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Feature-based sequential partial vision measurement method for large scale machine parts

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Abstract: To realize the high-precision vision measurement for large scale machine parts, a new vision measurement method based on dimension features of sequential partial images is proposed. Instead of mosaicking the partial images, extracting the dimension features of the sequential partial images and deriving the part size according to the relationships between the sequential images is a novel method to realize the high-precision and fast measurement of machine parts. To overcome the corresponding problems arising from the relative rotation between two sequential partial images, a rectifying method based on texture features is put forward to effectively improve the processing speed. Finally, a case study is provided to demonstrate the analysis procedure and the effectiveness of the proposed method. The experiments show that the relative error is less than 0.012% using the sequential image measurement method to gauge large scale straight-edge parts. The measurement precision meets the needs of precise measurement for sheet metal parts.

Key words: vision measurement; sequential image; texture feature; feature matching

As one of the innovative methods in measuring machine parts, the machine vision measurement is widely used to measure dimension parameters for microstructures or small size parts[1-3]. Because of the conflict between a wide imaging area and high inspection resolution, a whole part with a general or large scale cannot be directly measured from a single image by a vision measurement system. To obtain the whole image of the part at high inspection resolution, some measurement methods based on sequential partial vision (SPV) are adopted[4-5]. These methods follow the same thought of "break up the whole into pieces and make the whole from pieces". However, when a large number of sequential partial images need to be matched, restricted by the processing speed and mosaic precision, the existing measurement method based on SPV cannot meet the demand of fast and precise measurement.

The surface texture of the machine part can help improve the accuracy of matching for two images. The surface texture will help more if the definition of the texture features is clearly described for sequential partial vision image matching. Therefore, instead of mosaicking the partial images, extracting the dimension features of the sequential partial images and deriving the part size according to the relationships between the sequential images is a novel method to realize high-precision and fast measurement of machine parts.

1 Method Development

Before introducing the method, two image coordinate systems and six functions related to the coordinates are defined. Fig. 1 (a) shows the pixel coordinate system which takes each pixel as a coordinate unit. The r-axis indicates the row of the image array and the c-axis indicates the column of the image array. Functions pc(·), pcr(·) and pcc(·), respectively, represent the coordinate value, the value of the r-axis and the value of the c-axis of a point in the pixel coordinate system. Fig. 1 (b) shows the numerical coordinate system which takes the real number as a coordinate unit. Functions dc(·), dcx(·) and dcy(·), respectively, represent the coordinate value, the value of the x-axis and the value of the y-axis of a point in the numerical coordinate system. This numerical coordinate system corresponds closely to the pixel coordinate system in many aspects. For example, the numerical coordinates of the

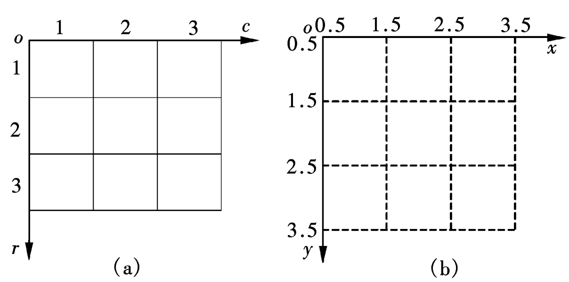

Fig. 1 Pixel coordinate system and numerical coordinate system. (a) Pixel coordinate system; (b) Numerical coordinate system

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center point of any pixel are identical to the pixel coordinates for that pixel, namely, $\mathrm{pc}(i,j)=\mathrm{dc}(i,j)$, $i,j=1,2,\ldots$.

1.1 Method overview

The proposed measurement procedure consists of three main steps:

Step 1 Take the images of small areas in the part and generate the sequential partial images which overlap at adjacent margins one by one.

Step 2 Make use of the spatial continuity of sequential partial images to extract the dimension features of each partial image and derive the relationship between sequential dimensions.

Step 3 Summate partial dimensions to obtain the whole dimension.

