Feedback Linearization based Arc Length Control for Gas Metal Arc Welding

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Abstract— **In this paper a feedback linearization based arc length controller for gas metal arc welding (GMAW) is described. A nonlinear model describing the dynamic arc length is transformed into a system where nonlinearities can be cancelled by a nonlinear state feedback control part, and thus, leaving only a linear system to be controlled by linear state feedback control. The advantage of using a nonlinear approach as feedback linearization is the ability of this method to cope with nonlinearities and different operating points. However, the model describing the GMAW process is not exact, and therefore, the cancellation of nonlinear terms might give rise to problems with respect to robustness. Robustness of the closed loop system is therefore investigated by simulation.**

I. INTRODUCTION

The gas metal arc welding (GMAW) process is one of the most frequently employed and important welding processes. The process is performed either as an automated robotic process, or as a manual hand-held process. In many applications of the GMAW process high weld quality is of concern, and therefore, it must be considered how such quality is obtained. In GMAW many different aspects contribute to the overall quality of the weld. In this paper one of these aspects are considered, that is, arc length control for spray mode GMAW, where the spray mode GMAW refer to the way the GMAW process is operated. A steady and stable arc is important for the weld quality and this can be obtained using closed loop arc length control. For example, in manual welding it is important to have a controller able to reject disturbances from the operator moving the welding pistol. Basically, for controlling the arc length of the GMAW process the electrode melting rate must be controlled and as the electrode melting rate is a nonlinear process, the arc length controller must be able to handle such nonlinearities.

Arc length control can be performed by a PI control strategy as reported in [8]. Another linear control strategy is reported in [9], in which robustness is also taken into account. In [1], in [5], and in [2] the GMAW process is considered as a MIMO system and nonlinearities are cancelled using an additional feedback signal for each control input. Same approach is used in [3], but in this work sliding mode control is applied for the purpose of robustness. However, in most welding machines used for manual welding only the machine output voltage can be used for controlling the process. Thus, the MIMO approach of [1], [5], [2], and [3] is less suitable for manual welding.

In general linear control methods have the disadvantage that a number of controllers must be tuned to cover a range of operating points, and also, some sort of gain scheduling must be implemented. This is not the case for the controller proposed in this paper. In this paper a feedback linearization based arc length controller is proposed. This nonlinear control method has the advantage that linear system theory can be applied when considering stabilization and performance, as nonlinearities are compensated for. Also, only one controller for all operating points needs to be designed and tuned. The feedback linearization controller proposed in this paper differ from other reported controllers in this area as the GMAW process is considered as a SISO system describing the manual welding process. For the MIMO system mentioned before feedback linearization is particular simple because of the freedom of having two control signals. However, such freedom is not available for the SISO system. Also, in this paper it is assumed that an inner current controller is included in the system.

II. THE GMAW PROCESS

The GMAW process is illustrated in Fig. 1. The welding machine outputs a voltage at the terminals, and thus, establishes an electrical circuit. Basically, the circuit consists of the anode wire, the cathode wire, the electrode, and the arc. The energy produced in the arc and the electrode melts the electrode causing drop growth and drop detachment from the tip of the electrode. The electrode, consumed in this way, is replaced by new electrode material as the electrode is pushed forward by a wire feed system. The energy developed in the arc also melts the workpiece and melted workpiece material and detached liquid metal drops from the electrode form a melting pool. When the melting pool cools down and solidify the weld is complete. During the welding process the arc is protected from the ambient air using some shielding gas, typically, pure argon or a mixed gas of argon and carbon dioxide.

GMAW can be divided into at least 3 modes of operation depending on the current. These modes are the short arc mode, the globular mode, and the spray mode. In the short arc mode the tip of the electrode with the pendant drop is periodically short circuited with the workpiece, causing a sudden increase in current and this release of energy detaches the drop. Typically, the short arc mode can be used up to an average current of around 200 A depending on the electrode material and diameter. In the spray

