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Design of Laser Scanning Optical System based on the Triangle Principle

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Abstract

In a three-dimensional laser scanning system, the measurement accuracy of the entire system is determined by the optical system. To improve the accuracy, this paper designs a three-dimensional laser scanning optical system. In order to improve the performance of scanning, to reduce the influence of stray light and the imaging geometric distortion is required, as far as possible to improve the distribution uniformity of the image illumination. In this paper, the semiconductor laser is chosen as the light source which is suitable for laser triangulation measurement. This system ensures accuracy in the first place, and obtain larger working distance later. The volume of the measuring system is reduced by introducing layout that the beam splitter and the normal are coaxial. The Scheimpflug conditions are deduced under this structure, and the experimental results of the laser triangulation optical system are analyzed finally.

***Keywords**: Laser scanning, the triangle principle, Three-dimensional laser scanning, Optical design, The Scheimpflug conditions*

1. Introduction

Non-contact detection can overcome the shortage of contact detection, and it will not cause scratches and damage on the surface to be measured, which can measure the workpiece made of various materials. The biggest advantage of non-contact detection is able to achieve real-time detection, so as to realize the control of machining process, and reduce the rejection rate. It can greatly save measure time, and improve production efficiency. Laser triangulation method is a non-contact measurement method, which is based on the classic principle of optical triangulation as the foundation. when the object plane moves, the displacement direction and receiving optical axis form an angel, therefore the method is called optical triangulation method. At present, the application of laser makes more and more attention to the laser triangulation measurement. It has the advantages of non-contact, high accuracy, fast response, measurable all kinds of materials, and simple structure. In order to further improve the measurement precision, in this paper, the design method of the laser triangulation probe optical system is improved.

2. Analysis of the Laser Beam Imaging

Although laser beam from the semiconductor laser has the advantages of very good directivity, narrower beam diameter and the smaller divergence angle are suitable for application in this design. The spot imaged by the laser beam on the surface of the CCD is still large compared with the CCD pixel, so the imaging spot will cover a number of pixels on the CCD. Inaccurate judgment about the spot

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location will seriously affect the scanning measurement accuracy. When the laser triangle measuring probe moves in this system, the image formed by the laser spot will move along the line array CCD image plane. The length and shape of the selected line array CCD photosensitive surface are determined. The range of spot imaging is larger compared with the CCD pixel. The image formed by spot may beyond the range of CCD effective pixels and scanning measurement. The spot which not beyond the range will result in a decline in measuring accuracy because of its large size. It is necessary to collimate and focus on the laser beam of semiconductor laser. First of all, to make the spot after target reflecting image on the CCD effective pixel, not beyond the range, so as to ensure the effectiveness of the spot. And then, in order to improve the measurement accuracy, the pixel number of spot is as little as possible. Therefore, need to treat the laser beam imaging to reduce the image size.

3. Laser Scanning Measuring Gaussian Beam Collimation Characteristics Analysis

The laser emitted by the laser will have a divergence angle. although the beam divergence angle of semiconductor lasers is small, there will be several mrad in generally. The magnitude of the divergence angle also affect the accuracy of scanning measurement. So in this paper, when laser scanning, an optical system is used to collimate the laser beam. The purpose of treatment is to obtain a better directionality of the laser beam, a smaller divergence angle, so that the measuring beam close to the parallel light eventually.

Gaussian beam far-field divergence angle formula shows:

$$\theta = \frac{\omega_0}{Z_0} = \frac{\lambda}{\pi\omega_0} \tag{3.1}$$

It can be analyzed that increasing its waist radius ω_0 or its equivalent public focal parameters Z_0 can reduce the divergence angle of Gaussian beams.

The double mirror group system which continuous exchange the laser beam twice can achieve the above functions, and can achieve the above functions. Generally the first lens group of double mirror group system has two composition which can be set up by also a positive power lens group or a negative power lens group. Relative to the positive power lens group, a negative lens group may be used to simplify the structure of the optical measurement system. The second lens group of double mirror group system use a positive power lens group generally, then the relationship of angular magnification is as follows:

$$\nu = \frac{2\theta_2'}{2\theta_1} = \frac{2\omega_{01}}{2\omega_{02}} = \sqrt{\frac{Z_{01}}{Z_{02}'}} \tag{3.2}$$

The $2\theta_1$ in formula (3.2) is divergence of the incident beam, and the $2\theta_2$ is divergence angle of the incident beam after transformation. $2\omega_{01}$ is waist diameter of the incident beam, and $2\omega_{02}$ is waist diameter of the incident beam after transformation. Z_{01} is equivalent confocal parameter of the incident beam, and Z_{02} is equivalent confocal parameter of the incident beam after transformation.

