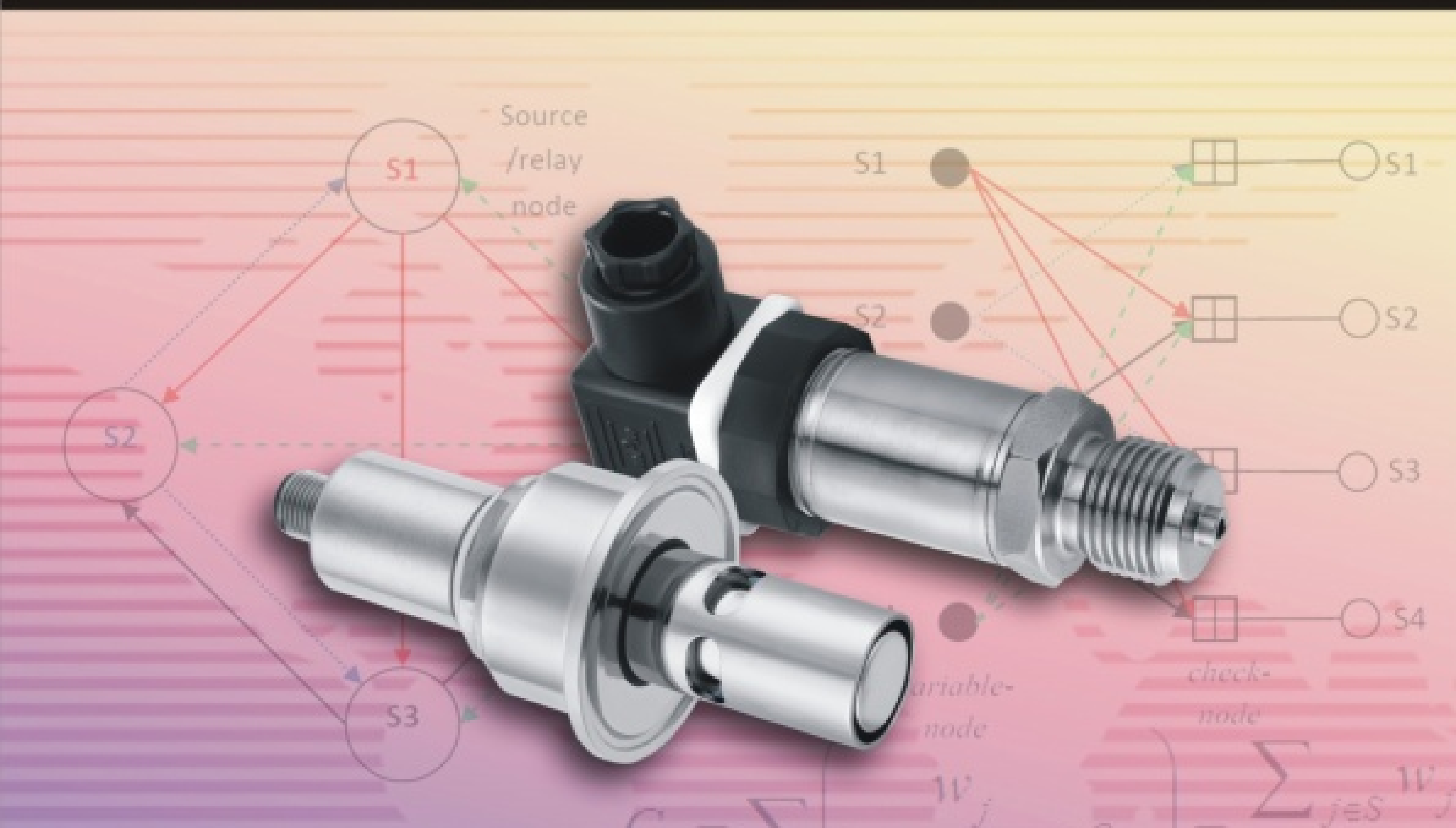
ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 20
Special
4/13



Sensors, Networks, Control Systems and Information Processing

International Frequency Sensor Association Publishing

Sensors & Transducers

International Official Journal of the International Frequency Sensor Association (IFSA) Devoted to Research and Development of Sensors and Transducers

Volume 20, Special Issue, April 2013

Editor-in-Chief
Sergey Y. YURISH

IFSA Publishing: Barcelona • Toronto

Sensors & Transducers

Volume 20, Special Issue, April 2013 | **www.sensorsportal.com** | **ISSN 2306-8515 e-ISSN 1726-5479**

Sensors & Transducers Journal

Contents

Volume 20
Special Issue
April 2013

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Authors are encouraged to submit article in MS Word (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com
Please visit journal's webpage with preparation instructions: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm


The Fourth International Conference on Sensor Device Technologies and Applications
IARIA
SENSORDEVICES 2013
25 - 31 August 2013 - Barcelona, Spain
Tracks: Sensor devices - Ultrasonic and Piezosensors - Photonics - Infrared - Gas Sensors - Geosensors - Sensor device technologies - Sensors signal conditioning and interfacing circuits - Medical devices and sensors applications - Sensors domain-oriented devices, technologies, and applications - Sensor-based localization and tracking technologies - Sensors and Transducers for Non-Destructive Testing
Deadline for papers: 30 March 2013
http://www.iaria.org/conferences2013/SENSORDEVICES13.html


The Seventh International Conference on Sensor Technologies and Applications
IARIA
Deadline for papers: 30 March 2013
SENSORCOMM 2013
25 - 31 August 2013 - Barcelona, Spain
Tracks: Architectures, protocols and algorithms of sensor networks - Energy, management and control of sensor networks - Resource allocation, services, QoS and fault tolerance in sensor networks - Performance, simulation and modelling of sensor networks - Security and monitoring of sensor networks - Sensor circuits and sensor devices - Radio issues in wireless sensor networks - Software, applications and programming of sensor networks - Data allocation and information in sensor networks - Deployments and implementations of sensor networks - Under water sensors and systems - Energy optimization in wireless sensor networks
http://www.iaria.org/conferences2013/SENSORCOMM13.html


