Comprehensive Analysis of Intelligent Welding Technology Based on Machine Vision

Zhuangzhuang Liu

College of Engineering, Ocean University of China, Qingdao, 266100, China
24090041028@stu.ouc.edu.cn

Abstract. With the increasing demands for welding efficiency and accuracy, intelligent welding technology has developed rapidly, and machine vision plays a significant role in it. In terms of image preprocessing, a system of grayscale processing, filtering and denoising, and image enhancement is formed to reduce image noise and enhance the operability of the picture. In the field of weld seam recognition, research focuses on image processing methods and deep learning networks, with the aim of enhancing accuracy and efficiency through innovation and improvement. The research on weld seam tracking is mainly based on the optimization of anti-noise and adaptation to specific scenarios. In the field of weld defect detection, based on deep learning networks, a process of model update and transformation is underway. In the future, research on intelligent welding technology based on machine vision will focus on improving algorithm efficiency and making corresponding adjustments in different environments. This article aims to distill and analyze the achievements of recent years, and predict the development trend and cutting-edge direction of this technology.

Keywords: Intelligent welding, Machine vision, Weld defect detection, Deep learning in welding.

1 Introduction

Welding is a technique with high precision requirements. In recent years, with the continuous improvement of the requirements for welding efficiency and accuracy in the industrial field, intelligent welding has developed rapidly. Among them, machine vision plays a significant role. Traditional welding techniques require a great deal of manpower and material resources, and their stability and accuracy cannot be guaranteed. The efficiency also varies from person to person. The intelligent welding technology introduced with machine vision enables machines to replace humans in welding and defect detection, making it more efficient and accurate. Moreover, it effectively resolves the safety issues of manual welding in some hazardous environments.

In terms of image preprocessing, a system of grayscale processing, filtering, and denoising, and image enhancement has been formed, which not only reduces image noise but also improves the operability of the received images. In weld seam recognition technology, research focuses on the proposal of new image processing

K. Subramanian (ed.), *Proceedings of the International Workshop on Advances in Deep Learning for Image Analysis and Computer Vision (IWADIC 2025)*, Advances in Computer Science Research 128,
https://doi.org/10.2991/978-94-6239-648-7_23

methods and the construction of deep learning networks, which complement each other to further enhance recognition efficiency and accuracy. In the field of weld seam tracking, many scholars have proposed their own solutions based on noise removal or improvements in specific application scenarios, which has promoted the maturity of this technology. In the field of weld defect detection, convolutional neural networks and object detection algorithms play a crucial role. Based on machine vision technology and the application of various deep learning models, the system can more accurately identify welding defects and their types, making the system's response more reasonable and efficient while reducing the system's computational load. This, in turn, has led to a leap in the system's real-time performance.

However, the field of intelligent welding based on machine vision still faces some problems at present. On the one hand, the continuous emergence of deep learning models is overly complex and requires a huge amount of computation, which has become the main factor restricting the further improvement of the technology's efficiency. On the other hand, for different materials and different environments, this technology does not have a universal and effective on-the-spot transformation ability.

This article mainly discusses the research achievements of intelligent welding technology based on machine vision, showcases the application of machine vision in the field of intelligent welding, and aims to summarize and generalize the current development of this field.

2 The Development of Dpecific Fields of Intelligent Welding Technology Based Machine Vision

2.1 Image Preprocessing

For intelligent welding technology, only the area around the weld seam is important. At the same time, due to the influence of sparks and dust in the welding environment, the images extracted based on machine vision contain a large amount of noise. Their presence is not conducive to the further processing of weld seams and greatly reduces the processing performance of intelligent welding technology. Therefore, it is extremely important to preprocess the obtained images and highlight the required image features. Generally speaking, the current image preprocessing techniques in this field include three parts: grayscale processing, filtering and denoising, and image enhancement.

Meanwhile, in this field, the shape of the weld seam is more significant than its color. Grayscale processing of images not only eliminates the interference of non-target colors but also significantly reduces the amount of image data, thereby enhancing the efficiency of image processing. Meanwhile, based on the gray-scale histogram, the luminance distribution can be identified to facilitate further adjustments to the processing.

