Vision sensing and surface fitting for real-time detection of tight butt joints

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Abstract. Weld joint detecting technology is significant and indispensable to intelligent welding manufacturing. And vision sensing is considered as a promising weld joint detecting technology, with the advantages of rich information, non-contact measuring, high accuracy and anti-electromagnetic interference. Many structural components used in the aerospace field are manufactured through welding with tight butt joints. However, the conventional structured light method is not suitable for the detection of tight butt joints, since they rely on the light stripes’ geometric distortion caused by the grooves. This study presents a real-time visual method for the tight butt joints’ detection. Uniform surface light is employed to highlight tight butt joint and acquire 2D information, and structured light with a double-line pattern is projected onto the seam to acquire 3D point cloud data by optical trigonometry. Surface fitting with moving Least Squares (MLS) method is conducted in an iterative manner to combine 2D and 3D information and calculate the seam’s positions and poses. Experimental results indicate that the proposed method is capable of detecting stably and accurately tight butt joints with a gap of less than 0.2 mm. The technique has the potential to be applied in tracking tight butt joints of complex structures in the aerospace industry for an automatic welding process.

1. Introduction
Welding is widely used in manufacturing complex structural components, and weld seam tracking technology plays an important part in intelligent welding manufacture and can work in the whole welding process. Firstly, automatic joint detection can be used in rapid path teaching of a complex weld trajectory before welding and helps achieve automatic path planning programming \([1,2]\). Secondly, the actual seam positions may deviate from the settled path during welding process due to machining error, installation error, and welding distortion. Real-time seam detecting and tracking can overcome such deviation and thus ensures welding quality \([3-5]\). Thirdly, weld seam tracking technology is used in defect detection after welding, guides the defect detector to move along the weld seam and improves the efficiency \([6-8]\).

Machine-vision-based seam detection methods have the advantage that they work in a non-contact manner, resist electromagnetic interference and contain rich information, and thus are of the hot research topics. Among various visual methods, the line structured light method \([9]\) is robust and probably real-time involving simple image processing work, and therefore widely used. However, the
structured light method requires distinct light stripes’ geometric distortion caused by the groove to locate the seam. The conventional structured light method will fail when the groove doesn’t exist.

Tight butt joints are widely adopted in many key structural components of aeronautics and space equipment, such as fuel tanks of rocket launchers, missile shells and aero-engine casing, and are welded by a precision welding process such as TIG welding, laser welding, electron beam welding and friction stir welding. The precise position of the joint and surface normal vectors are required because the molten pool during welding process is small and even slight deviation of the welding torch from the joint has a seriously bad effect on welding quality. The conventional structured light method can’t fulfill the task of tight butt joint detection. The gap between two workpieces is too small (typically less than 0.2 mm) to cause light stripes to distort. Figure 1 demonstrates that conventional line structured light method fails to detect the butt joint when the gap width is 0.2 mm [10].

Figure 1. Butt joint detection using line structured light method. (a) Line structured light is projected onto butt joint with a gap of a specific width; (b) Captured image when the gap width is 5 mm; (c) Captured image when the gap width is 1 mm; (d) Captured image when the gap width is 0.2 mm.

To overcome the mentioned problem in structured light detection methods, Zheng et al. cast a circular laser spot onto the workpiece surface [11]. The joint line appears as a continuous dark curve in the image and the position and the pose between the torch and the workpiece are calculated according to the shape distortion of the circular spot. But the presence of laser speckles lowers the signal-to-noise ratio of images, makes it difficult to extract the dark curve and consumes much time. Zeng et al. projected surface light and cross line structured light alternatively onto the joint, and acquires 2D pixel coordinates of the joint and 3D coordinates of points around the joint, respectively [10,12]. Surface normal vectors are obtained by plane fitting using Least Squares method (LS). And when the workpiece’s surface is curvy, the weighted LS method is used. But the proposed method has a low accuracy when the detected point on the joint line is far from the cross point of laser and the surface is curvy.

