# Analysis of Welding Robot Seam Recognition and Tracking Based on Visual Sensing

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**Abstract.** At present, traditional welding has the limitations of low efficiency, unstable quality, endangering the health of welders, and a weak ability to adapt to special operations. Intelligent welding robot has become an inevitable trend. This paper discusses the types of visual sensors and image processing algorithms in seam recognition and tracking, and defines the selection direction, advantages, and disadvantages of visual sensors. Starting from the stage of seam recognition and tracking, this paper compares the advantages and disadvantages of traditional and cutting-edge image processing algorithms and their application scenarios. Finally, the research results are summarized, and the relevant conclusions on the selection of sensors and algorithms are obtained, and the future development direction is projected. The analysis of this paper can provide a reference for related research.

**Keywords:** Welding Robot; Recognition; Visual Sensing

## 1. Introduction

In the era of Industry 4.0, the requirements of industrial production for efficiency and quality continue to improve. Welding, as the core process of heavy industry, has a direct impact on production efficiency. At this stage, manual welding is still dominant, with problems such as low efficiency, high dependence on welder technology, and large quality fluctuation. Moreover, the radiation and smoke generated by welding will harm the health of welders, and it is difficult to adapt to underwater welding and other special operations. Therefore, it is necessary for intelligent machines to replace manual welding.

The intelligent welding robot is mainly divided into "teaching reappearance" type and off-line programming type. The former requires manual debugging, with poor adaptive ability and a narrow application range. The latter has high flexibility and wide applicability, and is the core research object of this paper. The core link of the offline programming welding robot includes seam recognition, tracking, and quality detection, which rely on the sensor to collect information and combine with an image processing algorithm analysis. Sensors are divided into contact-type and non-contact type. Contact type sensors have limited information and require physical contact, whichmakes it difficult to meet the needs of complex welding. Non-contact sensors have gradually become the mainstream. Among them, the visual sensor has significant advantages due to its high accuracy and ease of use, such as the Dual Charge-Coupled Device Camera(CCD ) adopted by Liu et al. [1]. The image processing algorithm needs to adapt to different welding stages, such as the median filtering algorithm

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At present, the welding robot based on machine vision still has problems such as insufficient quality and accuracy when dealing with complex welds and harsh environments. This paper systematically reviews the application and research results of visual sensor types and image processing algorithms in seam recognition and tracking, and looks forward to the future development direction, providing support for the research in related fields.

## 2. Types and applications of visual sensors in seam tracking and recognition

The commonly used visual sensors for seam tracking and recognition are divided into passive and active. The passive sensor has no auxiliary light source and directly extracts environmental information. The active sensor can actively generate a light source and obtain weld information without depending on the environment.

### 2.1 passive vision sensor

The passive vision sensor needs no auxiliary light source, which is easy to use and has a wide range of information acquisition. Compared with the active structured light sensor, it has a wider application scene, especially in high specular reflection metal welding or strong light environments. The mainstream equipment is arc resistant ccd/cmos camera, and some scenes are supplemented by an infrared thermal imager.

**Arc resistant ccd/cmos camera.** As the most widely used passive sensor in this field, arc resistant ccd/cmos cameras are often carried on welding robots. Researchers improve the imaging quality by optimizing the number of cameras and filters. Liu et al. Designed a dual CCD cooperative system. The high-pixel camera was responsible for obtaining the global ROI and positioning the start and end points of the weld and the direction of motion. The low-pixel B camera carried out local high-frequency fine scanning to achieve accurate trajectory correction. The average error of the start point positioning was 0.98mm, and the tracking MAE was less than 0.12mm[1]. Filter technology is the core of anti-interference. Xu et al. Customized filter through spectral analysis [2], Shen et al. Developed a double-layer filter system to realize light intensity adaptation [2]. In addition, this kind of camera can be upgraded to a partially active sensor with an auxiliary light source. Nele et al. Used a color CCD camera and 90 LED arrays to improve the stability of image acquisition [2]. Its core advantages are controllable cost, high imaging accuracy, and fast response. The performance can be further improved after multi-camera cooperation or adding filters.

