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Research Progress of Welding Defect Detection Based on Machine Vision

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Abstract:

Welding defect detection is an important technical method and means to ensure welding quality in the welding process. The traditional manual inspection has the problems of low accuracy and low measurement efficiency, which cannot meet the requirements of modern industrial production. With the continuous development of artificial intelligence, using machine vision instead of human to detect welding defects intelligently has become the direction of development. The main processes of welding defect detection based on machine vision is to first collect images, then analyze and preprocess images, and finally use artificial intelligence to identify and classify welding defects. Therefore, this paper mainly summarizes and analyzes the current research progress of welding defect detection from two aspects: welding image acquisition and preprocessing, and defect detection and classification methods. It focuses on the defect detection and classification methods based on machine learning. Furthermore, this paper puts forward the problems to be improved and solved, and looks forward to the future development trend.

Keywords: Machine vision; Image acquisition; Artificial intelligence; Welding defects; Detection technology.

1. Introduction

As an important processing method in industrial production, welding has been widely used in many industrial fields such as automobile manufacturing, shipbuilding, aerospace and so on. Moreover, in the industrial production process, the level of welding quality has a decisive role in the quality of the entire product. Due to the complexity of welding process and the uncertainty of welding environment, welding defects are usually inevitable. These defects can seriously reduce the mechanical properties of welded parts, and even cause serious consequences. Therefore, the real-time monitoring and detection of welding defects in the welding process have very important practical significance. In the industrial production process, welding defect detection based on machine vision can improve efficiency and accuracy, and play an important role in ensuring welding quality. There are some limitations in the current detection technology, which lead to the problems of high noise and low contrast in the collected welding images and bring great difficulties to the evaluation of welding quality. At the same time, the complexity and diversity of welding defects also put forward higher requirements for the identification and classification of welding defects. The use of machine learning or deep learning methods can further improve the intelligence of welding defect detection, which has become the current research hotspot and development direction. Based on domestic and foreign research results, this paper summarizes and analyzes the current research progress and status of welding defect detection from two aspects: welding image acquisition and preprocessing, and defect detection and classification methods. Fig. 1 describes the basic flow path and framework of welding defect detection based on machine vision.

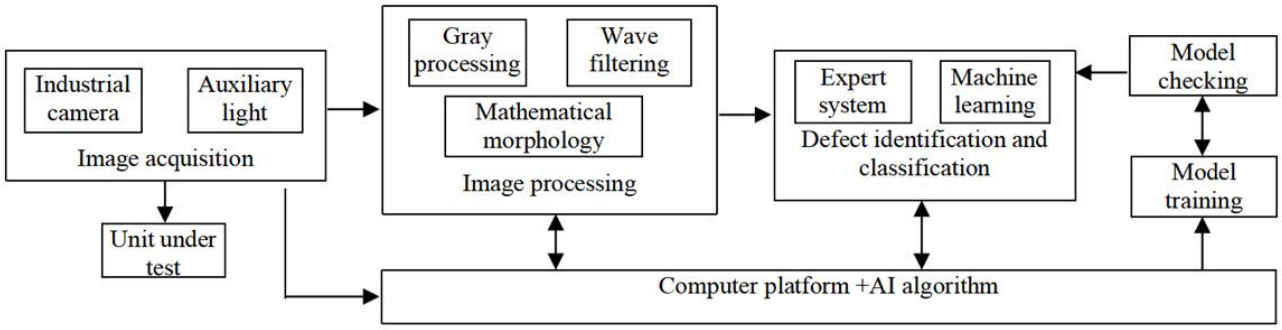

Fig. 1 The basic framework of welding defect detection based on machine vision

(Photo/Picture credit: Original).

2. Image acquisition technology and image preprocessing

Image acquisition technology is the premise and basis of intelligent welding defect detection. However, due to the complexity of welding environment, welding images will receive a lot of interference in the process of acquisition and transmission. Therefore, it is necessary to preprocess and optimize the acquired images to improve the image quality and lay the foundation for the subsequent identification and classification of welding defects. This part mainly summarizes and analyzes the application and research status of vision sensing technology and scanning technology in the process of image acquisition, as well as the analysis and preprocessing process of the acquired image.

2.1 Vision sensing technology

In machine vision-based welding defect detection, the vision sensing system plays a crucial role. It is primarily used to monitor the welding process status, provide characteristic information of the welding seam and welding pool, and collect real-time images for subsequent processing [1].