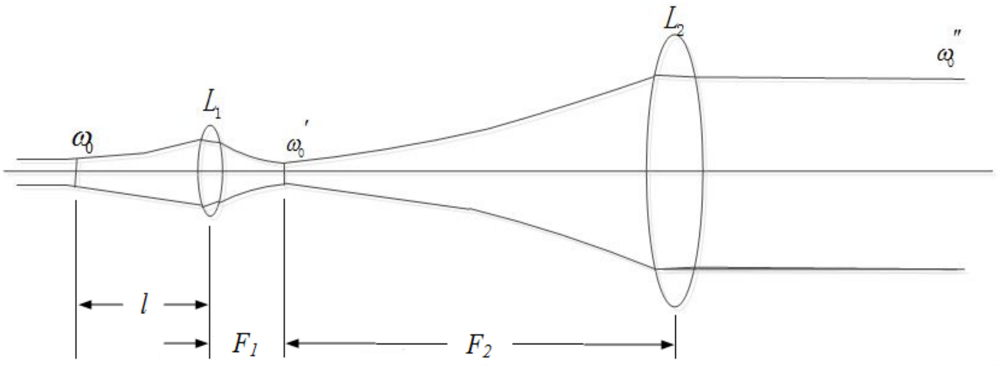

Figure 3.1. Gaussian Beams by the Double Lens Transform Sketch

The Gauss beam is from a laser transform to the double mirror optical system, and the transformation process as shown in Figure 3.1. The waist diameter of Gauss beam is $2\omega_{01}$, after the first lens group transformation, the position of beam waist is as follows:

$$\chi_1' = -\frac{\chi_1 f_1'^2}{\chi_1' + Z_{01}^2} \tag{3.3}$$

$$Z_{01}' = \frac{Z_{01} f_1'^2}{\chi_1^2 + Z_{01}^2} \tag{3.4}$$

It can be seen that the waist diameter after transforming through the first lens group is minimum. Then load on the front focal plane of the second lens group is to achieve transformation, to get the best laser beam parallelism. We can use Δ to represent the optical spacing in this case, namely $\chi_1' = \Delta$. Because in most practical designs, $Z_{01} >> f_1'$, therefore Δ is relatively small. Therefore, the above-mentioned two-mirror group system is similar to the telescope system, and the amount of defocus of the system is $\chi_1' = \Delta$.

For the second lens group, the converted beam is space beam, namely $2\omega'_{01} = 2\omega_{02}$, $Z_{01}' = Z_{02}$. So when $\chi_2 = 0$, we can obtain by

$$Z_{02}' = \frac{Z_{02} f_2'^2}{\chi_2^2 + Z_{02}^2}$$

Then:

$$Z_{02}' = \frac{f_2'^2}{Z_{02}} = \frac{f_2'^2}{Z_{01}'} \tag{3.5}$$

In the above case, the image space's equivalent confocal parameter Z_{02}' of the second lens group reaches a maximum value. We can calculate that the angle magnification of Gauss beam after dealing with the double lens optical system is expressed as:

$$\upsilon = \sqrt{\frac{Z_{01}}{Z_{02}'}} = \frac{f_1'}{f_2'}\sqrt{\frac{Z_{01}^2}{\chi_1^2 + Z_{01}^2}} \tag{3.6}$$

When $\Delta = 0$, double lens system is the telescopic system, then the angle magnification is obtained:

$$v = \frac{f_1'}{f_2'} \tag{3.7}$$

Through comparing formula (3.6) and (3.7), compared with the defocusing system, the telescope system has a smaller magnification and the beam divergence angle. When the waist of the first lens group transformed load on the front focal plane of the second lens group, the image space's waist will appear on the back focal plane of the second lens group, and therefore the optical system obtains a good collimation effect.

4. Design of Three-Dimensional Laser Scanning Measuring Optical System

The laser beam passes through the telescope beam expanding, collimating and focusing in the optical design of three-dimensional scanning measurement system, which reduce its the divergence angle of radiation to the surface of the object to be measured. The laser reflected by the object surface, through the beam convergence system, ultimately focused onto the image plane of CCD image sensor. Focusing is used to reduce the spot size of the laser beam on the measured object, so that it can be very good positioning analysis. The spot standard is to be able to meet the CCD minimum pixel size.

