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Repair Method of Data Loss in Weld Surface Defect Detection Based on Light Intensity and 3D Geometry

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ABSTRACT Weld surface quality inspection is an indispensable part in the welding automation engineering. When Laser Triangulation Method (LTM) is used to scan the weld surface, external factors will interfere with the laser center line, resulting in data loss and quality detection failure, and massive data loss is difficult to be repaired in the traditional way. In order to improve the quality of weld surface defect detection, it is necessary to find an effective and strong anti-interference method to fix the lost data. This paper presents a method of fixing the data loss caused by external environmental factors in the process of detecting flatbed lap weld surface defects by LTM. The paper includes the analysis of the causes of data loss, its impact for practical applications and a repair method. The repair method derives a formula which is suitable for expressing three-dimensional points on weld surface by combining Bidirectional Reflectance Distribution Function (BRDF) and weld surface section model. The accuracy of the algorithm is verified by experiments on standard block and single weld cross-section. The accuracy of the method up to 92% and the repair rate improved by 30%. The method was tested on flatbed lap weld to confirm its effectiveness in the field of catching surface defects hidden in the lost data.

INDEX TERMS Object detection, welding, laser beam.

I. INTRODUCTION

Welding is not only widely used in conventional manufacturing techniques, but also is the key technique of the manufacturing industry for which strict quality and safety are required. Weld quality defection can induce undesirable component cracking, corrosion and fracturing. Therefore, inspection and monitoring of weld quality are necessary [1], [2]. With the development of intelligent welding, online real-time weld defect detection has come up [3]. In online real-time weld defect detection, Automated Optical Inspection (AOI) is the most commonly used method, which including AOI based on image and AOI based on point cloud. In recent years, many scholars have conducted in-depth studies on the stability and efficiency of these two methods.

In the application of AOI based on image, [4] have presented a detailed explanation on a set of novel algorithms that can be effectively used to implement an automatic vision system which is capable of classifying the quality of Through Hole Technology (THT) solder joints very precisely and the system has an improved recognition rate and good resilience. A high-resolution AOI system based on parallel computing is developed in [5] to achieve fast inspection and classification of surface defects. Defect classification is simultaneously implemented with Hu's moment invariants and back propagation neural (BPN) approach, which can complete the accurate classification of surface defects for an image can be completed in less than 0.1ms. In the application of AOI based on point cloud, an extraction algorithm was proposed in [6] to efficiently and effectively detect rivets from the raw scanned point clouds which can assist in the rapid measurement of riveting quality. The manufacture process of the 3D scanning system with a high precision, miniaturization and lightweight was proposed in [7] to capture the information of micro-damage and depth of the modern civil architectural structures. At present, real-time detection is mainly realized by image AOI, while point cloud AOI also has quite high accuracy and real-time performance. However, in the process of plate lap welding, Laser Triangulation Method (LTM) is used to obtain the weld surface point cloud for quality detection due to the

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large interference of external factors such as spatter, which can better improve the accuracy of detection. Therefore, this paper mainly studies the point cloud AOI based on LMT.

Although the LTM has been relatively mature, data deviation still can occur under special circumstances especially in the condition which is particularly noisy [8]–[10]. To solve this problem, much research has been done on enhancing the ability to adapt to the external interference of the laser measure. The influence of oil film, position and orientation parameters on the accuracy of a laser triangulation probe was reported in [11]. It corrected the effect of oil film on accuracy in structured light laser measurement. A scheme for enhancing precision in 3-Dimensional (3D) positioning for non-contact measurement systems based on laser triangulation was presented in [12]. The digital speckle correlation method for measuring the displacement of rough interface with strong scattering, which overcome the disadvantage of triangulation system in the condition of rough interface with strong scattering was used in [13]. In view of the special working conditions and considering the external influencing factors, the above paper strengthens the laser robustness, thus improving the measurement accuracy.

One of the research emphases of laser measurement is to improve the quality of laser centerline because that the laser stripe is also seriously affected by ambient noise. The quality of laser beam is dual influenced by the ambient light and the surface material of the measured object, which results in partial data loss. To solve this problem, many scholars have improved the algorithm of extracting the laser centerline in order to improve the robustness of laser stripe extraction. The effective area extraction for the laser highlights on the metal surface was performed in [14], which improves the accuracy of the laser centerline. The connectivity of laser lines of blade contours was repaired in [15], which improves morphological repair algorithm. The centerline extraction algorithm was improved in [16] so that the irregular speckle laser centerline can be better extracted. Although the improvement of laser extraction algorithm is becoming more and more perfect, some fatal data loss is unavoidable.