The Sixth International Conference on Advances in Circuits, Electronics and Micro-electronics
IARIA
CENICS 2013
25 - 31 August 2013 - Barcelona, Spain
Deadline for papers: 30 March 2013
Tracks: Semiconductors and applications - Design, models and languages - Signal processing circuits - Arithmetic computational circuits - Microelectronics - Electronics technologies - Special circuits - Consumer electronics - Application-oriented electronics
http://www.iaria.org/conferences2013/CENICS13.html

Sensors & Transducers, Vol. 20, Special Issue, April 2013, pp. 69-78

Sensors & Transducers

Sliding Mode Tracking Control of Manipulator Based on the Improved Reaching Law

[1, 2] Wei-Na ZHAI, [2] Yue-Wang GE, [1] Shu-Zhong SONG, [2] Yan WANG
[1] Electronic and Information Engineering College, Henan University of Science and Technology, No. 263 Kaiyuan Road, Luolong District, Luoyang, 471023, China
Tel.: 15138111723
[2] Dept. of Electric Engineering and Automation, Luoyang Institute of Science and Technology, Luoyang, 471023, China
E-mail: zwn_008@163.com

Received: 8 February 2013 /Accepted: 17 April 2013 /Published: 30 April 2013

Abstract: Due to the mechanical hand often have serious uncertainty, as the state in which the different and external changes, also its parameters are changing, this is very adverse to achieve precise control. In this paper, the traditional sliding mode variable structure was improved, the sign function is replaced by saturated function based on the double power reaching law, by adjusting the values of ε_1, ε_2, α, β, γ and k to effectively improve the manipulator joint reaching speed, track expected trajectory fast and shorten the system response time. Finally, the method is used for simulation of manipulator trajectory tracking, compared to two reaching law control algorithms. The simulation results show that the control algorithm has good dynamic performance, which can effectively restrain the chattering and quickly track the desired trajectory. Therefore, the improved reaching law can effectively improve the performance of robotic manipulator. *Copyright © 2013 IFSA.*

Keywords: Robotic manipulator, Sliding mode control, Reaching law, Fast.

1. Introduction

Robotic manipulator structure normally are consist of a series of mutually hinged or sliding members, with several degrees of freedom for gripping or moving objects [1]. Although manipulator greatly facilitates the production, it is a multiple input and multiple output nonlinear system with time-varying, strong coupling and nonlinear dynamic characteristics, it is difficult to achieve high precision control by conventional means. So for different tasks it often needs to plan robot trajectories in joint space in order to make the composition of end pose. Therefore the robot joint space control precision is very important.

Sliding mode variable structure is a kind of robust control methods which can be used to achieve linear and nonlinear system, in view of controlled objects with the nonlinear, strong coupling dynamic characteristics, so it is conducive to manipulator control. But it is a discontinuous control method, when the state trajectory reach the sliding surface it is difficult to move along with the balance point strictly, but generate buffeting in the sliding surface on both sides of back and forth across. On the one hand, it can effects sliding mode variable structure of dynamic character and induce steady-state error; On the other hand, it may stimulate the oscillatory system and reduces the energy of system, so it's negative to system. Now how to reduce the chattering is the important content in the study of sliding mode variable method.

In the light of the chattering problem, in recent years, many scholars have put forward different solutions, divided into two directions, one is traditional control direction: the double power reaching law of Mei Hong et al, the algorithm reduced chattering and improved the system dynamic performance [2]. Reference [3] ,the combination of the principle of sliding mode control and the saturation function characteristic, weakened the vibration phenomenon in sliding mode control and had the effective suppression of the actuator saturation; the other one is mixed control direction: T .C. Kuo et al proposed a neural network global sliding mode control of PID [4], which was used to solve with bounded uncertainties in the robot trajectory tracking problems, they built the system controller gain by RBF neural network in order to eliminate the chattering. Reference [5], the fusion of Fuzzy control and Variable structure, they used fuzzy controller to adjust the parameters of reaching law on real time and introduced the saturated function, this method not only ensured the controlled system was fast and robust, but also suppressed buffeting effectively.

According to the manipulator's characteristics, on the basis of deep analysis, this paper puts forward a new improved reaching law, which designs to overcome the shortcomings that it can't approach strictly to the equilibrium point but move back and forth across the buffeting when from the switch to close the origin point. In addition, it can improve the rate of convergence, track expected trajectory fast, reduce the response time of the system and improve the robustness. When changing the initial joint position, this method can change the reaching law parameters to obtain good dynamic quality. Based on the improved reaching law, it designs sliding mode control scheme, and its control effect is verified. Compared it with the two kinds of sliding mode control algorithms, it shows the feasibility and rationality of the new algorithm.

2. Establishment of Mathematical Model of Manipulator

This paper uses Lagrange dynamics equation to establish the mathematical model of manipulator, this equation is suitable for the analysis of mutual constraints of multi-joint movement. It's an Energy balance equation. Selecting two joint manipulator as the object, coordinate configuration is shown in Fig. 1, parameter configuration is shown in Table 1.

Table 1. Parameter configuration of two joint manipulators.

Joint	Length l/m	Focus l_c/m	Weight m/kg	Inertia I/(kg · m^2)	Acceleration of gravity G/(m/sec^2)
1	0.45	0.091	23.90	1.27	9.8
2	0.55	0.105	4.44	0.24	9.8

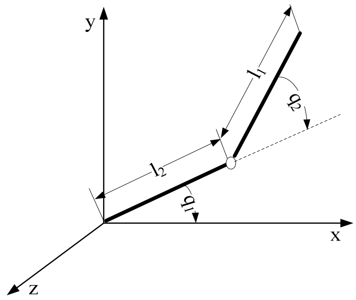


Fig. 1. Coordinate configuration of two joint manipulators.

