compared two edge detection algorithms from the point of view of whether the edges are continuous or consistent, and has come to an ideal conclusion [3]; Zhang Xiaobo and others have developed automatic detection and classification methods which are independent of subjective factors and can quantitatively analyze the effect of detection; aiming at the defect detection, size measurement and analysis of aero-engine turbine blade, Cheng Yunyong and others have developed a nondestructive testing system based on CT technology [4]; according to the optimization theory, Ma Qiang and others have used affine transformation technology, and have studied the contour detection system based on machine vision; Feng Bin and others have studied the rapid processing algorithms for fruit morphology and defects, and have summarized the related techniques and theories [5].

3. Methodology

In order to realize the vision measurement and automatic assembly of the parts, the coordinate value of the target position and the central position of the assembly parts are required, and so two vision systems are needed in this paper. Moreover, the correct selection of visual system is the prerequisite and guarantee for subsequent image processing. Through the correct selection of the visual system, image acquisition can be carried out and high-quality images will be obtained. Thus the difficulty of image preprocessing can be reduced, so as to facilitate the extraction of image features, and ultimately to reduce visual measurement errors and assembly errors (Ma et al. 2004) [6]. The visual hardware system is mainly composed of industrial cameras for photographic imaging, lenses for changing light paths, and light sources providing illumination. The selection of these three kinds of vision acquisition hardware is analyzed.

Industrial cameras can obtain more stable images, and can transmit image signals quickly while resisting external interference. At present, the industrial camera's photosensitive sensors include CCD or CMOS sensors. In the process of image acquisition, the CCD camera firstly performs photoelectric interchange, stores the obtained charge, and then realizes the transmission of the electrical signal through the charge movement, and finally reads the signal. The CCD sensor is a typical imaging sensor with charge as signal [7]. CCD is not easy to be burned in the process of imaging, with fast response, no delay and low working power. With the development of large-scale integrated silicon manufacturing process, CMOS sensors are also developing rapidly. In the process of CMOS imaging, the weak image signals are modulated and transformed, and the digital signals are analyzed and processed on the signal processor, and finally the image signals are output. CMOS sensors can integrate photosensitive devices and processing circuits on small chips. Its power is small, and the speed of signal transmission is fast, thus becoming the first choice for users.

The camera lens acts on the camera just as the lens does to the eye, which enables the object to be imaged clearly on the image sensor. When the lens is imaged, there may be aberrations that can affect the quality of the image, which can make the beam of light unable to meet the spherical aberration at the same location of the main axis, and sharp points, astigmatism can't be formed on the ideal plane. Therefore, it is necessary to select the proper parameters of the lens according to the environment and object of the lens, so as to reduce the aberration effect on output image [8]. Generally, it is necessary to judge the industrial lens selection according to the resolution, the maximum relative aperture, and the depth of field. Resolution reflects the extent where the lens senses the detail, and the depth of field reflects the extent of the spatial depth range in the image plane, and the maximum relative aperture location reflects the degree of illumination of the lens. Since the assembled parts may vary in thickness, if the zoom lens is used, the measurement plane of all parts can't be guaranteed on the focal plane. Two telocentric lenses were selected in this paper, in which, the magnification of the lens used to determine the center of the component was 0.2, the focal length of the object was 118 mm, and the view size was $15\times20\,\mathrm{mm}^2$; the magnification of the lens having the position of the assembly target was 0.34, the focal length of the object was 113 mm, and the view size was $33\times36\,\mathrm{mm}^2$.

In the vision system, the light source plays an important role in guaranteeing the quality of the image. Choosing the appropriate light source can improve the contrast between the target and the background, and provide convenience for feature extraction and analysis. Common light sources are shown in Table 1.

Depending on the visual system, the incident angle of the light source can be different [9]. When the angle between the illumination direction and the target is small, the contour of the object to be measured can be displayed better; when the angle between the illumination direction and the target is larger, the brightness of the image is higher, which is used for the illumination of the object with more rough surface; when illuminated from multiple angles, the image is softer and used to detect curved surfaces; when the backlight is illuminated, the object is black and the surface details of the object can't be seen, so that the size of the object to be measured is detected; and when the light is irradiated by the coaxial light, the light is uniform, and the utility model is suitable for detecting the defect of the surface of the object.