4.1 Analysis of Direct Triangulation Structure

According to the relationship between the incident and the normal of measured surface, laser triangulation measurement generally has two measurement structure, which are direct structure and oblique structure. The volume of direct measurement method is small and suitable for integration in a triangular probe. Its imaging spot is small, and is suitable for CCD positioning and segmentation. Its intensity is focused, and has a higher signal to noise ratio. Moreover, direct structure has small movement restrictions to the object to be measured. It is not easy to cause changes of imaging light.

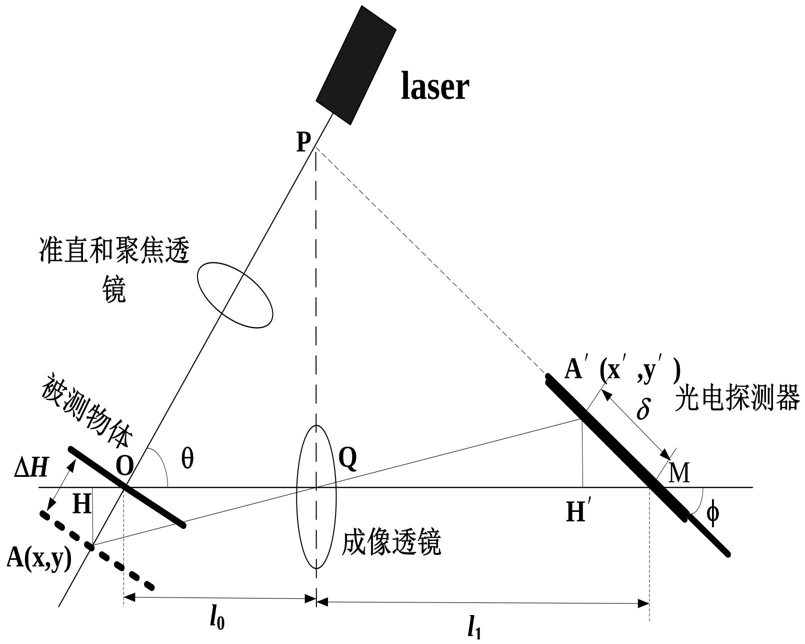

Figure 4.1. Laser Triangulation Measurement Optical Path of Direct Structure

4.2 Improvement of Direct Laser Triangulation Measurement Principle

Now a beam splitter is introduced to the direct laser triangulation measurement optical path. And the focusing and imaging lens are into one. The beamsplitter, detector, and condenser lens are coaxial in the space layout, which can ensure the structure more compact and the volume of the system smaller. It not only has the important meaning for the integration of the triangulation probe, but also can reduce the requirements about the measurement environment. The specific optical path is shown in Figure 4.2.

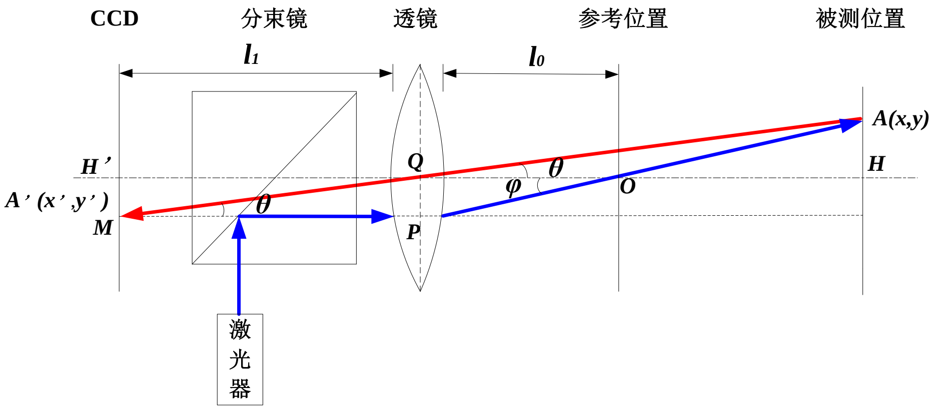

Figure 4.2. Optical Path Diagram of Laser Triangulation System

The optical path with the beam splitting mirror at an angle of 45 degrees makes the light emitted by the laser reflect to the condenser lens in the direction of parallel to the lens optical axis. And then irradiate onto the measured object surface after the action of converging lens. Because the object reflection (scattered light) is to be measured on the incident light, the light can be projected to the beamsplitter through the focus lens. The beam splitter on the part of the light transmission, is incident on the image sensing unit CCD, so CCD can capture these light and get on integral photoelectric conversion to form an electrical pulse output. These pulses data are collected, analyzed and processed. Eventually the transport signals that include distance information of the object can be measured and calculated to the host computer for correlation analysis, so as to realize the measurement of micro displacement of the object to be measured.

