Measurement of spatial object's exterior attitude based on linear CCD

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It is difficult to realize real-time measurement of exterior attitude by the traditional systems based on the area image sensor which have conflict between speed and accuracy. The subsystem for three-dimensional (3D) coordinate reconstruction of point target (S3DCRPT) which is composed of three one-dimensional (1D) cameras based on linear charge-coupled device (CCD) can determine the distant light spots' spatial position. The attitude angle of the measured object is determined by the spatial solution while the coordinate reconstruction is separately carried on by the S3DCRPT with some point cooperation targets (PCTs) on the measured object. A new optical system is designed to solve the interference problem with one-to-one relationship between the PCTs and the S3DCRPT optical subsystems, which improves the measurement accuracy and saves space. The mathematical model of the attitude measurement is established, and partial and global calibrations are realized for the multi-camera attitude measurement system. The test results show the feasibility of the exterior attitude measurement based on linear CCD.

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Attitude of spatial object usually can be described by rotating angle of its axis relative to the certain fixed reference coordinate system, which has three directions: pitch, yaw, and rolling, all named attitude angle. Attitude measurement of spatial object also is the measurement to its pitch, yaw, and rolling angles, which can be divided into interior and exterior attitude measurement according to measuring installation placed in interior or exterior of spatial object. At present, there are primarily two ways for exterior attitude measurement based on the "body object": one is laser interferometry[1−3], the other is based on machine vision[4−8]. The third generation laser tracker (Automated Precision Inc., USA) is a representative of the laser interferometry. It can realize the high accuracy attitude measurement of moving objects, but there exist some shortcomings such as complex cooperative target, poor applicability, difficult to realize dynamic measurement and expensive. The attitude measurement model based on machine vision is different, which is based on camera number and whether point cooperation targets (PCTs) are placed on the measured object, but cameras adopted are based on area image sensors.

The light-spot's three-dimensional (3D) movement track with linear charge-coupled device (CCD) was originally applied to the COSTEL system developed by Macellari, which was used to analyze human motion[9]. Researchers did the correlative research based on the above theory for high precision positioning of the measured object and so on[10,11]. However, it is not circumstantiated to realize measurement for the spatial objects' exterior attitude with linear CCD. In this paper, we present an attitude measurement based on linear CCD, which overcomes the conflict between speed and accuracy with area image sensors, obtains the ideal high accuracy and real-time measurement with the advantages of simple cooperation targets, low costs, and so on.

The imaging principle of cylindrical lens is introduced briefly as follows. If the object distance of light-spot is bigger than the focal length of lens, it becomes a striated pattern parallel to the axial lead of cylindrical lens on the focal plane of cylindrical lens. When the light-spot moves along the direction perpendicular to the axial lead, the striated pattern will make the countermovement accordingly. However, when the light-spot moves along the axial lead, the striated pattern will make the horizontal motion accordingly. Therefore, one-dimensional (1D) camera composed of cylindrical lens and a linear CCD located on its focal plane can realize 1D capturing of the distant light-spot. The fundamental structure and projection relation of 1D imaging unit with linear CCD are given in Fig. 1. In the figure, there are the world coordinate system (WS) $oxyz$, the camera coordinate system (CS) 1 $o_{c1}x_1y_1z_1$, and the CCD coordinate system (CCS) 1. The origin of assistant coordinate system (AS) 1 $ou_1v_1w_1$ coincides with WS's, and the directions of coordinate

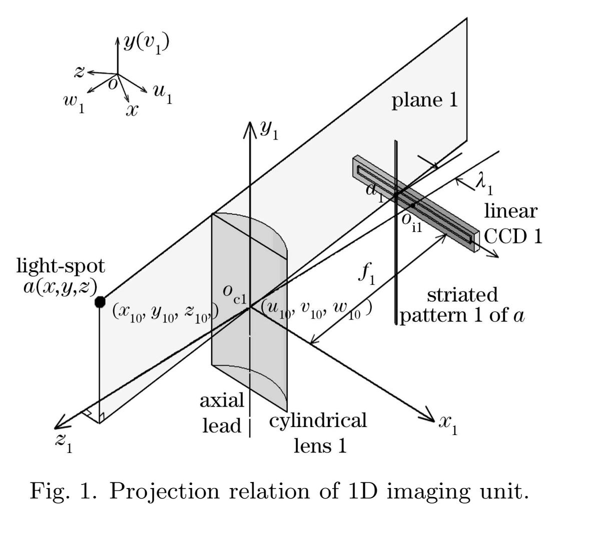

Fig. 1. Projection relation of 1D imaging unit.

