

Integral Sliding Mode Control for GMAW Systems

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Abstract: Gas metal arc welding (GMAW) process is one of the most popular manufacturing processes in industries such as automotive, aerospace, ship buildings, and boiler. To increase the consistency in welding quality, the automation of the welding process with feedback controllers is inevitable. This paper presents an Integral Sliding Mode (ISM) controller, a robust controller, to control the welding current and arc voltage of a GMAW system. The concept of ISM controller design technique is to combine a discontinuous control with a nominal control to achieve robustness against matched perturbations. The proportional plus integral (PI) and composite nonlinear feedback (CNF) controllers are used as nominal controllers. It is shown in the paper that the CNF controller performs better than PI controller. A linear multi input multi output (MIMO) system model has been considered here for the design. The performance of the controller is analyzed in the presence of model parameter uncertainties and external disturbances and the simulation results are presented and discussed in order to establish a comparison framework.

Keywords: Robust control, Discontinuous control, Disturbance rejection, Proportional plus Integral Control

1. INTRODUCTION

Gas metal arc welding (GMAW) is the most popular industrial welding process today, preferred for its versatility, speed and relative ease of adapting to robotic automation. This process has been used extensively by many industrial environments especially, the automobile industry. The advantages of automated welding process with feedback controllers include increased productivity, consistency in welding quality, as well as health and safety benefits for the welder.

To achieve automation in the welding process a model based control strategy is essential. In practical GMAW process the main controlled variables are the arc voltage and the welding current. In fact, these two variables affect many features of the weld such as weld geometry, metallurgical characteristics, metal transfer mode, residual stresses, weld stability, weld defects and the weld quality as in Anzehae and Haeri (2011).

In a model based control strategy, it is essential to have a mathematical model which will exactly replicate the physical system. Many researchers have worked on the modeling of the GMAW process. A fifth order nonlinear model of a GMAW process has been used by many researchers like Ozcelick et al. (1998), Moore et al. (2003), Thomsen (2005) for the control process.

To enhance the quality of welding, the control objective is to achieve the desired mass and heat values which determines the quality of welding, even in the presence of various types of uncertainties in the GMAW system. One of the approaches to control the quality of the weld is to maintain the set values of welding current and arc voltage to achieve the desired values of heat and mass transfer to the workpiece. A robust controller is then used for the set point tracking, under the assumption that, the contact tip to work piece distance and weld speed are held

constant during the welding process.

In Abdelrahman (1998), a model-based controller design has been proposed based on the feedback linearization where, the linearized system is controlled by PI-controllers with random parameters variation. Its performance however deteriorates in the presence of huge parametric uncertainties. In Moore et al. (1998), the authors have argued that, it is reasonable to approximate the GMAW system by a two-by-two linear multivariable process and it is shown that simple multi-loop, PI control is effective for both the set point tracking as well as disturbance rejection. In their work, the unexpected changes in contact tip to workpiece distance is considered as a disturbance.

A model predictive control (MPC) based on ARMarkov has been designed to control the welding current and arc voltage in a linearized GMAW process in Anzehae and Haeri (2011). Even though the above proposed controller outperforms the PI and feedback linearization based PID with respect to transient response, desired output tracking and robustness against the process parameter uncertainties but, the computational load is enormous.

The GMAW process joins materials through the coalescence of a consumable metal electrode and the workpiece. A wire feed mechanism continually draws the electrode wire from a spool and pushes it through the torch assembly. This wire feed plant is corrupted by a severe torque disturbance which is reported in Green (1990). The welding current changes with the rate of wire feed as a consequence, the arc voltage also changes. The torque disturbance will badly affect the performance of the GMAW system with the generation of spatter and irregular bead forming.

The main motivation behind the proposed work in this paper is to design a robust controller for a GMAW process which will outperform any other existing controller taking into account of

the torque disturbance which has not been considered elsewhere till date.

Sliding mode control is a well accepted technique for the systematic design of robust controllers for complex nonlinear dynamic systems operating under uncertain conditions. To explore the main features of the sliding mode, like its insensitivity to matched disturbances and parameter variations, the system trajectories are steered to the predesigned sliding manifold and then maintained on the manifold thereafter by means of high frequency switching control which is well documented in Utkin (1992), Edwards and Spurgeon (1998).