4.3 Improvement of Direct Structure Scheimpflug Conditions

In order to make the spot on the CCD receiver image clearly, optical path design need to meet the Scheimpflug condition. The imaging lens's focal length is expressed as f. The distance from the intersection of imaging lens axis and the incident beam axis to the front main surface of imaging lens is said by l_0, The distance from imaging center point of image sensor CCD to the back main surface of imaging lens is expressed as l_1. The angle between the incident laser beam axis and the imaging lens axis is φ. The angle between the reflection laser beam and the imaging lens axis is θ. We have to select measured reference point firstly, when the light spot that the incident beam irradiates to the object surface to be measured just falls at the axis of an imaging lens. It is the most conducive to measure. The point O is as the measured origin of coordinates to establish a Cartesian coordinate system, and the X axis of the coordinate system is the optical axis. The right of origin O is defined as "+", and the left of origin O is defined as "-". According to the imaging conditions of paraxial optical system, to make the light spot that passes through the origin O clearly image on the image sensor CCD after through the imaging lens. It is need to meet the formula (4.1):

$$\frac{1}{l_0}+\frac{1}{l_1}=\frac{1}{f} \tag{4.1}$$

If the measured point along the direction of the incident optical axis from the original reference position to target point is A in the figure, the point coordinate can be represented by *A(x,y)*. Then the imaging lens will image a corresponding image point, the coordinate of the point image will be represented by $A'(x', y')$(also named as the point *M*). According paraxial imaging conditions, in order to clear imaging, the image point A' which is formed by the target point A through the lens need to meet the formula (4.2):

$$\frac{1}{x-l_0}+\frac{1}{l_0-x'}=\frac{1}{f} \tag{4.2}$$

Because of $\Delta AHQ \backsim \Delta A'H'Q$, the relationship $\frac{\overline{AH}}{\overline{\overline{HQ}}}=\frac{\overline{A'H'}}{\overline{\overline{H'Q}}}$ can be obtained, namely:

$$y'=(\frac{l_0-f}{f}\cdot\tan\theta)\cdot x'-\frac{l_0^2}{f}\tan\theta \tag{4.3}$$

From equation (4.3), there is a linear relationship between y' and x'. This linear relationship reflected in the CCD is that the object to be measured moves along the direction of the incident light, and the track of the light spot which is formed by the irradiation of a laser beam reflected by the object beam after through the imaging lens is a straight line on the CCD. In order to obtain a clear image and to meet the linear relationship corresponds to the image line, CCD should be placed on the track of this straight line that is corresponded to the linear relationship.

According to the coordinate system established previously with *O* as the origin and the optical axis of the X-axis, we can determine the relative positional relationship between the incident laser light, the imaging lens and the image sensor CCD through the geometric relationship, namely the formula (4.4).

$$\tan\varphi=\frac{\overline{PM}}{\overline{\overline{QO}}}\tan\theta=\frac{l_1}{l_0}\tan\theta \tag{4.4}$$

The "Scheimpflug" conditions in the formula (4.4) can overcome the phenomenon of defocusing, and the conditions is satisfied with constant focus system. The formula (4.5) can be obtained:

$$\tan\theta=\frac{l_0-f}{f}\tan\varphi \tag{4.5}$$

The placement of the CCD image sensor can determined with equation (4.5).

According to the design idea of this article, a beam splitter is introduced in the energy of laser source through the beam splitter twice, and result in a two splitting. While in the design of the paper the beamsplitter adopts splitting ratio of 50%, so that optical signal energy obtained by CCD reaches a maximum finally. However, the absolute energy obtained is only 25% of energy emitted by the laser light source. In order to obtain a good spot signal and a higher noise ratio, the laser light source have a high power and a more stable performance.

