A high precision collaborative vision measurement of gear chamfering profile

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Keywords: collaborative vision, precision measurement, gear chamfering

Abstract. In order to achieve higher measurement precision of the surface profile on chamfering gears in auto gearbox, this paper proposed a collaborative visual surface profile measurement system, researched image processing and measurement path planning algorithm in the system. The measuring process includes: collecting gear image using the area array image sensor, processing image edge, fitting gear center by utilizing edge points of the gear image, positioning local area through combining calibration algorithm. Then, planning measurement path according requirements, driving XY platform to carry high-precision point visual laser displacement sensors achieving local area of gear chamfering along the measurement path. Finally, processing the data obtained by laser displacement sensors and outputting measurement report. Experiments show that measurement accuracy of the system can attain 1 μ m when measuring the height (Z direction) of gear chamfering profile and 5 μ m when measuring the length(X direction) and width (Y direction) of gear chamfering profile. By combining their respective advantages of the two sensors, the collaborative vision measurement method which uses area array image sensor to achieve high-speed positioning and laser sensor can be used to improve the measurement precision for measurement of gear chamfering profile.

Introduction

In machine vision technology, measurement using only one single image sensor cannot meet the high accuracy, speed, and many other requirements in precision manufacturing. Therefore, it is very important to study a collaboration precision measurement method combined with two or even multi-level visual sensors on their different merits.

In a two-step collaboration measurement system, visual sensors are used to complete the wide range of rough measurement or measuring location on the first stage, and the local small-scale precision measurement on the second stage. The visual sensors on the second stage may be the visual sensor of different resolution or high-precision laser displacement sensor.

Due to the pixel size of the current 2D CCD is usually larger than 2.5μ m× 2.5μ m, and it is not enough to meet the measurement accuracy requirement. In this paper, a two-stage collaboration measurement system is designed to measure the gear chamfering profile. On the first stage of the measurement, combined with the calibration algorithm, work piece locating is completed using a 2D image sensor. On the second stage, the high accuracy of measurement is completed using a point visual laser displacement sensor carried by the 2D high precision electric platform on the planned path.

Measurement principle and coordinate relationship

Measurement principle. In this paper, the measurement system is used for measurement on the gear chamfering profile, and the precision is required to $1\mu m$ in the height value. Based on the calibration method, image processing and location of measuring part are finished in the first stage through collecting the gear image by a 2D camera. Then the gear chamfering contour measurement is completed by a laser displacement sensor with repeat measurement accuracy of $0.1\mu m$ on the second

stage. The designed measurement system is shown as Fig.1, which includes 2D camera, computer, XY platforms, laser displacement sensor, marble base, light source, and printer. Firstly, collect image of the gear through the CCD sensor, after the calibration and the gear images processing, computer will send planned path orders to the move the XY platform, then the XY platform will carry the laser displacement sensor to measure the contour of the gear chamfering profile. Finally, the measurement result will be saved in the computer and can be printed out.



Fig.1 Measurement system

1. XY platform, 2. laser displacement senor, 3. 2D camera, 4. marble base, 5. Gear, 6. light source, 7. Computer, 8. Printer.

Coordinate systems. During the measurement, the moving path of the XY platforms is designed after the calibration between the image and the world coordination, so it is needed to get the relationship between the different coordinate systems in the measurement system, which includes the world coordinate system (Xw, Yw, Zw), the XY platform coordinate system (X, Y, Z), the image sensor coordinate system (Xi, Yi, Zi) and the image point coordinate system (U,V), as shown in Fig. 2.



Fig.2 The four coordinates in the system

In this measurement system, the world coordinate system (Xw, Yw, Zw) is set to coincide with the XY platform coordinate system (X, Y, Z). Zi direction in the image sensor coordinate system (Xi, Yi, Zi) is set as the optical axis of the camera, the other two directions are set parallel with the U direction and V direction in the image point coordinate system (U, V), respectively. The coordination in the image point coordinate system (U, V) shows the point position in the image.

Put the gear to be measured on the XY platform, and calibrate the relationship between the XY platform coordinate system (X, Y, Z) and the image point coordinate system (U, V).