There has been several approaches till date, using sliding mode control (SMC) algorithms also, to control the arc welding systems as in Kharaajoo et al. (2003), Khatamianfar et al. (2008). The robustness property of the conventional sliding mode control with respect to variations of system parameters and external disturbances can only be achieved after the occurrence of sliding mode. During the reaching phase, however, there is no guarantee for robustness. The Integral sliding mode (ISM) concept which is proposed by Utkin and Shi (1996) seeks to eliminate the reaching phase by enforcing the sliding mode throughout the entire system response. In this concept, it is assumed that there exists a nominal system and a properly designed feedback control for this nominal system, like proportional-integral-plus-derivative (PID) control and its variant, optimal linear quadratic regulator (LQR) and composite nonlinear feedback (CNF) etc. To this nominal controller, a discontinuous term is added to ensure the desired performance despite parametric uncertainties and external disturbances.

The practical systems like GMAW require a fast response without any overshoot. To improve the transient performance as well as the tracking, a CNF can be used as a nominal control. The CNF, a nonlinear control technique was firstly proposed in Lin et al. (1998) for a class of second order linear system with input saturation to improve the performance of the closed loop system. Subsequently, this concept was extended for general higher-order single input single output (SISO) and MIMO systems in He et al. (2005) for the state feedback and output feedback cases.

The focus of the work presented in this paper is the design of ISM controller for a linear approximate model of a GMAW process with external disturbances and model uncertainties satisfying the matching condition. The ISM controllers are first designed with PI as the nominal control and to improve the transient performance as well as tracking, the nominal PI control has been replaced with a CNF controller as a second case. The organization of this paper is as follows; Section 2 reviews the modeling of a GMAW process and discusses the control objective. Section 3 discusses the design of ISM controller for uncertain GMAW system. The design of ISM-PI controller with the simulation results are provided to illustrate the capabilities of controller in section 4. Section 5 discusses the design of the ISM-CNF controller with the simulation results followed by the concluding section.

2. DYNAMIC MODEL OF A GMAW SYSTEM

In this Section, the dynamic model of a GMAW system has been discussed. A schematic representation of the GMAW system with its power source is shown in Fig-1. A constant voltage power supply is fed to the electrode and the workpiece. To get the the desired weld quality, the wire feed speed S , torch travel speed R , open circuit voltage V_{oc} , and contact tip to workpiece distance CT can be adjusted. Here, X is the distance

of the center of mass of the droplet above the workpiece. A

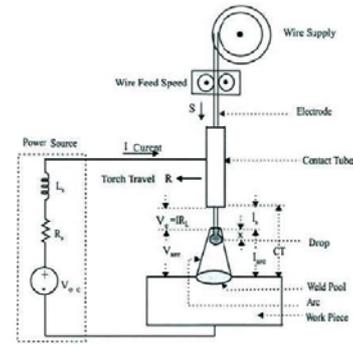


Fig. 1. Schematic diagram of GMAW process

fifth-order nonlinear model describing the total GMAW process which has been introduced in Moore et al. (2003). But, here we are considering the dynamics of the DC motor also, which is used for the electrode wire feeder to the welding pool, so as to improve the performance of the existing model as in Anzehae and Haeri (2011). The complete dynamics of the system with the DC motor dynamics can be represented by considering the following state variables

- $X_1(t) = x(t)$: droplet displacement (m);
- $X_2(t) = \dot{x}(t)$: droplet velocity (m/sec);
- $X_3(t) = m_d$: droplet mass (kg);
- $X_4(t) = l_s$: stick-out (m);
- $X_5(t) = I$: welding current (A)
- $X_6(t) = S$: welding wire speed (m/sec)

Considering the stick-out (l_s), welding current (I), welding wire speed (S) as the dominant states, the original sixth order nonlinear representation of the GMAW process is approximated by the following third order MIMO nonlinear model, with the dominant state X_4, X_5 and X_6 .

$$\begin{aligned}\dot{X}_4(t) &= X_6(t) - \frac{M_R}{\pi r_w^2} \\ \dot{X}_5(t) &= \frac{U_2(t) - (R_a + R_s + R_L)X_5(t)}{L_s} \\ &\quad - \frac{V_o + E_a(CT - X_4(t))}{L_s} \\ \dot{X}_6(t) &= \frac{1}{\tau_m}(K_m U_1(t) - X_6(t))\end{aligned}\quad (1)$$

