A theoretical and experimental study on no-guide light pen type 3D-coordinate measurement system

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A novel no-guide light pen type 3D-coordinate measurement system with three sets of position sensitive devices (PSDs) to realize intersection converge imaging is introduced. It is called as the light pen type measurement system, because the measuring head is shaped as a pen with several light sources on it. The structure design, measurement principle and experimental results are presented. The theoretical analysis and experimental results prove that this system has advanced features of simple structure, high automation, and high accuracy, and can be used in the measurement fields of mechanical manufacture, robot, auto, aviation and medicine effectively.

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With the developments of measurement technique, more demands for 3D-coordinate measurement technique have been put forward, which leads the technique into the direction of intelligence, high accuracy, multiple-degree-of-freedom, on-line and dynamic measurement. The 3D-coordinate measurement system which has the features of simple structure and convenient application is used as the base system in many measurement fields such as gamma knife medical technique, complex form and structure measurement in a factory measurement platform, on-the-spot and on-line measurement, computer aided design (CAD) and computer aided machinery (CAM), car body measurement and virtual location technique[1]. Because of its complex structure, heavy equipment and expensive price, the current 3D-coordinate measuring machine cannot meet the need of quick on-the-spot and on-line measurement, and is limited in use and promotion[2].

In this paper, the no-guide light pen type 3D-coordinate measurement system is presented, which overcomes the above disadvantages. In this system, three sets of PSD devices are used to realize intersection converge imaging, the measuring head is shaped as a pen with light sources on it, which makes the measurement flexible and simple. The dynamic measurement data are processed by a computer. The total system has the advantage of simple structure and convenient operation, which can meet the measuring requirements for real-time, dynamic state and on-line.

The no-guide light pen type 3D-coordinate measurement system consists of three sets of angle-measurement devices and measuring head: a light pen with four high-brightness laser fiber balls (the head of fiber is sintered to a ball, the light is coupled in the fiber to make the fiber ball be illuminant). The light signal is received by the three angle-measurement devices respectively, and is turned into electrical signals, which are disposed in the computer. According to the position relation between the light source and angle-measurement system, the 3D-coordinate of the pen-tip can be obtained. The three sets of angle-measurement devices consist of three linear array PSDs (with the same structure and parameters) and three cylindrical lenses (with the same focal length), which are placed in an adjustable bracket. The optical axes of them converge to a point.

Cylindrical lens imaging system is shown as Fig. 1. PSD with its photosensitive surface vertical to the bus-bar of the cylindrical lens is placed in the focal plane. A point light is imaged to a vertical line in the photosensitive surface of PSD. When the light point moves in the direction of X-axis, the image on the PSD moves in reverse, when the light point moves in the direction of Y-axis, the image on the PSD is stable. So the displacement change of the light point can be calculated by the position change of image.

Establish a Cartesian coordinate system shown as Fig. 2. PSD-1 is placed at the original point O; PSD-2 is placed at the point P which is at d_0 distance from O. O and P are optical epaxial points in the system. C is the optical axes' intersecting point of the two optical systems. $\overline{OC}$ and $\overline{PC}$ are optical axes of the two optical systems respectively, α_0 is the included angle between $\overline{OC}$ and X-axis, β_0 is the included angle between $\overline{PC}$ and X-axis. S_0 is the projection point in XOY-plane of the space point S, whose image heights (the distance between image in PSD and the center of PSD) in PSD-1 and PSD-2 are h_1 and h_2, respectively. Two main rays which correspond to S_0 are crossed with X-axis at A and B, the distance between A and B is d, α is the included angle between $\overline{S_0A}$ and X-axis, β is the included angle between $\overline{S_0B}$ and X-axis, γ is the included angle between $\overline{S_0A}$ and optical axis $\overline{OC}$, and θ is the included angle between $\overline{S_0B}$ and optical axis $\overline{PC}$. Cylindrical lenses 1 and 2 are placed at D and E, both the distances between D and PSD-1, E and PSD-2 are f (the focal length of cylindrical lens). The bus-bar of cylindrical lens is perpendicular to the photosurface linear array of PSD.

Formula can be got by the geometric relationship[3], shown as Fig. 2.

