Welding torch attitude-based study of human welder interactive behavior with weld pool in GTAW

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Abstract

Skilled human welder adjusts welding parameters including the welding torch attitude, moving speed and position to control weld quality and avoid weld defects based on real time observed varying weld pool surface for precision joining using gas tungsten arc welding (GTAW). However, welder behavior/adjustment appears to be a complex reactive response. To understand this complex response and develop intelligent robotic arc welding, a new scheme that correlated welding torch attitude to weld pool surface to study welder behavior in torch adjustment as response to weld pool was proposed and realized. The torch attitude and the 3D weld pool surface were synchronously measured using a wire inertial measuring unit (IMU) and a laser vision-based approach. An image processing algorithm was developed to extract the characteristic parameters of the weld pool surface from the laser stripes reflected by the specular pool surface. The improved quaternion-based unscented Kalman filter was used to estimate the torch orientation from its inertial measurement data, showing that the torch attitude has been obtained with an acceptable error in the order of 1°(x axis and y axis) and 2°(z axis). Several experiments were performed and the correlation of the corresponding data was detailed. It indicates that the change of torch attitude represents the welder’s operating skills, welding experience and smart decision. The three characteristic parameters reflect the welder’s reactive response on the torch adjustments. The curvature radius of laser stripes can predict the changing trends of the weld pool surface, providing the needed information for welders to make a smart decision. The proposed scheme is feasible for measuring and analyzing the welder’s skills and experience.

1. Introduction

Industrial robots are believed to further replace human workers. This is partially due to the increasing labor costs and shortage of skilled workers [1]. Most of welding robots are currently used in less critical components for highly repetitive operations [2]. For critical applications such as reactor pressure vessels, unless the parts are precisely prepared such that the variations are controlled to minimum, gas tungsten arc welding (GTAW) is still operated by highly skilled welders to assure the weld quality. However, inconsistent concentration, fatigue, and stress do build up such that the human welder’s capabilities may degrade. Equipping welding robots with human intelligence appears to be an effective solution. Though, the human welder’s intelligence is a long time trained, practiced welding experience and skills, and appears to be a complex reactive response on the varying weld pool. Currently, there does not find an intelligent welding robot that can fully perform the welding task like a skilled human welder for assuring the high-quality welds. To this end, human welder interactive behavior with weld pool, which is the major feedback available from the process, needs to be first studied.

Human welder’s intelligence has been studied using digital technology [3], robot-assisted manual method [4], modeling, simulation [5–7] and virtual reality technology [8–10]. These researches recorded and digitized some changes of human welder’s responses, and focused on the adjustment of human welder on heat input to work-piece. Important aspects of human welder’s adjustment/control in welding process, i.e., adjusting forces (e.g., arc pressure, gas shear stress) and thermal mechanical coupling of the weld pool, were ignored while they affected the weld pool geometry and the weld metal fluid flow in the weld pool. Unfortunately, many weld defects such as humping, undercutting, porosity or crack largely depend on the fluid flow in the weld pool [11–13]. Hence, learning of the complex human welder behavior would not be completed without understanding the human welder’s interactive process from the weld metal fluid flow control perspective.

As the weld pool surface was the object of human welder’s control and responses. To study its dynamics may be necessary for under-* Corresponding author.
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standing and learning the human welder intelligence. Lots of works have been conducted currently with theoretically numerical simulation and experiments [14–21]. However, the numerical simulation and experimental results have a relative large error with the actual weld pool surface in 3D, as well as cannot be real time calculated and obtained. Recently, Song et al. [22] proposed a new method to measure the 3D weld pool surface. Based on the acquired 3D information, the human welder’s response on the weld pool surface was modeled and analyzed in GTA W process [23–26]. Liu et al. [27–30] also developed a human-machine cooperative virtualized welding platform to obtain the data pairs of welding speed/current and weld pool surface characteristic parameters, and then employed a data-driven approach to identify the neuro-fuzzy or iterative local ANFIS model for learning the human welder intelligence and realizing the automated control experiment.

Most of the studies mentioned above concerned on the human welder’s behavior in adjusting welding current, welding torch speed, etc. and in response to the weld pool. In manual GTA W process, skilled human welders can avoid many weld defects by adjusting the torch orientation. Moreover, the welding current was always pre-set to fix at a constant. Only in a small range, the torch speed was adjusted. The torch orientation adjustments may thus better represent welders’ experience and operating skills. As such, Parvez et al. [31] simulated the effect of the torch angles, in stationary GTA W, on arc properties and on weld pool shape. Hashimoto [32] utilized four cameras to record the torch movement and calculated the orientation of the electrode tip in GTA W. Zhang et al. [33] utilized a miniature wireless IMU to measure the 3D welding torch orientation in manual arc welding process in an unconfined environment. In another study [34], a magnetometer was incorporated with the IMU sensor to improve the measurement accuracy for the torch orientation. The torch speed and position were also measured. However, in their studies, the needed input, i.e., the weld pool surface, and output, i.e., the torch orientation, to study the human welder’s response in adjusting the torch orientation are not measured at the same time, and them correlation is not detailed. In this paper, a new scheme showed in Fig. 1 was first proposed to measure these input and output at the same time and deeply illustrated the human welder’s behavior in the torch orientation adjustment as response to the weld pool surface.

This paper was organized as follows. The novel experimental system proposed to simultaneously capture the torch attitude and the weld pool surface were introduced in Section 2.1. A special image processing algorithm was detailed in Section 2.2. The sensor accuracies was calibrated in Section 2.2.3. Several experiments were performed with different level skilled welders. The corresponding data was obtained and then the correlation between the torch orientation and the characteristic parameters of the weld pool surface was carefully analyzed in Section 3.

2. Experimental procedure

2.1. Principle

In this scheme, a new combined MPU6050 IMU sensor without a magnetometer with an improved quaternion-based unscented Kalman filter was applied to estimate the 3D torch attitude. To obtain characteristic information of weld pool from the laser stripes reflected by the specular pool surface, in particular, the fluid flow information, a novel method was proposed to indirectly measure the weld metal fluid flow status, and its principle was illustrated in Fig. 2. Structured laser light-based method has been successfully applied to measure the 3D weld pool surface and the characteristic parameters (width, length and convexity) were extracted to describe the weld pool surface [35]. However, the weld metal fluid flow status cannot be well depicted by the average convexity of pool surface due to the fast flow of weld metal. Hence, in this work, three parameters, width, length and curvature radius of laser stripe were utilized to characterize the weld metal fluid flow caused by the welding torch adjustments [14,31]. Since the weld pool surface needs complex computation but the proposed laser reflection stripe parameters can be directly computed from the reflection images, the proposed use of laser reflection parameters appears to ease the analysis of the dynamic weld pool surface which reflects the laser stripes, thus the analysis of the fluid flow.

![Fig. 1. Illustration of studying human welder behavior with welding torch attitude.](image-url)
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