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Control of human arm movement in machine-human cooperative welding process

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A R T I C L E I N F O

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This paper studies accurate control of human arm movement in machine-human cooperative control of GTAW process. An innovative teleoperated virtualized welding platform is utilized to conduct dynamic experiments to correlate the human welder arm movement with the visual signal input. An adaptive ANFIS model is proposed to model the intrinsic nonlinear and time-varying characteristic of the human welder response. A model based predictive control algorithm is then proposed and an analytical solution is derived. Human control experimental results verify that the proposed controller is able to track varying set-points and is robust under measurement and input disturbances.

1. Introduction

GAS tungsten arc welding (GTAW) (O'Brien, 1998) is the primary process used for precision joining of metals. The GTAW process is illustrated in Fig. 1. In this process an arc is established between the non-consumable tungsten electrode and the base metal. The base metal is melted by the arc forming a liquid weld pool that joins the two pieces of base metal together after solidification. The shielding gas is fed through the torch to protect the electrode, molten weld pool, and solidifying weld metal which may be contaminated by the atmosphere.

Because GTAW is primarily used in applications where appropriate degree of full penetration (if and how much the liquid metal has fully penetrated the entire thickness of the base metal) is critical for the service, the process should be mechanized or automated as long as it can be justified for production cycle, cost, and quality. Welding process monitoring and control for automated welding machines has thus been an active research area in the past few decades (Renwick & Richardson, 1983; Zachsenhouse & Hardt, 1983; Hardt & Katz, 1984; Carlson & Johnson, 1988; Guu & Rokhlin, 1992; Nagarajan, Banerjee, Chen, & Chin, 1992; Song & Hardt, 1993; Beardsley, Zhang, & Kovacevic, 1994; Pietrzak & Packer, 1994; Andersen, Cook, & Barnett, 1997; Zhang & Kovacevic, 1998; Tsai, Hou, & Chuang, 2006; Ghanty, Vasudevan, & Mukherjee, 2008; Chen, Lv, & Lin, 2009; Liu & Zhang, 2013; Liu & Zhang, 2014a; Liu, Zhang, & Zhang, 2014; Liu, Zhang, & Kvidahl, 2014a, 2014b). Various control methods have been proposed to control the welding process. Depending on the sensing method used, these control systems can be categorized into pool oscillation-based control (Renwick & Richardson, 1983; Zachsenhouse & Hardt, 1983; Andersen et al., 1997), radiography-based control (Hardt & Katz, 1984; Carlson & Johnson, 1988; Guu & Rokhlin, 1992), thermal-based control (Nagarajan et al., 1992; Song & Hardt, 1993; Beardsley et al., 1994; Ghanty et al., 2008), and vision-based control (Pietrzak & Packer, 1994; Zhang & Kovacevic, 1998; Tsai et al., 2006; Chen et al., 2009; Liu & Zhang, 2013; Liu & Zhang, 2014b; Liu et al., 2014; Liu et al., 2014a, 2014b), etc. However, mechanized systems require significant amount of time for on-site installation and joints be prepared with great precision. The production cycle in many applications is adversely affected substantially. Further, the assurance of the weld quality might also be an issue. In manual welding, welders who observe the weld pool can assure the desired full penetration be produced. However, in mechanized welding, no welder has the capability to interfere with the system; they are not required or allowed in robotic welding to observe the welding process with the similar level of concentration as in manual operation. Mechanized/automated systems rely on precision control of joint fit-up and welding conditions and tedious programming of welding parameters to produce repeatable results. However, precision control of joints and welding conditions is very costly and not always guaranteed. Despite the success in sensing and controlling the welding process, up to date there are no satisfactory sensors/ways that can be conveniently carried by the torch to automatically monitor the penetration depth (how far the liquid metal penetrates along the thickness of the base metal) or the degree of the full penetration like a skilled welder.

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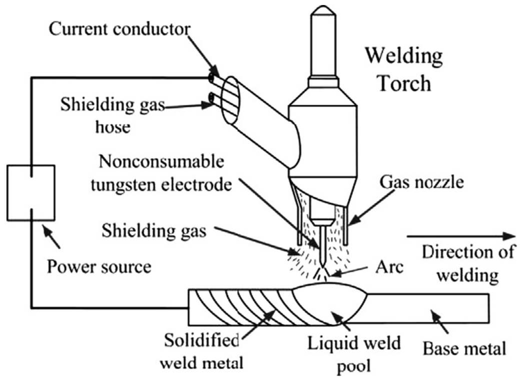

Fig. 1. Illustration of GTAW.

In manual GTAW process human welders can appraise the penetration status based on their observation of the welding process. Due to advantages in versatility and accessibility, human welders are often preferred in complex structure welding over mechanized or automated machines. Unfortunately, skills needed for critical welding operations typically require a long time to develop. Shortage of skilled welder has become an urgent issue the manufacturing industry is currently facing (Uttrachi, 2007). On the other hand, fatigue and stress build up quickly for critical applications so that welders' capabilities degrade rapidly.

