Automatic Seam Detection and Path Planning in Robotic Welding

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Abstract. To make robotic welding systems more flexible, vision sensors are introduced as they provide large amount of information about the welding components. In this paper a method is introduced to automatically locate the weld seam between two objects in butt welding applications. The proposed method provides flexibility for robotic welding by having the ability to locate the weld seam on arbitrarily positioned work pieces. This method is also cost effective as it is developed using images captured from a low cost web-cam. Furthermore, the proposed method is able to plan a robot path along the identified seam. Simulation and experimental results show that the method can be used successfully in detecting and locating seams on variously shaped work pieces and robot paths can be successfully generated to follow the weld seams.

1 Introduction

There are many Robotic applications in the real world which range from industrial applications such as material handling or manufacturing to medical tasks such as surgical procedures [12]. Vision guided robotics is a topic of continued interest and recent advances in visual servo control and the technology that supports it have made it possible for the creation of accurate and robust vision control systems. Using vision to guide a robotic manipulator is, however, still a challenging task [2].

At present, there are many welding robots being used to maintain the safety of workers and the work area, as well as the quality of work. Current welding robots used in industrial applications are programmed through teach and play-back methods [12, 13]. Weld paths for these types of robots must be manually re-taught and re-programmed for different work pieces as they cannot self-rectify any offsets in the welding process. This makes the set up of these systems time consuming and expensive.

To make the robotic welding more flexible in dealing with varying locations and shapes of weld pieces, vision is being introduced into robotic welding systems. Research has been reported where computer vision is used to detect and locate weld seams [1, 3, 9, 12, 13]. In addition, vision is also being used to control the weld quality by monitoring the weld pool dynamics [1, 5].

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Automatic weld seam detection and tracking is an important topic in robotic welding. It is an area of great interest as it is an important step in realising fully autonomous robotic welding [9]. Since vision systems can acquire information without interfering with the welding process, it is often used for seam tracking. There are a variety of approaches being adopted for seam detection and tracking in robotic welding.

The use of specialised lighting is reported in [9]. In this method, a single laser line was projected onto planar work pieces and was used to detect the seam when the line is no longer straight. The introduction of a second laser line [6] generates more accurate information from the images. Another weld seam detection method using a single image is given in [13]. The image is manually segmented by only considering a central, predefined viewing window. This reduces computational time by not having to eliminate the background and reducing the overall size of the image. Once the seam is located from the grey level image, the start and end points are found by shifting a smaller window along the length of the seam until a corner is detected. This method assumes that the seam location will be in the central in the image, and large in comparison to the window. Also, the work piece is assumed to be planar with known depth and height. In [12] a method for real time seam tracking is proposed. The vision system is setup to take images slightly ahead of the welding torch which continually update the robot with the new position coordinates extracted from the image information. Since the viewing window is a significant distance away from the welding arc, it is difficult to continually track the seam around curves and sharp corners, therefore limiting this method to straight lines, significantly reducing the flexibility of the system.

The methods presented above are suited mainly for the detection of simple seams. These methods are also developed to only deal with specific welding applications in mind. Significant modifications would have to be made to these seam detection algorithms before they could be implemented in multiple applications. In addition, these methods did not consider the effect that path planning plays on seam detection and tracking. Smooth and even paths are required to produce high quality welds.

In this paper an automatic, low-cost flexible seam detection method will be developed which can be accurately and easily implemented in an industrial setting. Furthermore, the proposed method will also incorporate path planning into the algorithm to develop a smoother welding path for robot to follow.

This paper is organised into four Sections. In Section 2, the methods used will be explained. Experimental results using an industrial robot are given in Section 3. Conclusions are then given in Section 4.

2 Methodology

In this paper, a method for weld seam detection is introduced. The algorithm is capable of determining the shape of the seam as well as the start and end points on straight and curved seams. This method is also capable of reducing the number of points on the weld seam to smooth the robot welding path. This method uses a single image captured by a robot mounted camera referred to as the eye-in-hand configuration. The overall method contains 6 steps: Boundary Detection, Conner/Curve Detection; Determine Initial Seam; Select Initial and Final Position; Seam Point Reduction; and Final Seam Path. Each step is discussed in detail in the following subsections.

