An Innovative Method for Locating the Welded Circular Seam on the Inner Surface of Cylinder Pipeline to Inspector Robot

Xiang Dong, Qiaosheng Feng*, Junfei Xia and Yaping Zhang

School of Computer Science and Information Technology, Yunnan Normal University, Kunming 650500, Yunnan Province, China
E-mail: vonqs2010@sohu.com

Abstract. Locating the welded seam on the inner surface of a pipeline from the frame image captured by the monocular optical camera is a key and challenging problem in intelligentizing the defect inspection robot. Due to the lack of feature points and feature straight lines on the image of the welded seam, the existing visual odometry method cannot be used to locate the welded seam relative to the inspector robot. In this paper, an innovative method is proposed for locating the welded circular seam on the inner surface cylinder pipeline to inspector robot. In this method, the whole shape of the welded seam is retrieved from the frame captured by the monocular camera of the robot and is used as the feature for the location. Through combining the retrieved shape features and the moving velocity of the robot, the distance from the robot to the welded seam can be calculated quickly based on the optical imaging principle. Experiments show that our method can effectively locate the welded seam. Our method can used in intelligent pipeline inspector robot to locate the welded seam to defect test.

1. Introduction
As a kind of conveying equipment, oil and gas isometric pipeline is widely used in petroleum, petrochemical and chemical industries. The current NDT (Non-Destructive Testing) robot also relies on the real-time image captured by the robot to determine whether a weld is present, and controls the robot to drive to the weld for NDT when the weld is present. Based on machine vision in this paper, we present an innovative method for locating the welded circular seam on the inner surface of cylinder pipeline to inspector robot, in order to get the welded inner circular seam on cylinder pipeline to inspector robot, thus eliminating the testing of observed weld work load, provide weld automatic control robot to weld position relative to the distance and posture information of the robot.

The NDT robots for coal gas, oil pipelines and other steel pipelines are mainly magnetic adsorption robots, which mainly rely on lithium batteries for power supply. So light weight and long endurance have become important performance indicators of this kind of robots. Therefore, carrying monocular vision sensors has become the first choice.

2. Related Works
At present, there are two main ways to restore camera pose and location: feature-based method and direct method. Feature -based methods first need to extract representative points of each frame image as feature points and use Descriptor to describe and distinguish feature points. The feature point method transforms the motion estimation of the image into the motion estimation between two sets of feature...
points. If the descriptors of the two feature points are similar, we think that this is the same point, so we can obtain two frame images corresponding to one-to-one points. Using the restored pose and environmental structure robust to polar geometry, the optimal solution is finally obtained by minimizing the reprojection error. Mainstream visual mileage calculations [1] all follow this flow, simply using different optimization frameworks. One reason for the success of these methods is the provision of robust feature points and descriptors that allow matching between images and even large inter-frame motions. The disadvantages are over-dependence on feature point extraction, poor effect in the environment of no corner features or less corner feature, such as in pipeline or against monochromatic wall, and when there is motion blur; feature matching depends on threshold setting when detecting and matching, and requires the necessary robustness to deal with incoherent feature points when matching, however, the actual situation is due to the huge amount of computation feature points and descriptors, most of the optimization is aimed at computational efficiency rather than accuracy.

The researchers have designed many stable image features, such as the SIFT [2] and the SURF [3]. To satisfy the real-time performance of the VO, Rublee et al. proposed the Oriented FAST and Rotated feature [4], which describes the way of sub-fusion by using the Feature from Accelerated Segment Test [5] and the BRIEF [6] descriptor. So that it has good robustness in scale, rotation, brightness and so on, and has a good calculation speed.

The direct method [7] evolved from optical flow [8] directly estimated the camera motion and environment structure based on the assumption that the pixel gray level is invariant. Compared to feature-based methods that only take into account the distance of some local features, the magnitude of local brightness and gradient is used for optimization. In the direct method, because there is no feature matching, the direct method uses the pose estimate of the current camera to find the position of the point in the next frame, but if the pose estimate is not good enough, the appearance of the two points may be significantly different. Therefore, in order to reduce this difference, the direct method uses the way of optimizing camera pose to find more similar points. So that the matching problem can be handled by solving an optimization problem. The error processed at this time is called photometric error, that is, the brightness error of two pixels. Direct method can take advantage of all the information in the picture, even the region with very small gradient, compared to the feature point-based method, which is obviously more robust in the case of less features [9] and motion blur [10]. However, because the direct method operates directly based on the assumption of photometric invariance, the computation of the feature points and descriptors can be saved.

