Development of Laser Stripe Sensor for Automatic Seam Tracking in Robotic Tailored Blank Welding

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Abstract - This paper describes the development of laser stripe sensor for automatic seam tracking system in robotic tailored blank welding. Laser stripe sensor which is used to obtain profile of weld seam plays an important part in seam tracking system. The sensor consists of a CMOS camera based on FPGA (Field Programmable Gate Arrays) and a stripe-type laser diode due to high speed requirement of tailored blank welding. Its measuring error and performance make a direct effect on the measuring accuracy and reliability of the seam tracking system. A mathematic model is established in order to analyse the influence on sensor error from the geometric parameters. And then the reasonable geometric parameters are yielded according to the simulation results. Additionally, careful considerations about laser diode have been under taken in this paper in order to obtain high quality raw images of laser stripe and the feature points for seam tracking of robot manipulation are calculated by feature extracting algorithm. Finally, some experiments are carried out for proving the efficiency of the laser stripe sensor.

Index Terms - laser strip sensor, seam tracking, tailored blank welding, error analysis, feature points extracting

I. INTRODUCTION

Tailored blank welding (TBW) is an advanced welding technique used to join multiple pieces of metal through the use of a laser. Tailored blank construction has widespread application in automotive including body side-frames, door inner-panels, motor compartment rails, center pillar inner-panels and wheelhouse/shock tower panels [1]. The laser welding system uses very narrow laser beam for welding and it requires accurate alignment of the work piece with the position accuracy up to sub-millimeters. Obviously, this critical requirement could not be satisfied by the accuracy of industrial robot [2]~[3] used in TBW when the seam is long. In addition, poor jig fixing and errors of materials could also cause the distortion during the welding process. For these purposes, the seam tracking system is needed to align the torch along the welding seam automatically. Therefore intelligent laser optical sensors such as the triangulation-based laser stripe sensor [4] are used to acquire information about the weld seam. Although laser stripe sensors have been available since the mid 1980s they are rarely found in industrial applications [5]. Reasons for this are the unaffordable prices and unreliability in harsh welding environment [6]. In present, many research organizations are bending their selves to the development and application of laser strip sensor for seam tracking including Servo-robot Inc, Meta Vision Systems Inc, Institute of Automation, Chinese Academy of Science [7] and Tsinghua University [8] etc.

Laser stripe sensor which is used to obtain the images of weld seam plays an important part in Seam tracking system. The sensor error is determined by the geometric parameters of its configuration, the parameters of the camera [9], speckle, and lens distortion. Its measuring error and performance make a direct effect on the measuring accuracy and reliability of the seam tracking system. In this paper, a mathematic transformation model is established in order to analyse the influence on sensor error from geometric parameters. And then the reasonable geometric parameters are yielded according to the simulation results. In addition, careful considerations about laser diode have been under taken in this paper in order to obtain high quality raw images of laser stripe and the feature points for seam tracking of robot manipulation are calculated by feature extracting algorithm.

II. SEAM TRACKING SYSTEM DESIGN

A. System overview

The seam tracking system consists of a laser stripe sensor, a monitor center and a motor controller. In robotic tailored blank welding, the laser stripe sensor is mounted in front of the welding torch, separated by a look-ahead distance between the sensor and the torch to acquire the profile information of the weld seam. The monitor center is an industrial PC used for setting hardware parameters in the seam tracking system and display the profile of weld seam. The industrial PC can be integrated in a TCP/IP network for data exchange with the camera. The motor controller was composed of two axis actuators, actuator driver and a motion – controller card based on DSP. The system contains its own processing unit, and transfers the necessary information to the robot controller via RS-232 interface. Fig. 1 is a block diagram showing the various components of the system and their relationships.