2.1 Boundary Detection

An image containing the two objects in position for the butt-weld operation must first be captured. This image must view the entire seam. Appropriate image processing is performed to allow for the boundary detection of the two objects {B_1, B_2} to take place (as depicted in red and green in Fig. 1). This will result in a sequence of n_1 and $n_2$digital points describing the boundary of each object B_1 and B_2,

$$B_k = \left\{P_{i,m} = \left(U_{i,m}, V_{i,m}\right), i = 1, 2, ..., n_i, \text{ and } m = 1, 2\right\}(0) \qquad (1)$$

Where image point $P_{i+1,m}$ is the neighbour point of the image point $P_{i,m}$, and $(U_{i,m}, V_{i,m})$ are the image coordinates of P_i of boundary m. An example of two objects with detected boundaries can be seen in Fig. 1.

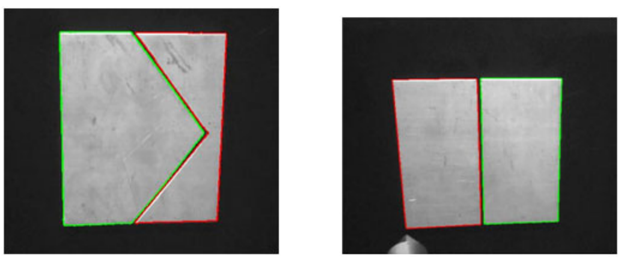


Fig. 1. Object Boundaries Detected and Highlighted

2.2 Corner/Curve Detection

Once the boundary pixel locations for each object are identified, the corner/curve pixels can then be determined. This is necessary as in a butt welding operation the two edges to be joined are relatively parallel and thus will begin and end on a sharp corner or curve. There are many methods available to determine corners in an image [7, 8, 10, 11]. In this paper, the corner detection method is based on the K-Cosine introduced in [15]. The K-Cosine detection technique is chosen for its low computational costs and simplicity. This boundary based corner detection technique determines the angle θ for each boundary pixel as shown in Fig. 2:

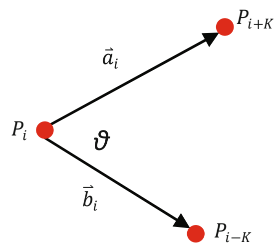


Fig. 2. Vector Diagram

$$\vec{a}_i \bullet \vec{b}_i = \|\vec{a}_i\| \bullet \|\vec{b}_i\| \bullet \cos\theta_i \tag{2}$$

$$C_i = \cos\theta_i = \vec{a}_i \bullet \vec{b}_i \Big/ \left(\|\vec{a}_i\| \bullet \|\vec{b}_i\|\right) \tag{3}$$

$$\theta_i = \cos^{-1}(C_i) \tag{4}$$

Where a_i and b_i are the vectors between image points $P_{i,m}$ and $P_{i+k,m}$, and $P_{i,m}$ and $P_{i-k,m}$, respectively, θ_i represents the angle between the two vectors a_i and b_i. $\|\bullet\|$ is the magnitude of vector $\bullet$. The number of pixels between the points used in calculating vectors a_i and b_i is represented by the value K . It is clear from (2) and (3) that if pixels $P_{i-k,m}$ and $P_{i+k,m}$, form a straight line, then C_i will be -1 or close to -1.

One of the limits of the K-Cosine corner detection method is the assumed prior knowledge of the number of corners in an image and an estimate of the widest angle to occur in the image. This prior knowledge will allow for the threshold value T to be established to determine what C_i value constitutes a corner.

This paper improves on the original K-Cosine corner detection method by allowing the number of corners in an image and angles of these corners to remain unknown. This improved method can also detect points that form curves in an image.