Image noise can be effectively processed through filtering. In the preprocessing stage, common filtering methods include Gaussian filtering and bilateral filtering. Among them, Gaussian filtering has a relatively small computational load and can effectively eliminate the interference of noise such as splashes and dust. It is most commonly used in image preprocessing. The computational load of bilateral filtering is relatively large and it is suitable for scenarios where the weld edge needs to be clearly preserved.

Image enhancement, that is, enhancing the contrast between key features and irrelevant features. The traditional method achieves this process by adjusting the distribution of gray values in the image. At present, the method of adapting and learning the degradation law of weld seam images through deep learning networks and then conducting enhancement processing is increasingly being applied due to its strong adaptability and significant effect.

2.2 Weld Seam Identification

Based on Image Processing. At present, machine vision is the foundation for realizing weld seam recognition technology. And based on machine vision, processing the extracted images is undoubtedly of Paramount importance. In recent years, many scholars have put forward their pioneering methods in this field.

Li et al. proposed an improved multi-type weld recognition algorithm to overcome the problems of noise interference and limited number of recognition types in conventional weld recognition technology. This algorithm focuses on the fringes intersecting with noise. Combined with the proposed IPCE algorithm, it greatly reduces the interference of noise through local adaptive thresholds and variable step size advancement. Combined with a proposed dynamic region of interest algorithm, it can identify broken welds, and the proposed SP algorithm is used to identify non-broken welds, which greatly improves the accuracy and robustness of weld identification [1].

Li et al. proposed a weld joint recognition algorithm based on laser profile sensors to address the problem that traditional weld joint recognition methods are difficult to identify narrow weld joints. This series of algorithms first proposed the IPCBE algorithm, taking into account the important features of the laser edge and shifting the approach from noise reduction to directly processing the noisy fringes. Then, an improved local adaptive method based on the Niblack approach is utilized to enhance the robustness and accuracy of the IPCBE algorithm, and ultimately position analysis is conducted to accurately identify narrow weld joints [2].

Based on Deep Learning networks. Due to its strong ability to process complex data, adapt to different scenarios and achieve high accuracy and efficiency, deep learning network algorithms have become the most suitable tool for realizing weld seam recognition technology. Constantly attempting, applying and improving various deep learning networks has been a major trend in the research of weld seam recognition technology in recent years.

Ma et al. designed a new method for identifying weak weld targets in order to improve the accuracy of weld seam recognition. This method re-labels the weld image using the outer envelope frame and the weld slope, and then trains it through a new recognition framework designed based on prior knowledge and the YOLOv5 recognition algorithm, achieving effective filtering of spatter and arc noise and an improvement in recall rate [3].

To accurately identify weld points in noisy environments such as spatter and arc light, Yu proposed an end-to-end key point regression network, which enhances the anti-interference ability through multi-scale feature fusion. Moreover, using the heat map as the loss function, the key points of the weld seam can be directly predicted. This network takes into account both accuracy and speed, and compared with traditional methods, it has more advantages in robustness and annotation cost [4].

Guo et al. proposed a key point detection method based on weld feature extraction to enhance the accuracy and adaptability of weld seam recognition. This method is based on convolutional neural networks and fuses deep features with shallow features to improve accuracy. By combining the heat map of weld seam images to predict the position of weld seam feature points, a set of weld seam feature extraction network was constructed. This network avoids the suppression of maximum values, improves the speed of feature extraction, and enhances the accuracy and adaptability of weld seam recognition [5].

2.3 Weld Seam Tracking

Based on Noise Processing.During the laser welding process, due to the power fluctuation of the laser generator, spatter, arc light and other factors generated during the welding process, noise is often produced. This can cause image deviation and further affect the accuracy of weld seam tracking. This is currently the biggest difficulty faced by weld seam tracking technology.