Without considering the modeling error and external disturbance, the Lagrange equation is:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau}(t) \tag{1}$$

where

$$\boldsymbol{M}(\boldsymbol{q}) = \begin{bmatrix} M_{11}\, M_{12} \\ M_{21}\, M_{22} \end{bmatrix}, \quad \boldsymbol{C} = \begin{bmatrix} C_{11}\, C_{12} \\ C_{21}\, C_{22} \end{bmatrix}, \quad \boldsymbol{q} = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix},$$

$$\boldsymbol{G} = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}, \quad \boldsymbol{\tau} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix}$$

$$\begin{aligned} M_{11} &= m_2[l_1^{\,2} + l_{c2}^{\,2} + 2l_1 l_{c2}\cos(q_2)] \\ &\quad + m_1 l_{c1}^{\,2} + l_1 + l_2 \end{aligned} \tag{2}$$

$$M_{12} = m_2[l_{c2}^{\,2} + l_1 l_{c2}\cos(q_2)] + l_2 \tag{3}$$

$$M_{12} = m_2[l_{c2}^{\,2} + l_1 l_{c2}\cos(q_2)] + l_2 \tag{4}$$

$$M_{22} = m_2 l_{c2}^{\,2} + l_2 \tag{5}$$

$$C_{11} = -m_2 l_1 l_{c2}\sin(q_2)\dot{q}_2 \tag{6}$$

$$C_{12} = -m_2 l_1 l_{c2}\sin(q_2)(\dot{q}_1 + \dot{q}_2) \tag{7}$$

$$C_{21} = m_2 l_1 l_{c2}\sin(q_2)\dot{q}_1 \tag{8}$$

$$C_{22} = 0 \tag{9}$$

$$\begin{aligned} G_1 &= (m_1 l_{c1} + m_2 l_1)g\sin(q_1) \\ &\quad + m_2 l_{c2} g\sin(q_1 + q_2) \end{aligned} \tag{10}$$

$$G_2 = m_2 l_{c2} g\sin(q_1 + q_2) \tag{11}$$

where $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$, $\ddot{\boldsymbol{q}} \in \boldsymbol{R}^n$ is the position vector, velocity and acceleration vector; $\boldsymbol{M}(\boldsymbol{q}) \in \boldsymbol{R}^{n\times n}$ is the positive definite inertia matrix; $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) \in \boldsymbol{R}^{n\times n}$ is the centrifugal force and the brother's force matrix; $\boldsymbol{G}(\boldsymbol{q}) \in \boldsymbol{R}^n$ is the gravitational vector; $\boldsymbol{\tau}(t) \in \boldsymbol{R}^n$ is the gravitational vector; Length of joint

1 is l_1; Length of joint 2 is l_2; Focus of joint 1 is l_{c1}; Focus of joint 2 is l_{c2}; Weight of joint 1 is m_1; Weight of joint 2 is m_2; Inertia of joint 1 is I_1; Inertia of joint 1 is I_2.

3. The Design of Sliding Mode Controller

3.1. The Design of Reaching Law

The sliding mode is divided into two types, a reaching movement, another for the sliding mode motion. By the principle of the sliding mode variable structure, sliding mode can achieve the alone condition and the guarantee object can reach the sliding surface from any initial state position point in limited time. Using the reaching law method can improve the dynamic quality of reaching movements. The typical approach law is included in the followings [6]:

1) The constant reaching law

$$\dot{\boldsymbol{s}} = -\varepsilon \operatorname{sgn}(\boldsymbol{s}),\ \ \varepsilon > 0 \tag{12}$$

The constant ε express the rate when the moving point of system approaches the switching surface $\boldsymbol{S}$ at 0.

2) The exponential reaching law

$$\dot{\boldsymbol{s}} = -\varepsilon \operatorname{sgn}(\boldsymbol{s}) - k\boldsymbol{s},\ \ \varepsilon > 0,\ \ k > 0 \tag{13}$$

where $\dot{s} = -ks$ is the exponent reaching items. The power reaching law

$$\dot{\boldsymbol{s}} = -k|\boldsymbol{s}|^{\alpha} \operatorname{sgn}(\boldsymbol{s}),\ \ k > 0,\ \ 1 > \alpha > 0 \tag{14}$$

Conventional reaching law has some shortcomings, in the constant reaching law, the smaller ε is, the more slowly reaching rate is; the bigger ε is, then the moving point reaches the sliding surface with greater speed and buffeting. Although increasing exponentially approaching item in the exponential reaching law, the velocity of approach from the larger values gradually decreases to zero, it can shorten the reaching time and make the motion to the switching surface in a low speed, the presence of the exponent reaching items cannot make system fundamentally eliminate chattering. Although the power reaching law can get into the sliding surface smoothly, the rapid is weak. Therefore, conventional reaching law can not reflect the current system on the given desired trajectory tracking condition.

Aiming at the real-time weak, fast and robust, by this shortcoming, the sliding mode variable structure was improved, there will propose a double power adaptive reaching law:

$$\dot{\boldsymbol{s}} = -\varepsilon_1 |\boldsymbol{s}|^{\alpha} \operatorname{sgn}(\boldsymbol{s}) - \varepsilon_2 |\boldsymbol{s}|^{\beta} \operatorname{sgn}(\boldsymbol{s}) - k|\boldsymbol{s}|^{\gamma} \boldsymbol{s} \tag{15}$$

where $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, $k > 0$, $1 > \alpha > 0$, $\beta > 1$, $\gamma > 0$.