Calibration method. After collecting the gear image on the XY platform, the gear position in the world coordinate system can be presented on the image coordinate system. Calibration means to get the relationship between the two coordinate systems. The relationship between the coordinate (x, y) on the object plane in the world coordinate system and the coordinate (u, v) on the image plane in the image coordinate can be shown as Eq. 1^[1]:

$$\begin{bmatrix} wx \\ wy \\ w \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix} \times \begin{bmatrix} u \\ v \\ 1 \end{bmatrix}$$
(1)

Where w is a relation factor, and m33=1. Then:

$$\begin{cases} x = m_{11}u + m_{12}v + m_{13} - xm_{31}u - xm_{32}v \\ y = m_{21}u + m_{22}v + m_{23} - ym_{31}u - ym_{32}v \end{cases}$$
(2)

So, if the 8 relation factors in Eq. 1, m_{11} to m_{32} , are known, the real coordination of any point on the object plane can be received basing on Eq. 2 from the coordinate on the image plane. And the 8 relation factors can be calibrated by the coordinates of the corner points of the grids on the calibration board.

Collaborative measurement of gear chamfering profile

First measurement step - center location.

Measurement object. The measurement object is the gear chamfering profile as shown in Fig.3. The lines in the (a) are the connection lines between the circle center and the addendum circle arc midpoint of each toot, and the 3 polylines in (b) are the measurement planes, which are perpendicular to the lines in the left side.



Fig.3 Real Object and partial enlarged detail figure of chamfering gear

Center location method. Since LED backlight resource is involved in the measurement system, edge of a clear grayscale image can be received from the image collection. After the image processing, the coordinates of boundary points can be extracted by the software. Fitting the root circle basing on the points extracted by least-squares fitting algorithm, the center point coordinate of the root circle can be received. Denote all the points extracted from the gear image as Set D, the distance from any point in set D, $D_i(u_i, v_i)$, to the circle center point is marked as R_i , and the circle area with radii R_i is s_i . The circle area of the fit circle with radii R is s, and the fit circle center coordinate is (x_0, y_0) . Then the error between the circle areas is expressed as Eq. 3:

$$\varepsilon_i = s_i - s = \pi R_i^2 - \pi R^2 = \pi [(u_i - x_0)^2 + (v_i - y_0)^2 - R^2]$$
(3)

And the squared error can be shown as Eq. 4:

$$F(x_0, y_0, R) = \pi^2 \sum_{i=1}^{n} [(u_i - x_0)^2 + (v_i - y_0)^2 - R^2]^2$$
(4)

Make F (x0, y0, R) to be the minimum, the value of x_0 , y_0 and R can be taken through Eq. 5:

$$\frac{\partial F}{\partial x_0} = \frac{\partial F}{\partial y_0} = \frac{\partial F}{\partial R} = 0$$
(5)

Which can also be shown as Eq. 6:

$$\begin{cases} \frac{\partial F}{\partial x_0} = \pi^2 \sum_{i=1}^n (-4)[(u_i - x_0)^2 + (v_i - y_0)^2 - R^2](u_i - x_0) = 0\\ \frac{\partial F}{\partial y_0} = \pi^2 \sum_{i=1}^n (-4)[(u_i - x_0)^2 + (v_i - y_0)^2 - R^2](v_i - y_0) = 0\\ \frac{\partial F}{\partial R} = \pi^2 \sum_{i=1}^n (-4)[(u_i - x_0)^2 + (v_i - y_0)^2 - R^2]R = 0 \end{cases}$$
(6)

Solving Eq. 6, then the exact circle center coordinate O (Ou, Ov) of gear can be received by Eq.7.

$$\begin{cases} x_0 = \frac{hq - tc}{2(pq - c^2)} \\ y_0 = \frac{tp - hc}{2(pq - c^2)} \end{cases}$$
(7)

where:

$$p = n \sum u_i^2 - (\sum u_i)^2 \ q = n \sum v_i^2 - (\sum v_i)^2$$
$$h = n \sum u_i^3 + n \sum u_i v_i^2 - \sum (u_i^2 + v_i^2) \sum u_i$$
$$t = n \sum v_i^3 + n \sum u_i^2 v_i - \sum (u_i^2 + v_i^2) \sum v_i$$
$$c = n \sum u_i v_i - \sum (u_i) \sum v_i$$

Gear chamfering profile measurement.

Main parameter to measure. The main parameter of gear chamfering profile to be measured includes: the angle between the two chamfering surface M, the distance from the chamfering surface to the specified plane N, as shown in Fig.4.

Measurement requirement. The measuring planes on the tooth of the gear chamfering profile is shown as Fig. 5, and the data, 43.7, 45.1 and 46.5 means the distance from the measuring plane to the circle center, and it will be different to gears of different size. Assuming the circle center is marked as O, the addendum circle arc midpoint of a tooth is marked as P, and the measuring planes must be perpendicular to line OP.