3. Detection of Distance between Weld and Robot
In the operation of calculating the distance between the robot and the welding joints, we divided it into five steps as shown in figure 1. Welding joints detection and removal of camera Mark and ribbon electromagnetic noise were performed by Ref. [11].

![Figure 1. The flowchart of algorithm processes.](image-url)
3.1. Frame Images Preprocessing
The pre-processing includes invalid frame filtering, removing camera mark and processing horizontal band noise. The pre-processing uses the way of the adjacent frame difference in Ref. [11]. By adjusting the filter threshold inside the experiment, the frame that does not contain the weld seam can be better filtered out, and the real-time requirement can be met. During the running of the camera, marking such as time channel and banded electromagnetic noise are marked in the video frame as shown in figure 2a. As shown in figure 2b, a large number of invalid edges will be produced during edge detection, which will affect the accuracy of weld positioning.

![Figure 2](image)

Figure 2. (a) Current frame; (b) Canny edge in (a); (c) 5*5 median filtering in (a); (d) Canny edge in (c); (e) Using 5*5 mean filtering in (a); (f) Canny edge in (e); (g) removal of camera markings and banded electromagnetic noise in (a); (h) Canny edge in (g).

In order to remove the mask of camera time mark, we find that the watermark mark is obviously different from the surrounding pipeline environment, so the white watermark pixel points are detected by setting the threshold value in the algorithm design, and the average value of the pixels in the range of 7*7 is used to fill the detected current pixel points. In the processing of horizontal band noise, we find that the pixel gray mean of the row where the banded electromagnetic noise is located in the difference graph is obviously higher than that of the other rows, so we adopt the method of detecting the banded electromagnetic noise by threshold comparison. The detected banded noise points are filled by the mean of the three consecutive pixel points in the upper part of the current pixel. Figure 2g for the video frame after removing the camera mask and horizontal banded electromagnetic noise, we found that the invalid edge was obviously reduced by canny edge detection. The experiment shows that the proposed algorithm for removing camera watermark and banded electromagnetic noise has a better removal effect and can meet the subsequent detection requirements.

3.2. Weld Contour Image Shape Modeling
In the aspect of shape detection, the more mature method is to use Hough transform for detection. Its basic principle is to establish the mapping between image space and parameter space, describe the point in parameter space, “vote” on all possible parameters, and select the group of values with the most “votes” in parameter space as the optimal solution. The essence of Hough transformation is to transform the image coordinates into parameter coordinates, so that the transformation results are easier to identify and detect. In the selected range, Hough transform can detect the corresponding shape parameters through the edge. The first condition for designing Hough transform algorithm is to know the shape of the detected graph, so we need to use the geometric relationship of pinhole model to deduce the equation of ring weld on the imaging plane. The coordinate system we set is shown in figure 3.
The z-axis runs through the optical center and moves in the same direction as the robot, the Y-axis is vertically downward, and the X-axis conforms to the right hand rule. The imaging principle conforms to the pinhole model. The wheelbase of the robot is I, the wheelbase height of the camera is, and the radius of the circular pipe is R. These three values can be obtained through actual measurement. The general equation of weld in the camera coordinate system is \( (x + x_0)^2 + (y + y_0)^2 = r^2 \), without considering the left and right bumps, it can be obtained by calculation \( x_0 = 0, y_0 = h_0 \), where \( h_0 = \sqrt{r^2 - \frac{I^2}{4}} - h_c \).