The method is illustrated in Fig. 2. As shown in Fig. 2(a), collect sequential partial images $S_i(i=1,2,\ldots,n)$ along the dimension direction and let the adjacent partial images overlap in area w_i. Then, in the overlapped area shown in Fig. 2(b), extract the dimension feature lines $l_i(i=1,2,\ldots,n-1)$ that are perpendicular to the dimension direction. Thus the dimension features $D_i(i=1,2,\ldots,n)$ of the partial images can be obtained. Finally, summate all $D_i(i=1,2,\ldots,n)$ to obtain the dimensions of the part.

Steps 2 and 3 will be presented in sections 1.2 and 1.3, respectively.

1.2 Exacting dimension features of sequential partial images

As shown in Fig. 2(b), the partial images are supposed to have $R\times C$ pixels. The overlapped area of S_i and S_{i+1} has $w_i(w_i\geqslant C/10)$ pixels along the x-axis. The proposed procedure for extracting the dimension features consists of four steps.

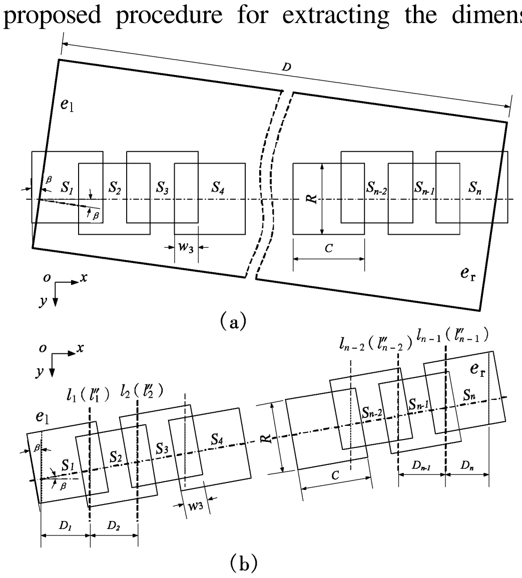

Fig. 2 Schematic diagram of the dimension measurement method based on SPV. (a) Collecting sequential partial images; (b) Constructing the dimension feature lines

1) Pre-process image to find the measurement direction

As shown in Fig. 2(a), the angle β between the left edge e_l and the y-axis can be calculated using the straight edge fitting method[6]. Then, all sequential images need to be rotated with the angle β, so that the edge e_l can be parallel to the y-axis in image S_1. Furthermore, the rectifying method based on texture features, which are proposed in section 2, can be applied to eliminate the effects of the relative rotation between two sequential partial images of the machine part. Finally, all sequential images have the same reference x-axis, that is to say, the x-axis is the measurement direction.

2) Construct the dimension feature line l_i in S_i

Set up a line segment AA' in the sequential partial image S_i. Suppose that AA' consists of s pixel points and its midpoint is A''. AA' satisfies three conditions: ① AA' is in parallel with the c-axis; ② $\mathrm{pc}(A'')=(R/2, C-\mathrm{fix}(w_i/2))$; and ③ The length of AA' is $(\mathrm{fix}(w_i/4)\times 2-3)$ pixels, where $\mathrm{fix}(\cdot)$ is a function of rounding towards zero. For example, $\mathrm{fix}(5.9)=5$ and $\mathrm{fix}(-5.9)=-5$. $A_i(i=1,2,\ldots,s)$ are s pixel points that make up AA', i.e., $A_i\in AA'$, and $s=\mathrm{fix}(w_i/4)\times 2-3$. For the sequential image S_{i+1}, in a square area which takes the pixel point $(R/2, \mathrm{fix}(w_i/2))$ as the center and $(\mathrm{fix}(w_i/4)\times 2-1)$ pixels as the side length, apply the correlation coefficient method[7] to search the matching points $A_i'(i=1,2,\ldots,s)$ of $A_i(i=1,2,\ldots,s)$. Suppose that A_k and A_k' are the pair with the maximum similarity degree in all matching point pairs. For the sequential image S_i, construct a line l_i which crosses point A_k and is perpendicular to AA'. l_i is the dimension feature line of S_i and

