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Control of heat diffusion in arc welding using differential flatness theory and nonlinear Kalman Filtering

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Abstract: Control of the heat diffusion in the welded metal is of primary importance for succeeding welding of high quality (the latter being a prerequisite for efficient ship building). The paper proposes a distributed parameter systems control method that is based on differential flatness theory for solving the problem of heat distribution control in the arc-welding process. Besides, it proposes a nonlinear filtering method, under the name Derivative-free nonlinear Kalman Filtering for reducing the number of real-time control measurements needed to implement the feedback control loop. The stability of the control method is confirmed analytically, while its efficiency is also evaluated through simulation experiments.

Keywords: ship-building, arc welding, heat diffusion, differential flatness theory, nonlinear control, nonlinear Kalman Filtering.

1. INTRODUCTION

Arc welding is one of the primary tasks in ship building (Tzafestas and Rigatos, 1997). Automated welding in ship-building is required because of the low productivity of hand welding, which is the result of the severe environmental conditions produced in the intense heat and the fumes that are generated by the welding process. The dynamics of the welding process is given by a diffusion-type partial differential equation which describes the spatiotemporal variations of the temperature distribution in the welded workpiece. The parameters (inputs) that affect this temperature distribution are the velocity of the torch and the heat input power. It is important to control heat diffusion in the welding process and the associated temperature distribution in the welded material, because this finally determines the quality, strength and endurance of the weld.

According to welding theory, the temperature of the heat affected zone determines the quality of the weld (Silver et al., 1998), (Lee et al., 2010), (Wu et al., 2009), (Kuo and Wu, 2002). The heat affected zone is defined as the area round the weld bead where the temperature of the melted material varies between a lower and upper limit, where each limit is associated with transition to a different phase and structure of the material. The structure of the material that is formed after welding as well as the defects appearing in the weld depend on the temperature that is developed in the heat-affected zone and its variations during the welding process. For the monitoring of the thermal distribution in the welded workpiece several methods have been implemented, such as the use of thermocouples, infrared thermometers and infrared cameras. Efficient control of the thermal distribution during welding is still an open problem. In this manuscript a solution will be developed based on previous results on control and state estimation for distributed parameter systems with the use of differential flatness theory (Rigatos, 2011), (Rigatos, 2013), (Rigatos, 2015).

Feedback control of diffusion-type (parabolic) PDEs has been a subject of extensive research and several remarkable results have been produced (Maidi and Corriou, 2014), (Zwart et al., 2011), (Woittennek and Rudolph, 2012), (Winkler et al., 2009). Following the procedure for numerical solution of the nonlinear PDE of the nonlinear heat diffusion, a set of coupled nonlinear ordinary differential equations is obtained and written in a state-space form (Pinsky, 1991), (Gerdes et al., 2006). For the latter state-space description, differential flatness properties are proven. Thus, it is shown that all state variables and the control inputs of the state-space model can be written as functions of a vector of algebraic variables that constitute the flat output and of the flat output derivatives (Mounier and Roudolph, 2001), (Rudolph, 2003), Lévine (2010), (Fliess and Mounier, 1999), (Bououden et al., 2011). By applying a change of coordinates (diffeomorphism) which is based on differential flatness theory it is shown that the state-space model of the heat diffusion PDE can be written in a linear form, in which the previously noted nonlinear ordinary differential equations are now transformed into linear ones. Next, feedback control is applied to the heat diffusion PDE. For each local linear model of the aforementioned differential equations the state feedback control is selected such that asymptotic stability is assured. This can be done using for instance pole-placement methods. By computing the control input of the heat diffusion PDE, which varies both in space time one can also compute the velocity that the welding torch should have a specific time instant at a point of the cartesian frame, so as the temperature distribution of the workpiece to convergence to the reference setpoints.

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Another objective of the article is to implement state-feedback control of the nonlinear heat diffusion PDE using measurements from a small number of sensors (Rigatos, 2012), (Marino and Tomei, 1992). This implies that for state vector elements of the PDE's state-space description which cannot be measured directly, state estimation with filtering methods has to be be applied. Filtering for nonlinear PDEs is again a non-trivial problem (Woittennek and Rudolph, 2012), (Bertoglio et al., 2012), (Salberg et al., 2010), (Yu and Chakravotry, 2012). Both observer and Kalman Filter-based methods have been proposed (Haine, 2012), (Hidayat, 2011), (Demetriou, 2010), (Guo et al., 2012), (Chauvin, 2011)]. To this end, in this paper, a new nonlinear filtering method, under the name Derivative-free nonlinear Kalman Filtering, is proposed. The filter consists of the Kalman Filter recursion for the linearized state-space model of the heat diffusion PDE (Rigatos and Tzafestas, 2007), (Basseville and Nikiforov, 1993), (Rigatos and Zhang, 2009)]. It also includes an inverse transformation that enables to obtain estimates of the state variables in the initial nonlinear description.

