Seam Tracking Control of Welding Robotic Manipulators Based on Adaptive Chattering-free Sliding-mode Control Technology

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Keywords: Seam Tracking Control, Chattering-free, Adaptive Sliding-mode Control (ASMC), Welding Robotic Manipulator, Large-scale Structure Component.

Abstract: A novel adaptive sliding mode control (ASMC) algorithm is derived to deal with seam tracking control problem of welding robotic manipulator, during the process of large-scale structure component welding. The controllers robustness is verified by the Lyapunov stability theory, and the analytical results show that the proposed algorithm enables better high-precision tracking performance with chattering-free than classic sliding mode control (SMC) algorithm.

1 INTRODUCTION

Large-scale structure component holds a large proportion in the large engineering machinery, with a very high importance. As main bearing component, its connection mode is mainly composed of welding parts. Therefore, the welding quality directly affects the performance of the large-scale structure component, to some extent, determines the overall quality of the engineering machinery product itself, and the cost of the production.

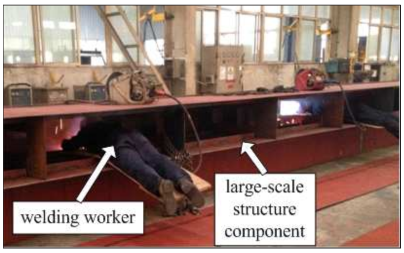

Figure 1: Manual welding is still dominated and adopted (Provided by Weihua Group in Henan, China).

Unfortunately, manual welding is still dominated and adopted in the manufacturing of the large-scale structure component, as shown in Figure 1 above. Currently, welding robotic automation improves the welding quality, increases productivity and sets men free from unhealthy, monotonous and poor working conditions in industrial areas, as illustrated in Figure 2.

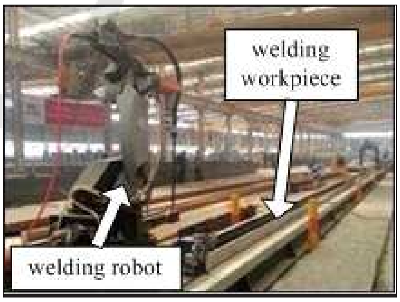

Figure 2: Welding robot in crane welding production line (Provided by Nucleon (Xinxiang) Crane Co., Ltd in Henan, China).

However, due to its main characteristic is big size and large tonnage, it leads to difficulties in the process of robotic welding. For example, the beam of large crane is about 100 meters long. And the large-scale structure component has diverse forms of weld seams, such as flat, vertical and horizontal, which would form welding residual deformation, such as flexural deformation, distortion, waves of panel, etc. In general, the robotic welding process of large-scale structure component in the large engineering machinery is more difficult, and needs higher technical requirements than in the general structure component.

In order to overcome or restrain various uncertain influences, caused by the large-scale structure components weld seam, on welding quality, it is promising to develop and improve intelligent technologies for welding robots (Chen and Lv, 2014). Among these

Hu Y., Liu J., Wu B. and Ge M..
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DOI: 10.5220/0005055104170420
In *Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics* (ICINCO-2014), pages 417-420
ISBN: 978-989-758-040-6

intelligent technologies, tracking control of robotic manipulators has a great of attention. Tracking control is needed to make each joint track a desired trajectory as close as possible. Many control algorithm such as computer torque method (Craig, 1989), optimal control (Ruderman, 2014), adaptive control (Slotine and Li, 1987), variable structure control (VSC) (Cao and Ren, 2012), neural networks (NNs) (Yan and Wang, 2012) and fuzzy system (Cruz and Morris, 2006) have been proposed to deal with this robotic control problem. However, robotic manipulators are highly nonlinear, highly time-varying and highly coupled. Moreover, there always exists uncertainty in the system model such as external disturbance, parameter uncertainty, sensor errors and so on, which cause unstable performance of the robotic system (Guo and Woo, 2003).