Its principles and conventional is similar to the reaching law, the $\boldsymbol{s}=1$ as the critical value, the system reach the sliding surface is divided into two stages. $-\varepsilon_1|\boldsymbol{s}|^{\alpha}\operatorname{sgn}(\boldsymbol{s})$ expresses $|\boldsymbol{s}|<1$, the dynamic quality of the system when closing to the sliding surface, when ε_1 is larger, reaching becomes faster but buffeting is increasing; α is smaller, buffeting is smaller but reaching speed becomes slow. $-\varepsilon_2|\boldsymbol{s}|^{\beta}\operatorname{sgn}(\boldsymbol{s})$ expresses $|\boldsymbol{s}|>1$, the dynamic quality of the system when Far away from the sliding surface, When ε_2 is larger, reaching becomes faster but buffeting is increasing; β is smaller, buffeting is smaller but reaching speed becomes slow. $-k|\boldsymbol{s}|^{\gamma}\boldsymbol{s}$ is the adaptive reaching items, which can be able to change the approaching speed of double power reaching items adaptively, based on the exponential reaching law it enriches $|\boldsymbol{s}|^{\gamma}$, so it should expect the controlled object that has the fast velocity of approaching speed to response tracking timely and has good dynamic quality when closing to the sliding surface when $|\boldsymbol{s}|<1$. So by the $-k|\boldsymbol{s}|^{\gamma}\boldsymbol{s}$, it shows that the rate will become fast while γ is bigger and system responses quickly; the controlled object will close to the sliding mode and the dynamic quality will improve while k is bigger.

But on the type (15) the system improved finite, in view of the simulation experiment shortcomings that the joint 2 is slowly contrast to the joint 1 in response. The paper is improved, reference [7, 8] show that the saturation function is one of the effective methods to eliminate the chattering, using saturation function replaces sign function, because that using the method of saturation function when the original relay characteristics will be replaced by saturated characteristic [9], so it can alleviate the discontinuity when switching and can make the switching process smoothly, It is very important for the inhibition of movement process and improvement of the buffeting of the controlled object speed. Combined the type (15), using the hyperbolic tangent function in the original reaching law, it can be expressed as:

$$\dot{\boldsymbol{s}} = -\varepsilon_1 |\boldsymbol{s}|^{\alpha} \tanh(\boldsymbol{s}) - \varepsilon_2 |\boldsymbol{s}|^{\beta} \tanh(\boldsymbol{s}) - k|\boldsymbol{s}|^{\gamma} \boldsymbol{s} \tag{16}$$

where $\varepsilon_1 > 0$, $\varepsilon_2 > 0$, $k > 0$, $1 > \alpha > 0$, $\beta > 1$, $\gamma > 0$.

Illustrate a point, $-\varepsilon_1|\boldsymbol{s}|^{\alpha}\tanh(\boldsymbol{s})$ plays a major role when $|\boldsymbol{s}|<1$ and ignores $-\varepsilon_2|\boldsymbol{s}|^{\beta}\tanh(\boldsymbol{s})$ at this time, there is $\dot{s} = -\varepsilon_1 |s|^{\alpha} \tanh(s) - k|s|^{\gamma} s$; Empathy, there is $\dot{s} = -\varepsilon_2 |s|^{\beta} \tanh(s) - k|s|^{\gamma} s$ when $|s| > 1$. Because the design is considered in two cases, one is closing to the sliding mode surface and the other is away from the sliding surface, so that the controlled object can response rapidly according to the status, and because of the introduction of saturation function is instead of sign function, the switching process will be continuous and smooth and can reduce the response time of the system effectively to improve the velocity of approach, so the system performs the given desired trajectory tracking quickly to improve the robustness of the system.

3.2. The Design of Control Law

The simulation design in robotic manipulator by sliding mode control algorithm diagram is shown in Fig. 2.

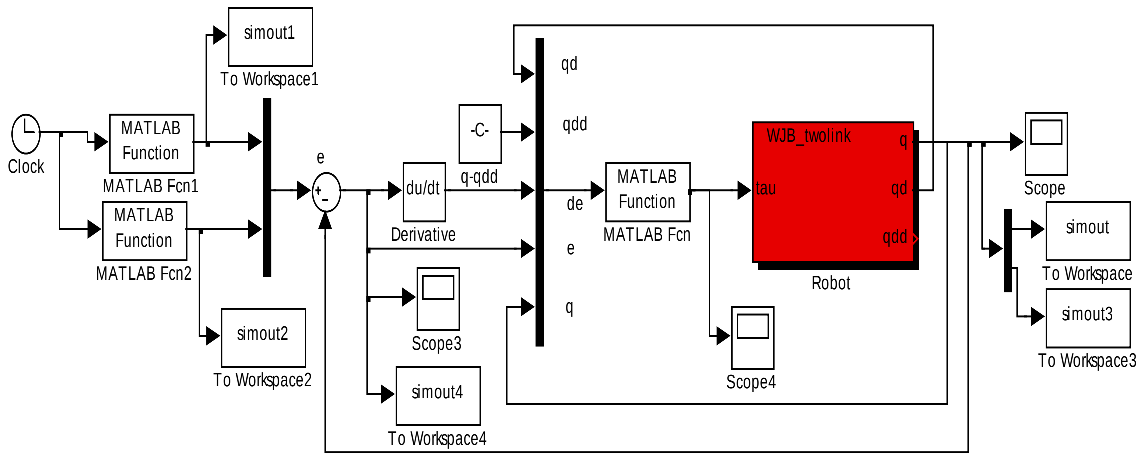


Fig. 2. Manipulator based on improved reaching law sliding mode control algorithm simulation chart.

(1) The selection of switching function

$$s = ce + \dot{e} \tag{17}$$

where $c = diag(c_1, \cdots, c_n)$, $c_i > 0$ is constant; $e = q - q_d$ is the error signal of system, q_d is for a given trajectory. When the system reaches the sliding mode surface, the system achieves stability and can reach the equilibrium point in the limited time, which is not affected by external interference and system model. For a given arbitrary initial state, by adjusting the constant matrix c can make the controlled object to obtain a good dynamic quality.