axes of AS 1 accord with those of CS 1. Linear CCD 1 is perpendicular to the axial lead of the cylindrical lens 1 and is located on its focal plane. Coordinates of light-spot a are (x, y, z) under WS and (x_1, y_1, z_1) under CS 1 ($z_1 \gg f_1$). λ_1 is the coordinate of image point a_1 at which the striated pattern of the light-spot a intersects linear CCD 1 in the CCS 1. o_{c1} is the position on the axial lead of cylindrical lens 1 which have the same distance between bottom surface and top surface, and its coordinates are (x_{10}, y_{10}, z_{10}) under WS and (u_{10}, v_{10}, w_{10}) under AS 1. f_1 is the focal length of cylindrical lens 1. Plane 1 is defined by the light-spot a and the axial lead containing image point a_1. o_{i1} is the midpoint of linear CCD 1, and o_{i0} instead of o_{i1} will be focused on by a beam of the parallel light perpendicular to bottom plane of the cylindrical lens 1 considering the installation error. If the coordinate of point o_{i0} is λ_{10} in the CCS 1, then the coordinate of image point a_1 is $\lambda_1 - \lambda_{10}$ to actual reflect the movement of light-spot a in the CCS 1.

As above, a plane can be uniquely defined by the distant light-spot, the axial lead of the cylindrical lens and a striated pattern of the light-spot. So the subsystem for 3D coordinate reconstruction of point target (S3DCRPT) which is composed of three 1D cameras based on linear CCD uniquely determines the spatial position of the light-spot, as shown in Fig. 2.

In theory, in order to better manifest the position change of the light-spot, the linear CCD and the optical axis of middle camera should be vertical with those of both side cameras, separately. In practice, in order to satisfy the request for the biggest viewing field in common, the cross angle of the both side cameras' optical axes should be smaller than 90°, and the accurate positions of cameras can be obtained by the calibration for camera exterior parameters. The attitude angle of the measured object is determined by the spatial solution, while the coordinate reconstruction is carried on by the S3DCRPT with some PCTs on the measured object. Two random points in the lines parallel to be axis in the measured object can determine the measured object pitch angle α and yaw angle β. When α and β are known, two random points in the lines perpendicular to the axis in the object can determine rolling angle γ. The PCTs are placed on the measured object surface for convenience. If either pair of the PCTs to measure α and β or to measure γ are placed separately on two end surfaces of the measured object, the three PCTs on measured object can determine its attitude angle. For the cylinder measured object in this paper, when γ is zero, the PCTs b and c separately are placed on the two endpoints in the intersection between the reference plane abc_0 and the front end surface, then b should be located in the axis of measured object, and a is placed on the cross point between the back end surface and the axis of measured object (see Fig. 3).

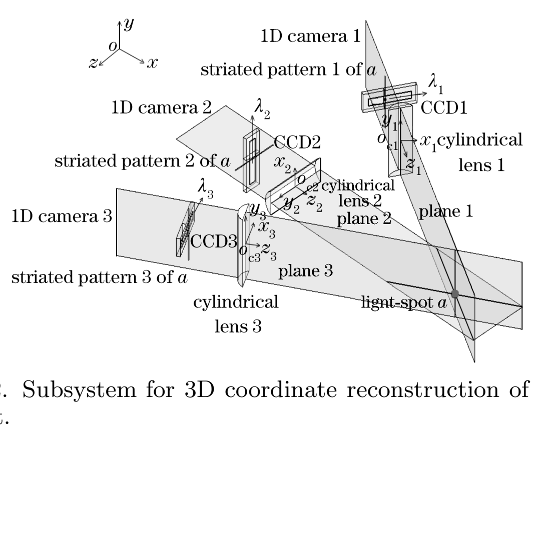

Fig. 2. Subsystem for 3D coordinate reconstruction of point target.