To achieve this, a low threshold T, defined as -0.99(which is almost equal to a straight line $\theta = 172°$) and a value of $K = 3$ was used in the method. This modification results in a large number of pixels being identified as corner or curve points. Based on these points, regions can be formed if points are connected.

To reduce these regions to a single point, the value of θ_i is calculated for each pixel in the region using (2) – (4) and is then compared to the θ values of the neighbouring pixels in the same region. The pixel with the smallest angle θ is retained as the pixel with the greatest curvature for that region.

The corner/curve detection method introduced above is more advantageous than the original K-cosine method as it not only identifies corner points but also identifies points around curves allowing for an accurate path planning along the seam. By determining the local maximums, a significant reduction in the number of points used in the preceding sections of this paper is achieved.

2.3 Determine Seam Edges

The next step to this method is to identify the points that lie along edges which form the weld seam. This is done using the knowledge that the points along the weld edges are the points of interest when determining the seam location. To eliminate the redundant corner/curve points, the distance between all the corners of one object and all the corners of the second object is determined using the Euclidian distance:

$$D = \sqrt{(V_2 - V_1)^2 + (U_2 - U_1)^2} \tag{5}$$

It is assumed that the corners are situated at coordinates (U_1, V_1) and (U_2, V_2). Each corner/curve point on one boundary is paired with the closest corner/curve point on the opposing object boundary. During this process, pairs that have separation greater than a set minimum pixel distance are regarded as redundant and will be eliminated.

Once the above process is complete, the initial seam edge arrays are generated and can be used to determine the points that make up the initial seam. For the butt-weld operation the weld seam is made of the mid-points between the two objects, therefore the location of the seam points can be calculated.

The initial seam made up by these midpoints is then used to determine the start and end points of the weld seam and also in determining the accurate path for the robot to follow during the welding operation.

2.4 Initial and Final Position Selection and Seam Point Reduction

Using the initial seam from Section C the initial and final points along the seam are determined using the process described below.

Where *U* represents the x-axis in the image plane and *V* is the y-axis representation. This method is limited as the initial and final positions must be on opposite sides of the weld objects. Once the initial and final positions of the seam are determined, a path for the robot to follow is determined. The number of points found along the seam will vary significantly depending on the style of each individual seam.

```
   Find pixel with minimum and maximum pixels in both the U and V
direction
   Calculate the distance between the min U and max U = dist U,
   Calculate the distance between the min V and max V = dist V,
               If dist u > dist V
                        Initial position = min U,
                        Final position = max U,
               Else
                        If dist V is > dist U
                                 Initial position= max V,
                                 Final Position = min V
```

The process of corner detection developed in this paper identifies not only points on a corner but also a significant number of points situated around curves. The disadvantage of detecting many points around curves is that each of these points will be used to drive the robot. This will affect weld quality and requires a great deal of memory space in the robot controller. However, by detecting all these points curves can then be identified along the seam that increases the overall flexibility of the system.

A suitable method is developed in the paper to reduce the number of points whilst maintaining the shape and accuracy of the seam. The steps to perform this operation are shown below.

```
                    Seam Edge Reduction Method
1.  Compare Cosine Value of Pi with Pi+1
                  i.  If Cθi not equal Cθi+1, Go to (2);
                 ii.  If Cθi equal Cθi+1, Go to (3);
2.  Is Cθi = Cθi-1?
                  i.  YES, Go to (4);
                 ii.  NO,     Store in Corner Array, Go to (5);
3.  Store in Curve Array
4.  Reduce Curve Array
5.  IF Number of points in Curve array = 2 or 3 Store Points as the
    Final Seam Edge, Go to (5);
6.  IF Number of Points >=3 Take the First, Middle and the Last
    points, store these points as the Final Seam Edge, Go to (5);
7.  Is this Final Point?
                  i.  YES, Go to (7);
                 ii.  NO, Go to (6);
8.  Next Point
                  i.  Go to (1);
9.  END
```

The above process results in a significant reduction of points along the seam edges. The final seam is then determined. Consequently the robot will be able to perform a smoother path along the seam resulting in an improved weld quality. The extent of this reduction is revealed in Section III.