Table 1. Performance comparison of four kinds of light sources

Light source	Fluorescent lamp	Halogen lamp	LED lamp	Laser
Lifetime (h)	5000–7000	5000–7000	6000–10000	more than 10000
Brightness	bright	bright	bright	very bright
Response speed	slow	slow	fast	fast
Other features	less expensive, less fever	less expensive, more fever	less expensive, less fever	good quality and low power consumption

In traditional camera calibration methods, the size of calibration objects must be known. By establishing the relative relation of the points in the two coordinate systems, the internal parameters that reflect the property of the camera itself and the external parameters that can reflect the spatial position of the camera can be obtained according to the related algorithms. And the calibration object can be two-dimensional or three-dimensional [10]. Since the former is easy to manufacture and preserve, the method of calibrating multiple images from different angles is used to find all the parameters. When the requirement of the application is higher and the camera parameters do not change frequently, the traditional camera calibration method can achieve higher calibration accuracy. The calibration method of self-calibration camera is a very flexible calibration method. It can be calibrated according to the image of the object which is used to determine the motion information. Table 2 shows the comparison of the three classes of calibration methods in four ways.

When assembling precision parts, it is necessary to determine whether the assembly is qualified according to specific technological requirements, technical requirements, and through inspection. In this paper, the process and technical requirements for the assembly problem are based on the thickness of the parts. There are three kinds of parts to be assembled. The first class includes the base and nut, and the second class consists of metal parts, including parts 3, parts 4, parts 7, and the third kind is quartz flake. Moreover, the second and third kinds are round.

The mathematical model for the problem is as follows: the thickness of the part 5 which is assembled in a set is x_{1j}, the number of slices is e, the thickness of part 6 is x_2, the thickness of part 3 is x_3, the thickness of part 4 is x_4, the thickness of part 1 is x_{5k}, the number of pieces outside the part 3 is a, the number of pieces outside the part 4 is c, the thickness of part 2 is x_{6l}, the number of pieces outside the part 3 is b, the number of pieces outside the part 4 is d, the thickness of part 7 is x_8.

Table 2. Comparison of three calibration methods

Calibration method	Accuracy	Calibration process	Dependence on device	Dependence on calibration objects
Traditional calibration method	high	tedious	low	high
Active vision method	higher	more complicated	commonly	commonly
Self-calibration method	low	simple	high	low

If the ith suit is qualified, then $y_i = 1$; if the ith suit is not qualified, then $y_i = 0$. The model consists of six following equations:

$$1.02 < x_3 - \left(\sum_{k=0}^{a} x_{5k} + \sum_{l=0}^{b} x_{6l} \right) < 1.15\,, \tag{1}$$

$$1.02 < x_4 - \left(\sum_{k=0}^{c} x_{5k} + \sum_{l=0}^{d} x_{6l} \right) < 1.15\,, \tag{2}$$

$$4 < \sum_{j=1}^{e} x_{1j} + x_2 + x_3 + x_8 + x_4 < 4.1\,, \tag{3}$$

$$1.57 < \left(\sum_{k=0}^{a} x_{5k} + \sum_{l=0}^{b} x_{6l} \right) < 1.61\,, \tag{4}$$

$$2.05 < \left(\sum_{k=0}^{c} x_{5k} + \sum_{l=0}^{d} x_{6l} \right) < 2.12\,, \tag{5}$$

$$y_i = \begin{cases} 1, i \text{ sets of assembly qualified,} \\ 0, i \text{ sets of assembly unqualified.} \end{cases} \tag{6}$$

The objective function is

$$f_{\max}(y) = \sum_{i}^{4} y_i\,. \tag{7}$$

Aiming at the precise parts which make up the precision products, the requirements of high-precision measurement and automatic assembly are achieved, a high precision measurement and automatic assembly system is designed, and an experimental prototype is built. The overall block diagram of the system is shown in Fig. 1.

