Robotic tool positioning process using a multi-line off-axis laser triangulation sensor

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Abstract: Proper positioning of a friction stir welding head for pin insertion, driven by a closed chain robot, is important to ensure quality repair of cracks. A multi-line off-axis laser triangulation sensor was designed to be integrated to the robot, allowing relative measurements of the surface to be repaired. This work describes the sensor characteristics, its evaluation and the measurement process for tool positioning to a surface point of interest. The developed process uses a point of interest image and a measured point cloud to define the translation and rotation for tool positioning. Sensor evaluation and tests are described.

Keywords: laser triangulation, 3D measurement, tool positioning, robotics.

1. INTRODUCTION

Laser triangulation sensors integrated to robots have been used to measure three-dimensional shapes of complex objects [1] and following joints in welding [2][3][4], usually with the projection of a single laser line [1][2][3]. A measurement model for this type of system extends the classic pinhole camera model associated with a mathematical plane defined by the laser "light sheet"[1][8][9][10]. Multi-line sensors [4][5] can determine further information about the relative angle of the surface of interest in a single acquisition, as well as, to acquire a larger number of points.

Correct positioning and alignment of a friction stir welding head, driven by a developed closed chain robot, is essential to repair cracks appropriately on a damaged surface. Figure 1 shows the closed chain robot. Surface positioning and orientation at pin insertion point must be known and it motivates the development of a special measurement process and sensor that can measure a point cloud that represents the surface and the 3D position of the pin insertion point. Special characteristics of the developed sensor includes (1) measuring position and orientation in a single acquisition, (2) measurement coordinate system aligned to tool center point (TCP), (3) inability to remove the sensor during repairs and (4) spatial restrictions to avoid self-collision with the robot.

Figure 1. Closed chain robot with a friction stir welding head.

2. LASER TRIANGULATION SENSOR

2.1. Configuration

The mechanical and optical configuration was designed to position the laser emitters and the camera in an off-axis configuration regarding the robot tool axis. The sensor can detect surface position and orientation in a single acquisition, thus the measurement of the relative surface normal direction do not depend directly on the robot absolute accuracy. Figure 2 shows the actual developed sensor integrated with the robot.

The optical configuration was defined for maximum sensitivity with 50 mm range in Z direction (tool axis) using a camera with 1280 x 960 pixels and a 12 mm focal length lens.

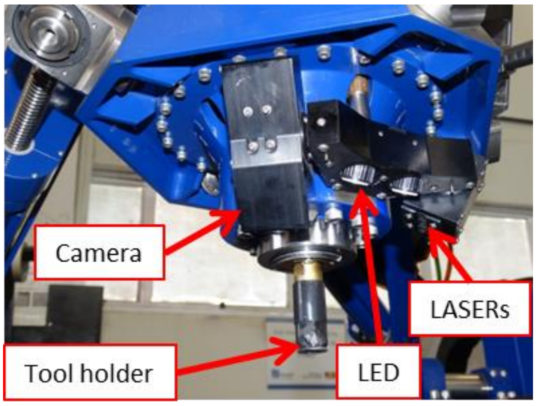

Figure 2. Sensor integrated with the robot.

2.2. Sensor model and calibration

The sensor measurement model and its calibration was based on [8][9][10]. The measurement model uses the pinhole camera model and a fitted mathematical plane for each projected laser light plane. For each laser peak detected in the image a line can be defined through the lens center using the pinhole projection matrix. The intersection of this line with the laser mathematical plane leads to a 3D measured point. In [9] a special part is used to calibrate the sensor and the sensor TCP simultaneously. In this work, a planar reference grid with controlled displacement is used for calibration.

2.2. Sensor TCP Calibration

For a complete surface scan, each posture of the robot and consequently the sensor, the 3D measured points in the sensor coordinate system (SCS) must be transformed to a fixed reference, e.g. the robot base coordinate system (RCS). For this, the transformation between the SCS and the robot mechanical interface coordinate system (ICS) must be determined through a sensor TCP calibration using a structured pattern similarly as described in [6] but with only three planes and only one measurement acquisition.

3. TCP POSITIONING PROCESS

After an initial sensor approximation two acquisitions are made, a point cloud in SCS and a point of interest image with lasers off and leds on. A plane is defined with the point cloud by a least-squares orthogonal distance fitting, as described in [7]. As a result, the plane normal direction $\boldsymbol{n_p}$ is determined.

The goal of the alignment is to bring the TCP Z axis parallel to $\boldsymbol{n_p}$ and the TCP origin to a surface point of interest $\boldsymbol{M}$. The rotation axis $\boldsymbol{\hat{e}}$ is defined by a cross product between $\boldsymbol{n_p}$ and Z axis $\boldsymbol{Z_a}$ = [0 0 1], and the angle of rotation θ is defined as arccosine of the dot product between the same vectors, defining the axis-angle rotation.

To define the 3D point of interest $\boldsymbol{M}$, the point cloud fitted plane coefficients (A, B, C, D) are used. Image processing define the point of interest $\boldsymbol{m}$ = (u,v) in image coordinates. The intersection of the line, starting at $\boldsymbol{m}$ and passing through lens center $\boldsymbol{c}$, with the point cloud fitted plane define the 3D position of the point of interest $\boldsymbol{M}$ = (X, Y, Z), as seen in Figure 3.