$$\mathrm{pcc}(l_i)=\mathrm{pcc}(A_k) \tag{1}$$

3) Search the matching line l_i'' of l_i in the sequential image S_{i+1}

With the starting point A_k and the step size h $(1\leqslant h<R/20, h\in\mathbf{Z})$ along the line l_i, select pixel points $B_j(j=1,2,\ldots,t)$ in the positive and negative r direction, respectively. $B_j\in l_i$ and $\mathrm{fix}(w_i/4)<\mathrm{pcr}(B_j)<R-\mathrm{fix}(w_i/4)$. In the rectangle area, $\mathrm{pcc}(\cdot)\in[\mathrm{pcc}(A_k')-1, \mathrm{pcc}(A_k')+1]$ of S_{i+1}, apply the correlation coefficient method[7] to search the matching points $B'_j(j=1,2,\ldots,t)$ of $B_j(j=1,2,\ldots,t)$ in the pixel level.

To obtain high measurement precision, it is necessary to seek the matching point B_j'' of B_j in the subpixel level so that the matching line l_i'' of l_i in the sub-pixel level can be obtained. Therefore, we propose a dimension feature matching method in the sub-pixel level.

Suppose that $n = 2m$ ($m \geqslant 10, m \in \mathbf{Z}$) and the center of B_j is B_{mm} (see Fig. 3(a)). The centers of the other eight pixels around B_j are B_{00}, B_{0m}, B_{0n}, B_{m0}, B_{mn}, B_{n0}, B_{nm} and B_{nn}, respectively. The nine points form four equirotal square areas. Divide every square area into $m \times m$ equal parts and obtain the $n \times n$ subdivided areas which have $(n+1)^2$ nodes B_{ij} ($i, j = 0, 1, \ldots, n$) (see Fig. 3(b)). Among these nodes, the values of the coordinates and the gray scale of nine nodes B_{00}, B_{0m}, B_{0n}, B_{m0}, B_{mm}, B_{mn}, B_{n0}, B_{nm}, B_{nn} are known. The values of coordinates and the gray scale of other nodes can be obtained by the bilinear interpolation methods[8]. For the sequential image S_{i+1}, an $n \times n$ subdivided area around B'_j and the corresponding $(n+1)^2$ nodes B'_{ij} ($i, j = 0, 1, \ldots, n$) can be obtained in the same way.

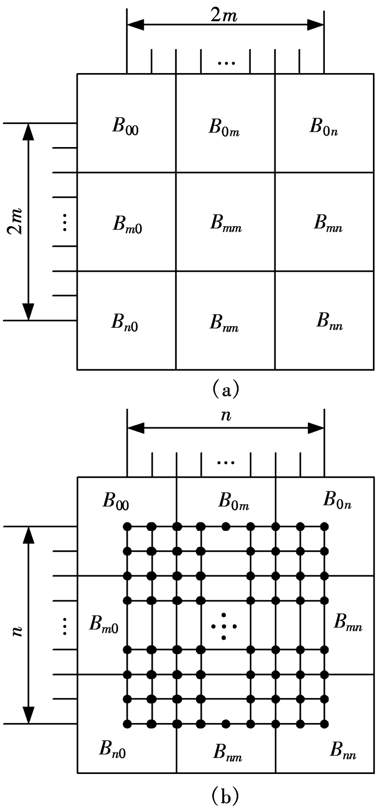

Fig. 3 Schematic diagram of sub-pixel subdivision. (a) Blocks in pixels; (b) Blocks in sub-pixels

Then, take the $2u \times 2u$ ($2u < m, u \in \mathbf{Z}$) sub-pixel square area with the center B_{mm} as the template. For the sequential image S_{i+1}, in the $(2u+m) \times (2u+m)$ square area which takes B'_{mm} as the center, apply the correlation coefficient method[7] to search the sub-pixel matching points B''_{mm} of B_{mm}. B''_{mm} ; i. e., B''_j is the $1/m$ level sub-pixel matching point of B_j. $\mathrm{dc}(B''_j) = \mathrm{dc}(B''_{mm})$. Thus, the sub-pixel matching point B''_j ($j = 1, 2, \ldots, t$) of B_j ($j = 1, 2, \ldots, t$) and their numerical coordinate values are obtained. Further, the matching line l''_i for l_i can be derived. Line l''_i is in parallel with the y-axis and its x-axis coordinate value is

$$\mathrm{dcx}(l''_i) = \frac{1}{t}\sum_{j=1}^{t}\mathrm{dcx}(B''_j) \tag{2}$$

4) Calculate dimension feature D_i of S_i

After finding the dimension feature lines, the dimension feature D_i of the sequential partial image S_i can be obtained.