2.5 Final Seam Points Input to the Robot

The seam detection method results in a path made up of pixel locations in the image coordinate plane. This requires the transformation of the pixel locations from the image coordinate plane to the world coordinate plane. It is well known that the conversion of a 3-D point (x, y, z) into an image point (u, v) can be expressed as:

$$w \times (u, v, 1)^T = P \times (x, y, z, 1)^T \tag{6}$$

Where P is a 3x4 homogeneous transform and w is a scaling factor. To convert a point from the image plane (u, v) to the 3-D coordinate frame (x, y, z),one will need to know one of the values of x, y or z, alternatively, a stereo vision system is required to calculate the location of x, y and z from two images. In this paper z is assumed to be known, as is usually the case that a workstation is at a certain height. Using linear algebra, knowing *u*, *v* and *z* will allow the values of *x* and *y* to be calculated.

To achieve this, the *P* matrix in (6) should be determined. In this paper, the *P* matrix is obtained using the method introduced in [4]. This hand-eye calibration technique was used as it is low cost, using a single web cam and has an accuracy in the x and y direction to within ±1mm. The accuracy achieved in the *x* and *y* directions are acceptable for the robotic arc welding process.

With known seam points in image plane with their *z* values, the welding seam points' world coordinate positions can be obtained. These real-world coordinates can then be loaded into the robot's control system as a set of path points so that the robot can be operated to follow the seams.

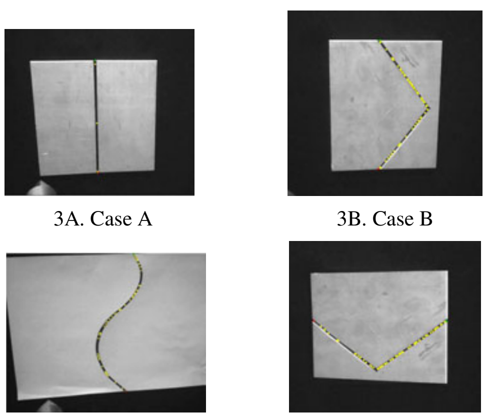
3 Results

This section contains the seam detection program test results, as well as the verification that the seam detection method is applicable to a real world system.

3.1 Seam Detection and Reduction Results

To test the effectiveness of the seam detection program, objects with a variety of seam shapes were used. Case A contains a straight edged seam, Case B contains two straight edges creating a distinct corner, Case C requires the detection and navigation around various curves and finally Case D reveals a seam can be detected with parts placed in arbitrary orientations.

Fig. 3 shows the points (in yellow) that make up the final seam for each individual situation. These seam points are by using the point reduction method along with the initial (green) and final (red) positions of the seam are shown.



3A. Case A

3B. Case B

3C. Case C

3D. Case D

Fig. 3. Initial Seam points for different welding shapes

Fig. 4 reveals that a path for a robot to follow along the seam can be determined. The method proposed also meets the flexibility demands of seam detection. The resulting path for the horizontal seam in Figure 3D shows that not only is the seam detection method developed in this paper capable of detecting various shaped seams but can also determine the path if the objects of interest are placed in an arbitrary orientation in the workspace. Table 1 shows the results of the point reduction.

Table 1. Point Reduction Results

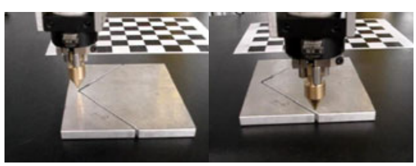
	Number of Points		
	On Initial Seam	On Final Seam	Reduction Percentage
Case A	16	5	68.75%
Case B	125	62	50.40%
Case C	157	54	65.61%
Case D	110	63	42.73%

The reduction results revealed in Table 1 are significant as this reduction will save significant memory space in the robots controller, doing so without the loss of path accuracy.