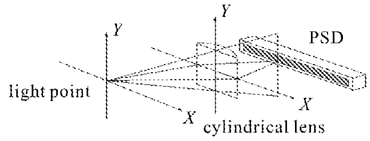


Fig. 1. Imaging system model.

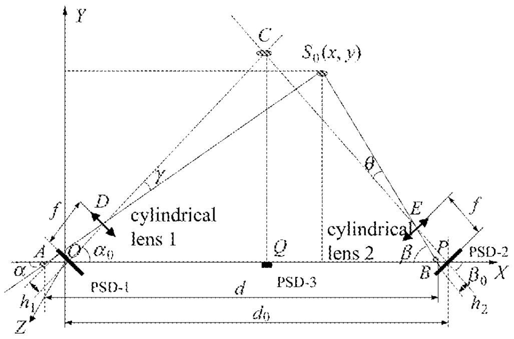


Fig. 2. The principle of coordinate measurement.

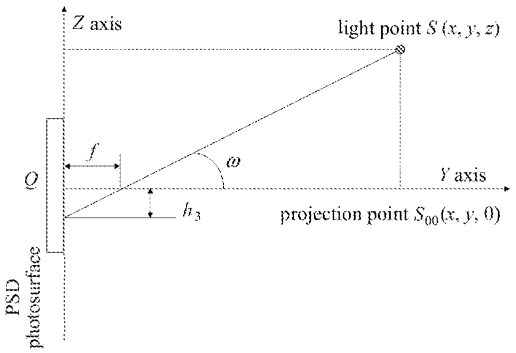


Fig. 3. The measurement principle of Z-coordinate.

$$d = d_0 + f\left(\frac{\sin\gamma}{\sin\alpha} + \frac{\sin\theta}{\sin\beta}\right). \quad (1)$$

The 2D-coordinate of space point S is got as

$$x = \overline{AS_0}\cos\alpha - \overline{AO} = d\cdot\frac{\sin\beta\cos\alpha}{\sin(\alpha+\beta)} - f\frac{\sin\gamma}{\sin\alpha}, \quad (2)$$

$$y = \overline{AS_0}\sin\alpha = d\cdot\frac{\sin\beta\sin\alpha}{\sin(\alpha+\beta)}. \quad (3)$$

$\overline{QC}$ (shown in Fig. 2) is the optical axis of the third imaging system which is perpendicular to XOY-plane (Q is the mid-point in $\overline{OP}$), $\overline{QC}$ is at right angle to Z-axis, PSD-3 is placed in the direction parallel to Z-axis and its center is at Q. S_{00} is the projection point in Y-axis of the light point $S(x, y, z)$, whose image height in PSD-3 are h_3 (shown as Fig. 3), in the same way, the Z-coordinate of S is got as

$$z = (y - f)\cdot\frac{h_3}{f} = \frac{y}{f}h_3 - h_3. \quad (4)$$

From formulas (1 − 4) we can conclude that, as long as the focal length f, baseline d_0, angle α_0, β_0 and image heights h_1, h_2, h_3 are determined by signals from PSD, the 3D-coordinate of a space point in the measurement range will be got. The focal length f, baseline d_0, angle α_0, β_0 are called structure parameters, from the differential of the formulas, the structure error formula can be got. And the designs of structure parameters affect the measurement accuracy.

The error of d

$$\Delta d_1 = \Delta d_0,\ \ \Delta d_2 = \left(\frac{\sin\gamma}{\sin\alpha} - \frac{\sin\theta}{\sin\beta}\right)\cdot\Delta f,$$
$$\Delta d_3 = -\frac{f\cdot\sin\gamma\cdot\cos\alpha}{\sin^2\alpha}\Delta\alpha,\ \ \Delta d_4 = \frac{f\cdot\sin\theta\cdot\cos\beta}{\sin^2\beta}\Delta\beta,$$
$$\Delta d_5 = \frac{f\cdot\cos\gamma}{\sin\alpha}\Delta\gamma,\ \ \Delta d_6 = -\frac{f\cdot\cos\theta}{\sin\beta}\Delta\theta,$$
$$\Delta d = \pm\sqrt{\Delta d_1^2 + \Delta d_2^2 + \Delta d_3^2 + \Delta d_4^2 + \Delta d_5^2 + \Delta d_6^2}. \quad (5)$$