$$D_i = [\mathrm{pcc}(l_i) - \mathrm{dcx}(l''_{i-1})]\delta \qquad i = 2, 3, \ldots, n-1 \tag{3}$$

where δ denotes the pixel equivalent value[9].

1.3 Measurement calculating based on dimension features of sequential partial images

After the dimension features of sequential partial images are obtained, the dimension of the part to be measured can be figured out by performing summation. It should be noted that the partial images including part edges need to be treated by the edge-pixel compensation method[9]. That is,

$$D_1 = (\mathrm{pcc}(l_1) - \mathrm{dcx}(e_1) + \lambda)\delta \tag{4}$$

$$D_n = (\mathrm{dcx}(e_r) - \mathrm{dcx}(l''_{n-1}) + \lambda)\delta \tag{5}$$

where λ is the edge-pixel compensation value[9].

According to Eqs. (3) to (5), the dimension D of the part can be derived by

$$D = \sum_{i=1}^{n} D_i = \Big[\mathrm{pcc}(l_1) - \mathrm{dcx}(e_1) + \mathrm{dcx}(e_r) - \mathrm{dcx}(l''_{n-1}) + \sum_{i=2}^{n-1}(\mathrm{pcc}(l_i) - \mathrm{dcx}(l''_{i-1})) + 2\lambda\Big]\delta \tag{6}$$

When measuring large scale machine parts, the whole dimension is divided into pieces so that the advantages of vision inspection are exerted. Then, sum the pieces to obtain the whole so that the advantages of computing are exploited. The accumulation of measurement errors depends on the selection of matching features and matching precision between sequential images. The transformation of the issue creates a new way to improve the measurement precision for large scale parts.

2 Rectifying Technique for Sequential Images Based on Texture Features

To reach high measurement precision by the sequential image measurement method, many technique problems must be solved, such as imaging technology, matching technology, and rectifying technology, etc. The most important one is the rectifying technique for sequential images. When collecting the sequential images, if the camera is rotated with the angle θ around the optical axis or the part to be measured is rotated with the angle $-\theta$, the sequential image S_{i+1} will differ with S_i along the dimension direction with the angle θ. Before using the correlation coefficient method to search the matching line of l_i, the sequential image S_{i+1} must be rotated with the angle θ in order to rectify S_{i+1} (see Fig. 4). Otherwise, the correlation coefficient method does not work correctly[10]. The key technique to rectify the sequential images is to identify the rotated angle θ. We will obtain the angle according to the texture features of the part images by the image processing methods.

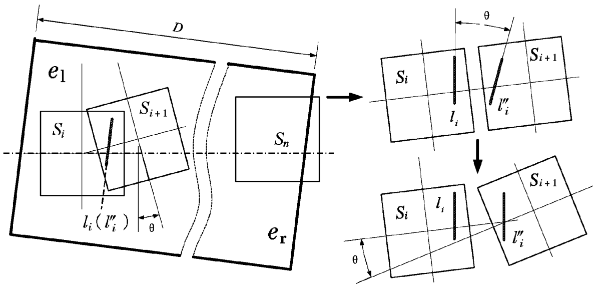

Fig. 4 Schematic diagram of rectifying sequential images

There often exist some special textures on the machining surfaces of parts. Fig. 5 shows a pair of sequential images of a part which bears strip-shaped textures. According to the surface features of machine parts, we propose a rectifying method of sequential images based on texture features. The rectifying procedure for the sequential image S_{j+1} shown in Fig. 5 is used as an example to demonstrate the proposed rectifying method, which consists of eight steps:

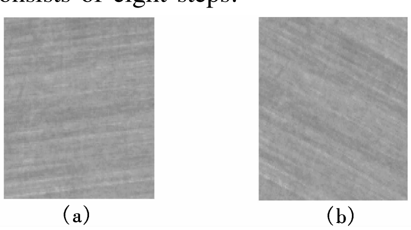

Fig. 5 Pattern of surface textures for sequential partial images of machine parts. (a) Sequential image S_j; (b) Sequential image S_{j+1}

① Select the texture circle. In the overlapping region w_i of the images S_j, we can select some circular areas, so-called texture circles O_i ($i = 1, 2, \ldots, t$) with the diameter $D = 2n$ pixels. These texture circles must follow constraints: The diameter must be greater than the half of the width of the overlapping region; the center of the circle O_i is located at the center of a pixel; the distance between the two centers is not less than the radius of the circle.

② Generate the diameters of the texture circle. The circle O_i is evenly divided into $2m$ ($90 \leqslant m \leqslant 360$) fan-shaped regions by m diameters $D_{i\alpha}$ ($\alpha = \pi/m, 2\pi/m, \ldots, m\pi/m$), where α is the angle between the diameter and the x-axis.

③ Determine the feature points on the diameter $D_{i\alpha}$ of the texture circle. Feature points selected in turn from the diameter are sequential points. The distance between two feature points will be the length of multiple pixels. Therefore, the $2n+1$ feature points on the diameter $D_{i\alpha}$ can be marked as $D_{i\alpha}^k$ ($k = 1, 2, \ldots, 2n+1$), the corresponding numeric coordinates are

$$\mathrm{dcx}(D_{i\alpha}^k) = \mathrm{pcx}(O_i) + (k-n-1)\cos\alpha$$
$$\mathrm{dcy}(D_{i\alpha}^k) = \mathrm{pcy}(O_i) + (k-n-1)\sin\alpha$$

④ Calculate the gray scale $f(D_{i\alpha}^k)$ of the feature point $D_{i\alpha}^k$. Suppose that the four nearest pixel points of $D_{i\alpha}^k$ are $D_{i\alpha}^{k1}$, $D_{i\alpha}^{k2}$, $D_{i\alpha}^{k3}$ and $D_{i\alpha}^{k4}$. Their pixel coordinates can be calculated as

$$\mathrm{pc}(D_{i\alpha}^{k1}) = (\mathrm{rd}(\mathrm{dcx}(D_{i\alpha}^k) - 0.5), \mathrm{rd}(\mathrm{dcy}(D_{i\alpha}^k) - 0.5))$$
$$\mathrm{pc}(D_{i\alpha}^{k2}) = (\mathrm{rd}(\mathrm{dcx}(D_{i\alpha}^k) - 0.5), \mathrm{rd}(\mathrm{dcy}(D_{i\alpha}^k) + 0.5))$$
$$\mathrm{pc}(D_{i\alpha}^{k3}) = (\mathrm{rd}(\mathrm{dcx}(D_{i\alpha}^k) + 0.5), \mathrm{rd}(\mathrm{dcy}(D_{i\alpha}^k) - 0.5))$$
$$\mathrm{pc}(D_{i\alpha}^{k4}) = (\mathrm{rd}(\mathrm{dcx}(D_{i\alpha}^k) + 0.5), \mathrm{rd}(\mathrm{dcy}(D_{i\alpha}^k) + 0.5))$$

where $\mathrm{rd}(\cdot)$ is a function of rounding towards the nearest integer. Since the gray scales of $D_{i\alpha}^{k1}$, $D_{i\alpha}^{k2}$, $D_{i\alpha}^{k3}$, $D_{i\alpha}^{k4}$ are known, the gray scale $f(D_{i\alpha}^k)$ of the feature point $D_{i\alpha}^k$ can be calculated using the bilinear interpolation algorithm[8].