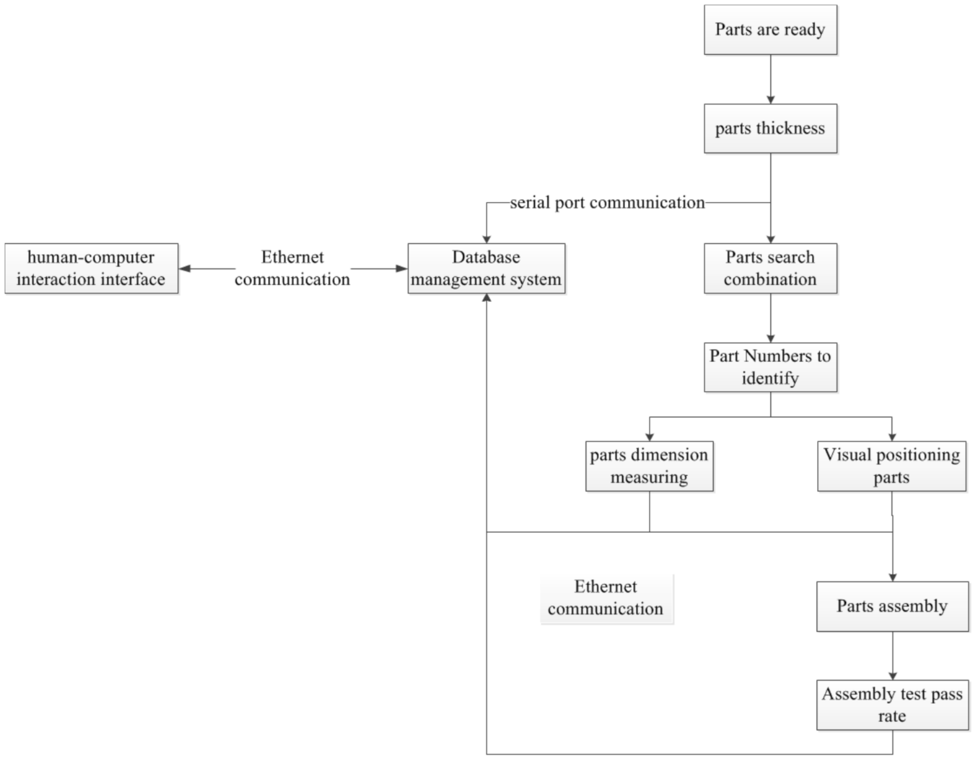

Fig. 1. Overall block diagram of the system

As can be seen from Fig. 1, the overall design of the prototype includes software system design and hardware system design. The software system design mainly includes: the visual system program design, combination search algorithm design, character recognition program design, program design, database management system and communication system design and human-computer interface design; the hardware system design includes: the mechanical structure design, the origin of the manipulator, and the establishment of the tool coordinate system.

Mechanical structure design is the basis of the whole system design. The machining and installation accuracy of the mechanism will directly affect the realization of the system function. And perfect and reasonable mechanical structure can reduce the difficulty of software system design and make the whole system more stable. The three-dimensional appearance of the experimental prototype of the system designed in this paper is shown in Fig. 2.

The main mechanical structure of the prototype is as follows:

Feed mechanism: the mechanism consists of a tray for placing precise parts, a parallel guide rail, and a servo motor that drives the tray into and out of the assembly space, and is used to deliver the assembly parts to the measuring and assembling stations.

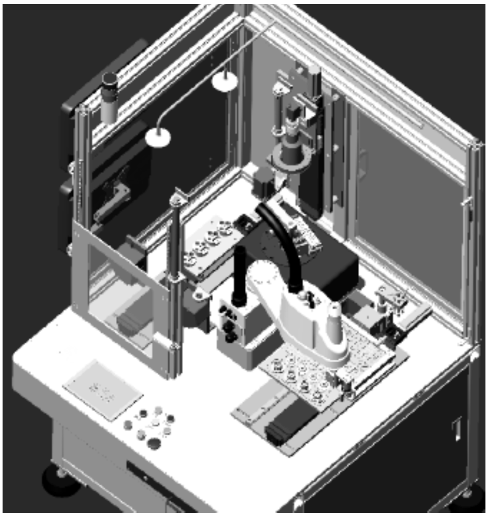

Fig. 2. 3D appearance of the prototype

Discharging mechanism: the discharging mechanism is composed of a servo motor, a discharging tray and a sealing guide rail, a finished product is arranged on the discharging tray, the adjusting nut is used to adjust the levelness of the tray, and the pallet level is guaranteed as much as possible, and the specifications and models of the servo motor are the same as that of the feeding mechanism. In the process of finished product delivery, the qualified rate of the finished product is tested. In order to meet the requirements of non-contact measurement of polishing parts and parts with surface topography requirements, Keyence high-speed and high-precision CCD measuring instruments are selected. Through servo drive system, the finished product is controlled by the detecting device in turn. The system will obtain the height of the finished product, so as to determine the qualified rate of the assembly.