In this paper, a novel adaptive sliding mode control (ASMC) algorithm is derived to deal with seam tracking control problem of welding robotic manipulator, during the process of large-scale structure component welding. Its well known that classic sliding mode control (SMC) will cause chattering, which is a crucial disadvantage to the stability of the system, making the controller designing become extremely troublesome. The controllers robustness is verified by the Lyapunov stability theory, and the analytical results show that the proposed algorithm enables better high-precision tracking performance with chattering-free than classic SMC.

The layout of the paper is as follows. Section 2 presents the dynamic model of welding robotic manipulator, and some relevant properties are discussed. In Section 3, a novel adaptive sliding mode controller is developed and analyzed for the tracking control of welding robotic manipulators. Simulation examples are given to demonstrate the performance of the proposed controller in Section 4. Finally, we offer brief conclusions and suggestion for further research.

2 DYNAMIC MODEL OF WELDING ROBOTIC MANIPULATORS

In general, the dynamic model of the 3-link welding robotic manipulator is given as follows

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)+d(t)=u, \tag{1}$$

where $M(q)=M^T(q)\in R^{3\times 3}$ is the symmetric positive definite inertia matrix; $q\in R^3$ denotes the joint position vector; $C(q,\dot{q})\in R^{3\times 3}$ is the Coriolis and centrifugal torques; $g(q)\in R^3$ is the vector of gravitational torques; $d(t)\in R^3$ denotes the bounded disturbance; and $u\in R^3$ represents the torque input vector.

Several fundamental properties of the robot model (1) can be obtained as follows.

Property 1. *The matrix $\dot{M}(q)-2C(q,\dot{q})$ is skew symmetric matrix, i.e.*,

$$x^T\left(\dot{M}(q)-2C(q,\dot{q})\right)x=0,\ \forall x\in R^3.$$

Property 2. *For arbitrary $x,\ y\in R^3$, we get that*

$$M(q)x+C(q,\dot{q})y+G(q)=Y(q,\dot{q},x,y)\theta,$$

where $Y(q,\dot{q},x,y)$ denotes the regression matrix, θ is the constant unknown parameter vector.

Property 3. *The unknown disturbance $d(t)$ is assumed to be unknown, but bounded, i.e.*, $\|d(t)\|<\eta$.

3 CONTROLLER DESIGN

3.1 Adaptive Sliding Mode Controller

The objective of designed controller is to drive the joint position q to the desired trajectory position q_d. First we define the tracking error as following:

$$\tilde{q}=q-q_d. \tag{2}$$

Let the sliding surface

$$s=\dot{\tilde{q}}+\beta\tilde{q}, \tag{3}$$

where $\beta=diag[\beta_1,\beta_2,\beta_3]$ in which β_i is a positive constant.

The objective of controller can be achieved by choosing the control input u, so that the sliding surface satisfies the sufficient condition (Slotine and Li, 1989; Slotine and Li, 1991). Let the reference state

$$\dot{q}_r=\dot{q}-s=\dot{q}_d-\beta\tilde{q}, \tag{4}$$

and

$$\ddot{q}_r=\ddot{q}-\dot{s}=\ddot{q}_d-\beta\dot{\tilde{q}}. \tag{5}$$

Then the control law u is designed as

$$u=\hat{M}(q)\ddot{q}_r+\hat{C}(q,\dot{q})\dot{q}_r+\hat{g}(q)-K_r\mathrm{sgn}(s)^{\alpha}, \tag{6}$$

where $\hat{M}(q)$, $\hat{C}(q,\dot{q})$ and $\hat{g}(q)$ are the estimations of $M(q)$, $C(q,\dot{q})$ and $g(q)$ respectively; $K_r=diag[K_{r11},K_{r22},K_{r33}]$ is a diagonal positive definite matrix; $\mathrm{sgn}(s)^{\alpha}$ is defined as

$$\mathrm{sgn}(x)^{\alpha}=\left[|x_1|^{\alpha}sign(x_1),|x_2|^{\alpha}sign(x_2),|x_3|^{\alpha}sign(x_3)\right]^T, \tag{7}$$

and $x\in R^3$, $0<\alpha<1$.