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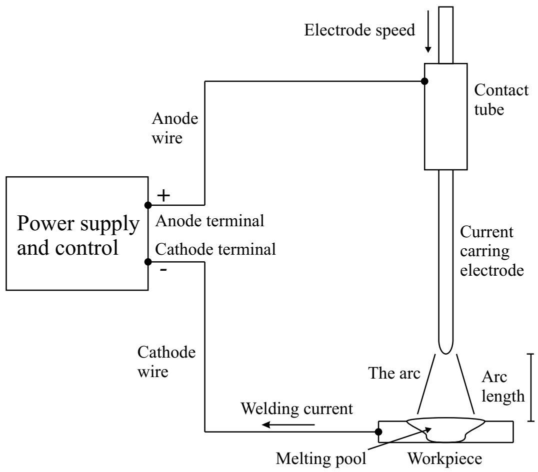

Fig. 1. Illustration of the GMAW process. A consumable electrode is fed by a wire feed system (not shown) through the contact tube (tip). The electrode melts and drops detach and fall into the melting pool.

mode the electrode is ideally never short circuited with the workpiece. In spray mode the current is stronger, typically, a minimum of 250 A, and because of the strong current drops are detached from the electrode without touching the workpiece. The globular mode refers to the region, with respect to current, between the short arc mode and the spray mode. In this mode the size of the drops detaching from the electrode is in general larger and more irregular compared to the drops in the spray mode. Normally, the globular mode produces a poor weld, and thus, this mode is avoided. In this paper arc length control for the spray mode is of concern.

As stated before it is important to be able to control the arc length for stabilization and performance of the process. From a performance point of view, a controlled arc length is important, as disturbances, for example, in the tip to workpiece distance can be rejected. Therefore, in the following sections an arc length model, and afterwards, an arc length controller is developed.

III. DYNAMIC ARC LENGTH MODEL

The GMAW process constitutes an electrical circuit. This circuit is described below in (1). Such model of the electrical circuit can be found in numerous works, as for example [6] or [2]. U_t is the machine terminal voltage, R_w is the wire resistance, L_w is the wire inductance, R_{cc} is the sum of all contact resistances, l_s is the electrode length, ρ_r is the electrode resistivity, and I is the welding current. The function $h(I, l_a)$ describes the arc voltage, and thus, the arc voltage is modelled as some function of the current and the arc length l_a.

$$U_t = R_w I + L_w \dot{I} + R_{cc} I + l_s \rho_r I + h(I, l_a) \quad (1)$$

Equation (1) describes the current dynamics in the GMAW process. However, many welding machines are equipped with an inner current control loop that determines the current dynamics. In this way the machine can be considered as a controlled current source (CCS) rather than a controlled voltage source (CVS). In Fig. 2 the inner current control loop is shown together with the GMAW process and the arc length controller considered in this paper.

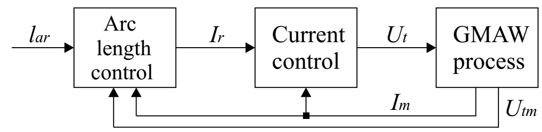

Fig. 2. An inner controller controls the current of the GMAW process. The arc length controller controls the arc length using a current reference, I_r, as control signal. I_m is the measured current and U_{tm} is the measured terminal voltage at the power supply. l_{ar} is the arc length reference.

The inner closed loop dynamics, that is, the inner loop in Fig. 2 can be approximated by a first order system as in (2). τ_i is the time constant for the system and I_r is input, that is, the current reference.

$$\dot{I} = -\frac{1}{\tau_i} I + \frac{1}{\tau_i} I_r \quad (2)$$

The arc length l_a changes with the electrode speed, with the melting speed, and with changes in the contact tip to workpiece distance l_c. Changes in l_c can be considered as disturbances, and thus, with respect to a nominal model such changes are not included. However, if considering performance issues such as disturbance rejection a changing l_c must be considered. Using the melting rate model, as described in [7], a nominal model for the arc length dynamics is reached in (3). Notice that, instead of a melting rate (m^3/s), the melting is expressed as a melting speed (m/s). v_m is the melting speed, v_e is the electrode speed, and k_1 and k_2 are constants.

$$\dot{l}_a = v_m - v_e = k_1 I + k_2 I^2 (l_c - l_a) - v_e \quad (3)$$

Let us use (2) and (3) for setting up a state space description of the arc length process. Let x be a vector containing two states x_1 and x_2, where $x_1 = I$ and $x_2 = l_a$. Moreover, $u = I_r$ is the input and $y = l_a$ is the output. Now, the nonlinear dynamic system can be formulated.

$$\dot{x} = f(x) + g(x)u \quad (4)$$
$$y = h(x) \quad (5)$$

where

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \end{bmatrix} = \begin{bmatrix} -\frac{1}{\tau_i} x_1 \\ k_1 x_1 + k_2 x_1^2 (l_c - x_2) - v_e \end{bmatrix} \quad (6)$$
$$g(x) = \begin{bmatrix} g_1(x) \\ g_2(x) \end{bmatrix} = \begin{bmatrix} \frac{1}{\tau_i} \\ 0 \end{bmatrix} \quad (7)$$
$$h(x) = x_2 \quad (8)$$

In the following this model will be used for developing a feedback linearization based arc length controller.

