Study on welded seam recognition using circular laser vision sensor

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A novel visual robotic arc welding system based on circular laser vision sensor is developed. After image de-noising, image segmentation, and image thinning, the relation of depth value of workpiece and off-axis angle γ, three-dimensional (3D) calculation, and seam tracking experiments are carried out. Finally, the error for seam tracking system is analyzed. The results show that 1) 3D information can be obtained using the proposed visual robotic arc welding system and the real-time seam tracking is realized; 2) the seam tracking error is small enough for gas tungsten arc welding (GTAW) process, and this system can be used for seam location and seam tracking or seam finder.

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A rapid development in computer technology and robot technology has greatly promoted the automaticity of welding process. There were many factors that influenced the welding quality, which not only include thickness of the materials to be welded, the chemical element composition of the welded material, surface status of the workpiece, but also include such parameters as welding voltage, welding speed, welding path, and three-dimensional (3D) of workpiece, whether or not were detected in real time. The automation and artificial intelligence control of the welding process require the development of both the joint shape and the seam tracking control, so that the robot may select correct path automatically when the deviation between welding path and actual seam has been found. In order to meet the requirement of automatic welding process, all kinds of sensors have been investigated[1,2]. Among them, "spot laser" was the simplest measurement method among active vision sensors and other vision sensors. According to laser triangular rules, different pattern laser vision sensors were put forward to apply structured light and scanning light using single laser stripe, two laser stripes, five laser stripes, and circular laser stripe as light source. However, "spot" or "line" type laser sensors have such shortcomings as less information, explanation ambiguity, and only be used to single or two direction seam tracking[3−6]. Xu *et al.* set up a whole of circular laser vision sensor system[7]. On the basis, a novel vision sensor was developed. Based on "radius–depth relation" of laser cone and imaging law of camera, 3D model for feature points of weld seams under gas tungsten arc welding (GTAW) process was established. Subsequently, seam location and tracking in robotic welding process can be realized.

In our proposed system, an articulated robot with six degrees of freedom was carrying a welding torch and a vision sensor system. The vision sensor views the welding joint ahead of the welding torch while the robot travels along the welding seam. The images from the vision sensor were analyzed by an image grabber card and used to reconstruct the dimensions of the welding seam, which computes the location of the welding seam with respect to the vision sensor. In order to compensate for variations in part or joint geometry, this processing result was then used in the robot control module to correct the welding path.

For hardware, the overall system was composed of two modules: a robot control module and a vision processing module. The robot control system consists of two units: main processing unit and joint servo unit. The main processing unit (INTEL Pentium III CPU operating at 780 MHz) operates major processing such as coordinate transformation for trajectory control, sensory feedback control for seam location and seam tracking, and so on. The vision processing module grabs and analyzes the image data obtained from the vision sensor to recognize the type of weld joint and compute the position of the weld joint center.

The principle of vision sensor was that: circular laser trajectory was used as a active light to project onto the workpiece to be welded, and when the tasks of seam location and seam tracking were carried out by welding torch, the 3D of weldment can be measured by vision sensor using calibration model and depth calculation algorithm, and the error of welding torch and weldment can be further detected and sent back to robot[7].

The vision sensor consists of charge couple device (CCD) image sensor and light scanning system based on rotated lens that generates circular laser beam, as shown in Fig. 1. The camera was fitted with a narrow-band optical interference filter having a narrow bandpass of 0.99 nm centered at 611.49 nm. The narrow-band interference filter efficiently removes much of the ambient and welding arc light from the image. The camera circuitry generates an NTSC standard video signal that was stored in the vision grabber as a 768×576 array of 8-bit pixel. One pixel in the image plane corresponds approximately to 8.3 μm on a focused object. The sensor field of view and resolution were reconfigurable depending on the application requirements.

As a light source, the 10-mW laser diode emitting at

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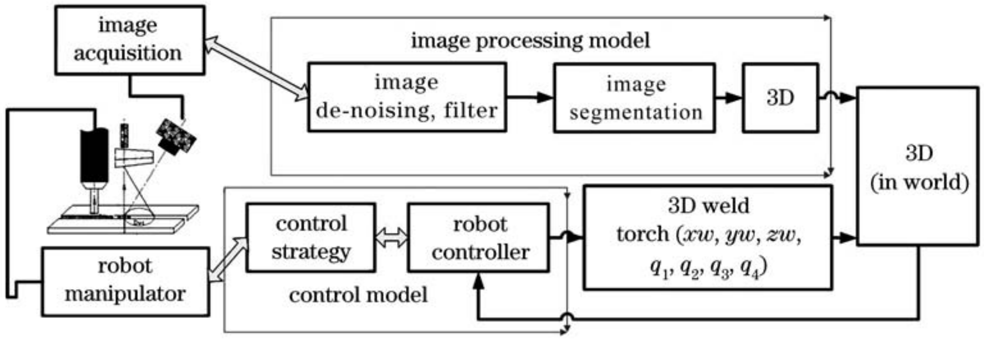

Fig. 1. Configuration of the vision sensor by scanning technique.