2.1.1 Passive vision technology

Passive vision uses the arc light generated during welding to illuminate the welding area without external light sources and obtain images of the welding pool. This method provides well-synchronized information, but it is easily affected by natural light. At the same time, the strong arc light generated in the welding process will also affect the quality of the acquired image. The interference of arc light on image acquisition can be effectively reduced by the filter method and the base value image acquisition method [1]. Wu Yifei et al. designed an automatic circular seam welding machine based on passive vision technology to solve the problems of low welding efficiency and poor weld quality in circular seam welding of spherical tanks. The welding seam tracking system is based on CMOS industrial camera, combined with the use of composite filter to collect clear welding images, and extract the deviation between the welding seam and the welding pool in the images. The system solves the welding error caused by track installation and greatly improves the welding accuracy of the circumferential seams [2]. This paper compares different filter systems through experiments, but does not compare and analyze the image acquisition effect of different kinds of industrial cameras such as CCD. Xu et al. designed a set of real-time welding seam tracking and controlling system based on passive vision sensor for welding robots, which mainly used CCD camera and dimming filter system to obtain clear and stable welding images. By analyzing the features of welding images, a new improved Canny algorithm is proposed to detect the edge of welding seam and welding pool, and extract the feature parameters of welding images. This technology improves the accuracy of real-time welding seam tracking and helps to improve the efficiency and quality of welding [3].

2.1.2 Active vision technology

Active vision uses an external light source to illuminate the workpiece surface. The reflected light is captured by an industrial camera, which generates an image that is then processed by a computer to obtain relevant welding process information [1]. Niu Zhangqi proposed a measurement method of welding seam geometry parameters based on active vision by studying the feature extraction technology of laser fringe images. A center line extraction algorithm based on improved gray value square weighting method was used to achieve subpixel extraction of the center line of the target area of stripes, but the measurement accuracy of this method needs to be further improved [4]. In this paper, the measurement method of welding seam geometry parameters based on active vision is analyzed theoretically and verified by examples, but the corresponding measurement system has not been developed yet. Huang Seji carried out research on welding seam tracking based on active vision. The linear structured light laser vision sensor is designed and developed. The filter system and filter algorithm are used to reduce the interference of ambient light and welding arc light to the image acquisition process, and ensure that the sensor can obtain clear welding images [5]. This paper mainly discusses the application of active vision technology in welding seam tracking, but it does not involve welding defect detection. Lu et al. studied the automatic welding process in fusion welding and additive manufacturing, developed an active vision welding seam tracking system based on linear structured light, and used an improved PSPNet welding seam feature extraction algorithm to realize synchronous and accurate extraction of welding feature point information. The welding seam tracking system based on active vision can quickly identify the deviation of welding seam in the welding process, and ensure the accuracy and real-time of welding seam tracking. At the same time, the improved PSPNet welding seam feature extraction algorithm significantly improves the accuracy of line and point segmentation, and has high precision [6].

2.2 Scanning technology

Besides vision-based techniques, scanning technology is also widely used in the process of welding image acquisition. In the process of robot welding, ultrasonic and X-ray detection methods are usually used to detect the internal defects of welding seams. This part mainly summarizes and analyzes the development and research status of ultrasonic scanning technology and X-ray scanning technology.

2.2.1 Ultrasonic scanning technology

The principle of ultrasonic C-scan imaging involves converting extracted echo information into corresponding colors. This process forms a two-dimensional image where the area around scanning points is filled with different colors, describing the signal characteristics of sampling points [7]. Zhao Xinyu et al. designed a defect recognition algorithm that involves three main steps: detecting brazed parts using ultrasonic microscopic technology, binarizing C-scan images through threshold-based segmentation, and marking defects with an identification algorithm. The defect area is then calculated by setting a threshold value. The algorithm can obtain the result of workpiece defect recognition and detection in a very short time, which significantly improves the efficiency and accuracy of defect recognition [7]. Zeng et al. proposed a new method for detecting internal defects of welding seam using laser ultrasound technology. The interaction between laser-generated LR waves and internal defects on both sides of the welding seam was analyzed in detail by B-scan images. Through FEM simulation, it is pointed out that the differential B-scan images of the upper and lower sides of the welding seam can be used to detect the internal defects of the welding seam [8]. However, this study focuses on direct simulation of scanned images without incorporating pre-processing steps such as filtering and denoising. Luo et al. proposed a graphic enhancement defect recognition algorithm for phased array ultrasonic testing (PAUT) of tubular TKY joints. Based on PAUT Sector scanning (S-scan) technology, spatial clustering method is used to segment the scanned image. The converted S-scan data is overlaid with the TKY welding seam geometry to extract the geometric features of the identified defect indication to estimate the size and depth of the defect. Compared to traditional single element ultrasonic inspection, PAUT technology offers superior suitability for detecting geometrically complex parts, along with enhanced flexibility and visualization capabilities [9]. However, the reliability of this algorithm needs to be further verified with more data from testing.

