A Novel Double Triangulation 3D Camera Design

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Abstract— In this paper, a novel structure of 3D camera based on laser double triangulation displacement sensor is proposed. By placing two mirrors in the optical routes, double triangulation can be gotten by using only one CCD. Through designing the place and angle of these mirrors, the Scheimpflug condition could be met in whole measurement range of the sensor. And results of experiment have showed that this design could overcome some problems caused by inclination and blocking of work piece’s surface. This design make the 3D camera much more cheaper and improved the measurement precision.

Index Terms— 3D Camera, Non-contact Measurement, Double Triangulation, Scheimpflug Condition

I. INTRODUCTION

Three dimensional images are much more important in scientific and industrial field now days for measurement and quality assurance. One of the most important methods to get 3D images is laser triangulation because it has some good properties such as non-contact, simple structure, high precision and fast measurement speed. 3D sensors based on laser triangulation have been used widely in geometric parameters inspection, surface profile measurement, 3D modeling and reverse engineering [1].

Designing of 3D camera based on laser triangulation mainly include optical route designing, algorithm to calculate centre of laser strip or laser spot, and sensor calibration. The measurement precision will be effected by some factors such as model of imaging for laser strip, inclination and reflective properties of work piece surface, another problem is the blocking near the steps or holes.

A lot of works have been done by some researchers to overcome these problems, and some other papers present smart structures of laser triangulation for special applications. Errors analysis and some ways to eliminate them were presented [2]. Some novel structures were presented as solutions for surface inclination and blocking in measurement. [3] [4] [5]. Some algorithms for calculate centre of laser strip were given and their performance were compared [6] [7] [8]. Some methods for calibrating laser triangulation sensor were presented in [9] [10]. And free surface modeling and presenting based on dot cloud gotten by laser 3D camera were given in reference [5] [9].

In this paper, a novel optical route structure for laser triangulation based 3D camera is presented. By adding two mirrors in optical route, double triangulation is realized by using only one CCD sensor. This design reduces the cost of 3D camera a lot, make the sensor much more smaller and lighter, overcome errors arose by inclination and avoid information lost by blocking of work pieces surface effectively. At the same time, through designing the places and angles of mirrors, the Scheimpflug condition is met, and this makes the laser strip can be well focused in detector in whole measurement range, improves measurement precision more.

This paper is organized as follow. In the following section, foundation of laser triangulation is introduced. In the third section, the optic route design, the algorithm for peak detection of laser strip, and the calibration of this 3D camera is introduced systemically. In the fourth section, some experiments are given including measurement precision analysis and measuring and modeling results. The last section is a summary for this 3D camera.

II. PRINCIPLE OF LASER TRIANGULATION

The principle of laser triangulation is shown in Fig.1. In this arrangement, laser source projects a laser strip on the surface of the work piece, this strip will gives the cross section profile of work piece in the laser plane. This strip will be imaged on a detector, and every point in this strip presents a corresponding point’s poisiton on the surface. Where $\alpha$ is the angle between the axis of projected laser and the axis of the imaging lens; $\beta$ is the angle between surface of the detector and the axis of the imaging lens; $s$ and $s'$ are object distance and image distance; $d$ and $\delta$ are the offset of the imaged point on the detector and the offset of the work piece surface. Other relational parameters of this system include the stand-off distance $D$ is the distance between the sensor to the reference point of the object, it’s also known as work distance; the measurement range is the maximum of $\delta$ ; another important parameter is the resolution, normally vertical resolution, it means the ratio of the measurement precision to the measurement range.
In order to focus the laser strip on the detector well in whole measurement range, design of the optical route must meet the Scheimpflug Condition: the image plane, the object plane and the main plane of the imaging lens should intersect in one line, as the point X in Fig.1.