635 nm was used. The main advantage of illumination by the light source in this band was its visibility and intensity, which considerably facilitates the calibration of the sensor in the stage of development of the vision sensor. Simultaneously, it still facilitates the segmentation of the laser light from the welding seam image because most significant spectral components of scattered light from the arc exist in the ultraviolet (UV) and visible bands. Also, it guarantees good transmission of the laser light through the smoke and fume generated during welding. The sensor operates on a principle of proposed 3D calculation model based on "radius-depth relation of laser cone and camera amplification coefficient".

The experiment was carried out in computerized numerical control (CNC) platform, and IRB2400 welding robot was used to hold on the proposed vision sensor based on circular laser. GTAW method was operated, and the parameters used in this sensory system were shown in Table 1.

During the course of image acquisition, imperfect circular laser trajectory always appeared because of the limitation of scanning motor and charge coupled device (CCD) camera. Here, we address order-statistic filter based on 1/3 value rather than mid-value. In contrast with linear filter method, order-statistic filter could better solve certain types of image processing problems. This filter method makes the circular laser trajectory perfect. In addition, its ability to reduce random noise without blurring edges was as much as a comparable linear low pass filter. The laser-strengthening and noise-reducing effects that order-statistic filter has on an image depend on two relative things: the spatial extent of the mask and the number of pixels involved in the median computation. Here, they were in the five-by-five mask, and 9 points were selected for the mask.

Taking GTAW process as example, the original welded image during GTAW process using circular laser vision sensor as welding seam detector was illustrated in Fig. 2(a). Because of the high-intensity arc light interference, one novel barrier layer was adopted to remove most of the arc light. Therefore, the welding seam was separated into two parts: one was for circular laser zone; the other was arc light zone. De-noise method based on 3-level

Table 1. Specification of Sensory System Used for Seam Tracking Experiment

Item	Specification
Distance between Torch Tip and Coordinates of Laser Cone	$W = 84$ mm; $H = 5$ mm
Distance between Lens Center and Coordinates of Laser Cone	178 mm
Focal Length of Lens (after Calibration)	6.21 mm
Height of Image Plane	4.8 mm
Width of Image Plane	6.4 mm
Cone Angle α	12.88°
Separation Angle β	39.25°
Seam Tracking Speed	300 mm/min
Detect Range y	±20 mm
Detect Range z	±25 mm
Weld Current	52 A
Argon Flow Rate	9 L/min
Sampling Rate	28 frame/s

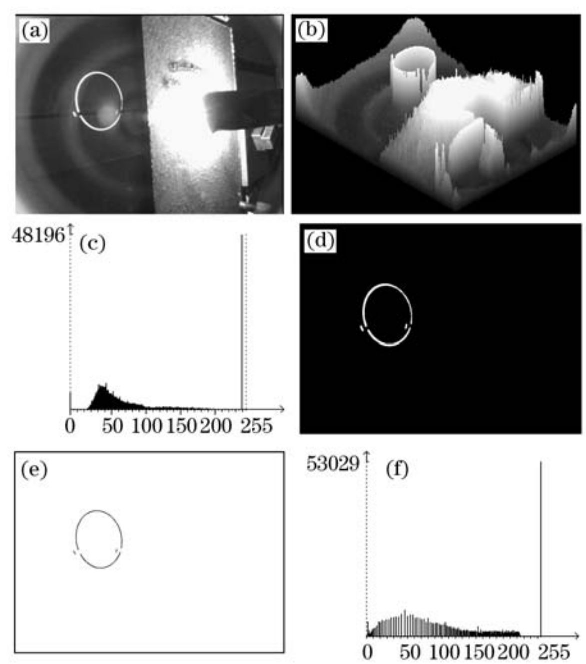

Fig. 2. Results for "image pre-processing". (a) Original image; (b) 3D image; (c) histogram; (d) image segmentation; (e) 5×5 image thinning; (f) histogram after image equalizing.

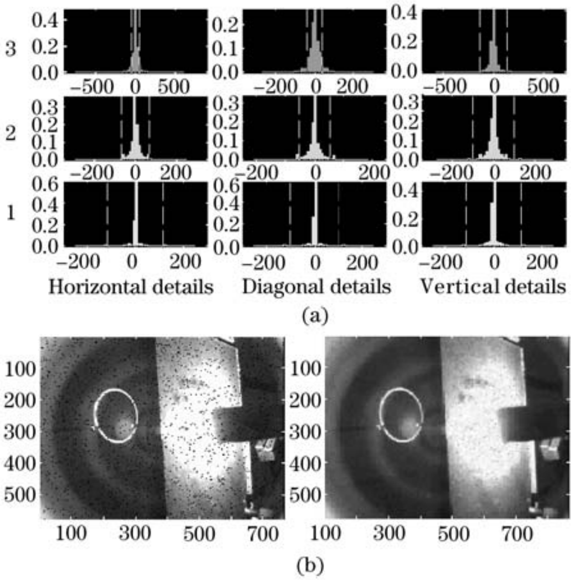

Fig. 3. De-noise parameters and result for circular laser seam image of 3-level wavelet. (a) Wavelet graph; (b) original image (left) (I joint, butt, GTA welding, $I = 52$ A, $v = 5$ mm/s, 100 kgf/cm^2) and de-noise image (right).

wavelet technique was put forward to de-noise the welding seam image, which is illustrated in Fig. 3. Figure 3(a) illustrates the wavelet graph for de-noise process, the contrast effect image of original image and de-noised image is shown in Fig. 3(b), the welding parameters are: $I = 52$ A, $v = 5$ mm/s, 100 kgf/cm^2.