2.2.2 X-ray scanning technology

In robot welding, X-ray detection is highly suitable for identifying internal defects in metal materials [10]. Its advantages include intuitive imaging, sensitivity to volumetric defects, accurate size measurement, and minimal requirements for surface roughness of the measured object. R. Vilar et al. built a system that can automatically identify welding defects in X-ray images of welding seams based on the fuzzy reasoning system of adaptive networks, which mainly consists of three parts: image preprocessing, defect feature extraction and image pattern recognition [11]. Neury et al. designed a welding seam image acquisition system based on double-wall double-image X-ray images. Firstly, DWDI exposure technology was used to collect welding images, and then median filtering method was used to process the images such as noise reduction and enhancement, and ROI region was determined for feature extraction. The parameterized defect features are then used as inputs to Feed Forward Multilayer Perceptron (MLP) to identify defects [12]. In this paper, double-wall double-image (DWDI) radiography has been explored, but due to the small number of defect types, the accuracy of defect classification is low. D ‘Angelo et al. combed and summarized five feature extraction and classification methods, namely Fast Fourier Transform (FFT), principal component analysis (PCA), linear discriminant analysis (LDA), wavelet decomposition and CBIR (content-based image retrieval), and then used soft computing algorithms to verify the above feature extraction methods. It is concluded that the key to improve the performance of the test system is to extract the parameters with good characterization characteristics and to represent these parameters more accurately [13].

2.3 Image analysis and preprocessing

In the collection and transmission process of welding images, images will be interfered by noise and other environmental factors. The quality of the collected images can be improved through image processing technology [14]. At present, the commonly used image processing techniques mainly include filtering method, gray transform method, and mathematical morphology operation and so on. Tang Maojun shortened the operation time by image enhancement, used the weighted average change method in linear change to process the gray transform of the image, used the median filter method to de-noise the image, and proposed an improved histogram equalization method to enhance the image contrast. The image processed by this method has no distortion, the contrast is improved, and the details are more abundant [14]. However, mathematical morphology operations such as corrosion and dilation were not used to improve the image connectivity. Guo Junlei used a variety of image algorithms to preprocess the collected weldment surface images. First, weighted average method was used to transform the gray level of the image, then Wiener filter was used to restore the weldment image, and median filtering method and mathematical morphology operation were used to reduce the image noise. Finally, homomorphic filtering is performed and then global histogram equalization is used to enhance image contrast. These processing steps significantly enhance the quality of acquired images, resulting in welded part images with higher signal-to-noise ratios. These improved images are then more suitable for subsequent segmentation and feature extraction processes [15].

3. Defect detection and classification methods

Various welding defects exhibit distinct appearances on the weldment surface. Consequently, following image acquisition and preprocessing, it's crucial to identify and classify these different defects. Identifying welding seam defects requires consideration of multiple factors: the characteristic parameters of the defect area, the machining methods employed, and the structural characteristics of the components [15]. This section summarizes and analyzes two approaches to defect detection and classification: inference-based expert systems and machine learning-based methods.

3.1 A review of inference-based expert system detection and classification methods

At present, the research of this method mainly focuses on the construction of knowledge base and the research of reasoning mechanism. Guo Junlei used the method of characteristic parameter description to describe the defect type through the analysis of defect topography, and set the characteristic parameters of defect description such as area, circumference and circularity. At the same time, a defect recognition expert system based on fuzzy inference is designed, which mainly includes fuzzy inference machine, knowledge base and database. By describing the appearance defects of the welded parts, the characteristic parameters of the defects are set up, and the calculation method of the characteristic parameters is proposed. The error analysis between the calculated value and the actual value of the defect characteristic parameter shows that the error between the calculated result and the actual measurement result is basically controlled within 10% except the circularity. Based on the description of the establishment of fuzzy reasoning expert system, the modules and design methods required for the establishment of fuzzy reasoning expert system are analyzed in detail. By means of fuzzy language transformation, the inference conditions are fuzzy, and the fuzzy transformation of defect feature parameters is realized. At the same time, the management module of knowledge base and database is developed to realize the maintenance of defect identification rules and the management of component quality information [15].