IV. FEEDBACK LINEARIZATION

The idea in feedback linearization is to use some transformation $z = T(x)$ and apply some feedback control law u that transforms the nonlinear system into a linear system, see [4]. Then, having obtained a linear system ordinary linear control design methods can be applied for stabilization and performance. Given the nonlinear system in (4) and (5), the goal is to find some transformation $z = T(x)$ that transforms the system into the system stated in (9) and (10).

$$\dot{z} = A_c z + B_c \gamma(x)[u - \alpha(x)] \tag{9}$$

$$y = C_c z \tag{10}$$

The terms $\gamma(x)$ and $\alpha(x)$ are functions of the original states, x. The matrices A_c, B_c and C_c are on the control canonical form stated in (11).

$$A_c = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \; B_c = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \; C_c = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{11}$$

Basically, if it is possible to find a transformation that transforms the original nonlinear system into a system on the form stated in (9) and (10), then the system is feedback linearizable. This means that the system can be linearized using the control law stated in (12).

$$u = \alpha(x) + \beta(x)\nu \; , \; \beta(x) = \frac{1}{\gamma(x)} \tag{12}$$

Inserting this control law into (9) gives a linear system having input ν.

$$\dot{z} = A_c z + B_c \nu \tag{13}$$

$$y = C_c z \tag{14}$$

In general it is not trivial (or if possible at all) to find a transformation $T(x)$ that transforms a nonlinear system into the form given in (9) and (10). Also, the nonlinear system might only be partially feedback linearizable, leaving some internal dynamics. However, for some nonlinear systems the system is fully linearizable, and moreover, a transformation can be found using a standard approach, see [4]. In fact, this is the case for the dynamic arc length model derived in the former section.

The relative degree ρ equals the number of derivatives of $h(x)$ before dependence on the input u is obtained. For the dynamic arc length model the relative degree is equal to two, as dependance of u is obtained for the second derivative of $h(x)$. As the system order also equals two the system is fully feedback linearizable. Standard expressions for $\gamma(x)$ and $\alpha(x)$ are stated in (15) and (16).

$$\gamma(x) = L_g L_f^{\rho-1} h(x) \tag{15}$$

$$\alpha(x) = -\frac{1}{\gamma(x)} L_f^{\rho} h(x) \tag{16}$$

L_f and L_g are Lie derivatives with respect to $f(x)$ and $g(x)$, respectively. For example, $L_f h(x) = (\partial h(x)/\partial x) f(x)$. Using $\rho = 2$, and (4) and (5) the functions $\gamma(x)$ and $\alpha(x)$ can be calculated.

$$\gamma(x) = (k_1 + 2k_2 x_1 (l_c x_2)) \frac{1}{\tau_i} \tag{17}$$

$$\alpha(x) = -\frac{1}{\gamma(x)} (\gamma(x) \tau_i f_1 - k_2 x_2 f_2) \tag{18}$$

The transformation $T(x)$ is given by the output equation $h(x)$ and its first derivative.

$$z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} T_1(x) \\ T_2(x) \end{bmatrix} = \begin{bmatrix} h(x) \\ L_f h(x) \end{bmatrix} = \begin{bmatrix} x_2 \\ f_2(x) \end{bmatrix} \tag{19}$$

Now, having found a transformation $T(x)$ and the functions $\gamma(x)$ and $\alpha(x)$ the system stated in (4) and (5) has been transformed into a system having the structure of (9) and (10). In this representation the first state z_1 is the arc length l_a, and the second state z_2 is the derivative of the arc length, that is, $\dot{l}_a$.

V. ARC LENGTH CONTROL

The objective is to control the arc length. This means, the arc length controller must be stable and be able to drive the arc length $l_a = x_2$ towards some reference arc length $l_{ar} = r$.