Then combining system (1) with the control law (6), we can conclude

$$[\hat{M}(q)-\tilde{M}(q)](\dot{s}+\ddot{q}_r)+[\hat{C}(q,\dot{q})-\tilde{C}(q,\dot{q})](s+\dot{q}_r)+\hat{g}(q)-\tilde{g}(q)+d(t)=\hat{M}(q)\ddot{q}_r+\hat{C}(q,\dot{q})\dot{q}_r+\hat{g}(q)-K_r\mathrm{sgn}(s)^{\alpha}, \tag{8}$$

where $\tilde{M}(q)=\hat{M}(q)-M(q)$, $\tilde{C}(q)=\hat{C}(q)-C(q)$ and $\tilde{g}(q)=\hat{g}(q)-g(q)$. Thus system (8) becomes

$$M(q)\dot{s}+C(q,\dot{q})s+d(t)=\tilde{M}(q)\ddot{q}_r+\tilde{C}(q,\dot{q})\dot{q}_r+\tilde{g}(q)-K_r\mathrm{sgn}(s)^{\alpha}. \tag{9}$$

By using property 2, since the matrixes $M(q)$, $C(q,\dot{q})$ and $g(q)$ are linear in terms of the manipulator parameters, system (9) can be written as

$$\tilde{M}(q)\ddot{q}_r+\tilde{C}(q,\dot{q})\dot{q}_r+\tilde{G}(q)=Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\hat{\theta}, \tag{10}$$

and therefore

$$M(q)\dot{s}+C(q,\dot{q})s+d(t)=Y(q,\dot{q},\dot{q}_r,\ddot{q}_r)\tilde{\theta}-K_r\mathrm{sgn}(s)^{\alpha}. \tag{11}$$

Based on the properties above, the adaptation law is designed as following:

$$\dot{\hat{\theta}}=-\Gamma Y^T s. \tag{12}$$

3.2 Stability Analysis

Considering the following Lyapunov function candidate for system (11)

$$V=\frac{1}{2}s^T M(q)s+\frac{1}{2}\tilde{\theta}^T\Gamma^{-1}\tilde{\theta}, \tag{13}$$

where θ is a 3-dimensional vector containing the unknown manipulator and load parameters, $\hat{\theta}$ is its estimate, and $\tilde{\theta}=\hat{\theta}-\theta$ denotes the parameter estimation error vector. According to the property 1, Equation (11) and (12), the derivative of the chosen Lyapunov function can be derived as:

$$\dot{V}=-s^T d(t)-s^T K_r\mathrm{sgn}(s)^{\alpha}.$$

By using property 3, we can conclude

$$\begin{aligned}\dot{V} &\leq \|s\|\,\|d(t)\|-\lambda_{\min}(K_r)\|s\|^{\alpha+1}\\ &\leq \|s\|\,\eta-\lambda_{\min}(K_r)\|s\|^{\alpha+1}\\ &= -\|s\|\,(\lambda_{\min}(K_r)\|s\|^{\alpha}-\eta).\end{aligned} \tag{14}$$

Then we have the following theorem.

Theorem 1. *For system (1) under controller (6) and (12), if $\lambda_{\min}(K_r)>0$, $1>\alpha>0$ and $\Gamma>0$, the system trajectory will converge to the neighborhood of $s=0$ as*

$$\|s\|\leq\left(\frac{\eta}{\lambda_{\min}(K_r)}\right)^{\frac{1}{\alpha}} \tag{15}$$

in finite time.

Proof. Notice that when (15) holds, from (14), we can conclude $\dot{V}\leq 0$. Then by the finite time stability theory, the neighborhood (15) can be reached in finite time. This completes the proof. □

4 SIMULATION

Simulation is performed by using a 3-link non-linear planer robot manipulator, as shown in Figure 3, which dynamic model is derived by methods in (Spong and Vidyasagar, 2008).

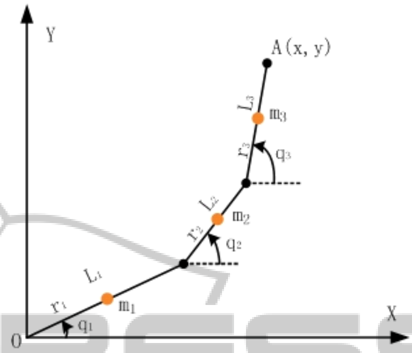

Figure 3: A 3-link robot manipulator.