The purpose of the above research is to strengthen and improve the laser. Even so, there will still be data loss in the collected images that need to be dealt with. In this paper, based on detecting weld surface defects with triangular laser measurement, it aims at solving the problem of data loss caused by speckle fuzzy of the part of laser center fringe under the circumstance of complex ambient light. An algorithm is proposed to repair and solve the blur problem of laser center line speckle, which is based on the 3D feature model of flatbed lap weld and the relational expression of light intensity and position.

II. PRINCIPLE

Fig.1 shows the pictures of the center line of flatbed lap weld extracted by Steger algorithm under different ambient light conditions. It can be seen in Fig.1 that the center line of the laser displays a few missing segments called speckle

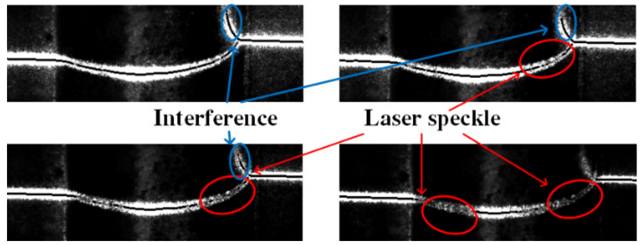

FIGURE 1. Flatbed lap weld laser centerline under different ambient light intensities. The bule arrows indicate the interference and the red indicate the speckle.

and some redundant bifurcation interference that can be addressed by ROI. The cause of these speckles is that during the process of extracting the laser centerline of flatbed lap weld, the intensity of laser fringe is not enough for center line extraction due to the complexity of ambient conditions. These speckles can cause some information about the laser center line lost and this kind of loss cannot be solved completely by general image preprocessing method such as Mathematical Morphology operation (MMO) [15].

The data loss caused by speckle is large-scale, unlike the short crack. Therefore, this paper finds the relationship between other known parameters and the lost data parameters to fix the data. In the process of surface defect quality detection of flatbed lap weld, the most direct data is the light intensity per unit length of laser, which is also a reason for whether speckle will be caused. From this point of view, the method is to find the transformation of the relationship between light intensity and surface point coordinates.

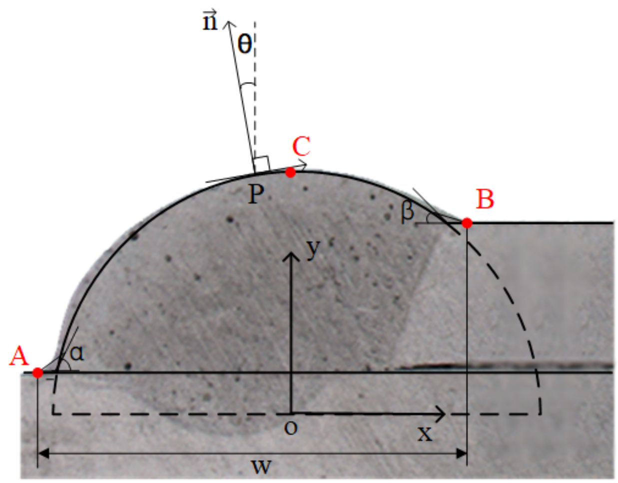

FIGURE 2. Typical cross-sections of the flatbed lap weld. The new coordinate is established on the weld cross section.

In order to make it easier to descript the 3D coordinates which is the key parameters of the measurement, a model needs to be built to simplify the representation of the coordinates firstly. The cross-sections of the flatbed lap weld are given in Fig.2 and the theoretical of this weld surface feature model is the characteristic of a droplet solidifying on a plane [17]. In the Fig.2, feature points include endpoint A, welded toe point B and the highest point C of the weld section. The ductility and wettability of the droplet make sure that the wetting angles (α, β) and the wetting length (w) are formed and the former is defined as the angle between the interface and the tangent. For the case of overlap joining, the wetting length is defined as the distance between the initial edge and the weld toe after solidification and the rest of the surface profile approximates a part of arc. However, a small part of extension is formed around the weld toe due to the fast solidification time and the difference of wettability. Based on the above forming principle, a geometric model which can adequately reflect the cross-section of the flatbed lap weld was established. This model approximates the weld section into a circular arc, and the coordinate system with the origin in the center of the arc is established, which in including the endpoints A, welded toe points B and the highest point C of the weld section. According to the model, the expression of the weld surface points can be expressed as $P(x, \theta)$, which x represents the relative distance of the point to the weld coordinate axis, θ represents the angle of the point relative to the Y-axis and the relationship between the relative height of point P and θ is tangent trigonometry. The main purpose of this model is to express the coordinates of the points in a convenient way by combining the geometric features of the weld section.