Now, the idea is to develop a state feedback controller that is able to drive the two states toward some settings. The first state z_1 is the arc length which must be driven towards some reference r. The second state z_2 equals the derivative of the first state, and thus, z_2 must be driven towards the derivative of the reference $\dot{r}$. Therefore, the error dynamics must be considered. First, let us define the error e.

$$e = R - z \; , \; R = \begin{bmatrix} r & \dot{r} \end{bmatrix}^T \tag{20}$$

Now, using (9), describing the system dynamics, the error dynamics can be derived.

$$\dot{e} = A_c e - B_c \gamma(x)[u - \alpha(x)] + B_c \ddot{r} \tag{21}$$

The error dynamics can be feedback linearized using a control law that cancels the nonlinear terms, and then leaves a linear part that can be stabilized by the state feedback $K_c e$, where $K_c = [k_{c1} \; k_{c2}]$.

$$u = \alpha(x) + \beta(x)[K_c e + \ddot{r}] \; , \; \beta(x) = \frac{1}{\gamma(x)} \tag{22}$$

If the control law, stated in (22), is inserted into the error dynamics the following result is obtained.

$$\dot{e} = (A_c - B_c K_c) e \tag{23}$$

So, using (22) for the control law the error dynamics becomes linear, and moreover, the error dynamics is stable if the matrix $(A_c - B_c K_c)$ is stable (Hurwitz). Thus, ensuring stability, and also performance, are a matter of choosing K_c.

However, disturbances and uncertainties might result in a steady state offset in the arc length. For some disturbances and uncertainties an offset can be removed by including integral control in the control law. Therefore, let us introduce a variable σ which is the integral of the arc length error e_1. This dynamics can be added to the dynamics describing the arc length process to obtain an augmented system. Let us define a new state vector $\psi = [e_1 \ e_2 \ \sigma]^T$. Now, the augmented system is given by

$$\dot{\psi} = A_a\psi - B_a\gamma(x)[u - \alpha(x)] + B_a\ddot{r} \tag{24}$$

where

$$A_a = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} , \ B_a = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} , \ C_a = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{25}$$

Again, a control law can be found which linearizes the system, and now $K_a = [k_{a1} \ k_{a2} \ k_{a3}]$.

$$u = \alpha(x) + \beta(x)[K_a\psi + \ddot{r}] \ , \ \beta(x) = \frac{1}{\gamma(x)} \tag{26}$$

Now, the following closed loop dynamics is obtained.

$$\dot{\psi} = (A_a - B_aK_a)\psi \tag{27}$$

So, using (26) for the control law the ψ dynamics becomes linear, and moreover, the ψ dynamics is stable if the matrix $(A_a - B_aK_a)$ is stable. As before, ensuring stability and performance are a matter of choosing K_a. For instance, the feedback vector K_a can be obtained from a pole placement approach, in which, the closed loop is shaped to some prototype design. For example, a Bessel filter which is use in this work. For purpose of simulation in section VI the following feedback vector is used: $K_a = [6.23\text{e+}5, 1.22\text{e+}3, 1.27\text{e+}8]$. In Fig. 3 the arc length control system is shown.

From (26) we see that both the reference r, the first derivative $\dot{r}$, and the second derivative $\ddot{r}$ are needed. As shown in Fig. 3 these signals are provided from a second order system filtering the original reference signal l_{ar}.

The control law in (26) is a state feedback control law. Thus, it is assumed that the states $\psi_1 = e_1 = r - z_1$ and $\psi_2 = e_2 = \dot{r} - z_2$ can be measured. Both z_1 and z_2 depend on the states x_1 and x_2, that is, the current and the arc length. Normally, the current is measured directly in the system by a current sensor (hall sensor), but the arc length is only indirectly measured. The arc length can be estimated using some arc voltage model, $U_a = h(I, l_a)$. Here, the arc

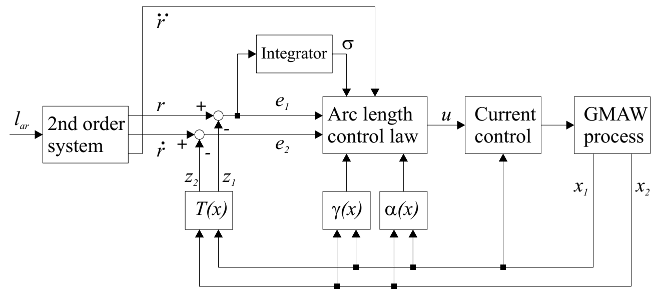

Fig. 3. The control structure. The second order system generates the reference signals. $\alpha(x)$ and $\gamma(x)$ feedback linearizes the system and $T(x)$ transforms the original process states into the z states.