Gao Changlin developed an expert system for detecting welding defects in aluminum alloy materials, comprising a knowledge base and a reasoning mechanism. In the construction of knowledge base, the welding characteristic information model of aluminum alloy tank is established first, and then the method of frame representation combine with production rule representation is used to express the knowledge. This paper constructs the knowledge base of welding expert system by MySQL, and the reasoning mechanism of welding defects of aluminum alloy tank based on fuzzy rules is proposed [16].

The method of welding defect detection and classification based on expert system relies on knowledge base and reasoning mechanism, and the construction of knowledge base is mainly based on the experience and knowledge of welding experts. However, the types of welding materials, technology and defects type are complex and diverse, and relying solely on the professional knowledge of experts to judge has certain limitations. At present, the common inference mechanism is fuzzy inference method. Although this method can improve the matching degree between the tested object and the knowledge base, but the detection accuracy needs to be further improved.

3.2 A review of detection and classification based on machine learning

As artificial intelligence technology continues to advance, machine learning has emerged as a pivotal tool in the detection and classification of welding defects. This part summarizes and analyzes the detection and classification methods based on ordinary neural network and deep neural network.

3.2.1 Defect detection and classification method based on ordinary neural network

Malarvel et al. adopted an improved anisotropic diffusion method to denoise and smooth the X-ray images of welding seam, and adopted the improved Otsu method to segment the images, and then, an autonomous technology for welding defect detection and classification based on multi-class support vector machine (MSVM) is proposed [17]. This method focuses on the identification and classification of circular and rectangular welding defects, but lacks the detection and classification of other types of defects.

Xu et al. proposed an improved porosity focusing decision tree, optimized the objective function in the traditional XGBoost model, and improved the training structure of the traditional prediction model. This paper proposed a parallel training structure based on pore defect types, which improve the training effect of the model. Compared with the traditional XGBoost model, the improved model has higher accuracy [18].

Ho et al. designed a welding defect prediction model based on artificial neural network (ANN), and the input data included three welding process measurements, which are welding current, welding speed and shielding gas flow. By training the model, four types of welding defects including bottom filling, non-penetration, incomplete fusion and porosity were predicted [19]. However, limited by the number of samples, this model can predict fewer types of welding defects.

Ordinary neural networks, characterized by fewer hidden layers and simpler structures, have lower computational requirements. However, this simplicity can lead to a tendency for the algorithm to fall into local optima, potentially compromising prediction accuracy. Moreover, these networks lack the ability to achieve global weight sharing, which can limit the comprehensiveness of defect identification.

3.2.2 Defect detection and classification method based on deep neural network

Zhu et al. proposed an intelligent recognition method for lossless identification of welding seam defects. This approach is based on deep learning and primarily utilizes a combination of convolutional neural networks (CNN) and random forest algorithms. Firstly, a CNN model consisting of 3 convolutional layers, 2 pooling layers, 1 fully connected layer and 1 softmax layer is designed, and the random forest algorithm is used for identification and classification. On the basis of preprocessing the welding seam defect images by image enhancement and threshold segmentation, a comparative experiment was carried out [20]. Due to the offline nature of feature extraction and recognition processes for welding seam defect images, this method faces challenges in real-time industrial applications. Chang et al. proposed an end-to-end welding defect identification method, which mainly includes three steps. In the first step, an improved algorithm based on deep belief network (DBN) is proposed to classify welding seam characteristic curves. In the second step, a new cylindrical projection method is used to enhance the image. In the third step, based on the traditional SegNet network architecture, the convolutional layer, pooling layer and activation function are optimized respectively, and a new network architecture WDC-SegNet is proposed, which is more suitable for welding images. The experimental results show that this method has higher accuracy and robustness for welding defect detection and identification [21]. Tang Maojun proposed an improved defect detection method for Faster-RCNN network. Based on ResNet101 structure of residual network, K-means algorithm is used to optimize the detection frame. Feature Pyramid Networks (FPN) are established to improve the detection accuracy and efficiency of small targets. The decoupled classification refinement structure is used to improve the classification capability of the network. Compared with the original Faster-RCNN algorithm, the improved model has higher accuracy and better overall performance [14]. However, this model mainly focuses on the detection of welding seam surface defects, and cannot identify and classify welding seam internal defects. The evolution of object detection structure is shown in Fig. 2.