⑤ Calculate the standard deviation of the gray scale of the reference points on the diameter line of the texture circle $D_{i\alpha}$,

$$\sigma(D_{i\alpha}) = \sqrt{\frac{1}{2n}\sum_{k=1}^{2n+1}[f(D_{i\alpha}^k) - E(D_{i\alpha})]^2} \tag{7}$$

where $E(D_{i\alpha})$ is the mean gray scale of all feature points on the texture circle $D_{i\alpha}$.

$$E(D_{i\alpha}) = \frac{1}{2n+1}\sum_{k=1}^{2n+1} f(D_{i\alpha}^k) \tag{8}$$

⑥ Find the texture angle of the texture circle O_i:

$$\theta_i = \alpha \tag{9}$$

where α can meet the optimization formula $\min\limits_{\alpha}(\sigma(D_{i\alpha}))$, $\alpha = \pi/m, 2\pi/m, \ldots, m\pi/m$. The feature angle θ_i can be the mean of the angles which can meet the above optimization formula.

⑦ Determine the texture angle ω_j using the gradual contraction method. Due to the discontinuities of texture and the effect of noise points, the texture angle θ_i ($i = 1, 2, \ldots, t$) of different texture circles are not the same. To eliminate the randomness of these values, a contraction method is applied to filter the set of possible texture angles $\{\theta_i, i = 1, 2, \ldots, t\}$ gradually. The method can be run as follows: first, for every texture angle θ_i in the set, to measure its distance to all other angles, the distance coefficient $\lambda_i (i = 1, 2, \ldots, t)$ can be defined as

$$\lambda_i = \sqrt{\sum_{k=1}^{t} (\theta_k - \theta_i)^2} \tag{10}$$

Secondly, the texture angle with the maximum distance coefficient can be eliminated from the possible texture angle set. Thirdly, the distance coefficient for the remaining angles in the set can be calculated using Eq. (10), and the texture angle with the maximum distance coefficient can be eliminated again. The above procedures can be repeated until the size of the set drops to h $(1 < h < t)$. Finally, we obtain the angle set $\{\theta'_i, i = 1, 2, \ldots, h\}$ and the possible texture angle of image S_j.

$$\omega_j = \frac{1}{h} \sum_{i=1}^{h} \theta'_i \qquad 1 < h < t \tag{11}$$

The value of h is affected by discontinuities of texture and the effect of noise. According to our experiments, the texture angle will be close to the expected value if we set $h = 3$ to 8.

Similarly, we can obtain the texture angle ω_{j+1} for the sequential images S_{j+1}.

⑧ Calculate the rectifying angle δ_{j+1} of images S_{j+1}:

$$\delta_{j+1} = \omega_{j+1} - \omega_j \tag{12}$$

So, we can make the images S_{j+1} and S_j the same texture direction if we rotate S_{j+1} by $-\delta_{j+1}$ using rotary transform[11].

3 Case Study

In the experiment, we adopt the MV-D1024-28-CL-10 CMOS camera from the Photonfocus Company. By making use of its ROI(region of interest) function, set a 512 × 512 pixels imaging area and locate it in the center of the photosurface. Thus, the image distortion can be reduced. Meanwhile, a frame rate with 105 frame/s can be reached. The measurement system is calibrated by two gauge blocks with first-class precision using the edge-pixel compensation method[9]. We obtain the pixel equivalent $\delta = 0.031\ 15$ and the edge-pixel compensation value $\lambda = 0.631$.

Then, the sequential partial images of large scale parts with straight edges are collected to evaluate the proposed method. During the experiment, the sequential image S_{j+1} is manually rotated with 10° around the camera optical axis. We select nine texture circles with 80 pixels diameter in the overlapping region of images S_j and S_{j+1}, which can be marked as O_i, O'_i $(i = 1, 2, \ldots, 9)$, respectively. Set $m = 90$ to evenly divide the circles. Fig. 6 shows the standard deviation for each angle in one circle. As shown in Tab. 1, the rectifying angle between images S_{j+1} and S_j are $\delta_{j+1} = \omega_2 - \omega_1 = 10.17°$. The difference with the actual rotation angle is less than 1°, which meets the follow-up requirement.