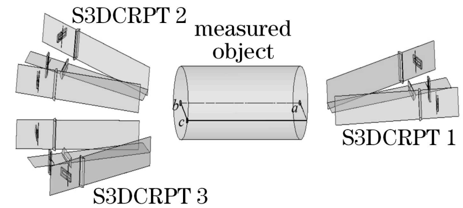

Fig. 3. Three S3DCRPTs determine the attitude angle of measured object.

The PCTs a, b, and c are respectively light emitting diodes (LEDs) at wavelength ranges of $515-530$, $580-595$, and $615-635$ nm. The corresponding optical filters are added separately into the optical subsystems 1, 2, and 3 of 3D coordinate reconstruction of point targets to solve the mutual interference among PCTs. The LEDs must be with larger divergence angle to avoid the targets missing. In this paper the divergence angle is 120°.

From above, the spatial object attitude measurement requires three S3DCRPTs to measure from two lateral surfaces on the measured object. The optical axis of 1D camera in the middle of the subsystem should plumb the front plane of PCT movement range and aim at its center. And the full viewing field range should be filled with the front plane to overcome the edge effect and ensure the theory measurement accuracy and uniformity. The 1D imaging optical subsystem of double point targets is shown in Fig. 4, which consolidates two 1D imaging units by a beam splitter and two optical filters, achieves synchronal capturing of two PCTs with different wavelength ranges.

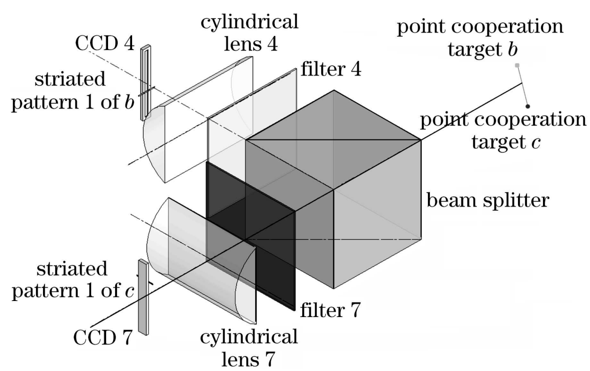

Fig. 4. 1D imaging optical subsystem of double point targets.

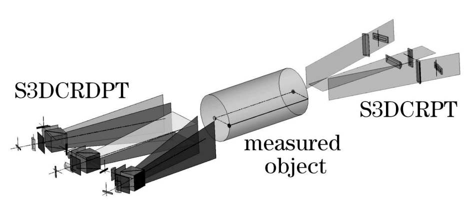

Fig. 5. A S3DCRDPT and a S3DCRPT determine the attitude angle of measured object.

The subsystem for 3D coordinate reconstruction of double point target (S3DCRDPT) is composed of three 1D imaging subsystems of double point targets, as shown in Fig. 5. It is a combination of S3DCRPT 2 and 3, namely, a combination of the six 1D cameras, realizes 3D positioning for two PCTs, improves the measurement accuracy and saves space.

In order to solve the attitude angle of spatial object, the coordinate systems are defined as follows. 1) WS $oxyz$ is determined using two electronic theodolites, and the coordinate planes oxz and oyx are respectively parallel to ceiling and lateral wall. 2) CS $o_{\mathrm{c}m}x_my_mz_m$ ($m = 1, 2, \cdots, 9$, it is used to distinguish different 1D cameras). The coordinate origin $o_{\mathrm{c}m}$ is located at the midpoint of axial lead of the cylindrical lens. The y_m and z_m axes are coincident separately with the optical axis and axial lead of the cylindrical lens. The x_m, y_m, and z_m axes constitute the right-handed coordinate system. The positive z_m-axis is outward, and positive x_m-axis or y_m-axis is upward. 3) AS $ou_nv_nw_n$ ($n = 1, 2, \cdots, 9$, it is used to distinguish the different contacts between WS and each CS). Its coordinate origin coincides with coordinate origin o of the WS, moreover, its coordinate axis direction accords with CS's. 4) CCS $o_{\mathrm{i}t}\lambda_t$ ($t = 1, 2, \cdots, 9$, it is used to distinguish different linear CCDs). The midpoint $o_{\mathrm{i}t}$ of the linear CCD is defined as origin of the coordinate system. The λ_t-axis direction accords with the x_m-axis of CS. WS, CS 1, 2, 3, and CCS 1, 2, 3 are as shown in Fig. 2.