Based on the problem that the existing weld seam tracking methods are severely affected by noise, Lu et al. proposed an anti-noise weld seam tracking algorithm based on a spatio-temporal memory mechanism. This method proposes a memory mechanism with welding history memory information and a memory frame evaluation function, enabling the system to better adapt to changes in weld appearance and noise interference. By constructing a laser stripe tracker based on spatio-temporal memory to search for historically valid information, the influence of noise and appearance changes is eliminated, and the anti-noise performance and adaptability are enhanced [6].

Tian et al. proposed a laser weld seam tracking sensing technology based on swing mirrors to eliminate the reflection on the surface of pipeline welds and the interference of strong welding arcs on laser weld seam tracking. This technology introduces point light sources. For the point light sources that move periodically after being reflected by the swing mirror, the image collector continuously collects and splices them, thereby achieving precise measurement of V-shaped, U-shaped, flat-bottom bevels, as well as extremely wide and deep welds and extremely narrow and deep welds under the interference of noise [7].

Gong et al. proposed a weld tracking algorithm based on an improved kernel correlation filter to address the issue of weld tracking failure caused by strong noise during welding in structured light vision. This algorithm extracts the centerline of the weld laser stripe from the processed image through the Steger algorithm, then filters and takes the derivative of the centerline to obtain the initial feature points of the weld, and applies it to the KCF algorithm that introduces the peak correlation index and the corresponding advanced controller model, ultimately achieving high-precision real-time weld tracking [8].

Based on Process Improvement.For various specific scenarios, the existing weld seam identification technology needs to be optimized in the process, as the situation requires, to meet the actual needs in different scenarios.

In order to improve the tracking accuracy of the weld trajectory of the bimetallic saw blade laser welding machine, Guan et al. constructed a control model for the tracking of the weld trajectory of the bimetallic saw blade laser welding machine. This model acquires the centerline of the weld seam trajectory through the horizontal projection method and determines the weld seam trajectory by scanning the centerline of the laser stripe. The Lagrange dynamics method is then used to describe the dynamics model. Further considering the various parameters of the bimetallic saw blade laser welding machine, the corresponding weld seam tracking control strategy is finally formulated [9].

In order to achieve the tracking of three-dimensional complex welds, Zhang et al. designed a new type of weld tracking system for three-dimensional complex welds. This system continuously collects multiple segments of data by scanning the weld seams in segments through a laser sensor installed at the end of the robot. Then, the combined filtering technology is used to correct the data. Finally, feature point collection, coordinate system calibration and welding path planning are carried out to achieve the complete weld seam tracking process [10].

Wang et al. proposed a full-position pipeline welding strategy based on laser vision for the weld seam tracking technology in the full-position welding process of large-sized bevel process pipelines. This strategy applies pre-fitted fuzzy paths for the initial planning of the welding torch attitude, and integrates deep learning and image processing algorithms to obtain feature points. Subsequently, it further processes the welding parameters and welding paths to achieve weld seam tracking [11].

2.4 Weld Defect Detection

Convolutional Neural Network.Convolutional neural networks have a powerful feature extraction capability. Therefore, they and their improved models are widely used for the collection of information on different types of weld defects and their detection and recognition.

Kim et al. designed two bidirectional convolutional recurrent reconstruction networks - one for high efficiency and the other for enhanced detectivity - to address the issue that the training based on convolutional neural networks was only for static images. They improved the detection performance by considering spatio-temporal data and extended the weld defect detection scenario to video input [12].

Shen et al. proposed a novel weld detection method named CRNet to address the issue of strong coupling of magnetic flux leakage signals between defects and welds in intelligent magnetic flux leakage detection systems, making it difficult to distinguish them. This method is based on convolutional neural networks. Firstly, it reduces coupled features through a feature extraction network with sparse attention. Secondly, it fully explores the coupling relationship through a multi-scale relationship exploration module. Finally, it achieves a more refined complementarity through multi-view collaborative detection. Ultimately, it realizes pixel-level magnetic flux leakage weld defect detection for the first time [13].

