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Laser vision seam tracking system based on image processing and continuous convolution operator tracker

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ABSTRACT

To address the problem of low welding precision caused by the poor real-time tracking performance of common welding robots, a novel seam tracking system with excellent real-time tracking performance and high accuracy is designed based on the morphological image processing method and continuous convolution operator tracker (CCOT) object tracking algorithm. The system consists of a six-axis welding robot, a line laser sensor, and an industrial computer. This work also studies the measurement principle involved in the designed system. Through the CCOT algorithm, the weld feature points are determined in real time from the noise image during the welding process, and the 3D coordinate values of these points are obtained according to the measurement principle to control the movement of the robot and the torch in real time. Experimental results show that the sensor has a frequency of 50 Hz. The welding torch runs smoothly with a strong arc light and splash interference. Tracking error can reach ±0.2 mm, and the minimal distance between the laser stripe and the welding molten pool can reach 15 mm, which can significantly fulfill actual welding requirements.

1. Introduction

With the development of automation, welding robots have been extensively used in the industrial field and have become the main welding automation equipment. Simultaneously, the development of an automatic seam tracking technology to replace the traditional working mode of teaching and payback has become an inevitable trend in welding automation and intelligence. This endeavor has become a significant approach to improve welding production efficiency and welding quality by capturing welding signal and information to directly simulate a welder to operate [1,2]. The traditional method to improve welding quality is by making some quality assessment or by adding some monitoring devices [3,4]. However, the seam tracking technology based on laser vision combines the advantages of computer vision and laser 3D visual measurement technology, which is more flexible and convenient than the traditional methods. It exhibits the benefits of capturing abundant information, and possessing evident weld characteristics and strong anti-interference capability. Therefore, the aforementioned seam tracking technology is being gradually favored by practitioners.

In recent years, considerable research and product development have been conducted in laser vision seam tracking technology. The Beijing Sai Cheng Industrial Corporation developed a laser vision seam tracking system used in welding spiral pipes with a high real-time precision of ±0.5 mm. The British Meta Vision System Corporation developed the Laser Probe Series laser vision seam tracker, which is suitable for a variety of weld types and exhibits an accuracy of up to ±0.2 mm. During the welding process, the laser stripes and the molten pool maintain a certain distance between them because the laser vision sensor is ahead of the welding torch (Fig. 1). The shorter the distance, the higher the tracking accuracy will be. The distance is typically less than 30 mm. However, a short distance will lead to strong arc and splash during the extraction of the image information using a visual detection system, thereby reducing measurement accuracy and generating numerous error data, particularly when the current is over 300 A [5]. Therefore, the above seam tracking systems cannot work well under such situations, so learning how to identify the weld feature points from an image with strong noise interference is significant for obtaining accurate location rapidly in real-time seam tracking. A schematic diagram of the seam tracking process is shown in Fig. 1.

Kawakara et al. designed a laser vision seam tracking system for a V-type weld seam through the continuous operation of multiple images to eliminate noise, and then fitting the straight line and intersection to obtain weld seam points [6]. Jae et al. proposed a method that used text analysis to improve the robustness of a structural light visual tracking system [7]. The original data of the laser stripes were extracted and processed using the text analysis technique to detect feature points. Their methods can only resist a certain degree of arc and splash interference. Wu and Smith designed a vision sensor using structured light as illumination; they designed a high-performance Transputer Image Processing

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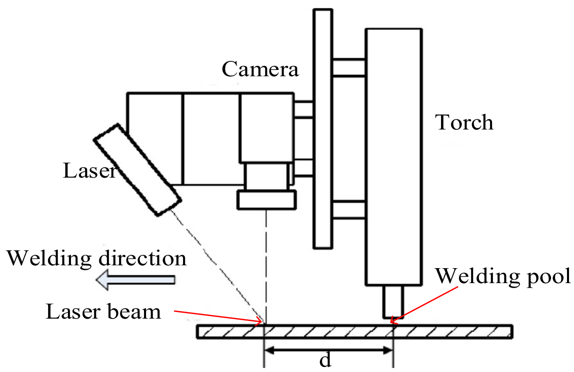

Fig. 1. The schematic diagram of the weld seam tracking.

System (TIPS) to accelerate image processing speed [8]. Bae et al. used vision sensing technology to measure groove gap based on gap size; they then applied welding knowledge to establish fuzzy logic for the real-time control of welding speed [9]. Though accuracy has been improved but these methods still cannot cope with the aforementioned harsh situations. Yang et al. proposed a method that combined a CCD camera with weld detection and process control method based on adaptive Hough transform; their method could extract feature points from laser stripes in real time [10]. However, this method requires the use of neural networks to obtain the corresponding welding parameters, thereby making the process cumbersome. Moreover, this method only analyzes the type of line weld seam, and sensor measurement frequency is relatively low. Xu proposed a real-time tracking and control technique for 3D weld seams during robotic gas tungsten arc welding based on vision sensor and arc sensor [11]. The tracking error for all types of weld seam can be controlled at ±0.4 mm, but the sampling frequency of the system is only 2 Hz, which is difficult to meet welding processes with high real-time requirements.