Using a machine to cooperate a welder controlled process represents another type of operation and control, which is referred to as machine-human cooperative control scheme. In this scheme, it is a welder controlled process rather than purely machines and physical processes. A machine algorithm determines (based on model prediction of human and process responses) adjustment to human welder controlled process. With the proposed cooperative control, quality welds may be better produced by less experienced welders with less intensive concentration during a longer lasting period. The long-term health of welders may be improved and the supply of qualified welders may be better stabilized.

In manual GTAW process two major adjustable welding parameters are the welding current and welding speed. An increase in the welding current and a decrease in the welding speed increase the heat input into the welding process thus influencing the weld pool surface geometry considerably. Other possible welding parameters include torch orientations, arc length, heat transfer condition, material, thickness and chemical composition of the workpiece and shielding gas, etc. In many pipe welding applications the pipe joint is often fixed and cannot be rotated during welding (5G fixed position—that is, the axis of the pipes is horizontal; the pipes stay stationary during welding; and the welding torch will be moving along the weld joint (Cary & Helzer, 2005)). In order to achieve a high-quality weld bead, the welding parameters need to be adjusted based on different welding positions. Normally welders choose a pre-defined welding current and move the torch along the pipe. The human welder's hand movement (i.e. the welding speed) thus is controlled by the human welder as a main source to compensate for possible variations. A stable and accurately controlled human arm movement is essential in accomplishing the proposed machine-human cooperative control scheme.

This paper serves as the first study in machine-human cooperative control and aims to study welder's arm movement as a response to given visual signal (arrows with directions and amplitude) and control his/her arm movement using an adaptive predictive neuro-fuzzy controller. The remainder of the paper is organized as follows. In Section 2 the experimental setup is detailed. Principle of machine-human cooperative control is first described, and human hand movement tracking system is then introduced. Training experiments are conducted to improve the response consistency and the experimental data are presented. System modeling is performed in Section 3. Step responses are first presented and analyzed. Linear model is then used to model the correlation between the arm movement adjustment and visual signal. Nonlinear ANFIS model is utilized to improve the modeling performance. Since the human responses are intrinsically nonlinear and time varying, an adaptive ANFIS model is proposed and the model performance is further improved. In Section 4 an adaptive nonlinear Model-based Predictive Control (MPC) algorithm is developed and an analytical solution is derived. To verify the robustness of the proposed control algorithm, tracking experiments under different set-points and various disturbances are conducted and the results are analyzed in Section 5. Conclusions are finally drawn in Section 6.

2. Experimental setup

2.1. Principle of machine-human cooperative control

Fig. 2 illustrates the schematic of the proposed machine-human cooperative control system where two identification blocks are used to on-line identify models for the welding process and welder reaction process, respectively. The dynamic model for the welding process relates output Ω (3D weld pool characteristic parameters, i.e., the weld pool length, width, and convexity (Zhang, Liu, Wang, & Zhang, 2012)) to the welding speed S (i.e., human arm movement speed). To identify this model, the system will have to measure Ω and S and use sampled data pairs $(S(k), \Omega(k))'s$ (where k is the discrete-time at which the process is sampled) in order to identify the parameters in the proposed dynamic model using an appropriate adaptive learning/identification algorithm. The dynamic model for welder reaction relates the welder reaction or arm movement to visual signal provided to the human welder.

The proposed cooperative controller performs three functions: (1) Welder reaction prediction: Use the identified welder reaction model to predict welder reactions/actions; (2) Welding process response prediction: Use the predicted welder actions (future control variables) and identified welding process model to predict the response of the dynamic welding process, i.e., to predict Ω. (3) Cooperative adjustment: The predicted Ω will be related to the adjustment to be made by the human and optimization will be done to minimize deviation of the predicted Ω from a desired trajectory Ω^* with respect to the machine adjustment. An optimized welding speed S^* is calculated and will serve as the desired

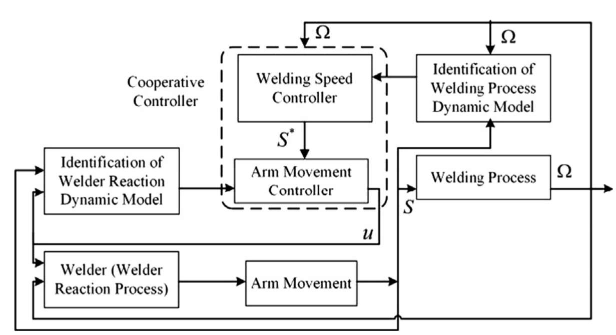

Fig. 2. Schematic of machine-human cooperative control. In this scheme human welder controls the welding speed determined by his/her arm movement. The welding speed controller determines the optimal welding speed for the human welder to follow. Arm movement controller calculates the visual signal for human welder to view. The human welder sees the visual signal and weld pool images and moves his/her arm accordingly. The welding process outputs the 3D weld pool characteristic parameters which will be inputted into the cooperative controller.