voltage model as stated in (28) is used. Such arc length model is used in numerous works, see for example [2].

$$U_a = U_0 + R_aI + E_al_a \tag{28}$$

U_0 is a constant voltage potential, R_a is the arc resistance, and E_a is a constant describing the relationship between arc length and voltage. However, in most welding systems the arc voltage is not measured, but instead the voltage U_t at the welding machine terminals is measured. The terminal voltage U_t includes voltage drops over the wires, the contact points, the electrode, and the arc. The contact points are the contact point from the anode wire to the electrode in the contact tube, and also, the contact point from the workpiece to the cathode wire, see Fig. 1. The wire current dynamics is very fast as the wire inductance is rather low, and therefore, a steady state expression for U_t can be used.

$$U_t = R_1I + U_a \quad , \quad R_1 = R_w + R_{cc} + \rho_r l_{s0} \tag{29}$$

R_w is the wire resistance, R_{cc} is the sum of all contact resistances, ρ_r is the resistivity of the electrode material, and the constant l_{s0} is some expected or average length of the electrode. Now, using (28) and (29), an arc length estimate, $\hat{x}_2 = \hat{l}_a = \hat{z}_1$, can be found.

$$\hat{l}_a = \hat{x}_2 = \hat{z}_1 = \frac{U_t - R_1I - U_0 - R_aI}{E_a} \tag{30}$$

So, the estimate $\hat{x}_2$ or $\hat{z}_1$ in (30) is used instead of x_2 or z_1 in (26).

VI. MODEL UNCERTAINTY

The feedback linearization controller described in the former section uses a model of the real process to cancel nonlinear terms. However, this model is not exact and therefore robustness should be addressed. Here, robustness of the closed loop system is investigated by simulation.

Fig. 4 shows a simulation of the nominal system with disturbances in the contact tip to workpiece distance l_c. In Fig. 4 the current I, the arc length l_a, and the contact tip to workpiece distance l_c are shown. The reference arc length is set to 3 mm, and bandlimited (20 Hz) noise is

TABLE I
MODEL PARAMETERS

Symbol	Unit	Value	Description
R_w	Ω	0.004	Wire resistance
L_m	H	15e-6	Wire inductance
ρ_r	Ω/m	0.2821	Electrode resistivity (steel)
k_1	$m/(sA)$	3.7e-4	Melting speed constant
k_2	$1/(A^2m)$	6.6e-4	Melting speed constant
r_e	m	5e-4	Electrode radius
U_0	V	15.7	Arc voltage constant
R_a	Ω	0.022	Arc resistance
E_a	V/m	636	Arc length factor
τ_i	s	6.7e-6	Time constant
l_c	m	0.015	Nominal tip to workpiece dist.
v_e	m/s	0.267	Electrode speed.

applied to l_c to simulate disturbances from the hand-held welding pistol. Also, at time $t = 0.5$ s the contact tip to workpiece distance is changed from an average of 15 mm to 10 mm. The parameters used for simulation are shown in Table I, where the melting speed constants are derived from melting rate constants in [6]. Also, values for U_0, R_a, E_a, and ρ_r are obtained from [6]. The other parameters are realistic estimates when considering a real welding process. However, it should be noted that precise values are not of concern in this paper, as the values are only used for enabling numerical simulation.

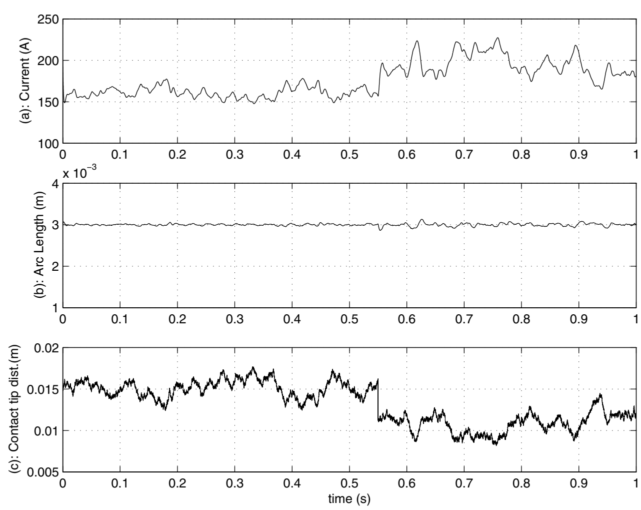

Fig. 4. Simulation of the nominal system. (a) The welding current I. (b) The arc length l_a. (c) The contact tip (tube) to workpiece distance l_c.