The control variables are

- $U_1(t) = V_{arm}$: DC motor armature voltage(V),
- $U_2(t) = V_{oc}$: open-circuit voltage (V)

The output variables are,

$$\begin{aligned}Y_1(t) &= V_{arc} = V_o + R_a X_5(t) + E_a(CT - X_4(t)) \\ Y_2(t) &= X_5(t)\end{aligned}\quad (2)$$

where Y_1 and Y_2 are the arc voltage and current respectively. In the state equations R_a and R_s are the arc resistance and source resistance respectively. r_w is the electrode radius, V_o is the arc voltage constant, E_a is the arc length factor, and L_s is the source inductance. τ_m , k_m are the motor time constant and motor steady state gain respectively. Melting rate M_R and the electrode resistance R_L are given by

$$M_R = C_2 \rho X_4(t) X_5^2(t) + C_1 X_5(t) \quad (3)$$

$$R_L = \rho \left[X_4(t) + \frac{1}{2} \left(\left(\frac{3X_3(t)}{4\pi\rho_w} \right)^{1/3} + X_1(t) \right) \right] \quad (4)$$

where C_1 and C_2 are the melting rate constants, ρ is the resistivity in ohm/m of the electrode. The droplet radius r_d is defined by $r_d = \left(\frac{3X_3(t)}{4\pi\rho_w}\right)^{1/3}$ where ρ_w is the electrode density. The above third order MIMO nonlinear model is valid under the assumption that the stick-out distance ($l_s = X_4$) is much larger than the sum of the droplet radius r_d and the drop displacement X_1 , it can be written as

$$X_4 \gg \left[\frac{1}{2} \left(\left(\frac{3X_3(t)}{4\pi\rho_w} \right)^{1/3} + X_1(t) \right) \right]$$

which simplifies R_L to

$$R_L = \rho X_4(t) + \rho \left[\frac{1}{2} \left(\left(\frac{3X_3(t)}{4\pi\rho_w} \right)^{1/3} + X_1(t) \right) \right] \cong \rho X_4(t)$$

The approximate nonlinear model is linearized about an operating point to obtain the linearized model of the GMAW system. The operating point chosen here are at an arc voltage of 25V and at a welding current of 250A by considering that the GMAW process works in globular-spray melted droplets transfer mode. The state space representation of the linearized model is,

$$\dot{x} = \bar{A}x + \bar{B}\bar{u}, \quad y = \bar{C}x \quad (5)$$

where, $x = \begin{bmatrix} x_4 \\ x_5 \\ x_6 \end{bmatrix} = \begin{bmatrix} \delta l_s \\ i \\ s \end{bmatrix}$, $\bar{u} = \begin{bmatrix} \bar{u}_1 \\ \bar{u}_2 \end{bmatrix} = \begin{bmatrix} v_{arm} \\ v_{oc} \end{bmatrix}$ and $y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} v_{arc} \\ i \end{bmatrix}$

x_4, x_5 and x_6 represent the linearized variables of X_4, X_5 and X_6 respectively. The linearized model matrices are,

$$\bar{A} = \begin{bmatrix} \frac{-C_2\rho}{\pi r_d^2} \bar{X}_5^2 & -\frac{C_1+2C_2\rho\bar{X}_4\bar{X}_5}{\pi r_d^2} & 1 \\ L_s^{-1}(E_a - \rho\bar{X}_5) & -L_s^{-1}(R_a + R_s + \rho\bar{X}_4) & 0 \\ 0 & 0 & -\tau_m^{-1} \end{bmatrix} \quad (6)$$

$$\bar{B} = \begin{bmatrix} 0 & 0 \\ 0 & L_s^{-1} \\ -k_m\tau_m^{-1} & 0 \end{bmatrix} \text{ and } \bar{C} = \begin{bmatrix} -E_a & R_a & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$\delta l_s, s, i, v_{arm}, v_{arc}$ and v_{oc} represent the respective linearized variables. \bar{X}_4, \bar{X}_5 are stick out and welding current at the operating point, mentioned above. y_1 and y_2 are the outputs, \bar{u}_1 and \bar{u}_2 are the inputs of the linearized model.