The robot manipulators parameter values are $m_1=0.5kg$, $m_2=1.5kg$, $m_3=1.3kg$, $l_1=1m$, $l_2=1m$, $l_3=1m$, $r_1=0.5m$, $r_2=0.5m$, and $r_3=0.5m$. The moment of inertia are $i_1=2kg\cdot m^2$, $i_2=2kg\cdot m^2$, and $i_3=2kg\cdot m^2$. The initial conditions of the robot manipulator are given as $q_1(0)=8$, $q_2(0)=-9$, $q_3(0)=1.5$, $\dot{q}_1(0)=8$, $\dot{q}_2(0)=-9$, and $\dot{q}_3(0)=1.5$. The reference signals are given by $q_{d1}=\sin(3\pi t)$, $q_{d2}=\cos(3\pi t)$, and $q_{d3}=\sin(3\pi t+\frac{1}{3}\pi)$. The bounded disturbance is selected as $d_1(t)=5\sin(t)$, $d_2(t)=2.5\cos(t)$, $d_3(t)=5\sin(2t)$.

Besides, the parameter α in Equation (6) is set as $\alpha=0.6$, and the gain K_r in Equation (6) is designed as $K_r=diag[300,300,300]$.

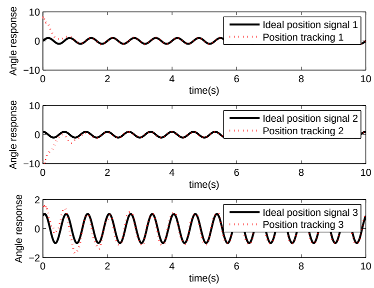

Figure 4: Ideal position signal and position tracking output.

The simulation results above show that the designed chattering-free ASMC can enable the ability of tracking control of the 3-link nonlinear planer robot manipulator under various disturbances. Furthermore, the proposed control algorithm doesnt require the precise dynamic model of the robot manipulator.

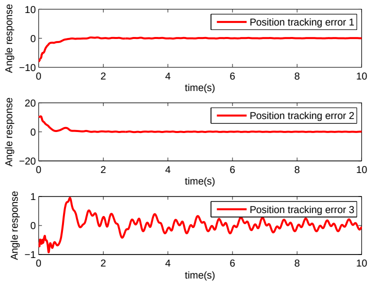

Figure 5: Position tracking output error.

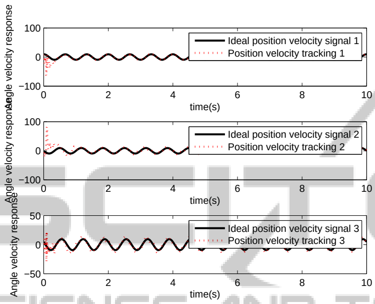

Figure 6: Ideal position velocity signal and position velocity tracking output.

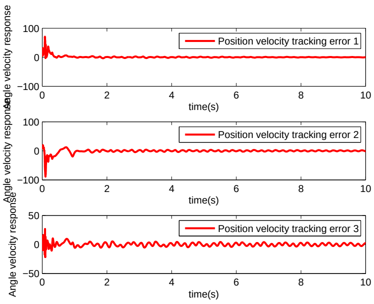

Figure 7: Position velocity tracking output error.

5 CONCLUSIONS

We have proposed a novel chattering-free ASMC controller for the seam tracking control of robotic manipulator. And the proposed algorithm is more practical than the traditional SMC controller. Besides, the simulation results have shown that the ability of the tracking control under various disturbances. In the end, a challenging work for further research is to perform the proposed algorithm in the seam tracking control during the process of practical welding, and verify its effectiveness.

ACKNOWLEDGEMENTS

The work here is supported by the National Natural Science Foundation of China (No. 51175208), the State Key Basic Research Program of China (NO. 2011CB706803), the Fundamental Research Funds for the Central Universities (No. 2013ZZGH001).

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