(2) The design of control law. The type (17) shows that:

$$s = \begin{bmatrix} c_1 e_1 + \dot{e}_1 \\ c_2 e_2 + \dot{e}_2 \end{bmatrix} \tag{18}$$

There is:

$$\dot{s} = c\dot{e} + \ddot{e} = \begin{bmatrix} c_1 \dot{e}_1 + \ddot{e}_1 \\ c_2 \dot{e}_2 + \ddot{e}_2 \end{bmatrix} \tag{19}$$

By type (1), type (16) and type (17), the control law is showed as:

$$\tau = M \begin{bmatrix} c_1 \dot{e}_1 \\ c_2 \dot{e}_2 \end{bmatrix} + M(\varepsilon_1 |s|^{\alpha} \tanh(s) + \varepsilon_2 |s|^{\beta} \tanh(s) + k|s|^{\gamma} s) + M \times \ddot{q} + C \times \dot{q} + G \tag{20}$$

4. The Accessibility of Sliding Mode Variable Structure

The existence condition is a premise of the application of sliding mode control, so the system movement must tend to switch $s=0$ to meet the accessibility condition:

$$\dot{V}(k) \le 0 \tag{21}$$

4.1. Accessibility

Based on the improved reaching law sliding mode type (16) meets the accessibility condition.

Proof: The Lyapunov function and hyperbolic function is:

$$V(k)=\frac{1}{2}s^2(k) \tag{22}$$

$$\tanh(s)=\frac{\exp(s)-\exp(-s)}{\exp(s)+\exp(-s)} \tag{23}$$

There is:

$$\begin{aligned}\dot{V}(k)&=s(-\varepsilon_1|s|^{\alpha}\tanh(s)-\varepsilon_2|s|^{\beta}\tanh(s)-k|s|^{\gamma}s)\\&=-\varepsilon_1 s|s|^{\alpha}\tanh(s)-\varepsilon_2 s|s|^{\beta}\tanh(s)-k|s|^{\gamma}s^2\\&=-\varepsilon_1|s|^{\alpha+1}-\varepsilon_2|s|^{\beta+1}-ks^{\gamma+2}\le 0\end{aligned} \tag{24}$$

In summary, based on improved reaching law sliding mode controller is satisfy to the accessibility condition of sliding mode.

4.2. It can be able to Reach the Equilibrium Point in Finite Time

Based on the type (16) improved reaching law sliding mode controller can be able to reach the switching surface $s=0$ from any initial state in limited time. By reference [10] it can be demonstrated as follows.

Proof: Assuming that the initial state is $s(0)>1$ and $\varepsilon_1>0$, $\varepsilon_2>0$, $k>0$, $1>\alpha>0$, $\beta>1$, $\gamma>0$, so that system can reach to the sliding equilibrium point from any initial position, which can be divided into two stages.

1) When $|s|<1$, $-\varepsilon_1|s|^{\alpha}\tanh(s)$ plays the major role, ignoring $-\varepsilon_2|s|^{\beta}\tanh(s)$, Type (16) changes into:

$$\dot{s}=-\varepsilon_1|s|^{\alpha}\tanh(s)-k|s|^{\gamma}s \tag{25}$$

So it is that the system reaches process of $s(t)=1$ from the initial state. When $s=1$, it has

$$\frac{ds}{dt}+ks^{\gamma+1}\ge-\varepsilon_1 s^{\alpha} \tag{26}$$

Type (26) takes the same $s^{-\alpha}$ on both sides and makes $z=s^{\gamma+1-\alpha}$, there is

$$\frac{dz}{dt}\ge(1-\alpha)s^{-\alpha}\frac{ds}{dt} \tag{27}$$

When t=0 and s=s(0), $c=s(0)^{\gamma+1-\alpha}+\frac{\varepsilon_1}{k}$, combining with type (27) it can be launched a desired time from an initial state to $s(t)=1$

$$t_1\le\frac{\ln(1+\frac{\varepsilon_1}{k})-\ln[s(0)^{\gamma+1-\alpha}+\frac{\varepsilon_1}{k}]}{k(\alpha-1-\gamma)} \tag{28}$$

2) When $|s|>1$, $-\varepsilon_2|s|^{\beta}\tanh(s)$ plays the major role, ignoring $-\varepsilon_1|s|^{\alpha}\tanh(s)$, Type (16) changes into:

$$\dot{s}=-\varepsilon_2|s|^{\beta}\tanh(s)-k|s|^{\gamma}s \tag{29}$$

Similarly available, due to $c=s(0)^{\gamma+1-\alpha}+\frac{\varepsilon_2}{k}$, it has little effects and can be ignored, then the reaching time of system that from $s(t)=1$ to the equilibrium time of the sliding surface is

$$t_2\le\frac{\ln\varepsilon_2-\ln(k+\varepsilon_2)}{k(\beta-1-\gamma)} \tag{30}$$

Combining type (28) and type (30), the total time of arrival is

$$t<\frac{\ln(1+\frac{\varepsilon_1}{k})-\ln[s(0)^{\gamma+1-\alpha}+\frac{\varepsilon_1}{k}]}{k(\alpha-1-\gamma)}+\frac{\ln\varepsilon_2-\ln(k+\varepsilon_2)}{k(\beta-1-\gamma)} \tag{31}$$

In summary, based on the improved reaching law sliding mode controller it can be able to reach the equilibrium point in finite time.

5. System Simulation and Verification

This paper uses the double power reaching law sliding mode control algorithm, double power adaptive reaching law sliding mode control algorithm and the improved reaching law sliding mode control algorithm for manipulator control, in order to verify the algorithm to improve the control performance. Two joint position command of manipulator are q_1, q_2, the initial system state is made as $[0\ 0\ 0\ 0]^T$.

5.1. It is Based on the Double Power Reaching Law Sliding Mode Control Algorithm

$$\dot{s}=-\varepsilon_1|s|^{\alpha}\operatorname{sgn}(s)-\varepsilon_2|s|^{\beta}\operatorname{sgn}(s), \tag{32}$$

where $\varepsilon_1>0$, $\varepsilon_2>0$, $1>\alpha>0$, $\beta>1$.

Taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=1$, $\varepsilon_2=50$, $\alpha=0.5$, $\beta=1.1$, joint 1 is controlled better. Fig. 3.is the position tracking curve of joint 1 and joint 2.

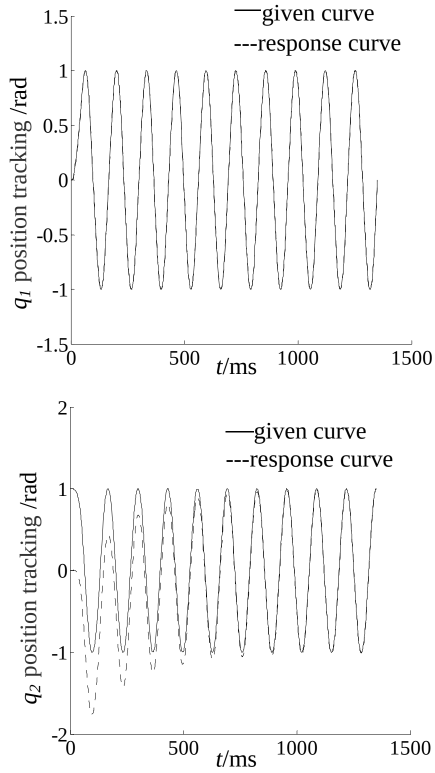


Fig. 3. The position tracking curve of joint 1 and joint 2.

Taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=1$, $\varepsilon_2=50$, $\alpha=0.8$, $\beta=1.1$, Fig. 4. is the position tracking curve of joint 1 and joint 2.When holding the ε_1, ε_2 invariant, increasing α ,the controlling of joint 2 is obvious, as shown in Fig. 4.

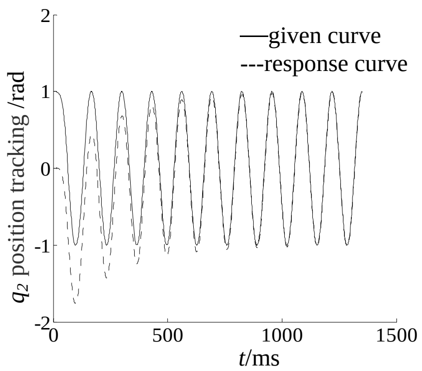


Fig. 4. The position tracking curve of joint 2.

Through several groups of contrast experiments, joint 1 is controlled better, so it only needs to adjust joint 2. When holding the ε_1 invariant, by decreasing ε_2 ,controlled effect of joint 2 becomes worse; When holding the ε_1, ε_2, α invariant, by increasing β, controlled effect of joint 2 becomes worse; When holding the ε_1, ε_2, β invariant, by decreasing α, controlled effect of joint 2 goes ahead worse; When holding the ε_1 invariant, by increasing ε_2, controlled effect of joint 2 becomes better; When holding the ε_1, ε_2 invariant, by increasing α, controlled effect of joint 2 goes ahead to become better.

In summary, when taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=1$, $\varepsilon_2=500$, $\alpha=0.8$, $\beta=1.01$, both joint 1 and joint 2 can be controlled well. Fig. 5 is the position tracking curve of joint 1 and joint 2, Fig. 6 is the position tracking error curve.

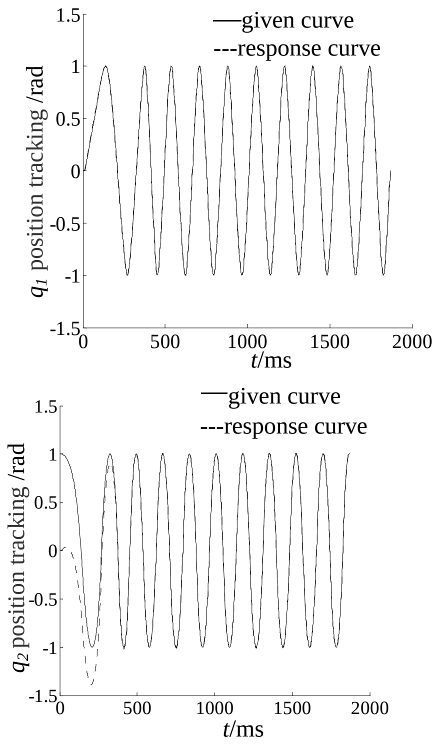


Fig. 5. The position tracking curve of joint 1 and joint 2.

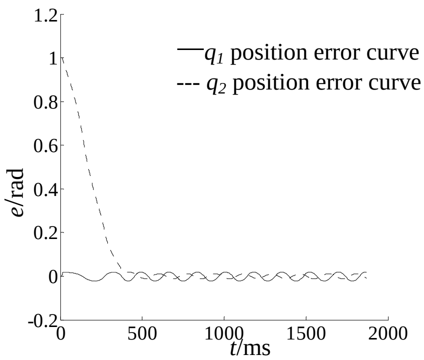


Fig. 6. The position tracking error curve of joint 1 and joint 2.

When using the double power reaching law control algorithm to conduct position tracking for the joint 1 and joint 2, Fig. 5 shows that the convergence speed of joint 1 is faster and the robustness is better; Joint 2 is restrained when t = 0.45 s. Fig. 6 shows that the algorithm controls well, but it still exists indelible phase-angle difference and fluctuates around ± 0.02 rad after t = 0.45 s.

5.2. It is Based on the Double Power Adaptive Reaching Law Sliding Mode Control Algorithm

Taking $c = \begin{bmatrix} 150 & 0 \\ 0 & 150 \end{bmatrix}$, $\varepsilon_1 = 2$, $\varepsilon_2 = 50$, $\alpha = 0.5$, $\beta = 1.5$, $\gamma = 0.5$, $k = 2$, it stands as the initialization value. Fig. 7 is the position tracking curve of joint. Joint 1 is controlled better, so the controller only needs to adjust the joint 2.