The intelligent camera captures images of the weld seam and processes the images to detect the seam points and the width and length of the weld groove. Subsequently, the seam points are passed to the motion controller for instructing the axis to move the welding torch and the sensor aligning the torch in relation to the weld seam.
B. Real-time hardware design

The tailored blank welding has a high speed up to 10m/min in normal applications. In order to satisfy the high accuracy of the seam tracking, the sensor’s frame rate should attain 100Hz and it results in a data stream of 70-80MByte/s. So the processor should have stronger calculation power and could be integrated in the sensor head due to the limited space. An intelligent camera based on FPGA and DSP was adopted for image acquisition and image processing in real time. For image processing operations FPGA offers the same performance as multiprocessor solutions at a drastically lower price. This is ideal for this application.

III. LASER STRIPE SENSOR CONFIGURATION AND ERROR ANALYSIS

A. Laser configuration

Laser-stripe sensors are based on active laser-triangulation [10]. A laser stripe (\(\lambda = 650nm\)) is projected onto the work piece surface and the scattered light is observed under the triangulation angle with a CMOS-matrix camera. A narrow band pass optical filter matched to the laser diode’s wavelength is typically used to improve the signal-to-noise ratio of the sensor while rejecting the majority of laser radiation. For welding applications, the laser light source, filters, lenses, and camera are housed within a protected enclosure that is water-cooled, and typically utilize positive air pressure and protective optics to protect the sensor from spatter and fumes associated with laser welding.

The total system is assembled into a compact module which can be attached to the head of welding robot system. All components are carefully selected to have light weight and small size due to the critical requirement of the weight and size of the sensor. The configuration of laser stripe sensor is shown in Fig. 2.

B. Measuring error analysis

Many factors will have effects on the measuring accuracy and reliability of the seam tracking system such as measuring error and performance of the sensor, speckle error and lens distortion error etc. The measuring error of laser stripe sensor will be analysed in this section.

A mathematic model is established according to the perspective transformation model of laser stripe sensor as shown in Fig. 3. At first, two coordinate systems will be defined as \(O_i - x_iy_iz_i\) and \(O_g - x_gy_gz_g\) which \(O_i - x_iy_iz_i\) is an image coordinate system and \(O_g - x_gy_gz_g\) is an object coordinate system. The original point \(O_i\) that laser diode emit laser on the work piece. Coordinate axis \(x_g\) and \(y_g\) are parallel and perpendicular to the direction of weld seam separately. Coordinate axis \(z_g\) is perpendicular to the work piece.

\[o_i(0,0,\text{Hi}_i)\]

\[o_g(O,0,\text{Hi}_g)\]

\[\alpha(\Omega,0,\text{Hi}_\alpha)\]

\(o_i\) is the centre point of image plane and coordinate axis \(z_i\) is optical axis of camera and have an angle of \(\beta\) to the vertical direction. The axis \(y_i\) is on the assumption that parallel to axis \(y_g\) in order to simply the configuration. The laser plane is projected to the work piece having an angle of \(\theta\) with axis \(z_g\) and the projected line is named \(AB\) which intersects a point with \(z_i\). Subsequently, define the coordinate of a point on line \(AB\) is \((x,y,z)\) and its corresponding coordinate in object coordinate system is \((x_g,y_g,z_g)\). Finally,
The mathematic model of laser stripe sensor is obtained as equation (1).

\[
\begin{align*}
X_s &= \frac{x_i[\cos \beta (H_L - H_i) - f + L \sin \beta]}{x_i[\sin \beta \cos \beta \cot \theta + f (\sin \beta \cos \theta - \cos \beta)]} + \frac{f [\sin \beta (H_L - H_i) - L \cos \beta]}{x_i[\sin \beta \cos \beta \cot \theta + f (\sin \beta \cos \theta - \cos \beta)]}, \\
Y_s &= \frac{\tan \theta (f \cos \beta + H_L) - (f \sin \beta - L) - H_i \tan \theta}{x_i (\cos \beta \sin \beta \tan \theta + f (\sin \beta - \cos \beta \tan \theta)}, \\
Z_s &= \frac{x_i (H_i \sin \beta \tan \theta + H_i \cos \beta + f - L \sin \beta)}{x_i (\sin \beta \tan \theta + \cos \beta) + f (\sin \beta - \cos \beta \tan \theta)}, \\
\end{align*}
\]

(1)

Where \( f \) is the focal length of camera, \( H_i \) and \( H_L \) are the vertical coordinates of point \( o_i \) and \( o_L \). \( H_L = l_{\text{Laser}} \cdot \cos \theta \) and where \( l_{\text{Laser}} \) is the distance from laser emit point to the work piece.