The reason for establishing the coordinate system in this way is that the most important parameter to determine the illumination intensity is the included angle of the illumination plane. In order to correlate with the illumination intensity more conveniently, the angle should be taken as one of the units to express coordinates.

Then the intensity of the light needs to be quantified so that it can be calculated. Light intensity refers to the amount of visible light received per unit area, which mainly depends on the reflectivity of the reflector, refraction angle and the initial light and in this formula, but it is not necessary to calculate the specific numerical of the light intensity which is just a comparison that between standard and calculated values so that we can get the corresponding relation between the loss point and the feature point.

The following equation is the complete calculation formula of light intensity:

$$L(p(t), \omega_S) = f_r(\omega_S, \omega_L)\, |n \cdot \omega_L|\, I_L e^{\frac{-2(x_0 - v_t)^2}{\omega^2}} \tag{1}$$

where $\left|\widehat{n} \cdot \widehat{\omega_n}\right|$ stands for cosine of the normal vector and the direction of the ray and f_r represents the Bidirectional Reflectance Distribution Function (BRDF) which is used to define how does the irradiance in a given direction affect the irradiance in a given direction of exit. Several major angles in the BRDF formula respectively represent:

θ : The Angle between the normal vector and the light source.

θ_o : The light comes from the Angle between the receiver and the point.

φ : The connection between the receiver and the point and the Angle between the plane. θ_o and φ are complementary.

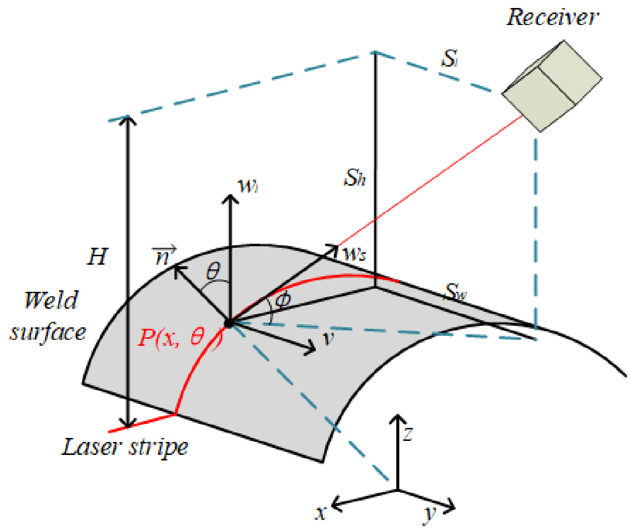

FIGURE 3. Schematic diagram of laser scanning model. The curved surface in the figure is the ideal weld surface model, and the red arc is the cross section of the weld.

Fig.3 shows the schematic diagram of the actual measurement process which can better descript each parameters of the whole model in the 3D space. In the actual test, the actual position of laser, receiver and welding plate is fixed, so it is more reasonable to regard the three originals as placed in the cube and calculate with the length S_l, width S_w and height S_h of the cube. The remaining parameters include direction of illumination $\vec{\omega}_l$, the normal vector of a single pixel $\vec{n}$ and the direction of the receiver relative to the pixel $\vec{\omega}_s$.

According to the established weld seam model, substitute the variables in the flatbed lap weld seam model into the formula, and the reflected light intensity of single pixel point is simplifying as follow:

$$L(p, \omega_S) = f_r(\theta, \theta_o, \varphi)\, |n \cdot \omega_L|\, I_L \frac{1}{2\pi\sigma^2} \tag{2}$$

For a single pixel point, the (2) simplifies the previous variable of time(t), and the parameters in BRDF are also more refined.