**Infrared thermal imager.** By collecting the infrared thermal image of the weld surface, the infrared thermal imager uses the temperature difference between the defect and the normal area ≥ 50 °C to highlight the weld characteristics and avoid the contour blur problem of visible light imaging. In a high smoke scene, ccd/cmos camera will fail due to arc overexposure and smoke scattering, while an infrared thermal imager can break through the limitation. Zhang et al. Used two high-speed infrared cameras with median filters to control the welding position error at about 0.2mm and adapt to vertical superimposed welding [3]. The device does not need additional filters. Li et al. Have shown that it can directly suppress the arc interference by virtue of the temperature field characteristics, and the image signal-to-noise ratio is increased to more than 35dB [4]. Although the cost is higher than that of ccd/cmos camera and the data needs to be processed in combination with the temperature field model, it is irreplaceable in complex scenes such as thick plate deep groove and high soot, and is an important supplement to the welding quality control of high-end equipment.

**2.2 Active vision sensor**

An active vision sensor transmits specific optical signals and receives reflected signals for imaging. Although the accuracy is affected in high reflection and strong light environments, it has strong anti-interference ability and high measurement accuracy in most scenes, and can obtain three-dimensional information, which is the core scheme of complex precision welding. The following focuses on line laser sensors and structured light sensors.

**Line laser vision sensor.** Based on the principle of optical triangulation, the linear laser vision sensor obtains weld characteristics by projecting a fan-shaped laser beam, which is widely used in high-precision and high-speed welding scenes. Its working principle is as follows: the laser emitter projects the laser line. After the laser line is distorted due to the geometric contour of the weld, it is collected by a ccd/cmos camera installed at a fixed angle. After filtering, the data unit extracts the center trajectory of the laser line and calculates the system calibration parameters to calculate the three-dimensional setting of the weld [5]. In terms of technical optimization, Kim et al. Repaired the laser line fracture caused by soot through multi frame image fusion algorithm, with a recognition success rate of over 97% [6]. The domestic team controlled the measurement error within ± 0.03mm through the double target technology, which is suitable for aerospace precision welding [7]. The high-speed system developed by a German company has a frame rate of 500fps, which can adapt to the welding speed of more than 3m/min [8]. The application scenarios cover the welding of automotive parts (gearbox shell weld tracking, dimensional error ± 0.1mm[9]), multi-pass welding of ship thick plates, nuclear power pipeline girth weld tracking [10], and are suitable for the welding of light materials such as aluminum alloy and titanium alloy.

**Structured light sensor.** The structured light sensor projects preset structured light, such as gray code and sine fringes, and obtains the complete contour of the weld through encoding and decoding and three-dimensional reconstruction. It has a wide measurement range and rich feature information, and is suitable for complex curved surfaces and special-shaped welds. The system is composed of a projection module, an image acquisition module, and a data processing module. Through structured light projection, distorted image acquisition, decoding, and three-dimensional reconstruction, it can accurately extract parameters such as weld center trajectory and groove angle [11], which is more efficient than the three-dimensional reconstruction of a line laser sensor. In terms of technological breakthroughs, Zhang et al. Combined u-net network with a decoding algorithm, and the recognition accuracy was improved by 40% [12]. Li et al. Proposed a dynamic error compensation model to correct the phase shift caused by thermal drift and reduce the measurement error by 35% [13]. The combined design of frequency and time coding can effectively distinguish interference signals and adapt to a high soot environment [14]. Its typical applications include aircraft wing skin butt weld tracking [15], engine blade welding posture guidance, and large steel structure splicing [16]. After special optimization, it can adapt to extreme environments such as underwater and space.

## 3. Application of image processing algorithm in seam tracking and seam recognition based on machine vision

A vision sensor provides high-quality information acquisition ability for a welding robot, and the image processing algorithm is the core to realize accurate recognition and tracking of the welding seam. The weld recognition algorithm focuses on the accurate extraction and classification of image information, and the tracking algorithm focuses on path planning and offset control. The two types of algorithms need to be accurately adapted according to the welding stage.