In practical scenarios, a GMAW system is affected by disturbances. The conventional wire feed mechanism of a GMAW system is shown in Fig-2. A DC motor is used to drive a set of spring-loaded pinch rollers through a reduction gearbox which pulls the electrode wire from a large spool, through a series of guides, and down to the torch head for consumption in the welding process. There is a large constant load due to the stiffness of the wire and the friction of the guides, rollers, and bearing. In addition, mechanical imperfections in the pinch roller assembly cause an eccentricity that gives rise to an approximately sinusoidal term. So the external disturbance which is the total torque disturbance can enter through the input channel u_1 which is modeled by Green (1990) $f(t) = f_1 + f_2 \sin(2\pi f_D t)$, where f_1, f_2 are constants and f_D is the frequency of the sinusoidal component which is proportional to the wire feed rate.

With this external disturbance and plant uncertainties, the GMAW system can be represented as

$$\begin{aligned} \dot{x} &= \bar{A}x(t) + (\bar{B} + \Delta\bar{B})u(x,t) + Df(t) \\ y &= \bar{C}x \end{aligned} \quad (7)$$

where $\Delta\bar{B}$ is the uncertainty of the input matrix and $D = [0 \ 0 \ 1]^T$ is disturbance matrix.

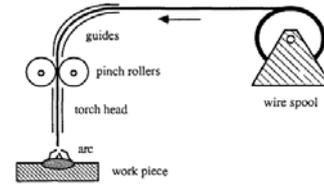


Fig. 2. Schematic diagram of wire feed mechanism of the GMAW process

3. THE ISM CONTROLLER FOR GMAW SYSTEM

In this section, ISM controllers are designed for a GMAW system (7). The dynamic model of the GMAW system in (5) is considered as a nominal system and to maintain the set values of welding current and arc voltage, the PI controllers are designed as nominal controllers. Once the system is subjected to external bounded disturbances and model uncertainties, it is natural to try with an auxiliary controller to compensate such disturbances retaining the effect of the nominal controller designed for the unperturbed system or the nominal system. Here, the ISM controller is designed as the auxiliary controller compensating the disturbances from the very beginning of the control action. The block diagram shown in Fig-3 represents the closed loop system with the ISM controllers.

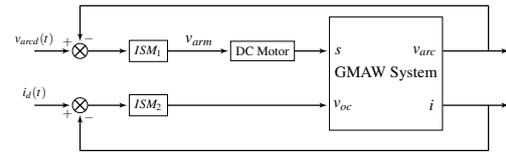


Fig. 3. Block diagram of the GMAW control system based on ISM controllers

3.1 Review of ISM Controller

Consider a linear system

$$\dot{x} = Ax(t) + (B + \Delta B)u(x,t) + \phi(x,t), \quad x(t_0) = x_0 \quad (8)$$

where $x \in \mathbb{R}^n$ is state vector; $u(x,t) \in \mathbb{R}^m$ is a vector of control inputs; $A \in \mathbb{R}^{n \times n}$ and $B \in \mathbb{R}^{n \times m}$ are known matrices. $\Delta B \in \mathbb{R}^{n \times m}$ and $\phi(x,t) \in \mathbb{R}^n$ represent the uncertainties affecting the system, due to parameter variations, unmodelled dynamics and/or exogenous disturbances. In order to design the controller it is assumed that, the pair (A, B) is stabilizable, the disturbance $\phi(x,t)$ is matched and the actual values of $\phi(x,t)$ and ΔB are unknown, but their Euclidean norms are bounded by the known values. It can be noticed that these assumptions are fairly reasonable and typical in almost any control problem.

In the ISM control approach, a control law of the form

$$u_{ISM}(x,t) = u_0(x,t) + u_1(x,t) \quad (9)$$

where $u_0(x,t)$ and $u_1(x,t)$ are the continuous nominal control and discontinuous control action respectively.

The continuous nominal control $u_0(x,t)$ is responsible for stabilization or tracking of the nominal system

$$\dot{x} = Ax(t) + Bu_0(x,t), \quad x(t_0) = x_0 \quad (10)$$

i.e. without uncertainties ($\Delta B = 0$ and $\phi(x,t) = 0$).

