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Technical Paper

Analytical reconstruction of three-dimensional weld pool surface in GTAW

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ABSTRACT

The reflective characteristic of mirror surfaces such as a liquid pool surface in arc welding makes many traditional 3D measurement/reconstruction methods fail. The authors proposed to intercept, image, and measure two points in each laser ray reflected from a mirror surface with two diffusive planes and cameras to analytically calculate the equation of the ray. The samples of the points on the mirror surface where the incident laser rays are reflected can thus be analytically calculated as the intersections of the reflection rays with the corresponding incident rays. In this paper, the proposed method is applied to reconstruct the samples on the specular three-dimensional weld pool surface in GTAW (gas tungsten arc welding). Since two diffusive planes are used and must be placed with considerable distance to assure the accuracy of the calculated equations of the reflected rays, focusing reflected laser rays on these two planes becomes an issue. A trade-off among the size of the projected laser pattern, the distances of the arc light with the two diffusive planes, the focus range of the laser rays and the quality of the reflected laser dot images on the diffusive planes has been made to resolve this issue successfully. Further, calibration errors in the locations of the diffusive planes directly affect the accuracy of the calculated equations of reflected rays and an accurate calibration appears to impractical. To resolve this issue, the authors found the least deformation principle and successfully applied it to minimize the calculation errors through calibration rectification. Several weld pool surfaces have been sampled and reconstructed and experimental results verified the effectiveness of the proposed analytical method.

1. Introduction

Many traditional 3D reconstruction methods will avoid reconstructing mirror surfaces because the reflection from mirror surfaces is view-angle dependent. It causes stereo vision methods to fail in finding correct correspondences between two images and also adds the ambiguity of normal and depth to the traditional structured light and phase shift methods [1].

In the case of sensing a weld pool surface [2–7], it is also interfered by the harsh welding environment. For instance, the work piece is melted by the arc and the bright arc light makes direct sensing of a weld pool surface difficult. To overcome these difficulties, laser patterns have been projected onto the weld pool surface and the reflections of the laser patterns from the weld pool surface are imaged on a diffusive plane. The images of reflected laser patterns on the diffusive plane are captured by a CCD camera and processed with image processing algorithms to calculate the distortion of laser patterns. From the distortion of the reflected laser patterns, the surface of the weld pool can be calculated [4–7]. The drawback of this method is that the reconstructed 3D surface is obtained by matching the calculated reflection pattern with the imaged reflection pattern and there is an iterative optimization process needed in order to achieve an acceptable matching.

To avoid the iteration, direct analytical solutions are needed for sampled points on the mirror surface reflecting the projected laser pattern. Another method has thus been proposed in a previous study [8] that uses two diffusive screens to capture the reflected pattern twice such that the equation for the linear trajectory of each reflected ray can be analytically computed. With known incident rays' equations and their corresponding reflected rays' equations, their intersection points can be directly computed, therefore obtaining the sampled points of the 3D mirror surface where the incident rays are intercepted and reflected. It thus proposes a method that may be advantageous over the previous iteration based algorithm [7] in computation speed.

2. Principle

Fig. 1 illustrates the principle of the previously proposed method for direction analytical solutions of the reflection rays [8]. As shown in Fig. 1, there are three cameras $c1$, $c2$ and $c3$ which aim at planes $p1$, $p2$ and $p3$, respectively. The origin of the world co-ordinate is

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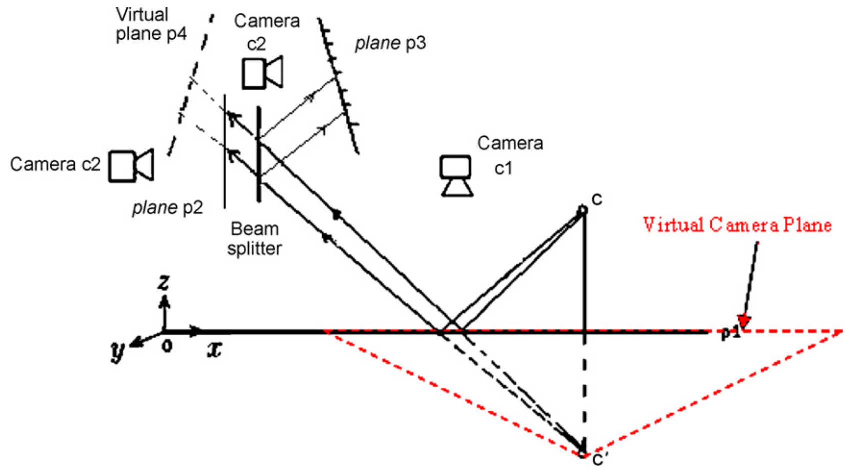