Figure 6 shows the pitch angle and yaw angle of the measured object. The pitch angle α is the angle between axis of the measured object and the reference coordinate plane oxz, which is positive when the angle rotates around the origin o of the WS towards the positive y-axis, contrarily it is negative. The yaw angle β is the angle between the axis of the measured object and the reference coordinate plane oyx, which is positive when the angle rotates around the origin o towards the negative z-axis, contrarily it is negative.

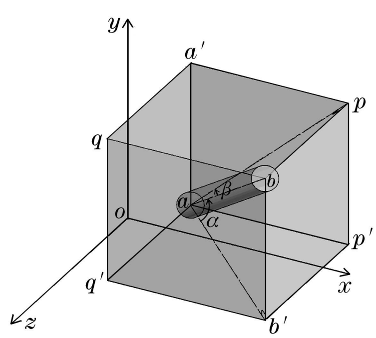

Fig. 6. Pitch angle and yaw angle of the measured object.

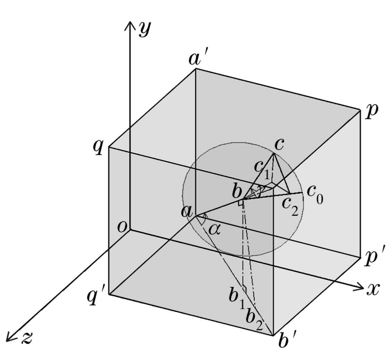

Fig. 7. Rolling angle of the measured object.

Figure 7 is the enlargement of cylinder front end surface. γ is the rolling angle that the lateral cross section abc of the measured object rotates around its axis ab, and the reference coordinate plane is abc_0. When γ is zero, the plane abc is coincident with plane abc_0. Observing γ angle along the direction of the ab axis, positive angle means clockwise rotation, and negative angle represents counter-clockwise rotation.

The steps to solve the attitude angle of spatial object include coordinate system transformation, 1D camera calibration, 3D coordinate reconstruction of PCT and attitude angle's spatial solution. These steps are described in detail as follows.

Firstly, the WS is transformed into the AS 1 by rotation matrix $R^{(1)}$, then the AS 1 is transformed into CS 1 through translation vector $T^{(1)}$:

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} = R^{(1)} \begin{bmatrix} x \\ y \\ z \end{bmatrix} + T^{(1)}, \tag{1}$$

where

$$R^{(1)} = \begin{bmatrix} r_{11}^{(1)} & r_{12}^{(1)} & r_{13}^{(1)} \\ r_{21}^{(1)} & r_{22}^{(1)} & r_{23}^{(1)} \\ r_{31}^{(1)} & r_{32}^{(1)} & r_{33}^{(1)} \end{bmatrix},$$

$$T^{(1)} = \begin{bmatrix} u_{10} \\ v_{10} \\ w_{10} \end{bmatrix} = R^{(1)} \begin{bmatrix} x_{10} \\ y_{10} \\ z_{10} \end{bmatrix}.$$

$r_{ij}^{(1)}$ ($i, j = 1, 2, 3$) is the element of $R^{(1)}$, translation vector $T^{(1)}$ is $(x_{10}, y_{10}, z_{10})^{\mathrm{T}}$ under WS and $(u_{10}, v_{10}, w_{10})^{\mathrm{T}}$ under AS 1.