In (9) the $u_1(x,t)$ is the discontinuous control action that rejects the perturbations satisfying the matching condition by ensuring the sliding motion. So the state trajectories should be on the

sliding manifold from the beginning under the influence of persistent disturbances. To ensure this, the discontinuous control $u_1(x, t)$ is usually selected as

$$u_1(x, t) = -\rho(x, t) \frac{(GB)^T s(x, t)}{\|(GB)^T s(x, t)\|} \quad (11)$$

where $\rho(x, t)$ is sufficiently a high gain which makes the sliding manifold $s(x, t)$ attractive.

The sliding manifold is defined by the set $\{x \mid s(x, t) = 0\}$ with

$$s(x, t) = G \left[x(t) - x_0 - \int_{t_0}^t (Ax(\tau) + Bu_0(x, \tau)) d\tau \right] \quad (12)$$

where the projection matrix $G \in \mathbb{R}^{m \times n}$ is chosen such that GB is invertible. The term $x_0 + \int_{t_0}^t (Ax(\tau) + Bu_0(x, \tau)) d\tau$ in (12) can be thought as a trajectory of the system in the absence of perturbations with the nominal control u_0 , which is, as a nominal trajectory for a given initial condition x_0 . With this concept, $s(x, t)$ can be considered as a penalizing factor of the difference between the actual and nominal trajectories, projected along G . At $t = t_0$, $s(x, t) = 0$, so the system always starts at the sliding manifold. The state trajectories, therefore, should be on the sliding manifold from the beginning under the influence of persistent disturbances. To ensure this, the η -reachability condition $s^T \dot{s} \leq -\eta |s|$ must be satisfied by the control law in (11).

4. DESIGN OF ISM-PI CONTROLLER

This section discusses the design of ISM-PI control for an uncertain GMAW system (7) which will maintain the set values of welding current and arc voltage. The third order linear model of an uncertain GMAW with bounded parametric uncertainties and external disturbances are considered here for the control law development.

The controller structure will be

$$\begin{bmatrix} v_{arm} \\ v_{oc} \end{bmatrix} = \begin{bmatrix} U_{ISM_1}(x, t) \\ U_{ISM_2}(x, t) \end{bmatrix} = \begin{bmatrix} u_{10}(x, t) \\ u_{20}(x, t) \end{bmatrix} + \begin{bmatrix} u_{11}(x, t) \\ u_{21}(x, t) \end{bmatrix} \quad (13)$$

where $u_{10}(t)$, $u_{20}(t)$ are the nominal control which are the PI controllers and $u_{11}(t)$, $u_{21}(t)$ are the discontinuous part of the ISM-PI control for uncertain GMAW system. The armature voltage (v_{arm}) of the motor and the open circuit voltage (v_{oc}) are chosen as manipulated variables to control the set values of arc voltage (v_{arc}) and welding current (i) respectively.

4.1 Design of PI Controller as a nominal control

The PID controllers are widely used in industrial control systems because of the reduced number of parameters to be tuned. The emerging features of automatic tuning methods have greatly simplified the use of PID control.

In this work the PI controller is designed as a nominal control based on the method discussed in Moore et al. (1998), Moore et al. (2003), Anzehae and Haeri (2011) by considering the nominal GMAW system with $\Delta \bar{B} = 0$ $f(t) = 0$ in (7).

The structure of the PI controllers are as follows

$$\begin{bmatrix} u_{10}(t) \\ u_{20}(t) \end{bmatrix} = \begin{bmatrix} K_{p_1} e_1(t) + K_{I_1} \int_0^t e_1(\tau) d\tau \\ K_{p_2} e_2(t) + K_{I_2} \int_0^t e_2(\tau) d\tau \end{bmatrix} \quad (14)$$

where $e_1(t) = v_{arcd}(t) - v_{arc}(t)$ and $e_2(t) = i_d(t) - i(t)$. $v_{arcd}(t)$ and $i_d(t)$ are the reference set point values of arc voltage and welding current respectively. The parameters K_{P_i} and K_{I_i} are the controllers proportional and integral term constants respectively and the values of the control parameters have been determined based on the Ziegler Nichols method.