The non-linear input-output function of this system is:

$$\delta = \frac{ds \sin \beta}{s' \sin \alpha - d \sin(\alpha + \beta)}$$ (1)

also can be written as:

$$\delta = \frac{dA}{B - d}$$ (2)

where $A = \frac{s \sin \beta}{\sin(\alpha + \beta)}$ and $B = \frac{s \sin \alpha}{\sin(\alpha + \beta)}$ is constant parameters of the triangulation measurement. And when $\delta$ is quite small, equation 1 can be simplified approximately to a linear equation as:

$$\delta = \frac{ds \sin \beta}{s' \sin \alpha}$$ (3)

III. SYSTEM DESIGN OF FOLDED OPTICAL ROUTE DOUBLE TRIANGULATION 3D CAMERA

A. Optical Route Design

In order to solve the problem of the inclination and blocking of work piece surface, a lot of industrial laser triangulation sensors adopt a double triangulation arrangement. In this method a symmetric detector and lens are used on the other size of the laser axis. But this method will increase the cost of sensor and 3D camera and make the image acquisition and information processing more complicated. In this paper, two mirrors are inserted in to the receiving optical system, and then the double triangulation can be realized by using only one CCD. The principle is shown in Fig.2.

During the design of optical arrangement, the key problem is how to place these mirrors to make the whole system meet the Scheimpflug Condition. Fig.3 gives the right half part of the optical arrangement. Laser is projected on work piece to form a measurement strip at point P, it will be imaged to P’ by lens L1, but actually it is imaged to point Pi because of the mirror M1. C1’ is the virtual CCD detector, and the planes of C1’, lens L1 and laser axis will insect in one line, which is presented by point X. This means the Scheimpflug Condition is met.

The angle $\alpha$ is determined by the equation of lens imaging. The line P’Pi is made from point P’ which makes the angle $\beta$ between P’Pi and P’X to be $1/2 \alpha$. If the CCD is placed at the point Pi which is the intersection of line P’Pi and the laser axis, the laser strip will be focused well on CCD detector in whole measurement range.
B. Calibration of the 3D camera

In order to get a precise description of the corresponding relation between the point coordinate in image and the point place in real world, calibration of the 3D camera is very important. Because of the lens aberration and perspective, a cubic polynomial is used to model the coordinate mapping relation between the image coordinate \((r, c)\) and the world coordinate \((y, z)\) [9].

\[
\begin{pmatrix}
  r^3 c^3 r^2 c^3 r c^2 r c \ 1
\end{pmatrix} \cdot M = z
\]

(4)

\[
\begin{pmatrix}
  r^3 c^3 r^2 c^3 r c^2 r c \ 1
\end{pmatrix} \cdot M = y
\]

(5)

where \(M\) is the calibration matrix. A serial of image coordinate \(r\) and \(c\) can be gotten at corresponding points in real world with known places, then by getting the least squares solution of this inconsistent system the calibration matrix \(M\) can be built. And the real world coordinate \(z\) and \(y\) can be calculated by take the peak position of laser strip in to equation (4) and (5). It will have form as:

\[
\begin{pmatrix}
  z_1 \\
  z_i \\
  z_n
\end{pmatrix} =
\begin{pmatrix}
  r^3 c^3 r^2 c^3 r c^2 r c \\
  \ldots \\
  r^3 c^3 r^2 c^3 r c^2 r c \\
  \ldots \\
  r^3 c^3 r^2 c^3 r c^2 r c
\end{pmatrix}
\begin{pmatrix}
  r_1 c_1 \\
  r_i c_i \\
  r_n c_n
\end{pmatrix}
\cdot
\begin{pmatrix}
  f_1 \\
  \ldots \\
  f_i \\
  \ldots \\
  f_n
\end{pmatrix}
\]

(6)

Where subscript \(n\) means we have gotten \(n\) points in the laser strip and \(p\) is 10.

Because two parts of the camera will be calibrated independently, the error of installation of mirror will have almost no effect on the measurement result.