Thickness measurement mechanism for precision parts: the measurement of the thickness of precision parts is the premise of assembly. In assembly, the search combination of parts is based on the thickness of the parts superimposed, and the thickness measuring device is mainly composed of a rotating cylinder, a magnetic grating ruler, a thickness gauge and a measuring platform.

Part holding mechanism: the part holding mechanism is used to measure and assemble parts during the process of parts measurement or assembly. In this paper, there are three kinds of parts to be taken, so the clamping mechanism of the parts must be multi-functional, and the three parts can be taken out. For different parts of the different ways to grab, the three point air is used to claw the base, and then parallel finger driven U card groove is used to take the nut. Finally, the vacuum suction head is used to absorb the precision sheet parts. There are four metal vacuum suction heads, and the vacuum suction is the maximum -101 kPa vacuum generated by a vacuum generator.

Nut tightening mechanism: tightening the nut on the base is the last step in the assembly process. Before tightening, the assembly shall be pressed with a pressure bar to prevent the shift of the parts.

4. Result analysis and discussion

According to the above research results, the final experimental prototype is shown in Fig. 3.

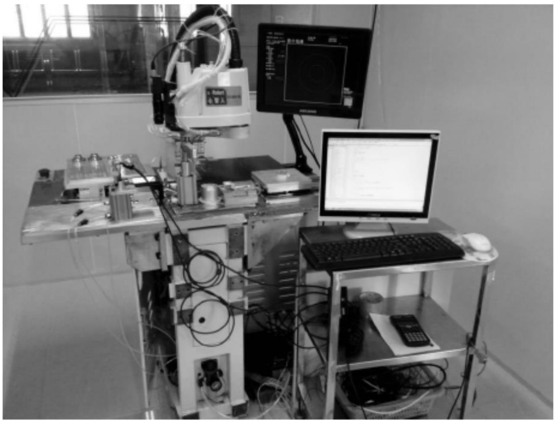

Fig. 3. Sample drawing of experimental prototype

In the system studied in this paper, the two processes of measurement and assembly should be completed. The high precision measuring procedure refers to the measurement of the outer diameter of each precise circular part, and the measuring accuracy is 0.01 mm. In order to verify the accuracy of the system for measuring the diameter of parts, measurements were made on the components of the 1 set of ligands. In each package, in addition to the base, nuts, and parts 8, the different parts in the 7 also remained to be measured, and each part was measured 10 times. The concrete steps are as follows:

Firstly, a part was repeatedly taken to the camera position, so as to obtain the part image.

Secondly, the target image was pretreated.

Thirdly, the sub-pixel outer diameter edge was extracted from the preprocessed image, and the outer diameter pixel size was obtained, as shown in Table 3.

Fourthly, the internal and external parameters of the camera were obtained by calibrating the camera, and the actual size of the outer diameter in the world coordinate was calculated. The measurement results are shown in Table 4.

According to the camera calibration, the imaging model was established and the distortion model was considered. The internal and external parameters of the camera were calculated, and the outer diameter results in pixels were converted to the actual size results in mm.

Table 3. Measurement results of outer diameter of parts (unit: pixel)

	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7
1	653.27	615.04	672.41	433.82	542.36	622.41	667.64
2	653.54	615.36	672.54	433.95	452.50	622.32	667.41
3	653.41	615.17	672.36	433.73	452.59	622.23	667.36
4	653.09	615.27	672.18	434.00	452.45	622.45	667.59
5	653.23	615.45	672.27	433.86	452.41	622.18	667.50
6	653.14	615.09	672.14	433.73	452.54	622.00	667.54
7	653.45	615.32	672.41	433.68	452.68	622.14	667.77
8	653.00	615.18	672.59	433.91	452.64	622.09	667.73
9	653.27	615.41	672.50	434.10	452.36	622.50	667.36
10	653.32	615.23	672.23	433.95	452.18	622.32	667.45

Table 4. Measurement results of outer diameter of parts (unit: pixel)