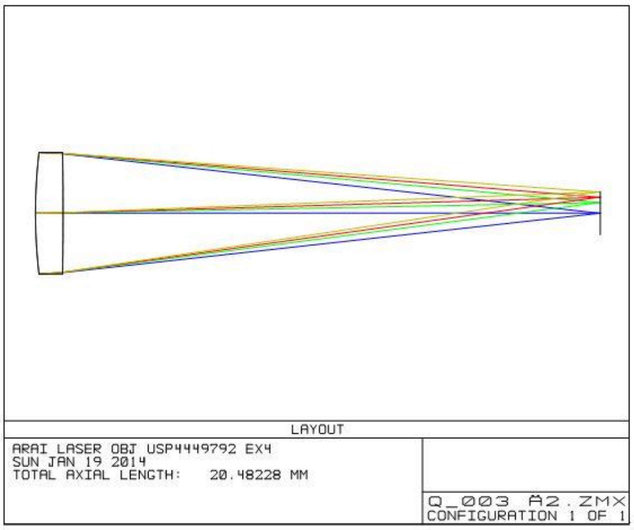

Figure 4.3. Optical System Structure Diagram

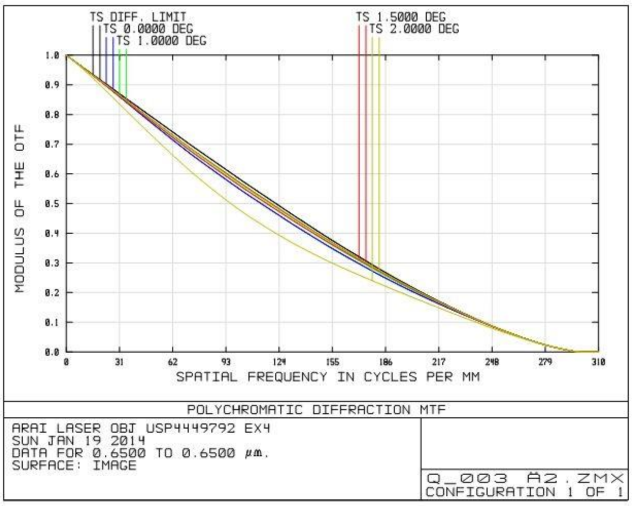

Figure 4.4. Modulation Transfer Function Curve

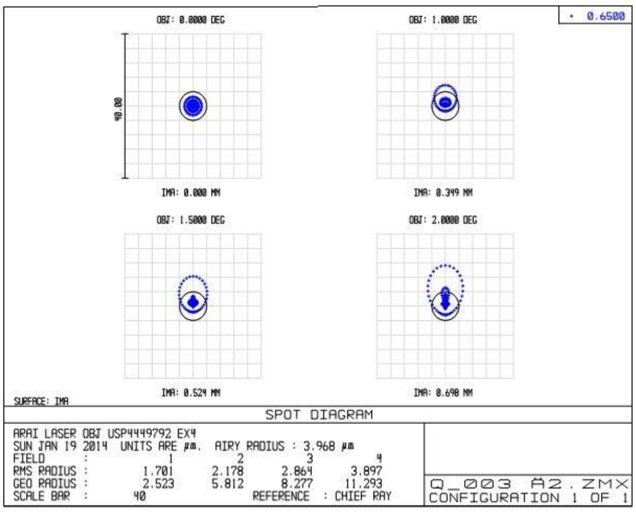

Figure 4.5. Spot Diagram

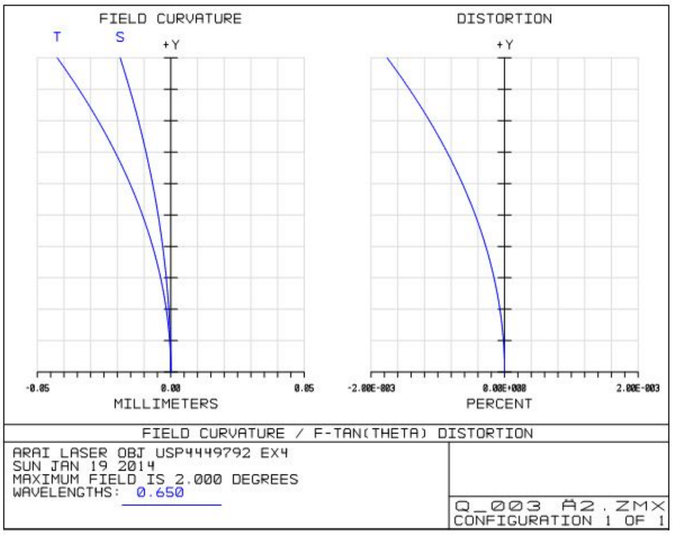

Figure 4.6. Astigmatism, Curvature of Field and Distortion Curve

5 Analysis of Design and Result

The number of lenses is reduced, which makes the image quality limited, so the first surface of the lens is even-order aspherical. This system's laser wavelength is $\lambda = 650nm$, and focal length is $f' = 20mm$. Entrance pupil diameter is 4mm, systems for a total length TOTR is 20.5mm. It meets the miniaturization of the entire system with the size of the beam splitter.

The image quality is as shown in Figure 4.3-4.6. By the cutoff frequency in the range, transfer function (MTF) is close to the diffraction limit, and only meridian transfer function in field edge is slightly worse. Spot diagram of the root mean square radius are basically within the Airy disk. Relative distortion is less than 0.002%. By properly selecting the lasers and photo detectors, it fulfils the high detection precision of laser triangulation with the optical system.

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