In the control law (26) values for $\gamma(x)$, $\alpha(x)$, $T_1(x)$, and $T_2(x)$ must be calculated. These terms depend on uncertain parameters and measurements. For example, $\gamma(x)$ depends on the melting speed coefficients k_1 and k_2, the contact tip to workpiece distance l_c, the current time constant τ_i, the current measurement, and the estimate of the arc length which again depends on the arc length model. Probably, all of these parameters and variables contain some uncertainty and this results in an overall uncertainty in $\gamma(x)$. To investigate uncertainty a number of simulations are performed

TABLE II
MODEL UNCERTAINTY

Fig.	K_γ	K_α	K_{T1}	K_{T2}
5.(a)	5	1	1	1
5.(b)	0.2	1	1	1
5.(c)	1	1.04	1	1
5.(d)	1	0.6	1	1
6.(a)	1	1	2	1
6.(b)	1	1	0.4	1
6.(c)	1	1	1	5
6.(d)	1	1	1	0.2

with perturbed terms $\gamma(x)$, $\alpha(x)$, $T_1(x)$, and $T_2(x)$. In turn, each of the terms are chosen either larger or smaller than the nominal value, while the other terms are held at the nominal value. In Fig. 5 and Fig. 6 the arc length for each simulation is shown. The uncertainties used in each simulation are shown in Table II. In Table II, K_γ, K_α, K_{T1}, and K_{T2} denotes the multiplicative uncertainty used for each term. For example, K_γ is the multiplicative uncertainty on $\gamma(x)$. Moreover, the disturbances in the contact tip to workpiece distance l_c, shown in Fig. 4.(c), are included in the simulations.

From Fig. 5.(a) and 5.(b) it can be seen that despite large perturbations (a factor 5 and a factor 0.2) in $\gamma(x)$ the closed loop system is stable and the disturbances in l_c can be handled. However, as it can be seen in Fig. 5.(c) and 5.(d) perturbations in $\alpha(x)$ affects the closed loop behavior much more. In fact, for a relative small positive perturbation in $\alpha(x)$ (a factor 1.04) the system almost becomes unstable. On the other hand, if $\alpha(x)$ is lowered to 0.6 times the nominal value the ability to handle disturbances is rather low.

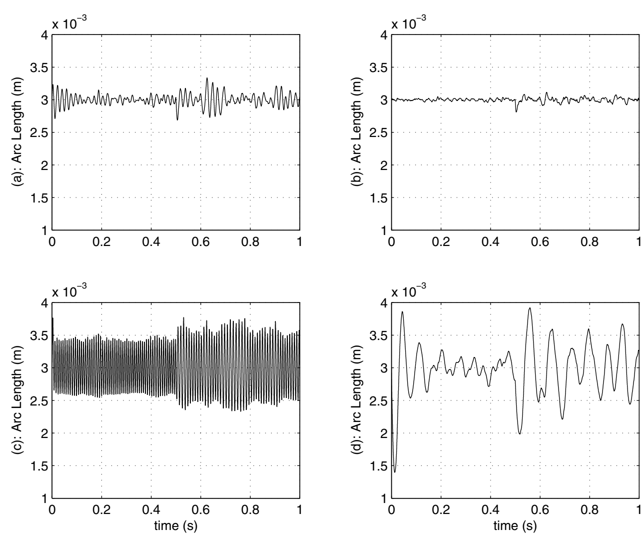

Fig. 5. The arc length for perturbations in $\gamma(x)$ and $\alpha(x)$. (a) Positive perturbation in $\gamma(x)$, (b) negative perturbation in $\gamma(x)$, (c) positive perturbation in $\alpha(x)$, and (d) negative perturbation in $\gamma(x)$.