C. Algorithm for peak detection of laser strip

There are several good algorithms for sub-pixel peak detection of laser strip, such as centroid of gray, Gaussian fitting and linear interpolation [6]. In this paper, the Blais and Rioux Detector (BR4) [6] is used. In this detector, 7 pixels around the peak is used in three serial linear filters:

\[
g_{4}(x - 1) = f(x - 3) + f(x - 2) - f(x) - f(x + 1)
\]

(7)

\[
g_{4}(x) = f(x - 2) + f(x - 1) - f(x + 1) - f(x + 2)
\]

(8)

\[
g_{4}(x + 1) = f(x - 1) + f(x) - f(x + 2) - f(x + 3)
\]

(9)

where \(f(x)\) is the gray level of the peak pixel, and \(x\) is the column of the peak pixel, and \(g(x)\) are filters which are some what like digital differential operators, and then equations for peak detection are:

When \(f(x + 1) > f(x - 1)\):

\[
i = \frac{g(x)}{g(x) - g(x + 1)}
\]

(10)

When \(f(x + 1) < f(x - 1)\):

\[
i = \frac{g(x - 1)}{g(x - 1) - g(x)} - 1
\]

(11)

IV. EXPERIMENTS AND RESULTS

The experiment system is built by general optical adjustable component. It’s shown in Fig.4. And at first a ground glass is placed in the optical route as the CCD detector.

Fig. 4. The experiment setup of the folded double triangulation 3D camera. 1-CCD camera, 2- ground glass screen, 3- mirrors, 4- LD projector, 5- imaging lens, 6- scanning system.

The laser strip is well focused in whole measurement rang, as shown in Fig.5.

Fig. 5. The laser strip is well focused in whole measurement rang.

In whole measurement range, 144 points with known place are used to get the calibration matrix, and there are 4 calibration matrixes for \(y\) and \(z\) in each half part of the image. the
results calibration matrix of left half of image are given as:

\[
M_{YL} = \begin{pmatrix}
8.95337177557112 \times 10^{-9} \\
6.19803716347407 \times 10^{-7} \\
-5.94762018504796 \times 10^{-9} \\
4.3104045365708 \times 10^{-8} \\
-4.70677134348739 \times 10^{-6} \\
0.00080125934412 \times 10^{-5} \\
2.91460453199633 \times 10^{-7} \\
0.007038925857713 \\
0.469155130719863 \\
-39.385134688073
\end{pmatrix}
\]  
(12)

\[
M_{ZL} = \begin{pmatrix}
-1.94024261130711 \times 10^{-9} \\
-6.6394619742872 \times 10^{-7} \\
-1.63409199195485 \times 10^{-8} \\
-8.9961803822577 \times 10^{-9} \\
1.32058609784045 \times 10^{-6} \\
-0.00011517695292 \times 10^{-5} \\
1.4701265640834 \times 10^{-5} \\
7.06835574355092 \times 10^{-6} \\
-0.140407153820926 \\
56.7880471064192
\end{pmatrix}
\]  
(13)

In Fig.6, the residual errors calculated by cubic polynomial fitting at 144 known points are given. From the figure, the measurement precision can be estimated as better than 0.03mm and the resolution of this design of 3D camera will be about 1/2000. At the same time, because of there are two measurement for each point in space, the average result is better than left or right result.

Fig.7 gives a measurement of a resinous gear which is built by rapid laser molding, and because of the double triangulation arrangement, inclination of the surface and the blocking by teeth are not very apparent.

Fig.8 gives another measurement result of a plastic work piece with steps, edges, and holes. The rebuilding result has shown that most of these details can be represented correctly.

V. SUMMARY

In this paper, a new design of folded double triangulation laser 3D camera is presented. By using two mirrors folds the optical route to realize double triangulation measurement with only one CCD detector. This design make the cost of 3D camera much more cheaper, and the structure of optical system is very flexible, can be used in a lot of applications.

The arrangement of optical system is realized as well as the signal (image) processing and a modified calibration method. Experiments for measurement and rebuilding have been done. The results have shown that this design is robust and precise, will have wide application future.

Some next work include: optimizing parameters of optical system, investigating more simple and precise calibration methods specially for virtual stereo-vision, and how to make improvement by using the information redundancy of virtual stereo-vision.
Fig. 7. Measurement and rebuilding of a resinous gear. (a) is photo of the gear, (b) is the rebuilt model of the gear, (c) displays some detail of it, from the point cloud, it can be seen that the inclination and blocking of teeth almost have no effect on the measurement result.

Fig. 8. The measurement and rebuilding of a plastic work piece with edges, steps, and holes. The rebuilt surface looks not very smooth because the material of this work piece is somewhat translucent, which affects the peak detector a little bit.

REFERENCES