### 3.1 Weld Identification Stage

The image processing in the weld recognition stage is divided into three parts: image preprocessing (de-interference and feature extraction), weld feature extraction (locking the weld and completing the fracture contour), and weld recognition and classification (determining the weld type).

**Image preprocessing algorithm.** Image preprocessing needs to achieve denoising and contrast enhancement, corresponding to two kinds of core algorithms. Median filter denoising algorithm is the traditional mainstream scheme, with a simple principle and low calculation cost (single frame processing time<5ms). When dealing with the problem of laser line fracture caused by welding fume, Kim et al First removed the isolated noise through median filtering, and thencombine with multi frame fusion algorithm to complete the laser line, so that the success rate of weld recognition increased from 82% to more than 97% [6], which provided an effective idea for the optimization of the traditional algorithm. But the algorithm is difficult to deal with a large area of dense noise and smoke.

The adaptive threshold segmentation algorithm is an advanced scheme to enhance the contrast. By dynamically adjusting the segmentation threshold to adapt to the real-time welding environment, the accuracy is better than that of the traditional fixed threshold segmentation algorithm. Li et al. Used the temperature adaptive algorithm to dynamically adjust the threshold according to the real-time welding temperature, and the accuracy was 32% higher than the fixed threshold algorithm [4]. However, the algorithm has a large amount of calculation and requires high hardware computing power, and it often needs to be equipped with special sensors such as an infrared thermal imager. At present, combining with a neural network to optimize the threshold has become an important direction to improve the accuracy.

**Weld feature extraction algorithm.** The core of this stage is to lock the weld by algorithm, and complete the contour completion when the weld is disturbed and fractured. Canny edge detection algorithm is a traditional classic scheme, with high edge positioning accuracy (error<0.01mm), which can effectively screen false edges, and the accuracy can be further improved after combining with double target localization technology. Wang et al. First used the Canny algorithm was used to extract the edge of the laser stripe (error<0.01mm), and then the three-dimensional coordinates of the weld through double target positioning to control the system measurement error within ± 0.03mm[7]. However, the algorithm is sensitive to image contrast, and the edge extraction isprone to fracture in the environment of high smoke and low signal-to-noise ratio, and it depends on manually setting the threshold, so it can not adapt to different welding materials.

RANSAC straight-line fitting algorithm is the leading-edge scheme to complete the fractured weld. It can complete the gap by automatically identifying the optimal straight-line trajectory, but it is difficult to take into account the details of the complex groove weld. Therefore, in practical applications, it is often combined with u-net neural network. For complex groove welds, Zhang et al. First used the RANSAC algorithm to fit the preliminary trajectory, and then optimized the details through u-net. The accuracy of feature extraction is 40% higher than that of the simple RANSAC algorithm [12]. The fusion scheme of such a traditional algorithm and deep learning has improved the accuracy, but the computational complexity has increased significantly, which needs to be furtherlightened to meet the real-time requirements.

**Weld target recognition and classification algorithm.** This stage is divided into simple and complex weld recognition scenarios according to the weld complexity. The template matching algorithm is the traditional mainstream scheme for simple weld recognition, which has a fast processing speed and small positioning error. Xiao et al. Used the template matching algorithm to locate the starting point of the straight weld in the welding of the automobile gearbox housing. The positioning error was less than 0.05mm, and the single frame processing time was less than 10ms[11]. However, the algorithm is only suitable for straight welds, simple fillet welds, and other fixed shape welds, and can not adapt to complex surface welds.

The U-Net semantic segmentation algorithm is the core cutting-edge scheme of complex weld recognition, which improves the recognition accuracy through large sample learning. Zhang et al. Built a lightweight U-Net model to perform semantic segmentation for butt welds of aircraft wing skin, with a recognition accuracy of 98.5%, 25% higher than the traditional template matching algorithm, and can simultaneously identify the weld position and groove type [12]. However, this scheme requires a largeamount of annotation data, which is expensive to collect and requires hardware computing power. The construction of a lightweight model is the key to its application.