In figure 4, \( A(x_c, y_c) \) represents the origin of the coordinate system, which B is the center of the graphics on the image plane, and \( C(x, y) \) is any point in the image plane. If the origin of polar coordinates is located at the center of the circle weld, then the coordinates of any point \( D \) on the weld in the camera coordinate system are \( (-r \cos \theta, -r \sin \theta - h_0) \). According to the geometric relationship of the pinhole model, it is easy to obtain equation (1):

\[
\frac{y - y_c}{-r \sin \theta - h_0} = \frac{f}{d} = \frac{x - x_c}{-r \cos \theta}
\]

where \( f \) represents the current focal length and \( d \) represents the distance between the robot and the weld. So it is easy to obtain
\[
\begin{align*}
  x - x_c &= -\frac{fr \cos \theta}{d} \\
  y - y_c &= -\frac{fr \sin \theta + h_b}{d}
\end{align*}
\]  

(2)

The equation of weld in camera coordinate system can be obtained by plugging in the equation of weld circle. Therefore, the equation of weld can be expressed as equation (3):

\[
\frac{(x - x_c)^2}{r^2 f^2} + \frac{(y - y_c + \frac{h_b f}{d})^2}{r^2 f^2} = 1
\]

(3)

Since a single pixel on the imaging plane is not a standard square, we assume that the length and width of a single pixel are \( \delta x \) and \( \delta y \) respectively, so the equation of the circular weld in the camera coordinate system can be expressed as

\[
\frac{(j - j_c)^2}{\delta x^2 d^2} + \frac{(i - i_c + \frac{h_b f}{\delta y d})^2}{\delta y^2 d^2} = 1
\]

(4)

It can be clearly seen from the expression (10) that since the length and width of a single pixel on the image plane are not equal, so \( a \neq b \), the hypothesis is valid. So we use Hough transform to detect the ellipse to detect the weld.

We used the Canny edge detection algorithm of 3*3 to extract the edge information of the weld from the video frame. The actual test proved that the Canny algorithm could obtain the edge features more ideal.

The sampling points in the binary edge graph are mapped to elliptic equations \( \frac{(j - j_c)^2}{a^2} + \frac{(i - i_c)^2}{b^2} = 1 \) in the Hough parameter space. In order to reduce the calculation amount and improve the calculation speed, the range of Hough transform ellipse detection parameters is reduced. Through the observation of video frames and experimental tests, the parameter range is set as follows:

\[
\begin{align*}
  \min(a_i, b_i) \cdot m &< a, b < \max(a_i, b_i) + n \\
  i_c - m &< i < i_c \\
  j_c - n &< j < j_c
\end{align*}
\]

(5)

where \( a_i \) and \( b_i \) represent the two half-axis lengths of the ellipse detected in the previous frame, and \( i_c \) and \( j_c \) represent the coordinates of the center of the ellipse detected in the previous frame. \( m \) and \( n \) represent range variables dynamically delimited on the basis of the previous frame detection parameters, which can be obtained by experiments. The elliptic parameters obtained directly through the Hough transform are based on the values relatively close to the threshold value, which are offset from the optimal position, as shown in figure 5d. Therefore, we adopt the method of fitting the extraction points of Hough transform to minimize the error. We set the error \( \varepsilon = \left| \frac{(j - j_c)^2}{a^2} + \frac{(i - i_c)^2}{b^2} - 1 \right| \) to refer to the distance of the pixel point to the ellipse. by setting the threshold \( \varepsilon < \text{THR} \) we select the advantages in the region to participate in the Hough transformation, we record the points that meet the conditions to participate in the fitting. As shown in figure 5d, the fitted ellipse is more suitable for the weld joints than the ellipse drawn directly by the Hough transformation.
Figure 5. (a) is the frame of welding joints detected by canny edge; (b) Ellipse detected by Hough transform; (c) Fit the ellipse based on the points detected by Hough transform; (d) is the comparison between (b) ellipse and (c) ellipse.

3.3. Distance between Robot and Weld

From equation (10), we can clearly see the parameters corresponding to the elliptic equation. In order to facilitate the calculation, we make the aspect ratio \( \alpha = \frac{\delta y}{\delta x} \), and \( f' = \frac{f}{\delta x} \), the robot advances at \( v \) constant speed, then the corresponding parameters are shown in equation (12):

\[
\begin{align*}
a &= \frac{rf'}{d} \\
b &= \frac{rf'}{\alpha d} \\
i_x &= i_x - \frac{h_b f'}{\alpha d} \\
j_y &= j_y - \frac{f'}{\alpha d}
\end{align*}
\]  

(6)