And in order to express these angles better, we can express them in terms of trig functions that we know are constant distances:

$$\theta_o = actan\frac{\sqrt{S_l^2 + S_w^2}}{H - z} \tag{3}$$

$$|n \cdot \omega_L| = \cos\theta(\delta\sqrt{(H - z)^2 + S_l^2 + S_w^2}) \tag{4}$$

where z is the height of the distance between the measured point and the coordinate system plane. Finally, the formula is sorted out, putting the known constant in front:

$$L\left(p,\omega_S\right)=I_L\frac{1}{2\pi\sigma^2}f_r\left(\theta,\theta_o,\varphi\right)cos\theta\left(\delta\sqrt{(H-z)^2+S_l^2+S_w^2}\right) \tag{5}$$

$$L(p)=k\cos\theta\phi(z) \tag{6}$$

Constants in (5) are converted, so that (5) can be expressed as (6). From the (6), it can see that the light intensity only depends on the Angle and z, which are the key parameters of point position coordinates.

In the process of repairing single cross-section laser centerline, this formula combined with the above model can complete the task. Firstly, the characteristic points of laser centerline data are identified, which include the highest point of the weld and the welding toe, then establish the coordinate system which the highest point is on the y-axis. Secondly, each point is represented by the new coordinate, and empty coordinate positions are set for the lost data points which have the x-axis coordinates. The process of determining specific coordinates for a single missing data point is as follow:

1) Set the initial z value according to the coordinate system and the model.
2) Calculate the coefficient k from the relevant parameters of the highest point and the weld toe
3) The adjacent point is combined to calculate the θ value, and z value can be obtained by simultaneous equations.
4) Starting at the edge of the data and run the operation for all data points.

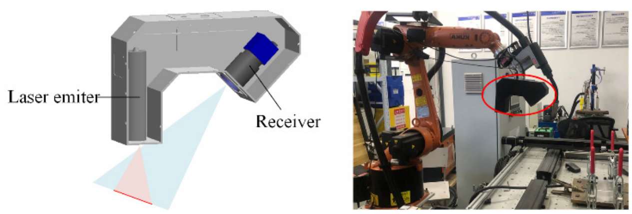

FIGURE 4. Overall schematic diagram and partial schematic diagram of experimental equipment.

III. EXPERIMENTS

As shown in Fig.4, the test system was set up. The laser scan image of weld seam used in the experiment was taken by classical monocular triangular laser measurement system which contains a receiver and a laser transmitter. The system includes: 650 nm laser illuminator which the focal length is 63mm, and the width of the laser is 0.1mm. The MER-130-30UM(-L) was used with a matrix with a resolution of 1280 $\times$ 1024 and the pixel's size is 5.2 μm which attaches a Computer lens(M2518-MPW2) with 5 million pixels, 25 mm focal length. The angle between the laser plane and the receiver plane is 45°. Experiments have shown that the system in this state produces the clearest and most stable images.

The diagram of repair process of lost data is as shown in Fig.5. Among them, the image acquisition used the guide

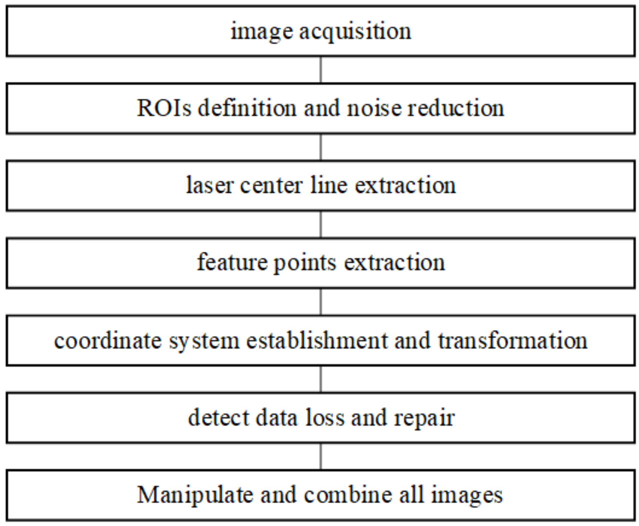

FIGURE 5. Schematic diagram of repairing data loss process.

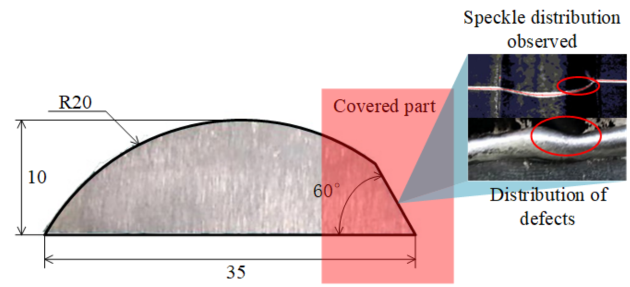

FIGURE 6. Measuring standard block and observation image. The red area is the data loss area thought to be produced, and the observation pattern on the upper right is the acquired image.