The error of x

$$\Delta x_1 = \frac{\sin\beta\cdot\cos\alpha}{\sin(\alpha+\beta)}\Delta d,\ \ \Delta x_2 = -\frac{\sin\gamma}{\sin\alpha}\Delta f,$$
$$\Delta x_3 = \left(\frac{f\cdot\cos\alpha\cdot\sin\gamma}{\sin^2\alpha} - \frac{d\sin 2\beta}{2\sin^2(\alpha+\beta)}\right)\Delta\alpha,$$
$$\Delta x_4 = \frac{d\cdot\sin 2\alpha}{2\sin^2(\alpha+\beta)}\Delta\beta,\ \ \Delta x_5 = -\frac{f\cdot\cos\gamma}{\sin\alpha}\Delta\gamma,$$
$$\Delta x = \pm\sqrt{\Delta x_1^2 + \Delta x_2^2 + \Delta x_3^2 + \Delta x_4^2 + \Delta x_5^2}. \quad (6)$$

The error of y

$$\Delta y_1 = \frac{\sin\alpha\cdot\sin\beta}{\sin(\alpha+\beta)}\Delta d,\ \ \Delta y_2 = \frac{d\cdot\sin^2\beta}{\sin^2(\alpha+\beta)}\Delta\alpha,$$
$$\Delta y_3 = \frac{d\cdot\sin^2\alpha}{\sin^2(\alpha+\beta)}\Delta\beta,$$
$$\Delta y = \pm\sqrt{\Delta y_1^2 + \Delta y_2^2 + \Delta y_3^2}. \quad (7)$$

The error of z

$$\Delta z_1 = \tan\omega\Delta y,\ \ \Delta z_2 = (y - f)\sec^2\omega\Delta\omega,$$
$$\Delta z_3 = \Delta f\tan\omega,$$
$$\Delta z = \pm\sqrt{\Delta z_1^2 + \Delta z_2^2 + \Delta z_3^2}. \quad (8)$$

The effective field of view of measurement system is the field that can be detected by the three PSDs, the field that is besides the effective field is called as blackout area. The effective field should be considered in structure design of measuring system. The 2D schematic of the effective field of view is shown as Fig. 4. 2θ is the field

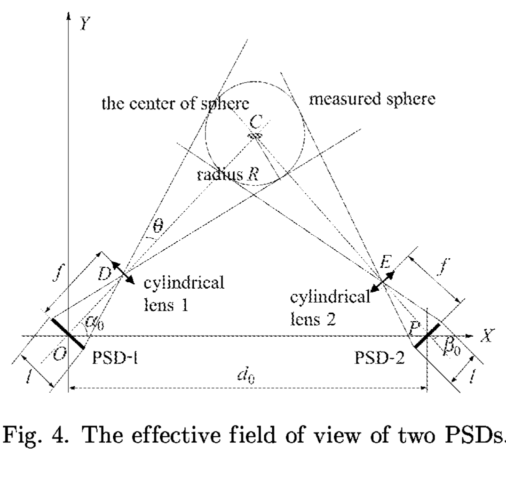


Fig. 4. The effective field of view of two PSDs.