2. DYNAMIC MODEL OF THE ARC WELDING PROCESS

The reference frame of Fig. 3 is introduced and the following nonlinear heat diffusion equation is considered, describing the spatiotemporal variations of the temperature in the welded workpiece (Silver et al., 1998),(Lee et al., 2010).

$$\frac{\partial\phi}{\partial t} = K\frac{\partial^2\phi}{\partial x^2} + f(\phi) + u(x,t) \quad (1)$$

where K is the heat conductivity and $u(x,t)$ is a term associated with the partial derivative of the temperature distribution with respect to the space variable x as well as with the velocity of the welding torch. This is given by

$$u(x,t) = \frac{\partial\phi(x,t)}{\partial x}v_s(t) \quad (2)$$

with $v_s(t)$ to stand for the velocity of the torch at time instant t. Moreover, about the nonlinear term $f(x,t)$ this is given by

$$f(x,t) = q(x)h(t) \quad (3)$$

The term $h(t)$ stands for the heating power provided by the torch. The term $q(x)$ denotes the spatial distribution of the heating input and can be approximated by a Gaussian, that is (Wu et al., 2009),(Kuo and Wu, 2002)

$$q(x) = ae^{-\frac{(x-x_s)^2}{\sigma^2}} \quad (4)$$

where a and σ are constant parameters and x_s is the position of the torch in the reference system used for the welding process. The previous dynamic model of the welding process is the result of the energy conservation principe. In the simplest scenario of welding the following assumptions are made: (i) the thermal conductivity coefficient K remains constant throughout the process and is not affected by temperature variations of the welded material, (ii) the only heat source provided to the welded material is the one given by the torch, (iii) no heat is either produced or lost at any other part of the workpiece.

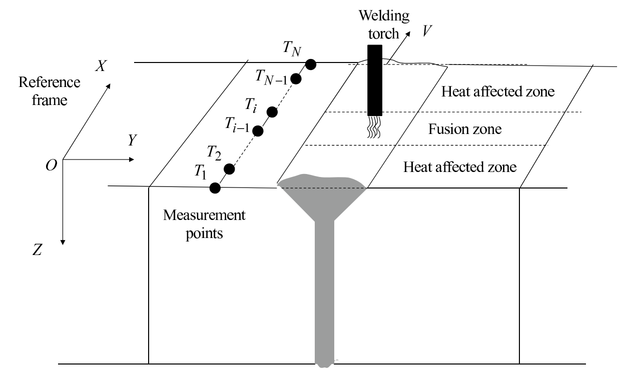

Fig. 1. Control scheme of the nonlinear heat diffusion in the welding process

3. STATE-SPACE DESCRIPTION OF THE NONLINEAR HEAT DIFFUSION DYNAMICS

Using the approximation for the partial derivative in the partial differential equation given in Eq. (1) one has

$$\frac{\partial^2\phi}{\partial x^2} \simeq = \frac{\phi_{i+1}-2\phi_i+\phi_{i-1}}{\Delta x^2} \quad (5)$$

and considering spatial measurements of variable ϕ along axis x at points $x_0 + i\Delta x,\ i = 1, 2, \cdots, N$ one has

$$\frac{\partial\phi_i}{\partial t} = \frac{K}{\Delta x^2}\phi_{i+1} - \frac{2K}{\Delta x^2}\phi_i + \frac{K}{\Delta x^2}\phi_{i-1} + f(\phi_i) + u(x_i,t) \quad (6)$$

By considering the associated samples of ϕ given by $\phi_0, \phi_1, \cdots, \phi_N, \phi_{N+1}$ one has

$$\begin{aligned}
\frac{\partial\phi_1}{\partial t} &= \frac{K}{\Delta x^2}\phi_2 - \frac{2K}{\Delta x^2}\phi_1 + \frac{K}{\Delta x^2}\phi_0 + \\
&\quad + f(\phi_1) + u(x_1,t) \\
\frac{\partial\phi_2}{\partial t} &= \frac{K}{\Delta x^2}\phi_3 - \frac{2K}{\Delta x^2}\phi_2 + \frac{K}{\Delta x^2}\phi_1 + \\
&\quad + f(\phi_2) + u(x_2,t) \\
\frac{\partial\phi_3}{\partial t} &= \frac{K}{\Delta x^2}\phi_4 - \frac{2K}{\Delta x^2}\phi_3 + \frac{K}{\Delta x^2}\phi_2 + \\
&\quad + f(\phi_3) + u(x_3,t) \\
&\cdots \\
\frac{\partial\phi_{N-1}}{\partial t} &= \frac{K}{\Delta x^2}\phi_N - \frac{2K}{\Delta x^2}\phi_{N-1} + \frac{K}{\Delta x^2}\phi_{N-2} + \\
&\quad + f(\phi_{N-1}) + u(x_{N-1},t) \\
\frac{\partial\phi_N}{\partial t} &= \frac{K}{\Delta x^2}\phi_{N+1} - \frac{2K}{\Delta x^2}\phi_N + \frac{K}{\Delta x^2}\phi_{N-1} + \\
&\quad + f(\phi_N) + u(x_N,t)
\end{aligned} \quad (7)$$

By defining the following state vector $x^T = (\phi_1, \phi_2, \cdots, \phi_N)$ one obtains the following state-space description