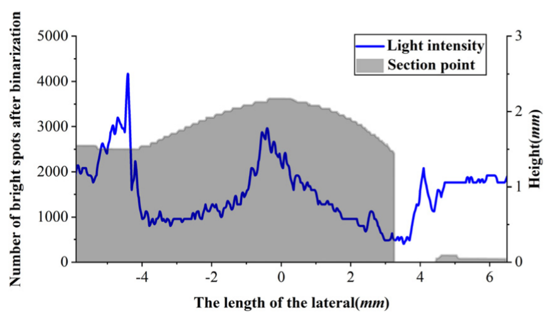

FIGURE 7. The combination of light intensity and raw data.

to uniformly collect about 1000 images and Steger algorithm was used to Sub-pixel extract the center line which is the mainstream extraction method present.

This paper carries out three experiments to prove the feasibility of this repair method. The experimental objects of three groups of experiment are standard block, separate weld cross section and whole section weld respectively.

Case 1: The purpose of the experiment which was performed on arc standard block is to validate the feasibility of the repair method. It is observed that the speckle phenomena

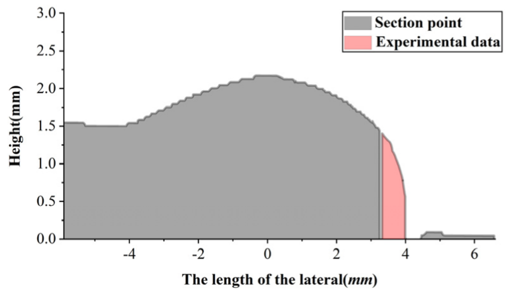

FIGURE 8. The comparison of the patch data and the original lost.

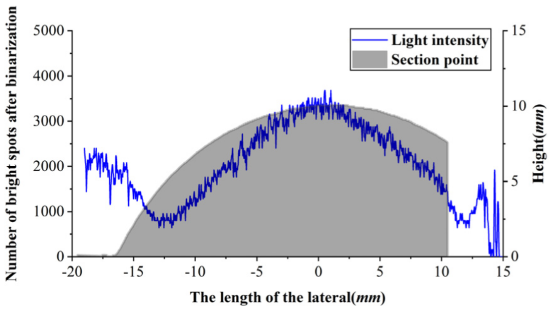

FIGURE 9. Light intensity line chart of missing part of data.

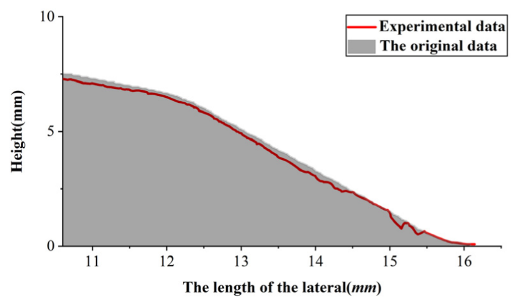

FIGURE 10. Flatbed lap weld section data after repair.

and defects are mostly found in the weld edge. Therefore, in order to reflect the weld cross-section with defects, a portion of the blocks which represents the edge of the weld removed to form a standard test block with defect characteristics, as shown in Fig.6. First of all, artificially erasing the data of the defective part, then the section was measured using the measuring system, the laser centerline was extracted and the intensity of light per unit length was counted, as shown in Fig.7. The special points A, B, and C on the cross-section data were located, and the relative parameter k was calculated by combining (6). Finally, for missing part, the value of illumination intensity and relative parameter k were used to repair the missing data, as shown in Fig.7. As shown in the Fig.8, the repaired section of this method conforms to the original section basically except for a few fluctuations at the end and the mean accuracy can reach 0.2mm after calculation.

Case 2: This case conducted experiment on the actual flatbed lap weld to verify the repair ability of the actual weld.

TABLE 1. Repair results of two different methods.

Method of repair	Number of repair points	Proportion of repairs (%)
MMO	1775	64.43
Method in this paper	586	21.16

First, the repair operation was carried out on the individual section. Fig.9 and Fig.10 show the weld cross-section before and after repair. It is difficult to find a control group in this case, so it is only proved that repair can be done on the weld cross section.