Fig. 1. System diagram.

defined at the point O. The equation of the plane $p1$ which is on the moving screen is defined as $z = 0$. The laser rays are projected onto the surface of the plane $p1$ from the projection center C. When the mirror reflected laser ray reaches the beam splitter, half power of it transmits through the splitter and hits on the semitransparent plane $p2$ while the other half of it is mirror reflected and hits on the plane $p3$. Both plane $p2$ and $p3$ are diffusive. Hence, the laser interception points on these two planes are imaged at camera $c2$ and $c3$, respectively. The symmetry plane of plane $p3$ with regard to the beam splitter is a virtual plane $p4$ as shown in Fig. 1. From the laser ray interception points with the plane $p3$, the laser interception points with the virtual plane $p4$ can be computed. Combined with the laser interception points on the plane $p2$, two points are known for each emergent laser ray. Hence, each ray is determined uniquely.

The three-dimensional coordinates of the interception points on the plane $p2$ and the virtual plane $p4$ can apparently be directly computed with the equations of these two planes and their corresponding camera image plane coordinates of the interception laser dots on these two planes, respectively [8]. In this study, the maximum likelihood estimation [9] is applied to compute the homography between camera $c2$ and diffusive plane $p2$, camera $c3$ and diffusive plane $p3$, respectively, in order to improve the reconstruction accuracy.

The projection center of the virtual camera is obtained by computing the point where all the incident laser rays intersect. To this end, each incident laser ray needs to be determined first. The method is to move the horizontal moving screens in the vertical direction and compute world coordinates of the interception points of incident laser rays with the horizontal screens. In theory, two points determine one line. However, in reality the noise affects the accuracy. Hence, six horizontal planes have been used to obtain six interception points for each incident ray. The equation for each incident laser ray is then computed by singular value decomposition algorithm as detailed in [8].

To reconstruct the mirror surface, the intersection point of the incident ray and its corresponding emergent ray is computed. In case they do not intersect exactly, the shortest line connecting the two rays is determined and its middle point is computed as the estimated intersection [8].

3. Experimental system

Fig. 2 shows the experimental system used to capture the weld pool reflected laser dots images. A 4 in. schedule 10 stainless steel pipe, the outside diameter is 114.3 mm (4.5 in.) and the wall thickenss is 3.1 mm (0.12 in.) [10], is used as the workpiece for stationary GTAW. The used tungsten is 2% ceriated and its diameter is 3/32 in. The tip of the tungsten is shaped into a cone with cone angle 30° and its distance to the work piece is 6 mm. Pure argon is used as the shielding gas and the flow rate is 8.5 l/min (18 ft^3/h). The welding power supply mode is CC and the current is 70 A. The angle of the center incident ray with the horizontal plane is 44°. During the welding process, the laser rays are projected onto the weld pool and reflected by the specular surface onto the beam splitter. Half of the laser energy passes through the beam splitter and imaged on imaging plane 1, the backside of the beam splitter. Another half is reflected by the front-side surface of the beam splitter and intercepted and imaged on imaging plane 2. The front surface of the beam splitter is placed at $y = -115$ mm and the thickness of the beam splitter is 3 mm. Imaging plane 2 is placed at $y = -30$ mm. Two Dragonfly2 cameras synchronically record images on the two diffusive imaging planes at 60 frames/s.

4. Imaging

The challenges are apparent: (1) the arc light radiation is strong and its power is much greater than that of a possible illumination laser; (2) two diffusive planes are needed and must be placed with a distance. Further, if the used laser is not "focusless", the focus brings an additional issue. To overcome the first issue, spectral band-pass filter [4,6] has been used to decrease the effect of arc light and imaging plane 1 is placed with a sufficient distance such that the arc light intensity decays significantly when reaching imaging plane 1.

To overcome the second issue, the authors had tried a "focusless" (Pico Laser) projector first. However, the manufacturer does not disclose the spectral data to customers such that the authors lack the knowledge to use an appropriate optical filter to reduce the arc light effect. As a result, a 660 nm 50 mW SNF laser with an adjustable focus is used in this study. To overcome the out-of-focus problem, the authors increased the size of projected pattern to decrease the diffraction effect between adjacent rays. On the other hand, the size of the projected pattern should be as small as possible to obtain more weld pool reflected rays as long as it covers the entire weld pool surface. Hence, a tradeoff, among the size of the projected laser pattern, the distances of the diffusive planes from the arc light, and the focus range of the laser rays, is needed to optimize the image quality. Fig. 3(a)–(e) shows the captured images with (a)–(c) for system calibration. It is seen that the laser dots on any image are not perfectly clear because of the trade-off. However, the image quality appears to be adequate for image processing