In addition, "two-step segmentation (TTS)" and image thinning technique were used for feature extraction of weld images under GTAW condition, as shown in Figs. 2(d) and (e). The results show that this technique can be used to segment welding seam image from background image accurately.

After image segmentation and image thinning, the 3D calculation experiment can be realized by the proposed circular vision sensor and mathematical model[8], including butt welding seam with gap, butt welding seam with groove, lap welding seam, fillet welding seam, and ramp welding seam etc.. Figure 4 illustrates the process of seam tracking for both I-type butt joint and sine welded joint.

Here, taking I-type butt welded seam as an example, circular laser trajectory was projected to I-type weldment as active light; the 3D calculation can be realized. One image was grabbed using circular laser vision sensor and 563 positions were measured at the same time. The 3D

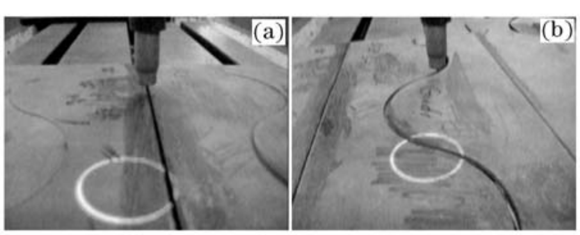

Fig. 4. Illustrate of seam tracking based on circular laser vision sensor. (a) Ion string welded joint; (b) sine welded joint.

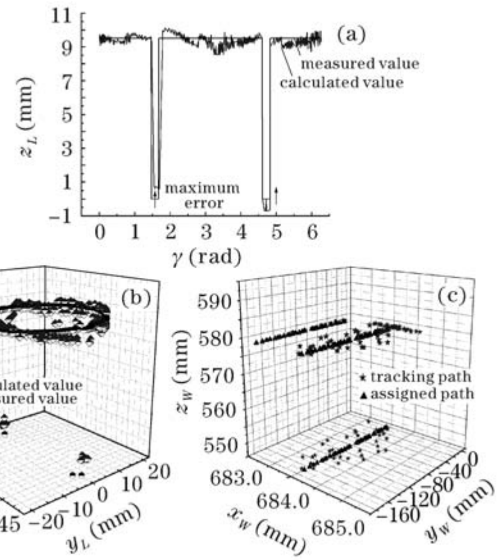

Fig. 5. Experimental results for I-type butt welded joint using circular laser vision sensor as seam guider. (a) Relation of depth value z_L and γ angle; (b) 3D calculation; (c) seam tracking.

calculation result was shown in Fig. 5(a). The relation of depth information of workpiece to be detected and off-axis angle γ was illustrated in Fig. 5(b).

Guided by circular laser vision sensor, seam tracking experiment for butt weld joint was carried out in ABB140 robot platform. Seam tracking can be realized by two types seam tracking model. One was off-line programming seam tracking, that is to say, seam tracking process was divided into two stages. Stage 1: 3D calculation of welded joint characteristic point from 2D in sensitivity plane through image acquisition, image processing, and 3D calculation algorithm; stage 2: seam tracking according to the obtained 3D position data of the welding seam. The other was seam tracking in real time, that is to say, seam tracking was simultaneous with the 3D position data calculation of the welding seam. When seam tracking was in process, two threads were occurring: computer thread used for image acquisition, image processing and 3D calculation from 2D in sensitivity plane, robot thread used for communication with computer and guidance for manipulator along the real welding seam. The seam tracking results were shown in Fig. 5(c).

Developed seam tracking system based on circular laser vision sensor was a multi-hardware consisting of image grabber, vision sensor, and robot; a multi-task data processing with image processing, weld seam 3D calculation, and communication between robot and computer; even a multi-node information transfer complex system. The precision of the system was affected by kinds of factors, including light scanning system, camera calibration and robot calibration, image processing and even welding seam 3D algorithm. The main error analysis was as follows. 1) Calibration error. In the seam tracking system, calibration consists of two parts: one was calibration for ABB robot; the other was camera calibration. Wherein, "4 points tool center point (TCP)" calibration method was used to calibrate the ABB robot. Consequently, welding torch coordinates can be determined by robot controller. The calibration error, mean error of 0.24

and maximum error of 0.67 was achieved. 2) Scanning system error. Scanning system error results from scanning lens, including spherical aberration (error caused by different distances of several lights when they illustrate the scanning lens, the thickness of which cannot be omitted). The error analysis manifest that while the distance between the light and center of lens was within 40 mm, the maximum error was 0.707 mm.

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