This paper presents a vision sensing and surface fitting approach for real-time detection of tight butt joints, fusing information from images captured under uniform surface light and double-line structured light. The surface light source is used to highlight the tight butt joint. The 2D pixel coordinates of the seam line are extracted using simple image processing. And the double-line structured light is used to obtain the 3D coordinates of points around the joint on the workpiece surface via optical trigonometry. Two types of light sources twinkle alternatively and rapidly, so the
2D and 3D information could be obtained nearly simultaneously. Moving Least Squares (MLS) method is used to approximate the surface around the joint. Then the 3D coordinates of the joint and the corresponding normal vectors of the surface are evaluated in an iterative manner.

2. Principle and algorithm
The proposed method consists of three steps. Firstly, a camera is used to capture the image of the tight butt joint illuminated by uniform surface light. The pixel coordinates of the seam are extracted from the image. Secondly, the same camera is used to capture the image of the stripes of the double-line structured light on the surface of the workpieces. The pixel coordinates of the stripes are determined and the corresponding 3D point cloud data in camera coordinate system are obtained by optical trigonometry. Thirdly, the coordinate of a specific point on the seam and the normal vector of the surface at that point are calculated in an iterative algorithm, where the 3D point cloud is fitted into a curvy surface implicitly using MLS method. Figure 2 demonstrates the procedure of the proposed method.

![Figure 2. The flow chart of the whole algorithm.](image)

2.1. Acquisition of seam image
The proposed joint detection method uses the image of the joint to directly determine the pixel coordinates of the seam, which, in the conventional structured light method, are determined according to light stripe’s geometric distortion. For the tight butt joint, the seam feature is not distinct in the image captured in natural light, with a low signal-to-noise ratio, making it hard to process images and locate seam rapidly and lowering the real-time performance. So uniform surface light produced by a LED array is employed to highlight the seam feature and hence the image processing is simplified. That means of improving image quality is effective because of the difference between the optical reflectivity of workpiece surface and that of joint gap. Workpieces are of high-reflectivity materials, such as aluminum alloy and ferrous materials, whereas the gap of the tight butt joint hardly reflects...
since the gap depth-to-width ratio is large and the width is considerably larger than the optical wavelength. In the image of the weld joint, therefore, the seam appears as a continuous dark curve while the other area must be bright, as shown in figure 3.

![Figure 3](image)

**Figure 3.** Comparison between images of the seam in different light condition. (a) Natural light, aluminum alloy workpieces (Ra=1.4 μm); (b) Uniform LED surface light, aluminum alloy workpieces (Ra=1.4 μm); (c) Natural light, stainless steel workpieces (Ra=0.8 μm); (d) Uniform LED surface light, stainless steel workpieces (Ra=0.8 μm).

The pixel coordinates of the weld seam can be extracted through some easy general image processing methods such as Canny edge detector. Here the seam pixels are simply determined via image binarization and centerline extraction by row, as shown in figure 4. We won’t go into detail about the whole image processing method used since it’s not the focus of the paper. The average time of image processing is less than 6.1 ms per frame by testing 1,000 frames of images (1600×1200 pixels).

![Figure 4](image)

**Figure 4.** The result of seam pixel extraction. (a) The image of seam captured in uniform LED surface light; (2) Image binarization with a threshold of 55 and the centerline of the seam (marked with red).

2.2. Acquisition of point cloud data around the seam

The point cloud data are acquired by optical trigonometry. The camera is modeled by the usual pinhole [13]. The camera coordinate system is built with the optical center as the origin and the optic
axis as Z axis. The relationship between a 3D point \((x, y, z)\) in camera coordinate system and its image projection \((u, v)\) is given by

\[
s[u \ v \ 1]^T = A[x \ y \ z]^T
\]

where \(s\) is an arbitrary scale factor, and \(A\), called the camera intrinsic matrix, can be obtained by general camera calibration tools. Equation (1) indicates that an arbitrary pixel coordinate \((u, v)\) stands for a straight line from the origin of the camera coordinate system. The image distortion is not considered in equation (1), which should be eliminated first in practical application.