### 3.2 Weld Tracking Stage

The core algorithm in the weld tracking phase is divided into three parts: early path planning (determining the approximate welding direction), real-time tracking control (correcting minor deviations), and complex scene optimization (dealing with extreme conditions).

**Track the early path planning algorithm.** Path planning is divided into two categories: offline preset and online correction. Offline programming path planning is a traditional preset scheme with clear logic, standardized path, and high repetition accuracy in batch production. In narrow gap GMAW welding, Li et al. Planned the "straight line+arc" mixed path through off-line programming software such as RobotStudio, and verified by the line laser sensor, the path deviation was less than 0.1mm, meeting the requirements of mass production [5]. However, this scheme can not deal with complex scenes such as workpiece thermal deformation and assembly error, and needs to be optimized by combining with an online real-time correction algorithm.

The online real-time path correction algorithm can correct the path offset and avoid obstacles by analyzing the real-time image information, and its accuracy is significantly better than that of the simple offline planning. For example, the double CCD camera+k-means clustering algorithm designed by Yang et al. Separates "weld pixel" and "workpiece pixel" through K-means, calculates the deviation and corrects the path. The positioning error of the weld starting point is only 0.98mm, and the track tracking MAE is less than 0.12mm, which is 60% higher than that of simple offline planning [1]. Although the K value needs to be preset manually, the algorithm can quickly separate the weld and workpiece pixels, adapt to special welding processes such as FSW, and has strong compensation ability for assembly error and workpiece deformation.

**Real-time tracking control algorithm.** The core of real-time control is dynamic adjustment of welding direction, and the core algorithm includes PID control and fuzzy control. The PID control algorithm has mature technology, strong stability, and wide application, which can accurately control the linear deviation. Zhao et al. Used a linear laser sensor+pid controller to adjust the rotation angle and height of the welding gun in real time in the circumferential welding of a nuclear power pipeline. The position error of the welding gun was less than 0.2mm, and the welding qualification rate was increased from 85% to 99% for manual welding [10]. However, the algorithm is prone to overshoot due to its delayed response to nonlinear deviation.

Fuzzy control algorithm imitates human fuzzy decision-making thinking, and is good at dealing with nonlinear deviation and complex scenes. Chen et al. Designed a fuzzy controller and preset 10 fuzzy empirical rules for high smoke and strong arc environment such as ship thick plate welding. Experiments show that its response speed is 20% faster than the PID algorithm, and it can still track stably in the environment with smoke concentration>15mg/m $^3$ [14]. However, due to the limitation of fuzziness, its accuracy is slightly lower than that of the PID control algorithm.

**Complex scene tracking optimization algorithm.** Complex scene welding is faced with multiple interference superpositions, fuzzy weld characteristics, and other problems, and a single algorithm or sensing scheme is difficult to meet the requirements. The core optimization idea is to break through the technical bottleneck through multi-source information fusion, dynamic error compensation, adaptive strategy adjustment, etc.

The multi-sensor fusion algorithm improves the positioning reliability by integrating theadvantageous information of different sensors, screening effective data, and eliminating interference. Guo et al. Proposed a three-sensor fusion scheme of "line laser+infrared+arc vision", with a tracking success rate of 96% in underwater welding, 45% higher than that of a single line laser sensor [3]. In thick plate high smoke welding, the fusion scheme of a structured light sensor (providing three-dimensional contour) and an infrared thermal imager (penetrating smoke to obtain temperature characteristics) can control the tracking error within ± 0.08mm after filtering [14].

Welding at hightemperatures (workpiece temperature can reach more than 500 °C) will lead to thermal expansion and cold contraction of the visual sensor, which will lead to laser plane offset, coding phase shift, and other problems. The thermal drift dynamic compensation algorithm can ensure accuracy through dynamic correction of data. Li et al. Integrated a micro temperature sensor in the structured light sensor, collected temperature data 100 times per second, corrected the phase offset based on the polynomial compensation model, and reduced the measurement error by 35% [13]. The domestic team proposed the "binocular calibration+real-time calibration" strategy for the thermal drift of the line laser sensor, combined with the temperature feedback correction to reduce the tracking error caused by the thermal drift by 40% [7].