A homogeneous transformation matrix, with R as the 3x3 rotation matrix notation of the axis-angle rotation, and translation as $-\boldsymbol{M}$ is defined to offset the TCP to align it with the surface normal and positioned at point of interest $\boldsymbol{M}$, as in

$$Offset = \begin{bmatrix} R & -M \\ 0 & 1 \end{bmatrix}^{-1} \quad (1)$$

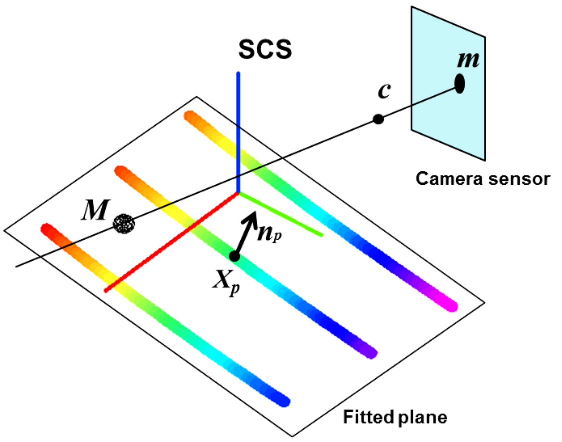

Figure 3. 3D point ***M*** defined at point cloud fitted plane.

Thus, the sensor can be used with two different modes, point cloud measurement and 3D point of interest measurement, the main contribution of this work.

4. EXPERIMENTS

Several experiments were done to evaluate the laser sensor and the procedure described in this work. Tests include sensor evaluation, TCP positioning tests and final integration and tests with the developed closed chain robot.

4.1. Sensor evaluation

After calibration, the laser triangulation sensor was evaluated. For each reference plane position, the acquired data was evaluated for errors in the Z direction. The systematic errors was negligible and a random error was less than ± 0.15 mm for 95,45% confidence. These random errors are mainly cause by laser speckle.

4.2. Angle measurement

A reference sine table was used to evaluate the sensor angle measurement error. For each table angle, several acquisitions were performed with the laser sensor in the same posture. The table was positioned for rotation evaluation in X and Y axis in the SCS until 15º. Angle measurement errors are greater for greater angles, and standard deviations of the measurements were negligible. In every case, the error is below 0.35º.

4.3 TCP positioning at reference target

The TCP alignment and positioning was evaluated using a steel part measured in a smooth region with relative low form variation. For each acquisition the offset was determined with (1), and the industrial ABB IRB140 robot was moved.

The images acquired by the sensor for an initial posture of the robot can be seen on figure 4. Left image is used for point cloud calculation and right image for target position ***M*** calculation.

Figure 5 shows the projected laser lines for initial (left) and final (right) posture for positioning procedure. Note the central laser line aligned with the reference target on final robot posture (right).

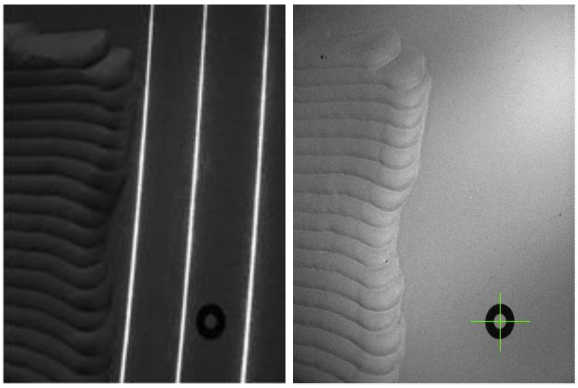

Figure 4. Laser image for point cloud calculation (left) and reference target image (already detected) for ***M*** calculation (right).

Figure 5. Laser lines for initial (left) and final (right) posture.

4.1. Closed chain robot tests

Final tests include the robotic tool positioning process applied to the developed closed chain robot. The positioning of the friction stir welding head was performed to a plane metal part with reference marks for pin insertion. Figure 6 show the robot TCP, consequently the central laser line and the SCS, aligned with the first mark (left) and the second mark (right). The process was repeated for all marks. Figure 7 shows the friction stir welding head positioned for pin insertion process (left) and the milling cutter tool aligned at first mark (right).

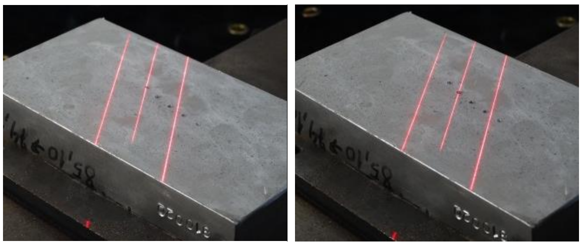

Figure 6. Central laser line alread aligned with the first mark (left) and with the second mark (right).

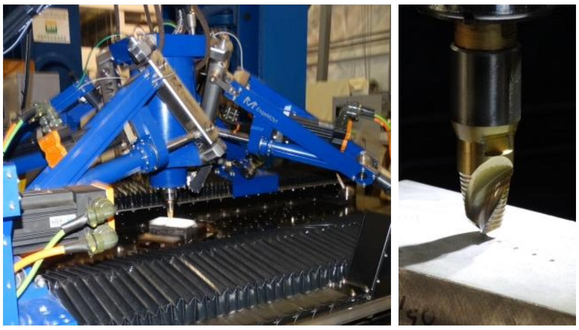

Figure 7. Friction stir welding head positioned for pin inserction process (left) and a detail of the tool aligned at first mark (right).

5. CONCLUSIONS

This work presents robotic tool positioning process using a developed off-axis multi-line laser triangulation sensor. The developed sensor has an off-axis configuration with coordinate system coincident with the TCP. The developed process uses the measured point cloud and a point of interest image to define the translation and rotation offsets to align the TCP to a reference point and normal to surface of interest, a significant contribution of this work.

Practical results were described and include laser triangulation sensor errors evaluation, angle measurement errors evaluation and actual TCP alignment and positioning at reference targets. The proposed process is much easier and with better accuracy than the manual positioning and alignment process.

6. REFERENCES

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