The image of light stripes is captured when the double-line structured light is projected onto the workpieces and the seam, as shown in figure 5. The image processing method of extracting pixel coordinates of centerlines of stripes is similar to that of extracting the weld seam’s pixel coordinates. And Hough transform [14] is used to exclude invalid pixel points. Let’s denote the equations in camera coordinate system of planes where two laser lines propagate, respectively, by

\[
n_i^T [x \ y \ z] = c_i, \quad i = 1, 2
\]

where \(n_i\) is the unit normal vector of the plane, and \(c_i\) is the directed distance between the plane and the origin of camera coordinate system. From equation (1) and (2), we have 3D coordinates \(\{x_k, y_k, z_k\}\) of points of light stripes calculated in camera coordinate system.

2.3. Surface fitting and Acquisition of seam position and pose

After the point cloud data \(\{x_k, y_k, z_k\}\) are obtained, MLS method [15] is used to fit the local curvy surface around the seam. In the MLS method, a weight function is introduced and the approximation of a local surface is only influenced by the nodes in a specific domain, reducing computational effort. Unlike Least Squares, Least Absolute Deviations, Maximum Likelihood or Spline Smoothing, MLS method doesn’t need to know the form of the function of the whole surface beforehand.

In local subarea of the surface to be fitted, the expression of fitting function \(f(x)\) is

\[
f(x) = \sum_{i=1}^{m} \alpha_i(x)p_i(x) = p^T(x)\alpha(x)
\]

where \(\alpha(x) = [\alpha_1(x), \alpha_2(x), \ldots, \alpha_m(x)]^T\) is the coefficient vector to be evaluated, \(p(x) = [p_1(x), p_2(x), \ldots, p_m(x)]^T\) is the basis function vector, and \(m\) is the number of basis function terms. For a two-dimensional problem, the linear basis function vector is

\[
p(x) = [1, x, y]^T, \quad m = 3
\]

and the quadratic basis function vector is

\[
p(x) = [1, x, y, x^2, xy, y^2]^T, \quad m = 6
\]
A target point \((u_T, v_T)\) whose 3D coordinate will be calculated is selected from all the seam pixels extracted in Section 2.1. The target point \((u_T, v_T)\) should be at the middle between two light stripes in order to make the best of the point cloud data.

Denote that the corresponding 3D coordinate of \((u_T, v_T)\) is \((x_T, y_T, z_T)\) in camera coordinate system, \(x = (x, y)\), and that \(z = f(x)\). The fitting function \(f(x)\) cannot be directly evaluated since \(x_T\) and \(y_T\) are unknown. Considering that \((u_T, v_T)\) and \((x_T, y_T, z_T)\) conform to the equation (1), \(f(x)\) and \((x_T, y_T, z_T)\) can be evaluated in an iterative algorithm as follows.

a. Use the point set \(\{(x_k, y_k, z_k)\}\) to fit a plane, and determine the initial estimate value \((x_0, y_0, z_0)\) of \((x_T, y_T, z_T)\) by the equation of the plane and equation (1), noting that \(x_0 = (x_0, y_0)\);  
b. Evaluate the coefficient vector \(\alpha(x)\) and thus fitting function \(f(x)\) at \(x = x_0\);  
c. Solve the equations (1) and (3) concerning variables \(x, y, z\), where \(u = u_T, v = v_T, x = (x, y), f(x) = z\), and consequently obtain a new value for \((x_T, y_T, z_T)\);  
d. When \(|[x_0, f(x_0)]^T - [x_T, y_T, z_T]^T| > \delta\), assign \((x_T, y_T)\) to \(x_0\), jump to the Step b, and repeat the procedure, otherwise exit the procedure.

The coordinate \((x_T, y_T, z_T)\) acquired through the above algorithm is the seam position, corresponding to the image projection \((u_T, v_T)\). And the normal vector of the surface \(z = f(x)\) at the point \(x = (x_T, y_T)\) is the seam pose in camera coordinate system.

3. Experimental verification

To validate the proposed method, a task of tight butt joint detection is carried out. Figure 6 demonstrates the shape of workpieces used and the workpieces are aluminum alloy. The actual path of the seam is part of the intersecting curve of two cylinders, and the average gap width of the tight butt joint is approximately 0.15 mm. The camera captures images of 1600×1200 pixels at 32 frames per second. The field of view is of 20 mm×15 mm. The wavelengths of LED surface light center at 635 nm, and that of the double-line structured light at 650 nm. The camera is equipped with a bandpass filter, of which the central wavelength is 650 nm, and the full width at half maximum (FWHM) 80 nm. Two types of light are turned on alternatively and the camera is exposed synchronously to achieve nearly simultaneous capture of images under two different light condition.