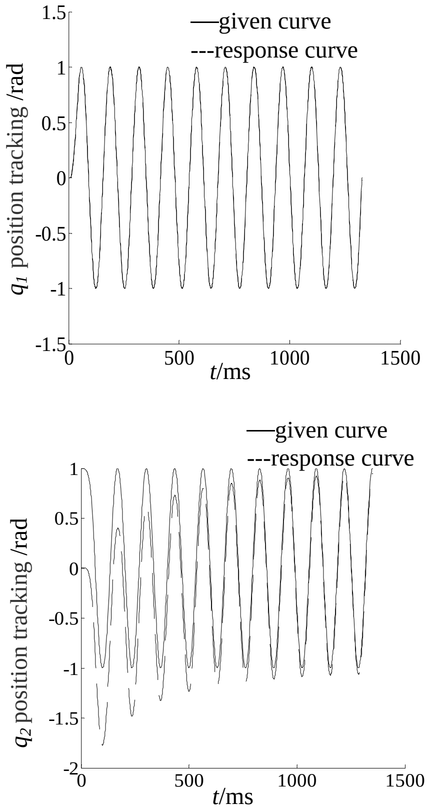


Fig. 7. The position tracking curve of joint 1 and joint 2.

By multiple comparison test can be found, When holding the ε_1, ε_2, β, γ, k invariant, ,controlled effect of joint 2 becomes worse obviously; When holding the ε_1, ε_2, γ, k invariant, by decreasing α and increasing β, controlled effect of joint 2 goes ahead to become worse; When holding the ε_1, ε_2, β, γ, k invariant, by increasing α, controlled effect of joint 2 becomes better; When holding the ε_1, ε_2, α, k invariant, by decreasing α and β, controlled effect of joint 2 goes ahead to become better. Selecting a different value, the response speed of the system is also different.

Taking $c = \begin{bmatrix} 150 & 0 \\ 0 & 150 \end{bmatrix}$, $\varepsilon_1 = 25$, $\varepsilon_2 = 150$, $\alpha = 0.6$, $\beta = 1.1$, $\gamma = 2$, $k = 50$, both joint 1 and joint 2 can be controlled well. Fig. 8 is the position tracking curve of joint 1 and joint 2, Fig. 9 is the position tracking error curve. From Fig. 9 the two joint are controlled better than the double power sliding mode control algorithm, and the buffeting is small.

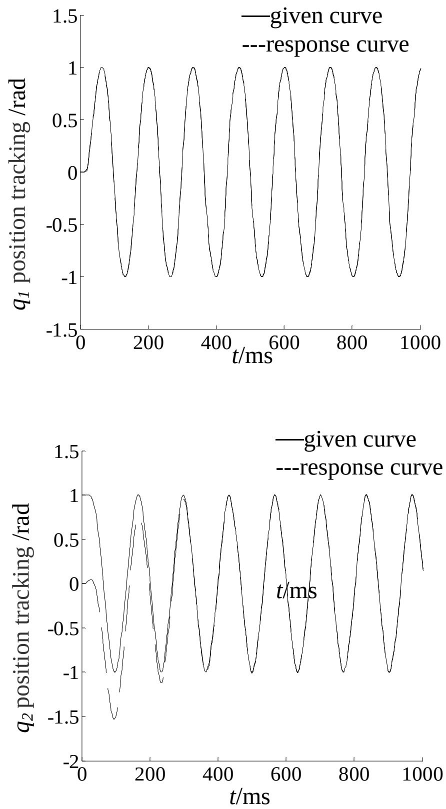


Fig. 8. The position tracking curve of joint 1 and joint 2.

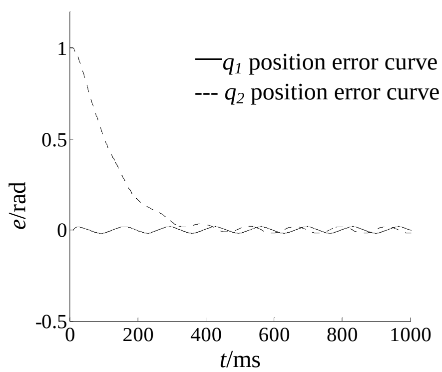


Fig. 9. The position tracking error curve of joint 1 and joint 2.

Continuing to adjust the test data, from the chart of the experimental simulation we can see that, taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=15$, $\varepsilon_2=150$, $\alpha=0.5$, $\beta=1.01$, $\gamma=0.8$, $k=50$, the controlled effect of joint 1 and joint 2 is best. Fig. 10 is the position tracking curve of joint 1 and joint 2, Fig. 11 is the position tracking error curve. From Fig. 11 buffeting of the two joint is significantly reduced to test the effectiveness of the algorithm.

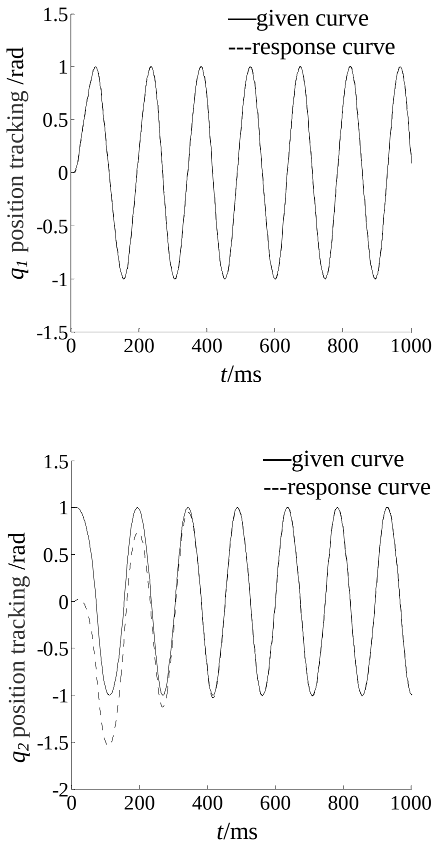


Fig. 10. The position tracking curve of joint 1 and joint 2.