Huang et al. constructed an improved lightweight U-Net model with an attention mechanism to address the problems such as the loss of low-level position information and the inundation of small defects during weld defect detection in traditional convolutional neural networks. This model is trained using convolution kernels and pooling kernels of different sizes. By fusing and learning multi-scale features, it significantly improves the accuracy of multi-scale defect detection, especially for small defects [14].

Object Detection Algorithm.Object detection algorithms can perform location and type recognition on specific objects in photos. Object detection algorithms based on deep learning networks can even achieve end-to-end location and classification. Due to its high accuracy and robustness, the object detection algorithm is widely used in weld defect detection. Among them, the YOLO series of algorithms are favored by many researchers due to their high speed and accuracy, which are in an appropriate balance.

Song et al. proposed a weld defect detection model based on YOLOv5, named GMVG-Net, to enhance the speed and accuracy of weld defect detection. This model reduces the parameter model and improves the reasoning speed and detection accuracy in weld defect detection by integrating Ghost Bottlenect into the backbone network, using lightweight VoVGSCSP, and replacing C3 with GSConv module, etc. [15].

Lu et al. proposed an enhanced strategy for YOLOv8 based on the problem of low detection accuracy of YOLOv8 in X-ray weld defect detection. They enhanced its detection capability for tiny targets by introducing an additional ultra-small target detection head and adopting a serpentine variable convolution. Through the proposed improved three-level BiFPN structure, its detection performance for medium and large targets has been enhanced, comprehensively improving the performance of the YOLOv8 model [16].

Facing the problems of low intelligence and low detection efficiency of the current train body welding defect detection technology, Ma et al. proposed an intelligent detection method for train body welding defects based on the improved YOLOvX. This method introduces the CSP structure and dense network to enhance the feature extraction network, and the BiFPN and ASFF networks to strengthen the feature fusion network, ultimately achieving an improvement in the performance of YOLOvX weld defect detection [17].

3 Challenges and Future Development

3.1 Technical challenges

At present, although intelligent welding technology based on machine vision has made some progress in the fields of weld seam tracking, weld seam inspection and weld seam recognition, it still faces the following risks and challenges. In the face of intense high temperatures, dust and other interferences during the welding process, the extraction process of machine vision will be disturbed, causing the image to be blurred and increasing the difficulty of processing. What's more, traditional machine vision systems have certain delays in data processing and transmission, which poses a challenge to meeting the high real-time requirements of intelligent welding. Moreover, in the face of different welding materials and different welding techniques, the welding process will also vary during the process, and the existing intelligent welding system is difficult to achieve such an adaptive function.

3.2 Development suggestions

In recent years, intelligent welding has shown a strong trend of becoming more intelligent and efficient. Specifically, intelligent welding technology based on machine vision should focus on the development of two areas: enhancing autonomous decision-making capabilities and expanding the application scenarios of the technology. The algorithm is the core factor influencing the autonomous decision-making ability of the welding system. Further optimizing the algorithm and iterating the deep learning model should become the main tasks of the current development of this technology. At the level of expanding application scenarios, subsequent research should focus on adjusting and correcting this technology and enhancing the recognition of different welding materials in various specific environments. At the same time, research in both fields should focus on the integration with AI technology. Empowering intelligent welding technology with AI holds great potential in terms of cost savings and performance enhancement.

4 Conclusion

This article mainly sorts out the research and application of intelligent welding technology based on machine vision in recent years. Among them, this article mainly focuses on three technologies: weld seam identification, weld seam tracking, and weld seam defect detection. It refines and analyzes them, and puts forward pioneering suggestions for the future development direction of this field.

The development of weld seam recognition technology benefits from the optimization of image processing algorithms and the construction of various deep learning networks. This has led to a significant improvement in both its recognition accuracy and processing efficiency. Research on weld seam tracking technology focuses on eliminating noise interference and optimizing specific processes. By continuously reducing the influence of spatter, dust and other interferences on the tracking process and constantly specifying the device and method configuration of the weld seam tracking system in various scenarios, this technology has matured. For weld defect detection technology, at present, based on various continuously improved deep learning models based on convolutional neural networks and object detection algorithms, the manual process has been further reduced, and the intelligence level of defect detection technology has been further enhanced. Meanwhile, traditional image-based processing methods still have irreplaceability in specific applications. The optimization and improvement of it is also an important factor in enhancing the efficiency of weld defect detection technology.