4.2 The Design of Discontinuous Controller

A discontinues part of control law in (13) is designed based on the ISM for rejecting the model uncertainties and external disturbances, which is then added to the existing PI control action. The model uncertainties and external disturbances which are considered here are matched because $rank(\bar{B}) = rank(\bar{B}|D) = 2$. In this work the projection matrix G is selected as $G = \bar{B}^T$. The selection of $G = \bar{B}^T$ has an advantage that, the discontinuous control is simplified to

$$u_{i1}(x, t) = -\rho_i \frac{s_i(x, t)}{\|s_i(x, t)\|} \quad i = 1, 2 \quad (15)$$

where ρ_1 , ρ_2 are the designed parameters and the sliding surfaces $s_i(x, t)$ are designed as

$$s_i(x, t) = \bar{B}^T \left[x(t) - x_0 - \int_0^t (\bar{A}x(\tau) + \bar{B}u_{i0}(x, \tau)) d\tau \right] \quad (16)$$

4.3 Simulation Result

This section discusses the simulation results of an GMAW system with parametric uncertainties and external disturbance using ISM-PI controller. The parameter values are chosen for the simulation study of the GMAW system as referred in Anzehae and Haeri (2011).

The control objective here is to track the reference set point values of arc voltage and welding current, which are chosen to be square waves with $\pm 0.5V$ and $\pm 10A$ amplitudes respectively around their corresponding operating points 25V and 250A. Here for tracking, the nominal controllers which are the PI controllers are designed based on (14). Fig. 4 and Fig. 5 illustrate the variation of the arc voltage and welding current of the nominal GMAW system using the designed PI controllers. Here the initial time of the simulation results are mostly affected by the initial states and the controller's effects appear mainly after one second. Therefore, this period of the simulations are not shown in the figures. The controller parameters are chosen as $K_{p_1} = -0.32$, $K_{I_1} = -0.12s^{-1}$, $K_{p_2} = 0.01VA^{-1}$, $K_{I_2} = 1VA^{-1}s^{-1}$. The simulation results show as shown in Fig. 4 and Fig. 5 that the simple multi-loop PI controllers are effective for the set point tracking. Now with the external disturbance $f(t) = 3.27 + 0.35 \sin(2\pi t)$ and with a 30% variation of the input matrix which is a parametric uncertainty, the performance of the PI controller deteriorates which is clear from the Fig. 6 and Fig. 7. To retain the performance of the PI controllers in the presence of disturbances, the ISM controller is designed with gains $\rho_1 = -4$ and $\rho_2 = -12$. It has been observed from Fig. 8 and Fig. 9 that the outputs of the system with such parametric variations and external disturbances, could retain the performance of the nominal controller, which proves the effectiveness of the ISM controller.