	Part 1	Part 2	Part 3	Part 4	Part 5	Part 6	Part 7
1	14.372	13.531	14.793	9.544	9.952	13.693	14.688
2	14.378	13.538	14.796	9.547	9.955	13.691	14.683
3	14.375	13.533	14.792	9.542	9.957	13.698	14.682
4	14.368	13.536	14.788	9.548	9.954	13.694	14.687
5	14.371	13.540	14.790	9.545	9.953	13.688	14.685
6	14.369	13.532	14.787	9.542	9.956	13.684	14.686
7	14.376	13.537	14.793	9.541	9.959	13.687	14.691
8	14.366	13.534	14.797	9.546	9.958	13.686	14.690
9	14.372	13.539	14.795	9.551	9.952	13.695	14.682
10	14.373	13.535	14.789	9.547	9.948	13.691	14.684
Average value	14.372	13.536	14.792	9.545	9.954	13.690	14.686

According to the above table, the standard deviation of the average value of the outer diameter of the 7 parts was obtained. The result is shown in Table 5.

Table 5. Average deviation of parts outside diameter (unit: mm)

Parts category	1	2	3	4	5	6	7
Standard deviation (‰)	3.7	3.1	3.4	3.1	3.3	3.6	3.2

Available from Table 5, in measuring the diameter of the 7 parts, the maximum standard deviation was $\sigma_{1\,\max} = 0.0037\,\text{mm}$.

In order to further validate and calibrate the visual measurement accuracy, in this paper, the 0 stage length standard block was used for calibration, and the length limit deviation was 0.14 m. The visual measurement method was adopted, and the standard blocks of nominal length 15 mm, 14 mm, 13 mm, 12 mm, 11 mm, 10 mm and 9 mm were measured respectively. And each standard block was measured 10 times. The measurement results are shown in Table 6.

The standard deviations of the 7 standard blocks were calculated. The results were shown in Table 7.

Table 6. Measurement results of standard blocks (unit: mm)

	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7
1	9.002	10.001	11.002	12.002	12.999	14.002	15.001
2	9.002	10.002	11.003	12.004	12.998	14.004	15.004
3	9.001	10.004	11.004	12.002	12.997	14.002	15.002
4	9.003	10.000	11.000	12.003	12.996	14.003	15.003
5	8.999	9.999	11.002	12.001	13.000	14.002	15.003
6	9.001	9.998	11.003	12.003	13.001	14.001	15.001
7	8.999	10.003	11.003	12.004	12.998	14.002	15.002
8	9.004	10.002	11.004	12.002	12.997	14.002	15.004
9	9.003	10.004	11.002	12.001	12.997	14.003	15.001
10	9.003	10.003	11.004	12.004	12.996	14.003	15.003

Table 6. Average deviation of parts outside diameter (unit: mm)

Standard block	1	2	3	4	5	6	7
Standard deviation (‰)	2.3	2.5	2.9	2.0	2.6	2.2	2.6

Available from Table 7, through the method of visual measurement in this paper, the maximum standard deviation of the standard block length was $\sigma_{2\,\max} = -0.0029\,\text{mm}$. For measuring the precision parts, the maximum standard deviation of the parts' outer diameter measurement value relative to the parts' true value was set as $\sigma_{\max}$, where $\sigma_{\max} = \sigma_{1\,\max} + \sigma_{2\,\max} = 0.0066\,\text{mm}$, thus meeting the industrial requirements.

5. Conclusion

In this paper, the precision measurement and automatic assembly system of precision parts based on machine vision was studied. Then software system design, related algorithm design, and visual system hardware design were completed. And the problem of measurement and assembly in automated production of precision electromechanical products was solved. The results of this paper were obtained as follows: the edge detection algorithm based on pixel precision was analyzed and compared; through the algorithm simulation, the detection effect of each detection algorithm was obtained; on this basis, the method of improving Canny edge detection algorithm was proposed, and the best edge extraction effect of the improved algorithm was proved; then, the sub-pixel edge detection algorithm was analyzed, and a sub-pixel edge detection algorithm was proposed according to the shape characteristics of the detected part; in addition, an improved Canny edge detection algorithm was used to obtain the pixel precision edge, and then the sub-pixel edge was obtained by ellipse fitting method. The experimental results show that the measurement and assembly system in this paper can achieve the measurement accuracy of 0.0066 mm, as well as the assembly accuracy of coaxiality of 0.017 mm. Both of the measurement accuracy of 0.01 mm and the coaxial assembly accuracy requirements of 0.05 mm for industrial design can be achieved. Of course, there are still some shortcomings in the process of system research and design, which need further studies. For example, the calibration process of the camera calibration algorithm used in this paper is done manually, and it is tedious.

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