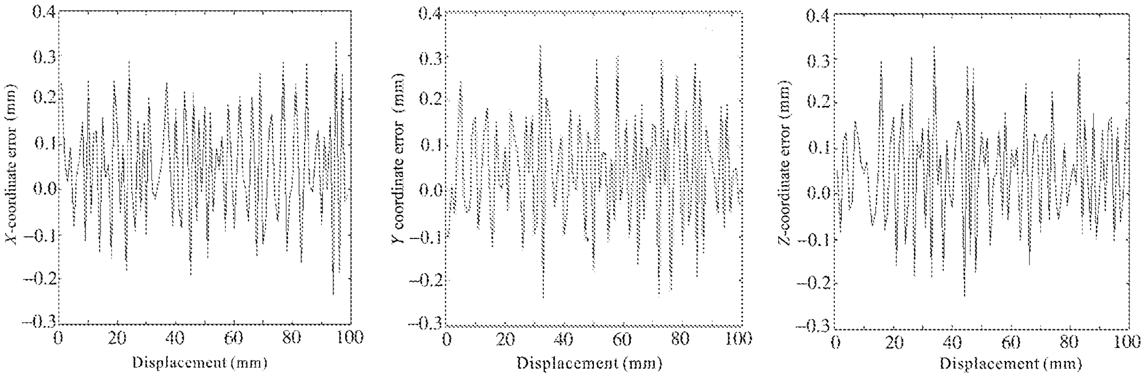
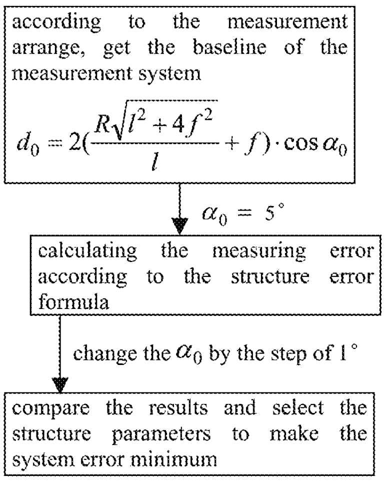


Fig. 5. The measuring error of no-guide light pen type of 3D-coordinate measuring system.

angle of PSD, $\theta = \arctan[l/(2f)]$, l is the length of photosurface, f is the focal length of cylindrical lens. An inscribed circle whose area is proportional to effective field is drew in the effective field of two PSDs, and can be used to represent the area of effective field of view. R is the radius of the inscribed circle, which can be got as $R = (d_0 \sec\alpha_0/2 - f) \cdot \frac{1}{\sqrt{l^2+4f^2}}$, d_0 is the length of baseline, α_0 is the included angle between X-axis and the optical axis of PSD angle-measurement device. The area of effective field of view of two PSDs is relative to the positions of PSDs and the parameters of angle-measurement device. In the direction of Z, the effective field of view is 2Ψ, the field angle of PSD-3, which is got as $2\Psi = \arctan[l/(2f)]$.

According to the effective field and the structure parameters, the optimization mathematic model of whole system can be got as follows.



The system structure parameters for required measuring range can be got by computer simulation according to the mathematic model.

The angle-measuring device is shaped as a square pipe with two ends bent to a certain angle. The signal processing system is shielded to avoid the noise. A/D card in the computer is used to realize the data sampling and treatment. The measured object is placed in the 3D-microstage (measuring accuracy is 0.01 mm). In our experiments, the light pen is fixed in the platform, the pen-tip can be moved in three directions. The range of displacement is 100 mm. The measuring resolution is 0.1 mm.

Comparing the 3D-coordinate of pen-tip got from the measurement system with the reading of microstage, we can get the measuring uncertainty as $\pm 3\sigma_x = \pm 0.39$mm, $\pm 3\sigma_y = \pm 0.37$mm, and $\pm 3\sigma_z = \pm 0.36$mm. The error curve is shown as Fig. 5.

Measuring one point three times in the same condition, the repeatability error is got as $\pm 3s = \pm 0.19$ mm.

When the pen-tip moves in one direction, the error caused by the other two directions is called intercross error. When the pen-tip moves in the direction of X, the intercross errors of Y, Z are $\delta_{y(x)} = \pm 0.1$ mm, $\delta_{z(x)} = \pm 0.08$ mm. When it moves in the direction of Y, the intercross errors of X, Z are $\delta_{x(y)} = \pm 0.1$ mm, $\delta_{z(y)} = \pm 0.12$ mm. And when it moves in the direction of Z, the intercross errors of X, Y are $\delta_{x(z)} = \pm 0.08$ mm, $\delta_{y(z)} = \pm 0.09$ mm.

The 3D-coordinate measurement system can develop the 3D-coordinate measurement to six-freedom measurement. It can change the behindhand status of complex body-measurement and is promising to measure curved line and surface. It can be applied to be the reference coordinate system in automotive body measuring field, and overcome the theodolite system[4]. So the light pen type 3D-coordinate measurement system is innovation and development in 3D-coordinate measurement field and its application is significance to mechanical manufacture, auto, aviation and iatrology fields.

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