Measurement path planning. The principle of measurement path planning is shown in Fig.6. Line AB is the measurement path for the laser displacement sensor, which is required to be perpendicular to OP, P_1 is the intersection of OP and AB, and the distance L from AB to O is a known value. Because the coordinate of point O in the image plane can be achieved by equ.7, line OP can be decided by determining the coordinate of point P (P_u , P_v) in the image plane. Line CD is the chord to the arc of the addendum circle, P2 is the midpoint of CD.





Fig.4 Measurement Parameters in section

Fig.5 figure of Single-tooth measurement location



Fig.6 Principle figure of system of image

When the system starts to measure the gear chamfering profile, click the mouth at a point near the gear tooth of gear on the gear image, the position of the point will be saved by the program. Supposing the point is marked as Q, its coordination is (Qu, Qv) in the image coordinate system (U, V). Scan a small area near the point to find all of the edge point of the gear tooth, which includes all of the points on the addendum arc $\overrightarrow{e}PD$, mark the first point on arc $\overrightarrow{e}PD$ as point C and the last point as D, extract the coordination of point C and D, get the midpoint position of line CD, and mark it as P2 (P2u, P2v). Because point P, P2, and O are on the same line, and the equation of the line can be solved out by the three points.

Converse the coordinate of point O and P2 in the image coordinate system to the XOY plain in the XY platform coordinate system and marked as (Ox, Oy) and (P2x, P2y). The slop of line OP2 is k, and the length of OP1 is L, the coordinate of P1(P1x, P1y) on XOY plain can be solved by Eq. 8:

$$\begin{cases} P_1 x = Ox - L \times \cos\left(\arctan\left(k\right)\right) \\ P_1 y = Oy - L \times \sin\left(\arctan\left(k\right)\right) \end{cases}$$
(8)

Since line AB is perpendicular to line OP1, and the length of AB is set as L1, so the coordinate of point A (Ax, Ay) is shown as Eq. 9:

$$\begin{cases}
A_x = P_{1x} - \frac{L_1}{2} \times \cos\left(\pi - \arctan\left(k_1\right)\right) \\
A_y = P_{1y} - \frac{L_1}{2} \times \sin\left(\pi - \arctan\left(k_1\right)\right) \\
k_1 = \frac{-1}{k}
\end{cases}$$
(9)

Coordinate of point B (Bx, By) can be solved by the same method.

Second measurement step-precision measurement by laser displacement sensor. The second measurement step depends on the laser displacement sensor to complete the precision measurement, and the measurement data are the height information in Z direction, cooperated with the movement of XY platform information, the 3D dimension measurement of the gear chamfering profile can be completed.

System movement. The movement is realized by the XY platform along the planned path. Commands controlling the movement of the XY platform are sent from the computer to the stepper

motors, and then the stepper motors drive the precision ball screw to complete the platform motion, which can control the movement precision to $1\mu m$. And the laser displacement sensor can be moved to the specified position on the XY plain by the platform under the different commands from the computer.

Measuring method. To finish the measurement, the laser displacement sensor can be moved along the planned path in the XY platform coordinate system, after the coordination of point A and B is solved by Eq. 9.

Gear chamfering profile measurement. The measurement result from the laser displacement sensor is the height value of the points on gear chamfering profile in Z direction, and the X and Y coordination can be achieved from the XY platform movements. So the 3D coordinate of points on the gear chamfering profile can be achieved by composing the above information from the laser displacement sensor and the XY platform movements. Set the Y coordinate as 0, then the gear chamfering profile can be drawn on one plain as shown in Fig.7. And Fig.8 shows the gear chamfering measurement results with different Y values in the 3D space.



Fig.7 Drawing result of gear profile

Fig.8 Surface profile of gear tooth

Conclusions

This paper designed a high precision collaborative measurement system for gear chamfering profile basing on the advantages of two different vision sensors. The system can meet the requirements of the high speed, precision and non-connect measurement. And this system is used to measure the gear chamfering profile, and the measurement precision is not lower than $1\mu m$. Moreover, this system needs no mechanical fixture, which makes a easy using and low cost measurement system.

Acknowledgements

This work was financially supported by the Tianjin Science and Technology Supporting Program (No.13ZCZDGX01400) and Tianjin University of Science and Technology Foundation (20130119).

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