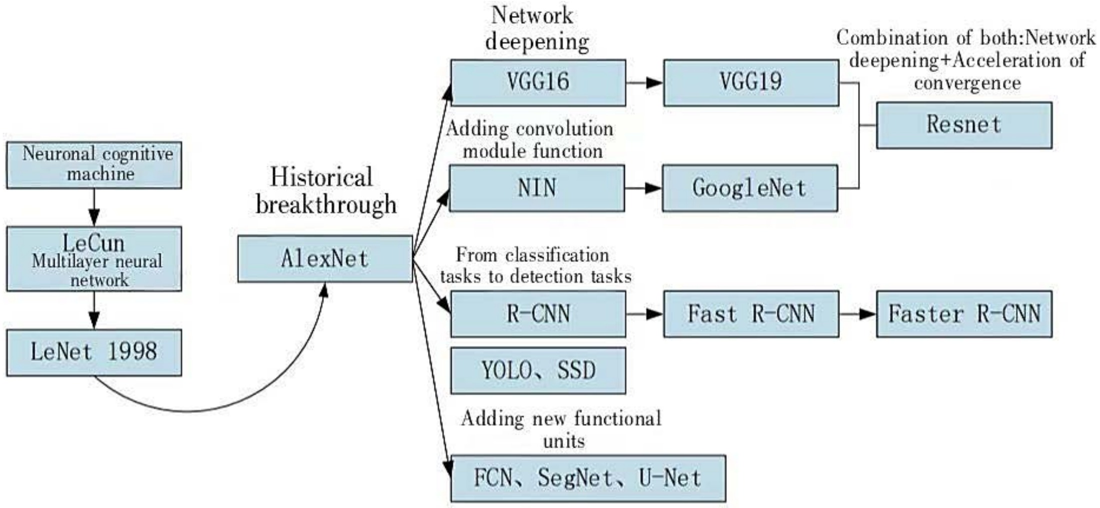

Fig. 2 Evolution of object detection structure [14]

Deep neural networks, characterized by numerous hidden layers and complex structures, require substantial amounts of data samples to achieve desired detection performance. However, with the continuous improvement of the level of industrial modernization, it has become more difficult to obtain sample data of welding defects. Consequently, addressing the challenge of insufficient defect sample data remains a critical issue for deep neural networks in this field.

4. Conclusion

In the welding process, due to the complexity of the welding procedure and the uncertainty of the environment, there are usually some inevitable welding defects, which will seriously reduce the mechanical properties of the welded parts. The accuracy of traditional manual detection is not high, the measurement efficiency is low, and it has been unable to meet the requirements of efficiency and quality of modern industrial production. Therefore, in the welding process, the realization of intelligent identification and detection of welding defects has become a development trend. By carding and analyzing relevant literature, this paper summarizes the current research progress of welding defect detection from two aspects: welding image acquisition and preprocessing, and defect detection and classification methods. In the future, with the continuous development of artificial intelligence and machine vision technology, the efficiency and accuracy of welding defect detection can be further improved and optimized, welding defect detection systems based on machine vision can also play an increasingly important role in modern industrial production.

At present, the welding defect detection research based on machine vision is mainly carried out independently for the welding pool, the formed weld surface and the internal defects of the welding seam during the welding process. This reflects the different welding stages and welding defect types, but the lack of comprehensive analysis and detection of the whole life cycle of the welding and various types of welding defects. Therefore, it is possible to study the application of machine vision technology in welding defect detection, which for the whole dimension-oriented of welding seam tracking, the formed welding seam and welding seam interior. At the same time, the corresponding automatic detecting platform is developed to improve the efficiency and effect of welding defect detection in the whole life cycle of welding.

On the basis of automatic detection of welding defects based on machine vision, the related technology of visual servo control can be further studied. Relies on detected welding defects, real-time control of welding robot to improve welding parameters and other related information can be achieved by means of coordinate transformation, camera calibration and other methods. The traditional location-based and image-based visual servos are evolved into defect-based visual servos, in order to improve the practical application effect of defect detection.

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