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An on-line shape-matching weld seam tracking system

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ABSTRACT

Automatic welding technology continues to find a broader application in diverse industries due to its high efficiency and accuracy. In this work, an on-line laser-based machine vision system for seam tracking was developed. To achieve a reliable and accurate seam tracking process that is adaptive to different groove types, a shape-matching algorithm was proposed and implemented. The algorithm uses the previous groove shape as the template to locate the next groove shape. Tests on U-groove, tap-groove and free form groove have verified its adaptability and robustness to different groove types with noise. The shape-matching algorithm also enables the seam tracking system to automatically localize the starting and finishing point of the weld seam. A FIFO based queue was defined and implemented to tackle the lag distance problem between the heat source and the vision sensor. The tracking algorithm, along with the FIFO queue was successfully verified on a sine-shaped seam. A tracking accuracy of ± 0.5 mm was achieved in this test, which is acceptable in most of the arc welding applications.

1. Introduction

Automatic welding technology continues to find a broader application in diverse industries such as shipbuilding, oil and gas, automobile, and so forth. It mainly includes the autonomous guidance of initial welding position [1], welding seam tracking [2,3], optimization of welding parameters during the welding process [4,5], and automatic localization of the finish point of the weld seam. As one of the key issues, welding seam tracking aims at on-line adjustment of the position of the heat source with respect to the seam to ensure a right welding position. Seam tracking saves time and achieves a better welding quality compared to an off-line teaching model. At present, the main sensors used to achieve an on-line seam tracker include an inductive sensor [6], ultrasonic sensor [7], electromagnetic sensor [8] and vision sensor [9–12]. Among them, the vision sensor is the primary option due to its high precision, fast speed, and non-contact. During the welding process, the vison sensor continuously captures images of the weld seam and extracts the geometrical features of the weld seam through digital image processing algorithms. The seam center determines the motion of the heat source with respect to the weld seam and is critical to the final weld quality. Current algorithms for determining the seam center mainly focus on the detections of the corner points of the weld groove. Huang et al. [11] developed a laser-based vision sensor for seam tracking. They extracted the corner points based on the second central difference of the row index of each pixel on the laser stripe and identified the center point of the corner points as the seam center. Gu et al. [13] searched for four predefined feature points on the seam profile to get the seam center during the seam tracking process for multi-pass welding. Nguyen et al. [14] proposed an extraction algorithm that used a sliding vector to find the corner points of the weld seam. Other algorithms for detecting the corner points include the Harris corner detector, SIFT detector, and the histogram-based detector [15]. All the existing image processing algorithms assume to know the groove type, and based on this knowledge, they determine the seam center by searching for the feature points (corner points) of a specific groove type. It is easy and fast to implement these algorithms to achieve real-time closed-loop motion control of the welding heat source. However, those algorithms are highly dependent on the groove types. The pre-defined threshold of these algorithms also varies for different sizes of the same groove type. When the groove type or size changes, the feature points and the pre-defined threshold need to be tuned again. The process is neither adaptive nor robust. The parameter learning and tuning process is also time consuming and sometimes impractical for industrial applications. Moreover, those algorithms are sensitive to the light noise induced by various disturbances near or in the seam region. Noise can significantly disturb the detections of the feature points and lead to inaccurate and unstable tracking [16]. Image filtering algorithms can reduce the noise, but they lose the details on the feature points and obtain an inaccurate seam center. The need still exists to develop a reliable and accurate seam detection algorithm that is not limited to a certain groove type.

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Besides the detection of a seam center, the motion of the heat source also needs to be considered. For the practical deployment of the in-situ on-line seam tracking, the heat source follows behind the vision sensor with a lag distance. Hence, the seam center that is detected cannot be immediately used to rectify the position of the heat source. Nele et al. [17] reported a tracking error of 0.66 mm due to the lag distance of 50 mm between the weld torch and the vision sensor (CCD camera). In practical scenarios where the welding direction changes frequently rather than walking a straight line [17,18], the tracking error is significant. An alternative solution to this problem is to perform seam detection and actual welding in two different passes [19]. But this solution significantly reduces the welding efficiency.

In order to tackle the above-mentioned challenges, an on-line laser-based machine vision system for seam tracking was developed in this work. Based on the principle of laser triangulation, a vision sensor was designed and calibrated. In order to achieve a reliable seam detection process that can work on different groove types, a shape-matching algorithm was proposed and implemented. Tests on U-groove, tap-groove, and free-form groove verified the algorithm's adaptability to different groove types and its ability to resist noise on the weld groove. Based on the shape-matching algorithm, the tracking system easily achieved an entire autonomous welding process including autonomous localization of the starting point of the weld seam, seam tracking of the welding process, and autonomous localization of the finishing point of the weld seam. A FIFO based queue was defined and implemented to tackle the lag distance problem between the heat source and the vision sensor. The entire autonomous process, combined with the FIFO queue was verified on a sine-shaped seam.