The coordinate of measured point on weld seam in object coordinate system is not only determined by its corresponding coordinate in image coordinate system but also determined by the configuration parameters of sensor such as \( H_i, H_L, L, \theta, \beta, f \).

\( p(x, y, z) \) is the function for calculating the coordinate of the measured point. The perspective transformation model show that \( H_i \tan \theta + H_L \tan \beta = L \). So, the function is denoted as equation (2).

\[
p(x, y, z) = F(H_i, H_L, \theta, \beta, f, x_i, y_i)
\]

(2)

The measuring error includes calibration error of these configuration parameters and extracting error of the image coordinate of the measured point. The measuring error could be denoted by the measuring error in different coordinate axis directions of \( x_i, y_i, \) and \( z_i \) according to the theory of error analysis.

The laser stripe sensor will be calibrated accurately before using, so the calibration error can be ignored. The measuring error \( \Delta \) are only caused by the extracting error of the image coordinate of the measured point in different coordinate axis directions.

The extracting algorithm will be supposed fixed and the extracting error will be a fixed value: \( \delta = \delta_x = \delta_y = 0.25 \cdot \text{pixel} \).

Where \( \text{pixel} \) is the size of image point.

The measuring error of laser stripe sensor is shown in equation (3).

\[
\Delta = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} = \sqrt{\left(\frac{\partial x}{\partial x_i}\right)^2 + \left(\frac{\partial x}{\partial y_i}\right)^2} + \left(\frac{\partial y}{\partial x_i}\right)^2 + \left(\frac{\partial y}{\partial y_i}\right)^2 + \left(\frac{\partial z}{\partial x_i}\right)^2 + \left(\frac{\partial z}{\partial y_i}\right)^2} \cdot \delta
\]

(3)

When design the geometric parameters of the laser stripe sensor, the measuring error should be minimum possible. The maximum value \( \Delta_{\max} \), the mean value \( \Delta_{\text{mean}} \) and the standard variance \( \sigma_{\Delta} \) of the measuring error will be as the parameters for designing the geometric parameters of the laser stripe sensor optimally in order to increase the accuracy. The criterion will be proposed that \( \Delta_{\max}, \Delta_{\text{mean}} \) and \( \sigma_{\Delta} \) should be minimum under constraint conditions.

\[
\Delta_{\max} = \max(\Delta_{ij}) \quad (4)
\]

\[
\Delta_{\text{mean}} = \frac{\sum \Delta_{ij}}{n}, (n = i\cdot j) \quad (5)
\]

\[
\sigma_{\Delta} = \sqrt{\frac{\sum (\Delta_{ij})^2}{n}}, (n = i\cdot j) \quad (6)
\]

Where \( \Delta_{ij} \) is the measuring error related to the \( i^{th} \) line and the \( j^{th} \) column image point.

The partial derivative of equation (1) respect to \( x_i \) and \( y_i \) can be calculated and then are substituted to equation (3), and the measuring error \( \Delta \) is achieved.

The measuring error of the laser stripe sensor is respect to \( x_i, y_i, \delta, f, H_i, H_L, \theta \) and \( \beta \). The measuring error is various according to the different position of the image point and its distribution is non-homogeneous.

The maximum measuring error in \( y \) axis direction of the image plane is occurred in edge points and the maximum measuring error in \( x \) axis direction of the image plane is occurred in one of the edge points and related to \( \theta \) and \( \beta \). The relationship between measuring error and coordinate of image points is illustrated in Fig. 4. The measuring error is direct proportion to extracting error of the image coordinate of the measured point. When \( \beta = 0 \), the camera and laser diode as well as the extracting algorithm is fixed, the parameter \( \theta \) will be the primary factor that will have a nonlinear effect on the measuring error.