It is found by observation that the aspect ratio can be easily calculated by calculating the ratio \( \alpha \) through \( b \) divided by \( a \). Parameters such as plane ellipse can be obtained by real-time calculation during the robot's progress. We use \( a \) and \( b \) to represent the axis length along axis \( i \) and Axis \( j \) of the ellipse corresponding to the current frame. In the process of robot moving, there are other detection operations, and the focal length needs to be adjusted according to different use scenes. Therefore, parameters such as the focal length of the camera in advance calibration are meaningless. As an unknown, focal length \( f \) needs to be calibrated dynamically during the robot movement. In addition, the distance information between the robot and the welding joints contained \( d_n = d_{n-1} + v\Delta t \) in the adjacent frame satisfies, where \( d_n \) is the distance between the robot and the welding joints in the current frame, and \( d_{n-1} \) is the distance between the previous frame and the welding. \( v \) is the traveling speed of the robot, which can be obtained through the speed sensor; \( \Delta t \) is the reciprocal of the frame rate. We use two consecutive frames to calculate the distance of the current frame. By detecting the length of half axis of two frames, equation (7) can be calculated by equation (6):

\[
\begin{align*}
d_n &= \frac{v\Delta t a_{n-1}}{a_n - a_{n-1}} \\
f' &= \frac{v\Delta t a_{n-1} a_n}{r(a_n - a_{n-1})} \\
\alpha &= \frac{a}{b}
\end{align*}
\]  

(7)

Through equation (7), we can easily calculate the distance between the detection robot and the weld. As figure 6 and table 1 shown. After the distance is detected, it can be used for further operations, such as automatic advance of the robot to the weld.
Figure 6. Continuous four frames.

Table 1. Parameters from continuous four frames contain wield.

| Frame | i    | j    | a      | b      | Distance (mm) |
|-------|------|------|--------|--------|---------------|
| F1    | 166.48 | 96.30 | 118.36 | 109.67 |               |
| F2    | 165.99 | 96.24 | 121.13 | 110.84 | 253.44        |
| F3    | 165.53 | 95.47 | 123.32 | 112.31 | 225.15        |
| F4    | 165.22 | 94.45 | 124.32 | 114.53 | 200.93        |

4. Conclusion
We implement the system with Visual C++ based upon OpenCV. We test our method by using the video file recorded by the pipeline robot. The experiment shows that our method can measure the distance between the robot and the weld more accurately, and can meet the requirement of real-time. The algorithm does not depend on features, so it has good robustness in the environment with few features such as pipeline.

Acknowledgements
This work is supported by National Natural Science Foundation of China under grant NO.61863037.

References
[1] Engel J, Sturm J and Cremers D 2013 Semi-dense visual odometry for a monocular camera Proceedings of the IEEE International Conference on Computer Vision pp 1449-56.
[2] Lowe D G 2004 Distinctive image features from scale-invariant keypoints International Journal of Computer Vision 60 (2) 91-110.
[3] Bay H, Tuytelaars T and Van Gool L 2006 Surf: Speeded up robust features European Conference on Computer Vision pp 404-17.
[4] Rublee E, Rabaud V, Konolige K and Bradski G 2011 ORB: An efficient alternative to SIFT or SURF 2011 International Conference on Computer Vision pp 2564-71.
[5] Rosten E and Drummond T 2006 Machine learning for high-speed corner detection European Conference on Computer Vision pp 430-43.
[6] Calonder M, Lepetit V, Strecha C, Fua P 2010 Brief: Binary robust independent elementary features European Conference on Computer Vision pp 778-92.
[7] Irani M and Anandan P 1999 About direct methods International Workshop on Vision Algorithms pp 267-77.
[8] Baker S and Matthews I 2004 Lucas-kanade 20 years on: A unifying framework International Journal of Computer Vision 56 (3) 221-55.
[9] Lovegrove S, Davison A J and Ibanez-Guzmán J 2011 Accurate visual odometry from a rear parking camera 2011 IEEE Intelligent Vehicles Symposium (IV) pp 788-93.
[10] Klein G and Murray D 2007 Parallel tracking and mapping for small AR workspaces 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality pp 225-34.
[11] Feng Q, Wang Y, Zhang Y and Shi S 2014 Automatic detection of the interiorly welded joints of pipelines from video for remote visual inspector 2014 IEEE International Conference on Mechatronics and Automation pp 2001-5.