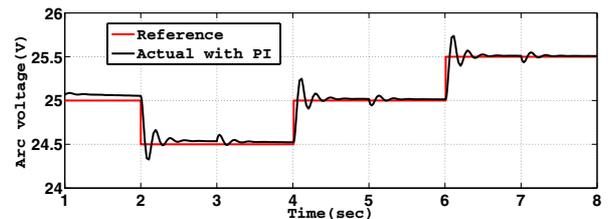


Fig. 4. Tracking of the arc voltage with PI controller for nominal system

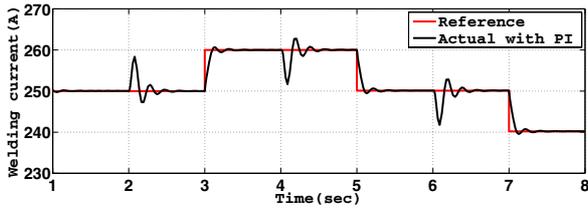


Fig. 5. Tracking of the welding current with PI controller for nominal system

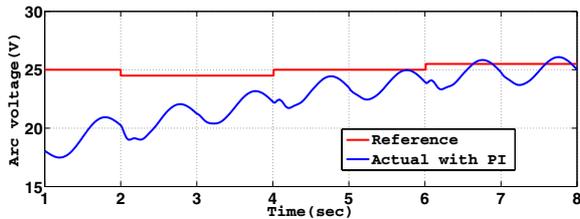


Fig. 6. Tracking of the arc voltage with PI controller for perturbed system

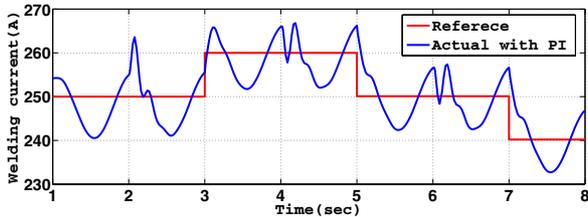


Fig. 7. Tracking of the welding current with PI controller for perturbed system

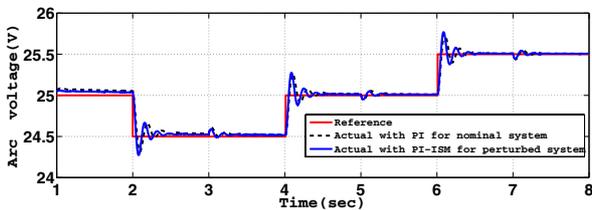


Fig. 8. Tracking of the arc voltage with ISM-PI controller for perturbed system

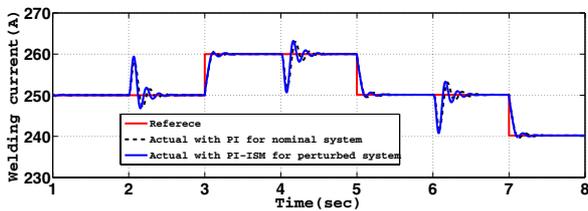


Fig. 9. Tracking of the welding current with ISM-PI controller for perturbed system

5. DESIGN OF ISM-CNF CONTROLLER

The objective of this section is to design a CNF controller as a nominal control for a GMAW system such that the closed loop system has perfect transient response and improved tracking performance with actuator saturation compared to the PI controller. The controller proposed in Bandyopadhyay et al. (2008) and Bandyopadhyay et al. (2009), combines the advantages of

CNF controller for better transient response and robustness of ISM controller which is made use in this present work also. The ISM-CNF based controller retains the actual performance of CNF controller while rejecting disturbances.

5.1 Design of CNF controller as nominal control

The CNF control law composed of a linear feedback part and a nonlinear feedback part which is in the form of

$$u_{CNF} = u_L + u_N \quad (17)$$

Initially, linear feedback part (u_L) keeps damping ratio to a low value to ensure the quick response by minimizing the rising time. The nonlinear part (u_N) is designed to increase the damping ratio to avoid overshoot when the output approaches to the set point.

Consider a linear multivariable system with an amplitude-constrained actuator

$$\dot{x} = Ax + Bs \text{sat}(u); \quad y = Cx \quad (18)$$

where $x \in \mathbb{R}^n$ is the state, $u \in \mathbb{R}^m$ the control input, $y \in \mathbb{R}^p$ the controlled output. The saturation function is defined by

$$\text{sat}(u) = [\text{sat}(u_1) \quad \text{sat}(u_2) \quad \dots \quad \text{sat}(u_m)]^T$$

$$\text{sat}(u_i) = \text{sign}(u_i) \min(|u_i|, u_{max_i}) \quad (19)$$

where u_{max_i} is the maximum amplitude of the i^{th} control channel. To design a state feedback CNF control law, it is assumed that the pair (A,B) is controllable and the system triple (A,B,C) is right invertible and has no invariant zeros at $s = 0$.

A state feedback CNF control law can be realized by the step-by-step design procedure which is discussed in detail in He et al. (2005).

The CNF controller is formed by combining the linear and nonlinear feedback laws

$$u_{CNF} = u_L + u_N = Fx + Gr + \Psi(r,y)B^T P(x - x_e) \quad (20)$$

where $r \in \mathbb{R}^l$ contains a set of step references. The state feedback gain matrix $F \in \mathbb{R}^{m \times n}$ is chosen such that $A + BF$ is asymptotically stable and the resulting closed loop system should have small dominating damping ratio in each channel. G is an $m \times l$ constant matrix and defined by $G := G_0^T (G_0 G_0^T)^{-1}$ with $G_0 = -C(A + BF)^{-1}B$. The x_e is defined as $x_e := -(A + BF)^{-1}BGr$ and given a positive definite matrix $W \in \mathbb{R}^{n \times n}$, P is the solution of the following Lyapunov equation

$$(A + BF)^T P + P(A + BF) = -W \quad (21)$$

and $\Psi_i = \Psi_i(r,y)$, $i = 1, 2, \dots, m$ are respectively some nonpositive function locally Lipschitz in y , which is used to change the damping ratio of the closed loop system as the output approaches the step command input.