C. Simulation results

According to the measuring error analysis above, the configuration of the laser strip sensor for seam tracking system can be designed optimally think of different requirements.
The laser stripe sensor developed in this paper will be applied for automatic seam tracking in tailored blank welding. There are two methods for designing the configuration of this sensor. Method 1 is $\theta = 0$ and method is $\beta = 0$. The field of view is 10~15mm and the resolution is 0.01mm. The frame of the CMOS camera selected is $1280 \times 1024$ and the size of one pixel is $5.2 \mu m \times 5.2 \mu m$. The focal length is 50mm. When the extracting error of the image coordinate of the measured point is $0.25 \text{pixel}$. Supposing $I_{laser} = 50mm$ and $H_i = 90mm$, the parameters are substituted to optimization equation for simulating. The simulation results are shown in Fig. 5~7 which indicate that the optimum solution is obtained when $\theta = 55^\circ$ of method 2.

IV. IMAGE PROCESSING

The system with the stripe type laser diode can capture the profile image which is inside the triangular plane projected by the laser stripe. In order to obtain high quality raw images of laser stripe, careful considerations should be under taken to select the line width and the power of the laser diode. Especially, the seam width is about 0.02mm in tailored blank welding, so the line width should be about 50 $\mu m$. The output power of the stripe laser will influence the quality of the raw image of weld seam. The high laser output power will cause the saturation of its intensity which is shown in Fig. 8 and more noise including speckle will be caused in high laser output power. When the adequate laser output power is selected, the high quality raw image of weld seam will be captured. Fig. 9 illustrates the raw image and intensity of it in adequate laser output power.

After capturing the image, a tracking region of interest is placed at first in order to save the image processing time. Subsequently, the image will be pre-processed due to the noise caused by the spatter and welding laser. Then the feature point for tracking should be extracted. Conventional profile extraction methods are based on the search for the pixel with the highest intensity in every row with some form of fine interpolation, e.g. by using a centre of gravity algorithm [5]. However, weld seam of tailored blank welding is slightly more difficult to measure, especially at smaller
gaps when the plate edges are very sharp. Sum the intensity in every row and the minimum sum value corresponding to the row will contains the seam point.

V. EXPERIMENTS

The developed sensor used in the seam tracking system which is attached to the end effector of the industrial robot shown as in Fig. 10 and some experiments are carried out. In the experiments, two mono-thickness tailored blanks of 0.8mm thickness will be for laser welding with butt seam. The profile data is obtained at 6m/min in moving direction.

After capturing and processing the image of weld seam, the profile of weld seam could be obtained and the feature point could be extracted which verify the accuracy of this design method. Fig. 11 is showing the results of the processing and the low point is the feature point that should be tracked.

VI. CONCLUSIONS

In this paper, the measuring error and performance from the geometric parameters is analysed and the reasonable geometric parameters are yielded according to the simulation results. The simulation results also indicate that the measuring error is not only related to the geometric parameters but also respect to the position of the measured point in image plane. Error caused by speckle and lens distortion will be discussed in future works. Subsequently, careful considerations about laser diode such as the line width and output power have been under taken in this paper in order to obtain high quality raw images of laser stripe. The feature extracting algorithm is discussed due to the weld seam of tailored blank welding is slightly more difficult to measure, especially at smaller gaps when the plate edges are very sharp. Finally, the experiments results illustrate the feasibility and effectiveness of the laser stripe sensor. The laser stripe sensor will be tested in a welding environment in order to optimize its performance. Its industrial application is expected for the coming year.

ACKNOWLEDGMENT

The author wishes to thank Shenyang Advanced Equipment Research and Design Center, Shenyang Institute of Automation (SIA) for supporting this research.

REFERENCE