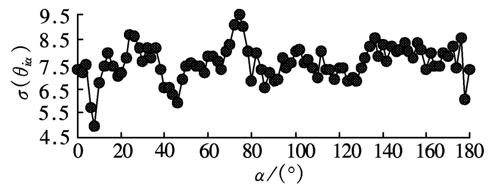

Fig. 6 Standard deviation of each angle in a texture circle

Tab. 1 Experimental data of the rectifying method of sequential images

Sequential image S_j			Sequential image S_{j+1}		
Texture circles	Texture angles/(°)	Eliminating order	Texture circles	Texture angles/(°)	Eliminating order
O_1	9		O'_1	16	
O_2	7		O'_2	18	
O_3	8		O'_3	19	
O_4	12	1	O'_4	17	
O_5	6		O'_5	19	
O_6	8		O'_6	19	
O_7	9		O'_7	15	2
O_8	4	3	O'_8	20	1
O_9	1	2	O'_9	15	3
Texture angle of S_j	$\omega_1 = \frac{1}{6}\sum_{i=1}^{6}\theta'_i = 7.83°$		Texture angle of S_{j+1}	$\omega_2 = \frac{1}{6}\sum_{i=1}^{6}\theta'_i = 18.00°$	

After pre-processing the sequential images, the C ++ language is adopted to realize the image processing algorithm. When applying the correlation coefficient method to search the matching points, the templates are selected in sizes of 9 × 9. While extracting the sub-pixel dimension features of the sequential images, the sub-pixel subdivision level is 1/100 (i. e., $m = 100$). The sequential images containing the left or right edge of the part are processed with the edge-pixel compensation methods. The experimental data are given in Tab. 2. The results indicate that the relative measurement errors are less than 0.012%, which reaches an IT6 tolerance grade. The images are processed on a personal computer with Pentium(R) 4 CPU 2.8 GHz and memory 1.0 GB. The processing duration is less than 4 s, which shows the feasibility of this method in high-precision and fast measurement for part dimensions.

Tab. 2 Experimental data of the sequential image measurement method

Part dimensions/mm	Dimension of sequential partial images/pixel			Measurement value/mm	Relative error/%
	D_1	$\sum_{i=2}^{n-1} D_n$	D_n		
101.2	286.38	2 681.61	281.17	101.211 3	0.011 2
201.5	293.42	5 871.37	304.61	201.522 0	0.010 9
291.8	317.25	8 719.45	329.85	291.767 9	0.011 0

4 Conclusion

The research shows that the sequential image measurement method can make use of images with little distortion to measure large scale machine parts by limiting the imaging area. It has the advantage of little accumulative errors. The measurement precision meets the demands of precise measurement for general machining. However, the matching of dimension features is based on the correlation between the sequential images. When acquiring sequential images, we assume that the sequential images should have the same imaging condition. Otherwise, the matching precision will degrade and the error accumulation will be exacerbated. This requires relatively strict conditions such as uniform illumination and stable measurement environments. On the other hand, the sequential image measurement method is introduced with the prototype of dimension measurement for straight-edge parts. This simplifies the measurement features but makes the application range comparatively narrow. How to extend the thought of "break up the whole into pieces and make the whole from pieces" to the measurement of complex features will be the direction for further study.

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基于特征的大尺寸零件序列局部视觉测量方法

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摘要:为了实现常规尺寸和大尺寸机械零件的视觉测量,提出一种新的基于序列局部图像尺寸特征的测量方法. 不进行图像拼接,而是提取序列局部图像的尺寸特征,并以图像序列之间的关联关系为依据求解零件尺寸. 针对影响测量精度的相面旋转问题,充分利用工件表面纹理信息,提出了基于纹理特征的序列局部图像校准方法,获得序列图像之间的相对旋转角度,解决了测量过程中相机抖动或零件旋转引起的尺寸特征方向变动问题. 通过实例说明了所提方法的实现过程及其有效性. 实验表明,对大尺寸零件采用序列图像测量法,相对测量误差在 0.012% 以内,满足板类零件的精密测量要求.

关键词:视觉测量;序列图像;表面纹理;特征匹配

中图分类号:TP274.5;TG806