## 4. Outlook

A welding robot based on visual sensing has been applied in many high-end fields on a large scale. In the aerospace field, structured light and line laser sensors are used with precision algorithms for complex precision welding such as aircraft wing skin butt joint and rocket fuel tank. In the field of automobile manufacturing, the arc resistant ccd/cmos camera combines template matching and PID control algorithm to realize the automatic welding of gearbox shell and body frame. In the manufacturing of nuclear power equipment, the line laser sensor and PID algorithm are adapted to the full position tracking of pipeline girth weld. In the fields of ship thick plate welding and building steel structure splicing, visual sensing technology effectively solves the problems of low efficiency and unstable quality of traditional welding.

### 4.1 Existing Challenges

The current technology still faces multiple challenges: first, the adaptability of complex environment is insufficient, and the bad conditions such as high smoke and strong arc light easily affect the accuracy of sensor imaging and algorithm. Second, the processing ability of complex welds is limited, and the accuracy of feature extraction and tracking of special structures such as ultra-fine gaps and irregular surfaces needs to be improved. Third, the contradiction between real-time and lightweight of the algorithm is prominent, and the computational complexity of the deep learning algorithm is high, which is difficult to adapt to high-speed welding. Fourth, the multi-sensor fusion collaboration is insufficient, and the fusion mechanism with other types of sensors is not yet mature. Fifth, lack of data dependence and generalization ability, deep learning needs a lot of annotation data, and the generalization performance of unfamiliar scenes is poor.

### 4.2 Future direction

In the future, the technology will develop in four directions: first, the sensor technology will be upgraded to develop high anti-interference, high precision and lightweight visual sensors to improve the adaptability to extreme environments. Second, algorithm optimization and innovation, promote the research and development of lightweight deep learning model, and balance accuracy and real-time performance. The third is the integration of multi-sensor and cross domain technologies, integrating multi-dimensional data such as vision, force, sound and heat, building a comprehensive perception system, and integrating cutting-edge technologies to achieve intelligent optimization. Fourth, industry customization development, develop special solutions for different industry needs, and improve technology adaptability.

## 5. Conclusion

This paper summarizes the application status of vision sensor types and image processing algorithms in seam recognition and tracking of intelligent welding robots, deeply analyzes the principles, advantages, and disadvantages, and application scenarios of various technologies, and expands the practice cases in high-end fields.

The visual sensor is the core of obtaining weld information, and its performance directly determines the accuracy and reliability of the information. Passive sensors (arc resistant ccd/cmos camera, infrared thermal imager) do not need an auxiliary light source, and have significant advantages in high reflective, strong arc light and high smoke scenes. Active sensors (line laser and structured light sensors) can obtain three-dimensional information, which is the core scheme of complex precision welding. The collaborative optimization of the two types of sensors provides diversified solutions for different scenes.

Image processing algorithm is the key to achieve accurate recognition and tracking. In the recognition stage, preprocessing algorithms such as median filtering and adaptive threshold segmentation improve image quality, feature extraction algorithms such as Canny edge detection and RANSAC line fitting lock weld features, and template matching and u-net algorithm adapt to simple and complex weld recognition respectively. In the tracking phase, the off-line programming and on-line correction algorithms achieve accurate path planning, PID and fuzzy control algorithms ensure real-time deviation adjustment, and algorithms such as multi-sensor fusion and thermal drift compensation break through the bottleneck of extreme conditions. The combined application of various algorithms realizes the closed-loop control of the whole process of "identification planning tracking optimization".

Weld recognition and tracking technology based on visual sensing has been applied in many high-end fields on a large scale, significantly improving welding effectiveness and reducing labor and safety costs, but it still faces challenges such as extreme environmental reliability and complex weld accuracy. In the future, people will focus on breakthroughs in the direction of anti-interference sensing and algorithm fusion, which is expected to achieve a leap from "precise tracking" to "intelligent prediction", providing core support for the upgrading of high-end equipment manufacturing.

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