Secondly, according to the similar triangle principle, the relation between the coordinates of PCT a under CS 1 and the coordinate of image point a_1 in CCS 1 is established as

$$\frac{x_1}{z_1} = \frac{-(\lambda_1 - \lambda_{10})}{-f_1}. \tag{2}$$

From Eqs. (1) and (2), we can obtain

$$\lambda_1 - \lambda_{10} = f_1 \frac{r_{11}^{(1)}x + r_{12}^{(1)}y + r_{13}^{(1)}z + u_{10}}{r_{31}^{(1)}x + r_{32}^{(1)}y + r_{33}^{(1)}z + w_{10}}. \tag{3}$$

Once 1D camera structural parameters and positions are fixed, f_1, λ_{10}, u_{10}, w_{10}, and $r_{ij}^{(1)}$ ($i, j = 1, 2, 3$) are determined correspondingly. If λ_1 in Eq. (3) is known, Eq. (3) determines a plane equation. As long as the coordinates of PCT a meet the plane equation (the image forming condition), its striated pattern and linear CCD 1 must intersect at image point a_1. $r_{ij}^{(1)}$ ($i, j = 1, 2, 3$) is the product with cosine angles between the two coordinate axes of CS 1 and WS, then it has only three independent freedoms. Thus only seven independent physical parameters are needed to confirm the coordinate relation between

PCT a and image point a_1. Further simplifying Eq. (3), we can obtain

$$l_1x + l_2y + l_3z + l_4 - \lambda_1 l_5 x - \lambda_1 l_6 y - \lambda_1 l_7 z = \lambda_1. \quad (4)$$

As long as 3D coordinates of seven light-spots under WS and 1D coordinate of their corresponding image points in CCS 1 are known, seven unknowns parameters l_i ($i = 1, 2, \cdots, 7$) in Eq. (4) can be solved. Because the relation between the parameters l_i and camera physical parameters can be expressed as

$$l_1 = \frac{\lambda_{10} r_{31}^{(1)} + f_1 r_{11}^{(1)}}{w_{10}}, \quad l_2 = \frac{\lambda_{10} r_{32}^{(1)} + f_1 r_{12}^{(1)}}{w_{10}},$$

$$l_3 = \frac{\lambda_{10} r_{33}^{(1)} + f_1 r_{13}^{(1)}}{w_{10}}, \quad l_4 = \lambda_{10} + f_1 \frac{u_{10}}{w_{10}},$$

$$l_5 = \frac{r_{31}^{(1)}}{w_{10}}, \quad l_6 = \frac{r_{32}^{(1)}}{w_{10}}, \quad l_7 = \frac{r_{33}^{(1)}}{w_{10}}, \quad (5)$$

the physical parameters of camera 1 can be solved after obtaining l_i. The step is a calibration process for interior parameters f_1, λ_{10}, u_{10}, w_{10} and exterior parameters $r_{ij}^{(1)}$ ($i, j = 1, 2, 3$) of camera 1. Usually, for reducing random error, it needs more than seven known light-spots' coordinates under WS to solve physical parameters of the camera 1. The interior and exterior parameters of other eight cameras can be also calibrated in the same way.

Thirdly, after bringing the physical parameters of camera 1 calibrated into Eq. (4), a plane equation is confirmed by coordinates of PCT a under WS and its corresponding striated pattern in CCS 1. Rewrite Eq. (4) as

$$(\lambda_1 l_5 - l_1)x + (\lambda_1 l_6 - l_2)y + (\lambda_1 l_7 - l_3)z = l_4 - \lambda_1. \quad (6)$$

Three plane equations brought with 1D cameras 1, 2, and 3 calibrated uniquely confirm 3D coordinates of the PCT a under WS. Similarly, the position of PCT b and c can be confirmed.