References

1. Li, W., Feng, M., Zeng, H., Gao, X., Yu, H., Housein, A.A., Wei, C.: Multiple weld seam laser vision recognition method based on the IPCE algorithm. Optics & Laser Technology 155, 108388 (2022)
2. Li, W., Wei, C., Chen, S., Gao, X., Yu, H.: Narrow weld joint recognition method based on laser profile sensor. IEEE Sensors Journal 23(2), 1295–1307 (2023)
3. Ma, H., Xu, Y., Liu, J.: Weak weld-target recognition based on prior knowledge. In: 2022 4th International Conference on Control and Robotics (ICCR), pp. 393–397. IEEE (2022)
4. Yu, X., Cao, G., Hu, H., et al.: A KPRN-based method for weld seam point recognition with strong robustness. In: 2023 29th International Conference on Mechatronics and Machine Vision in Practice (M2VIP). IEEE (2023)
5. Guo, Z., Liu, J., Yang, J.: Weld recognition based on key point detection method. Transactions of the China Welding Institution 45(1), 88–93 (2024)
6. Lu, J., Zhao, Y., Gao, P., Han, J., Zhang, Y., Zhao, Z.: Anti-noise weld seam tracking algorithm based on spatio-temporal memory mechanism. Measurement 242(C), 116054 (2025)
7. Tian, C., Song, X., Yin, T., Zhang, Y.: Laser weld seam tracking sensing technology based on swing mirror. In: 2022 IEEE 7th Optoelectronics Global Conference (OGC), pp. 278–281. IEEE (2022)
8. Gong, S., Zhang, G., Zhu, H.: Weld seam tracking method under strong noise based on kernel correlation filters. Laser Technology 49(2), 289–295 (2025)
9. Guan, J., Zhu, S.: Construction of seam tracking control model for laser welding machine of bimetal saw blade. Mechanical Science and Technology for Aerospace Engineering 41(9), 1381–1386 (2022)
10. Zhang, G., Huang, J., Wu, X., Yang, G., Di, S., Yuan, H., Cao, X., Shin, Y.: A novel 3D complex welding seam tracking method in symmetrical robotic MAG welding process using a laser vision sensing. Symmetry 15(5), 1093 (2023)
11. Wang, T., Meng, K., Cui, L., Li, X.: Weld tracking technology for all-position welding of pipes based on laser vision. Optics and Lasers in Engineering 188, 108912 (2025)
12. Kim, Y.-M., Yoon, I.-U., Myung, H., Kim, J.-H.: Bi-directional convolutional recurrent reconstructive network for welding defect detection. IEEE Access 9 (2021)
13. Shen, X., Liu, J., Jiang, L., Liu, X., Zhang, H.: A novel weld defect detection method for intelligent magnetic flux leakage detection system via contextual relation network. IEEE Transactions on Industrial Electronics 71(6), 6304–6314 (2024)
14. Huang, L., Zhang, S., Li, L., Han, X., Li, R., Zhang, H., Sun, S.: Modified lightweight U-Net with attention mechanism for weld defect detection. In: 18th International Conference on Intelligent Computing (ICIC), Lecture Notes in Computer Science, pp. 306–316 (2022)
15. Song, K., Huang, Q.: GMVG-Net: lightweight multiscale feature fusion network for welding defect detection. Signal, Image and Video Processing 19(6), 436 (2025)
16. Lu, W., Zheng, H., Xiao, S., Xue, W., Yang, S.: Application of the improved YOLOv8 algorithm for small object detection in X-ray weld inspection images. Journal of Nondestructive Evaluation 44(3), 91 (2025)

17. Ma, R., He, D., He, S., Chen, Y., Jin, Z., Shan, S.: Welding quality detection of metro train based on improved YOLOX. Journal of Railway Science and Engineering 20(10), 3998–4007 (2023)