In this paper, a seam tracking system based on the morphological image processing method and the continuous convolution operator tracker (CCOT) (2016) object tracking algorithm [12] is proposed. This algorithm can track target and feature points in image sequences or videos with high accuracy and robustness. Classical target tracking algorithms, such as the optical flow method (LK method), use the correlation between adjacent frames to find the optical flow pattern between them [13]. Dalal et al. first proposed the Histograms of Oriented Gradients (HOG) method to extract image characteristics [14]. Experiments show that the HOG descriptor exhibits good performance and can extract considerable information. Simultaneously, the support vector machine algorithm was used to realize pedestrian detection. Zhang et al. proposed a compressive tracking (CT) algorithm, which is a real-time target tracking algorithm based on linear stochastic measurement [15]. Kalal et al. proposed an object tracking algorithm (TLD) that combined detection and tracking algorithms with online learning [16]. This algorithm consists of a tracker, a detector, and a learning module that treats the tracking problem as an online learning classification problem. However, these algorithms cannot resist the strong interference in our tracking process and we will show in later part by performing a comparative experiment. Henriques et al. proposed a Kernelized correlation filters (KCF) algorithm that applied the filter method in signal processing to object tracking; this approach converted loss functions into the Fourier domain to significantly increase calculation speed [17]. To improve tracking accuracy, Galoogahi et al. proposed a multi-channel method for filter algorithms [18]. The CCOT algorithm used in this study is also a filter algorithm. However, its efficiency, accuracy, and robustness have been considerably improved compared with those of the traditional filter algorithms. Considering its superior ability to resist interference while keeping high accuracy compared with other algorithms, we designed this seam tracking system combining the morphological image processing method and continuous convolution operator tracker (CCOT). We use HOG to extract multi-resolution features instead of CNN because of the real-time requirements of our system.

2. Experimental platform

The hardware of the platform consists of an execution mechanism with six degrees of motion, welding equipment, a structured light vision, and an industrial control computer. The complete seam tracking system is shown in Fig. 2. The three-stripe laser vision sensor consists of a three-stripe laser generator and a camera mounted in front of the torch for obtaining weld information.

During the welding process, an image with weld seam profile information is captured by the camera and transmitted to the computer via Ethernet. The computer image processing module is based on the Visual Studio 2015 platform and the HALCON machine vision library. Accurate weld feature points can be obtained by the image processing module, and then, the control signal can be determined for real-time control of the torch movement, which can achieve accurate welding seam tracking.

BAO Shun-dong et al. carried out a detailed analysis on a variety of arc spectrums [19]. The arc spectrum of the pulse metal inert gas welding shows that the arc intensity in the neighborhood of 450 nm, 610–700 nm band and 850–1000 nm band is relatively weak. In the actual situations, we usually take visible laser in 400–760 nm as the light source for easily mounting and debugging. Therefore, a sensor that uses a 660 nm laser generator and an optical filter with a central wavelength of 660 nm help reduce the interference of arc light. The optical specifications of the laser used in this study are listed in Table 1. The camera resolution is 1024 × 1280, and the sampling rate is 50 fps.

The motion execution mechanism applied is that of the YASKAWA welding robot (model MA1440), which has six degrees of freedom and a repeat positioning accuracy of ±0.08 mm. The welding equipment adopts the MOTOWELD-RD350 welding system, with a maximum welding current of 350 A. The image processing module is an IPC-510 embedded industrial computer with a 3.4 GHz Intel i7-3770 quad-core processor and 12GB RAM.

3. Principle of structured light vision system

3.1. Basic measurement principle

The 3D measurement principle of the structured light vision system is shown in Fig. 3. A dot laser beam generated by a semiconductor laser is optimally formatted with three highly linear, stable, and uniform-density laser lines under a Powell prism. This beam is called the line structured light. It is projected onto the welding workpiece, thereby forming three laser stripes with the change in shape of the seam on the surface of the workpiece. The middle stripe is utilized as the measurement stripe to facilitate feature point extraction. A fixed angle exists between the CMOS camera and the laser plane, and thus, the point of the laser stripe on the image does not only contain the position of the plane, but also its depth.

3.2. Mathematical model of the 3D measurement of the structured light vision

The perspective imaging process of the laser stripe is shown in Fig. 4. Planes Π_1 and Π_2 represent the measurement and imaging planes, respectively. The 3D coordinates $O_CX_CY_CZ_C$ denote the camera coordinate system. The 2D coordinates $O_IX_IY_I$ denote the imaging coordinate system. $O_PX_PY_P$ denotes the pixel coordinate system. The straight line with O_CO_I is the optic axis of the camera, and f is the equivalent focal length. A laser line is formed by the intersection of the laser and the measurement planes. When P is assumed as a point on this laser line, then its coordinates in the coordinate system are (x, y, z). P' is an image of P and