![Figure 6. The workpieces used in the experiment. (a) The path of the seam is part of the intersecting curve of two cylinders; (b) The dimensions in millimeters of workpieces.](image)

The images captured are processed in the approach mentioned in Section 2. And surface fitting using MLS with linear basis functions are used to calculate the position and the pose of the seam. The cubic spline function is adopted as the weight function in surface fitting, since its second derivative is continuous, leading to a second-derivate-continuous fitting function. And it is fast to compute. Finally, the calculated coordinates and normal vectors in the camera coordinate system are transformed into the workpiece coordinate system described in figure 6(a), in order to be compared with the theoretical data.
Figure 7 illustrates the calculated seam position and pose, and figure 8 describes the errors between the calculated and the theoretical positions and poses. The theoretical positions and poses are obtained from the CAD model of the workpieces given in figure 6. And the difference between the actual and the theoretical sizes of the workpieces is negligible since the workpieces are manufactured by a high-precision CNC machining center. The position error is expressed by the absolute distance between the calculated and the theoretical 3D coordinates. And the pose error is expressed by the norm of the calculated unit normal vector minus the theoretical unit normal vector. Figure 8 indicates that the proposed method of detecting tight butt joints is effective and accurate. The position error is less than 0.8 mm, while the pose error is relatively large, especially at the beginning of welding, where the error reaches 17°. The pose error decreases along the welding direction, i.e. minus x-direction in figure 8. The reason for the error trend is probably that the top surface of the platform supporting the workpieces is not rigorously flat. The rotation matrix used in the transformation from the camera coordinate system to the workpiece coordinate system, is actually approximated by the rotation matrix from the camera coordinate system to the platform coordinate system, for the sake of feasibility. The platform coordinate system’s origin is near the end of the weld seam, and the x-y plane is located on the top surface of the platform. So it will introduce errors during the transformation from the camera coordinate system to the workpiece coordinate system, especially at the start of the weld seam, if the working surface is not flat.

Figure 7. The positions and the poses of the seam calculated by surface fitting with MLS in an iterative manner (the welding direction is minus x-direction).

Figure 8. The detection errors of the seam’s positions and poses (the welding direction is minus x-direction). (a) Errors of positions; (b) Errors of poses.

The detection errors are also introduced by the camera calibration and the uneven distribution of light stripes’ line widths. The detection errors can be reduced from at least three aspects. The first is
the camera calibration. The camera calibration gives the relationship between a 3D point in the camera coordinate system and its image projection, and hence the accuracy of the camera calibration has a huge impact on the detection accuracy. Usually, the camera is calibrated by shooting images of the specialized chessboard. Increasing the number of the images can improve the calibration accuracy and thus the detection accuracy. The second approach to improve the detection accuracy is to use the structured light of higher quality. The line-structured light with a smaller and more uniform line width is expected to give more precise 3D point coordinates. Last but not the least, increasing the resolution of the camera will reduce detection error. However, a trade-off between the detection accuracy and the equipment cost as well as the computational cost has to be made.

It takes 21.52 ms on average to calculate the position and pose of the seam for once through the proposed method when the image distortion introduced by the camera is considered, and 17.72 ms when the image distortion is not considered. It means that the proposed method has a good real-time performance.

4. Conclusions

The paper proposes a novel vision sensing and surface fitting approach for detecting tight butt joint in real-time. The approach combines the information contained in images under different light conditions and evaluates the position and the pose of the seam. Following conclusions can be drawn.

1) The method is effective in detecting the position and pose of a tight butt joint with the gap width of less than 0.2 mm, and the position detection error is less than 0.8 mm.
2) The detection can be carried out in real-time, with the time cost less than 22 ms.
3) The method does not rely on the light stripes’ geometric distortion caused by the groove, and thus could be applied in path teaching and real-time seam tracking in the welding process of complex structural components of aeronautics and space equipment.

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