From Fig. 6.(a) and 6.(b) it can be seen that perturbations (a factor 2 and a factor 0.4) in $T_1(x)$ affects the steady state value of the arc length, but otherwise the closed loop system is stable and disturbances in l_c can be handled. From Fig. 6.(c) and 6.(d) it can be seen that even large perturbations (a factor 5 and a factor 0.2) in $T_2(x)$ can be tolerated, that is, the closed loop system is stable and disturbances can be handled.

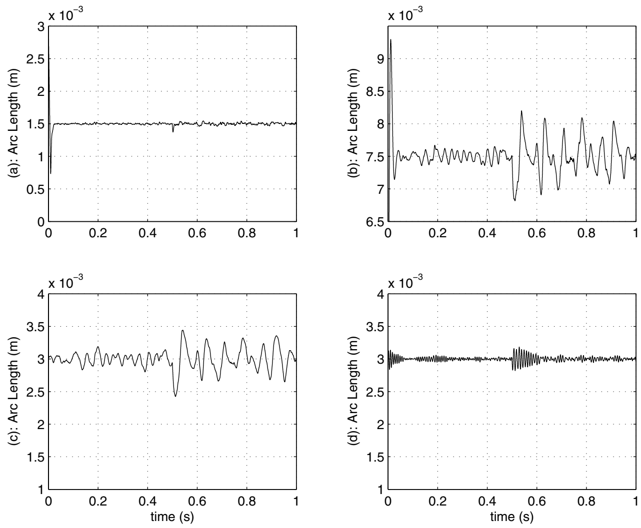

Fig. 6. The arc length for perturbation on $T_1(x)$ and $T_2(x)$. (a) Positive perturbation in $T_1(x)$, (b) negative perturbation in $T_1(x)$, (c) positive perturbation in $T_2(x)$, and (d) negative perturbation in $T_2(x)$.

From the simulations it can be seen that uncertainties in the four terms affect the stability and behavior of the closed loop system. However, some uncertainties have a significant effect on the closed loop system, while some uncertainties have a rather insignificant effect. For $\gamma(x)$ large perturbations can be tolerated, and thus, uncertainty in $\gamma(x)$ only has a small effect on the closed loop system. Uncertainty in $\alpha(x)$, on the other hand, has a significant influence on the closed loop system. If $\alpha(x)$ is a few percent too large the system becomes unstable, and if $\alpha(x)$ is too small the system easily becomes rather slow. However, $\alpha(x)$ does not have to be exact, and it seems that an $\alpha(x)$ around 60% and up to 100% of the real value could be used. Uncertainty in $T_1(x)$ and $T_2(x)$ are less significant than uncertainty in $\alpha(x)$. Especially for $T_2(x)$ large perturbations can be accepted. However, uncertainty in $T_1(x)$ affects the steady state offset on the arc length. Though, in practise such offset could easily be removed by tuning the parameters in $T_1(x)$.

VII. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper a feedback linearization controller has been described with the objective of controlling the arc length of the manual GMAW process. The controller is based on a nonlinear SISO model describing the arc length process.

The nonlinear model is transformed into the so-called normal form. It turns out that the system is fully linearizable, and thus, the whole system can be feedback linearized. In the normal form nonlinearities are cancelled by a nonlinear state feedback control part leaving only a linear system.

The goal of the arc length controller is to keep the arc length at some reference set point, and therefore, the error dynamics is considered. For the error dynamics the closed loop system is stable if a certain matrix is stable.

The advantage of using the feedback linearization controller is the ability to account for the nonlinearities. Also, no operating points need to be selected, and therefore, only one linear controller need to be tuned for all arc length settings and electrode speed (or current) settings.

However, it cannot be expected that the model used is exact. Therefore, robustness of the closed loop system is investigated by simulation. In particular, it is found that $\alpha(x)$ plays a significant role with respect to closed loop stability and performance. Though, an $\alpha(x)$ between 60% and 100% of the real value could be used. Thus, when estimating parameters for $\alpha(x)$ one must ensure that $\alpha(x)$ is rather too low than too high.

The simulation approach does not provide a precise robustness analysis, but rather, it provides information of practical value for the system designer. Also, it provides a fast way to investigate the effect of uncertainties.

B. Future Work

Only a few different uncertainty configurations have been investigated in this work. So in fact, robustness has only been investigated for these cases. To improve the validity of the results a higher number of configurations could be used or one could seek an analytical solution.

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