3.2 Experimental Results

To verify the image processing results on a real application, further experiments were carried out using a robot. The robot used to verify that the seam path detected is applicable in a real life situation was a Fanuc M-6i Robot. The end effecter uses a brass pointer to simulate the position of welding wire in a welding application and the camera is mounted in an eye-in-hand configuration. The resulting motion of case B is shown in the Fig. 4.

4A. Motion 1 4B. Motion 2



4C. Motion 3 4D. Motion 4

Fig. 4. Case B Cornered Seam

4 Conclusions

In this paper a flexible seam detection method has been introduced. The developed method successfully detects different shaped objects in an image. In addition, the seam detection method is capable of generating smooth welding paths using minimum available point which can potentially improve the welding quality of the system. Experimental verification has validated the effectiveness of this seam detection method. The experimental results show that the seam detection method is capable of detecting various shaped seams made up of objects placed in arbitrary positions hence proving the flexibility of the seam detection method developed.

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References

[1] Chen, S., Zhang, Qiu, T., Lin, T.: Robotic Welding Systems with Vision-Sensing and Self- Learning Neuron Control of Arc Welding Dynamic Process. Journal of Intelligent Robotic Systems 36, 191–208 (2003)

[2] Corke, P.: Visual Control of Robots: High Performance Visual Servoing. Research Study Press, Somerset (1996)

[3] Cook, G.: Feedback Control of Process Variables in Arc Welding. In: Proceedings of IEEE Joint Automatic Control Conference, vol. 2 (1980)

[4] Dinham, M., Fang, G.: Low Cost Eye in Hand Camera Calibration. In: Proceedings of The 2009 IEEE International Conference on Robotics and Biomimetics (ROBIO 2009), Guilin, Guangxi, China, December 18-22, pp. 1889–1893 (2009)

[5] Dudek, G., Jenkin, M.: Computational Principles of Mobile Robotics. Cambridge University Press, New York (2000)

[6] Gao, S., Zhao, M., Zhang, L., Zou, Y.: Dual-Beam Structured Light Vision System for 3D Coordinates Measurment. In: Proceedigns of the 7^{th} Annual Conference, World Congress on Intelligent Control Automation, Chongqing, China (2008)

[7] Lee, J., Sun, Y., Chen, C.: Multiscale Corner Detection by using Wavelet Transform. IEEE Transactions on Image Processing 4(1), 100–104 (1995)

[8] Li, L., Chen, W.: Corner Detection Interprestation on Planar Curves using Fuzzy Logic Reasoning. IEEE Transactions on Image Processing 2(11), 1024–1210 (1999)

[9] Liu, X., Wang, G., Shi, Y.: Image Processing of Welding Seam Based on Single-Stripe Laser Vision Systems. In: Sixth International Conference, Conference on Intelligent Systems Design and Applications (2006)

[10] Rattarangsi, A., Chin, R.: Scale-Based Detection of Corners of Planar Curves. IEEE Transactions on Pattern Analysis and Machine Intelligence 14(4), 430–449 (1992)

[11] Rosenfeld, A., Johnson, E.: Angle Detection on Digital Curves. IEEE Transactions on Computers 22, 875–878 (1973)

[12] Shen, H., Lin, T., Chen, S.: A Study on Vision-Based Real-Time Seam Tracking in Robotic Arc Welding. Robot. Weld Intelligence. & Automation, 311–318 (2007)

[13] Shi, F., Zhou, L., Lin, T., Chen, S.: Efficient Weld Seam Detection for Robotic Welding from a Single Image. Robot. Weld Intelligence. & Automation, 289–294 (2007)

[14] Sicard, P., Levine, M.: An Approach to an Expert Robot Welding System. IEEE Transactions on Systems, Man and Cybernetics 18(2), 204–213 (1988)

[15] Sun, T.: K-Cosine Corner Detection. Journal of Computers 3(7), 16–22 (2008)