From the image after repair, the defects close to the weld toe still cannot be repaired. It is due to the relatively steep characteristics of the weld surface around the weld toe. The change in light intensity in this part is relatively complicated.

Then experimental verification was carried out for the complete flatbed lap weld section. The same algorithm is used to process many images from previous data collection, then the different sections are arranged according to the time sequence and represented by the 3D point cloud model. At the same time, in order to verify the innovation of the method, conventional MMO method was used to repair the image, and the 3D model completed by this method was used as the control group, as shown in Fig.11.

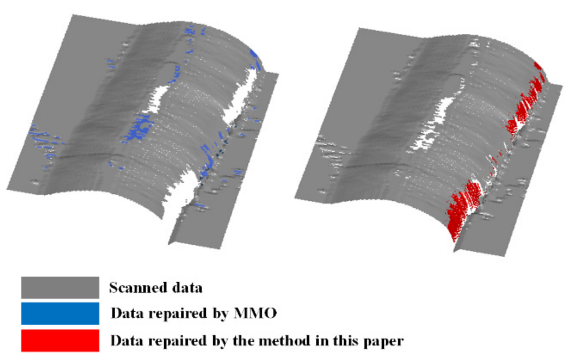

FIGURE 11. Flatbed lap weld surface point cloud data. The right is the repaired model, and the red part is the repaired area.

It can be seen from Fig.11 that MMO is mainly used to repair minor data fractures, while the method presented in this paper can repair large areas of data loss. The specific repair data is shown in Table 1, where the proportion of repairs is the number of repair points over the total number of losses.

Case 3: To demonstrate the influence of this repair method on the detection of weld defects three flat welding seams with certain representative characteristics were selected for experiments. The first one is a relatively ideal, complete flat welding seam. The remaining two pieces have the defects such as unsoldering and droplet deposition. Perform experiments on three experimental subjects. Scan results using a high-precision handheld 3D scanner as a standard control group. The experimental results are as follows.

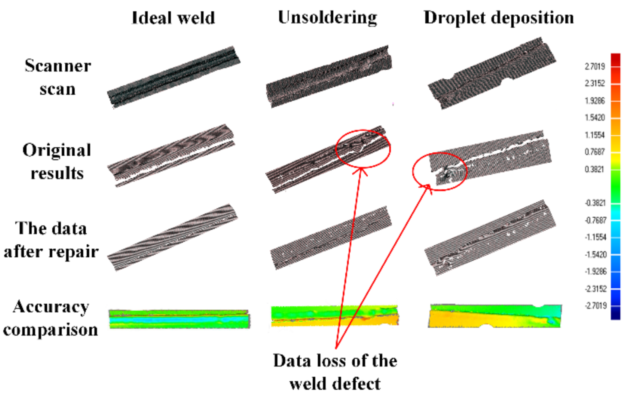

FIGURE 12. **The deviation comparison of different plate welding seams after scanning compared with the control group.**

As shown in Fig.12, except for some unrepairable points near the edge of the toe, the error of all the other points is very small. Meanwhile, for the weld defects which are in the part of the data loss area, this method also has the strong ability to restore the data so that it can be detected easily, especially for flying edge, welding seam too wide and other defects. Thus, it can be verified that this algorithm can be used in the quality inspection of slab lap welds in actual production.

IV. CONCLUSION

The repair method of data loss in the process of weld surface defect detection with LTM presented in this paper, based on light intensity and 3D geometry. In the process of detecting the weld surface quality of flatbed lap weld with triangle laser measurement, the extraction of the laser centerline is often affected by the ambient light, which results in a large segment data loss, especially in the real-time on-line weld detection. In this paper, a 3D model of flatbed lap weld seam was established from the perspective of 3D space combined with the law of light intensity, and a new method was developed to repair lost data. The method improves the repair rate from 21% to 64% compared to the conventional method. In this way, the interference of ambient light to triangular-laser measurement in on-line real-time weld detection can be solved to some extent. The experimental results show that the model can well reflect the 3D surface characteristics of plate lap welding. This method can repair the data loss caused by the complexity of ambient light, and the accuracy can be achieved 0.5mm and the accuracy rate can be 92%, which greatly improves the quality of real-time weld surface quality inspection. However, due to the overlapping and complex illumination at the edge of weld, some data loss still occurs, which will be further discussed in future studies.