It should be noted that the choice of $\Psi(r,y)$ is not unique and a possible choice is as follows

$$\Psi(r,y)_i = -\beta_i e^{-\alpha_i |y_i - r_i|}, \quad i = 1, 2, \dots, m \quad (22)$$

where α_i and β_i are the tuning parameters. The detailed proof of the asymptotic stability of the system (18) with the CNF control law (20) has been shown in He et al. (2005). The range of magnitudes of the step functions in r that can be tracked by such a control law without exceeding the control limit has also been discussed in He et al. (2005).

The u_{CNF} is the continuous nominal control in the ISM control law (9). Now as a part of ISM controller, the discontinuous controller is designed as in the same manner as explained in section 4. It acts as an auxiliary controller compensating

the disturbances retaining the effect of the nominal controller designed for the unperturbed system or the nominal system.

5.2 Simulation Result

We have considered the two-input two-output nominal GMAW system (5) to design the CNF controllers. The control objective is exactly the same as discussed in section 4. The saturation limit of both the control channels are given by $\bar{u}_1 = 24V$ and $\bar{u}_2 = 40V$ respectively. From the Fig. 8 and Fig. 9 where,

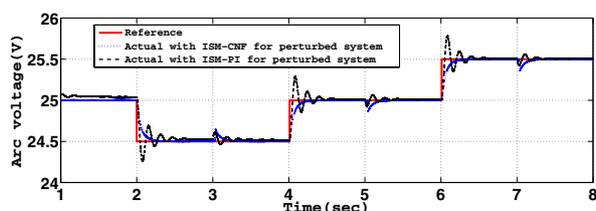


Fig. 10. Tracking of the Arc voltage with ISM-PI and ISM-CNF controllers for the perturbed system

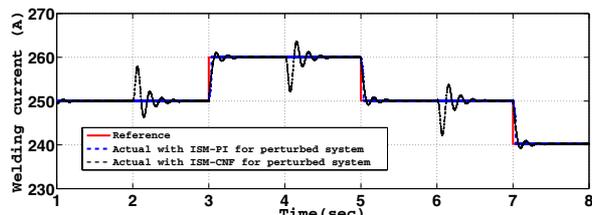


Fig. 11. Tracking of the welding current with ISM-PI and ISM-CNF controller for the perturbed system

the PI has been used as the nominal control, it is clear that the transient response is not satisfactory due to the relatively high overshoot and slow settling time. In order to improve the tracking performance, the CNF controllers are designed here with the motivation of improving the transient performance with no overshoot and better setting time, with perfect tracking of the output signals.

The structure of the CNF controller is given in (20) where F , G are calculated according to design procedure stated in section 5.1 and P is the solution of the Lyapunov equation (21) with $W = I_{2 \times 2}$ and $\Psi(r, y) = \text{diag}\{\Psi_1(r, y) \quad \Psi_2(r, y)\}$ where $\Psi_1(r, y) = -3e^{-30|y_1 - r_1|}$ and $\Psi_2(r, y) = -2e^{-20|y_2 - r_2|}$.

From Fig. 10 and Fig. 11 it is clear that the transient response and tracking performance is dramatically improved with ISM-CNF controller. Table 1 shows the percentage of overshoot (PO) and settling time (t_s) (based on 2% band) of the arc voltage and welding current for an ISM-PI controller as well as ISM-CNF controller. The table indicates that the performance indices chosen are better for an ISM-CNF controller.

Table 1. Transient response characteristics for the ISM-PI and ISM-CNF controllers

Output	Performance Indices	Controller	
		ISM-PI	ISM-CNF
Voltage	PO	52	0
	t_s	0.3819	0.19
Current	PO	69	0
	t_s	0.4671	0.0870

6. CONCLUSIONS

In this work the control of a GMAW system which is the most popular industrial welding process today, preferred for its versatility, speed and relative ease of adapting to robotic automation is addressed. Here, ISM controllers are designed which will ensure the performance of PI and CNF controllers even in the presence of external disturbance and parametric uncertainties for the tracking of reference trajectories of the arc voltage and the welding current for GMAW system. The CNF controllers outperform the PI controllers with respect to transient response and desired output tracking. The simulation results proves the effectiveness of the proposed method.

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