2. Seam tracking system

As shown in Fig. 1, the laser-based machine vision system includes three major modules: a laser-based vision sensor module, an image-processing module, and a multi-axis positioning module. The vision sensor module (see Fig. 2a) consists of a CCD camera, a diode laser with a line generator that emits a thin defocused light sheet with a wavelength of 658 nm and a power less than 500 mW, a focus lens, and a narrow-band optical filter centered at 658 nm. The image-processing module processes the image and detects the position of the weld seam. The multi-axis positioning module consists of three step motors in the *X*, *Y*, *Z* directions and a National Instrument (NI) 4-axis motion controller PCI-7344. The vision sensor is installed at the slide in the *Z* direction. During the tracking process, the weld sample moves in the *Y* direction so the vision sensor could fully scan the weld seam. The step motor in the *X* direction adjusts the *X*-position of the weld seam with respect to the heat source for achieving a right weld position.

2.1. Design of the laser-based vision sensor

As shown in Fig. 1b, the developed laser vision sensor consists of a CCD camera, a diode laser with a line generator that emits a thin defocused light sheet with a wavelength of 658 nm, and a power with less than 500 mW, a focus lens, and an optical narrow-band filter centered at 658 nm. The laser light sheet is scattered by the workpiece and reflects in different directions. The CCD camera installed at an angle with respect to the laser diode collects the reflected laser light. Based on the formed image of the laser stripe on the image plane of the CCD camera, the geometrical features of the workpiece are precisely determined. To ensure that the image of the workpiece always focused on the image plane of the CCD camera, the principle of laser triangulation is adopted to determine the relative geometrical position of the laser diode, the CCD camera, and the focus lens [20,21]. As shown in Fig. 2a, the gray scale image of the weld seam acquired by the CCD camera has a resolution of 640×480. To smooth the image for further processing, the intensity of each pixel is averaged by a median filter with a kernel size of 3×3. Then, the image is made binary by setting a threshold of 128. Since the laser stripe projected on the workpiece is thick, a basic morphology method called gradient-out [22] is used with a structuring element of 3×3 to extract the two edges on the laser stripe. The central curve between the two extracted edges is identified as the position of the laser stripe. Fig. 2 illustrates how the laser stripe is extracted from the original image.

Fig. 3 shows the relationship between the physical spatial world and the image pixel. The physical spatial position of the laser stripe is obtained through analysis in the depth direction (*Z* direction) and along the laser stripe direction (*X* direction) as follows:

- Depth direction (*Z* direction). Assume that point “A” in Fig. 3 is the intersection point of the laser sheet and the optical axis of the focus lens. Point “B” is on the axis of the laser diode. The images of point “A, B” are formed at point “a, b” on the image plane respectively. The distance between point “A” and “B” is *H*.

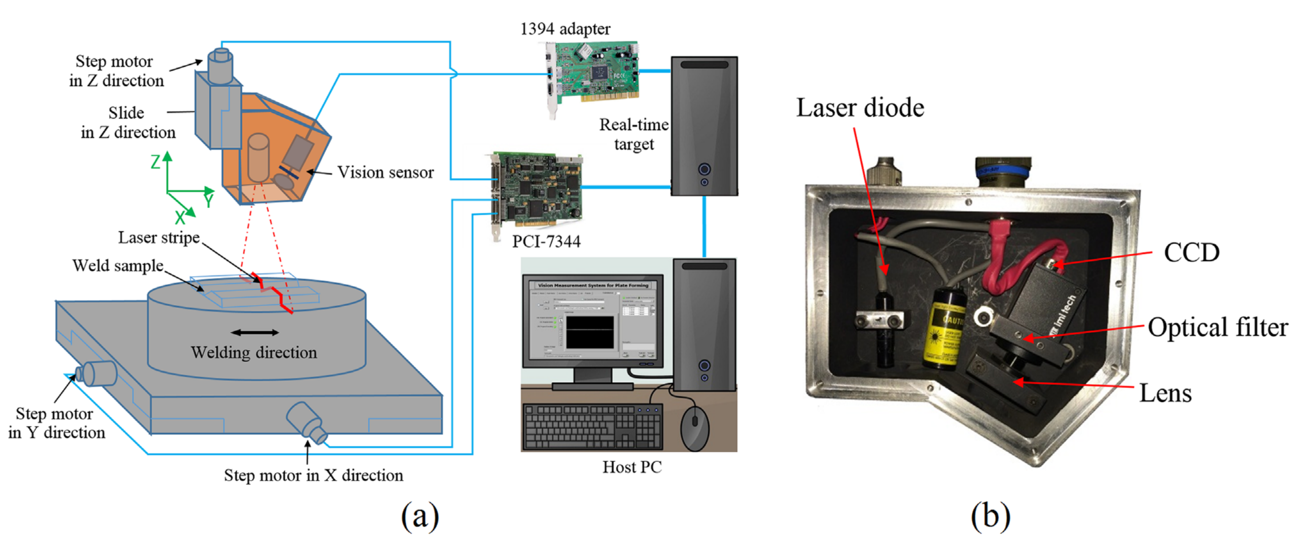

Fig. 1. (a) Real-time laser-based machine vision system for seam tracking; (b) laser-based vision sensor.