REFERENCES

[1] Z. Y. Cai *et al.*, "Study on multipass welding seam recognition based on wavelet transform," *J. Image Graph.*, vol. 12, pp. 2344–2350, 2008.
[2] X. Zhan, X. Bu, T. Qin, H. Yu, J. Chen, and Y. Wei, "X-ray online detection for laser welding T-joint of Al–Li alloy," *Mod. Phys. Lett. B*, vol. 31, no. 14, May 2017, Art. no. 1750154.
[3] Y. Li, Y. Fu Li, Q. Lin Wang, D. Xu, and M. Tan, "Measurement and defect detection of the weld bead based on online vision inspection," *IEEE Trans. Instrum. Meas.*, vol. 59, no. 7, pp. 1841–1849, Jul. 2010.
[4] C. L. S. C. Fonseka and J. A. K. S. Jayasinghe, "Implementation of an automatic optical inspection system for solder quality classification of THT solder joints," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 9, no. 2, pp. 353–366, Feb. 2019.
[5] R. Ye, M. Chang, C.-S. Pan, C. A. Chiang, and J. L. Gabayno, "High-resolution optical inspection system for fast detection and classification of surface defects," *Int. J. Optomechatronics*, vol. 12, no. 1, pp. 1–10, Jan. 2018.
[6] Q. Xie, D. Lu, K. Du, J. Xu, and J. Wang, "Aircraft skin rivet detection based on 3D point cloud via multiple structures fitting," *Comput.-Aided Des.*, vol. 120, Mar. 2020, Art. no. 102805.
[7] K. Li, J. Wang, and D. Qi, "The development and application of an original 3D laser scanning: A precise and nondestructive structural measurements system," *Frattura ed Integrità Strutturale*, vol. 14, no. 51, pp. 386–397, 2019.
[8] H. Kuhlmann and J. Dupuis, "High-precision surface inspection: Uncertainty evaluation within an accuracy range of 15 μm with triangulation-based laser line scanners," *J. Appl. Geodesy*, vol. 8, no. 2, pp. 109–118, 2014.
[9] S. Li, X. Jia, M. Chen, and Y. Yang, "Error analysis and correction for color in laser triangulation measurement," *Optik—Int. J. Light Electron Opt.*, vol. 168, pp. 165–173, Sep. 2018.
[10] H. Yang, W. Tao, Z. Zhang, S. Zhao, X. Yin, and H. Zhao, "Reduction of the influence of laser beam directional dithering in a laser triangulation displacement probe," *Sensors*, vol. 17, no. 5, p. 1126, 2017.
[11] C. Wu, B. Chen, C. Ye, and X. Yan, "Modeling the influence of oil film, position and orientation parameters on the accuracy of a laser triangulation probe," *Sensors*, vol. 19, no. 8, p. 1844, Apr. 2019.
[12] Y. Selami, W. Tao, Q. Gao, H. Yang, and H. Zhao, "A scheme for enhancing precision in 3-Dimensional positioning for non-contact measurement systems based on laser triangulation," *Sensors*, vol. 18, no. 2, p. 504, Feb. 2018.
[13] L. Shen, D. G. Li, and F. Luo, "Study on laser speckle correlation method applied in triangulation displacement measurement," *J. Opt. Technol.*, vol. 80, no. 10, pp. 604–610, 2013.
[14] L. Zhang, X. S. Cheng, H. H. Cui, N. Dai, and X. Pei, "Three-dimensional laser detection algorithm for highlight on metal surface," *Electro-Opt. Technol. Appl.*, vol. 28, no. 6, pp. 45–48, 2013.
[15] W. L. Li, H. Xie, Q. D. Li, L. P. Zhou, and Z. P. Yin, "Section curve reconstruction and mean-camber curve extraction of a point-sampled blade surface," *PLoS ONE*, vol. 9, no. 12, 2014, Art. no. e115471.
[16] J. Xi, H. Bao, and T. Li, "Research on the algorithm of noisy laser stripe center extraction," in *Proc. Chin. Control Decis. Conf.*, Jun. 2018, pp. 6297–6300.
[17] M. Gatzen, T. Radel, C. Thomy, and F. Vollertsen, "Wetting and solidification characteristics of aluminium on zinc coated steel in laser welding and brazing," *J. Mater. Process. Technol.*, vol. 238, pp. 352–360, Dec. 2016.

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