Fourthly, in the WS, if coordinates (x_a, y_a, z_a), (x_b, y_b, z_b), and (x_c, y_c, z_c) of PCTs a, b, and c were reconstructed, then the attitude angle of the measured object can be obtained through the spatial solution. Making the line between PCTs a and b placed on the measured object as diagonal line, we can obtain the angles α, β as shown in Fig. 6. And the distance between a and b can be expressed as

$$l_{ab} = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2}. \quad (7)$$

Then

$$\alpha = \arcsin\left(\frac{y_b - y_a}{l_{ab}}\right), \quad (8)$$

$$\beta = \arcsin\left(\frac{z_b - z_a}{l_{ab}}\right). \quad (9)$$

The distance between b and c and the angle γ shown in Fig. 7 can be expressed as

$$l_{bc} = \sqrt{(x_b - x_c)^2 + (y_b - y_c)^2 + (z_b - z_c)^2}, \quad (10)$$

$$cc_2 = \frac{y_c - y_a}{\cos\alpha} = \frac{(y_c - y_b) \cdot l_{ab}}{\sqrt{l_{ab}^2 - (y_b - y_a)^2}}, \quad (11)$$

$$\gamma = \arcsin\left(\frac{(y_c - y_b) \cdot l_{ab}}{\sqrt{l_{ab}^2 - (y_b - y_a)^2} \cdot l_{bc}}\right). \quad (12)$$

The system was designed to measure a cylinder object of 0.6-m length and 0.2-m cross-section diameter, and the object moves in a $3 \times 2 \times 4$ (m) space. The linear CCD (TCD1708D, Toshiba, Japan) was adopted. Optical characteristics parameters of cylinder lens were confirmed by the movement range of measured object, effective sensitization area of linear CCD, and the depth of field request, etc.. And structure parameters of the optical lens were optimized by the aberration request. The viewing field angle of the middle camera is 30°, and those of the two sides cameras are 20°, and the cross angle between their optical axis is 30°. In the movement space, the three kinds of LEDs at wavelength ranges of 515 − 530, 580 − 595, and 615 − 635 nm with ten of each were placed uniformly, and their positions under WS were measured with two electronic theodolites. The 7-parameter direct linear transformation (DLT) method introducing 1D installation error was adopted to calibrate the nine 1D cameras[12]. Adopting 3D coordinates of the same LED as PCT to calibrate every 1D camera under WS, the attitude measurement realized the unification of the measured data while partial calibration was carried on for every 1D camera, namely, realized global calibration of the attitude measurement system. The measured cylinder was placed on three-axis rotary table with the precision of 0.003° in the movement space, and given corresponding attitude by the rotary table. With the average value of six measurements for attitude angle, the measurement precision can reach 1′ (see Table 1). The image sampling frequency is 1316 frames per second when pixel clock of the linear CCD is 5 MHz.

Table 1. Measurement Average Error with Six Times for the Cylinder Object's Attitude Angle (unit arc minute)

Relative Truth Value of Attitude Angle			Average Error of Attitude Angle with Six Times		
α	β	γ	α	β	γ
−618.75	−618.75	−618.75	−0.83	0.98	−0.79
−506.25	−506.25	−506.25	0.54	0.73	−0.98
−393.75	−393.75	−393.75	−0.60	−0.66	−0.59
−281.25	−281.25	−281.25	−0.33	0.55	0.37
−168.75	−168.75	−168.75	−0.13	0.15	0.08
0	0	0	0.08	−0.07	−0.17
18.75	11.25	18.75	−0.27	0.18	−0.18
168.75	101.25	131.25	0.74	−0.57	−0.59
356.25	206.25	281.25	0.62	−0.75	0.92
506.25	393.75	468.75	0.97	−0.85	0.89
Maximum Measurement Error			0.97	0.98	0.98

This paper presents an exterior attitude measurement based on linear CCD for the moving object in fixed space, which can overcome the conflict between speed and accuracy with area image sensors for attitude measurement. Based on the research for relative positions and corresponding relations between the PCTs and the optical subsystems, the interference problem among many PCTs was solved. The optical subsystem for 3D coordinate reconstruction of double point targets based on linear CCD was designed to improve accuracy and save space. Linear imaging relation only introducing 1D installation error was adopted. The test results show that the measurement is validated.

It is reasonable to believe that the attitude measurement proposed would benefit to industrial and manufacturing applications as a novel metrology in dynamic condition. This paper concentrated on only the presentation of a new method and the feasibility of the method with small lens aberration. Further studies on foundation of nonlinear imaging model including all installation errors and lens aberrations for improving the measurement accuracy will be considered in the future.

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