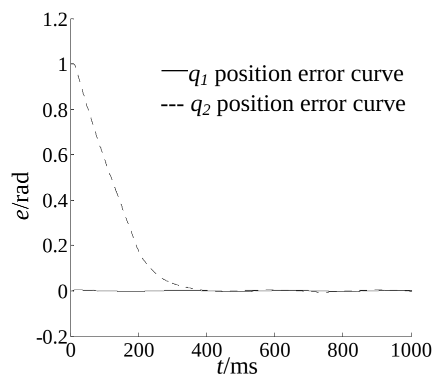


Fig. 11. The position tracking error curve of joint 1 and joint 2.

5.3. It is Based on the Improved Reaching Law Sliding Mode Control Algorithm

Taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=15$, $\varepsilon_2=150$, $\alpha=0.5$, $\beta=1.01$, $\gamma=0.8$, $k=50$, it stands as the initialization value. Fig. 12 is the position tracking curve of joint, it shows that tracking error of joint 2 is poor.

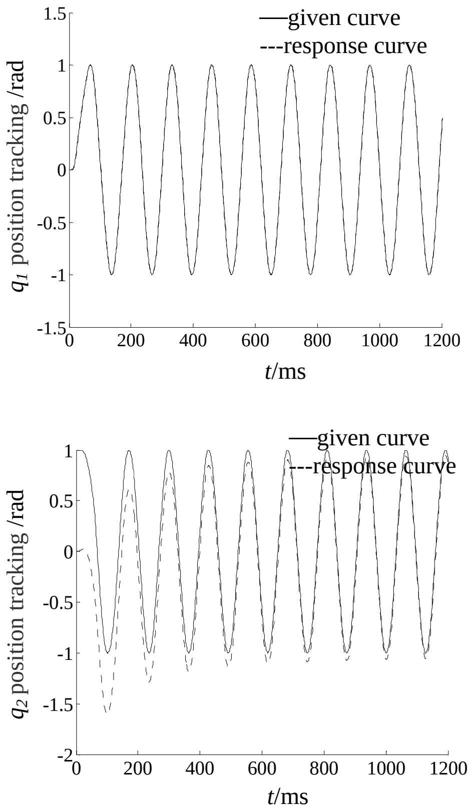


Fig. 12. The position tracking curve of joint 1 and joint 2.

By multiple comparison tests it can be found, when selecting a different value, the response speed of the system and tracking performance are also different. The controlled of joint 1 and joint 2 turns to be better when taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1=1$, $\varepsilon_2=500$, $\alpha=0.8$, $\beta=1.5$, $\gamma=0.8$, $k=50$, Fig. 13 is the position tracking curve of joint 1 and joint 2, Fig. 14 is the position tracking error curve.

Fig. 14 shows that the two joint controls are better than the former two kinds of control algorithms especially for joint 2. When taking $\varepsilon_1=15$, $\varepsilon_2=500$, $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\alpha=0.8$, $\beta=1.01$, $\gamma=6$, $k=120$.

Fig. 15 is the position tracking curve of joint 1 and joint 2, Fig. 16 is the position tracking error curve. Figures show that the rapidity of joint 2 becomes good, besides indelible phase-angle difference.

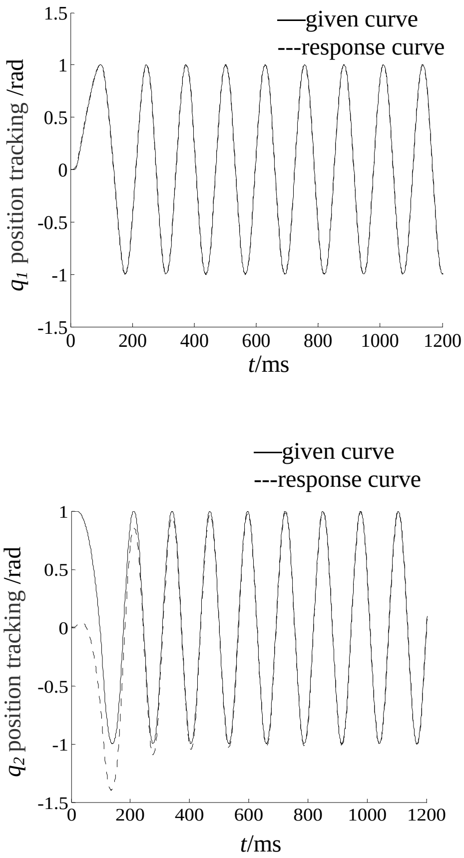


Fig. 13. The position tracking curve of joint 1 and joint 2.

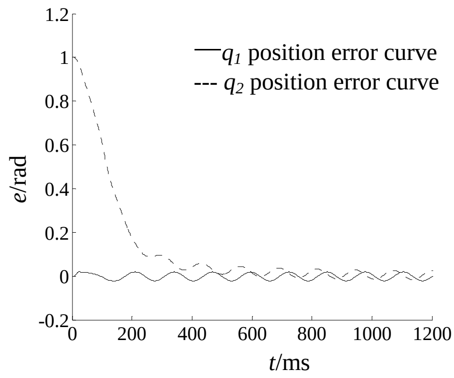


Fig. 14. The position tracking error curve of joint 1 and joint 2.

When taking $c=\begin{bmatrix}150 & 0\\ 0 & 150\end{bmatrix}$, $\varepsilon_1 = 15$, $\varepsilon_2 = 500$, $\alpha = 0.8$, $\beta = 1.01$, $\gamma = 6$, $k = 125$, the controlled effect of joint 2 is best. Fig. 17 is the position tracking error curve.

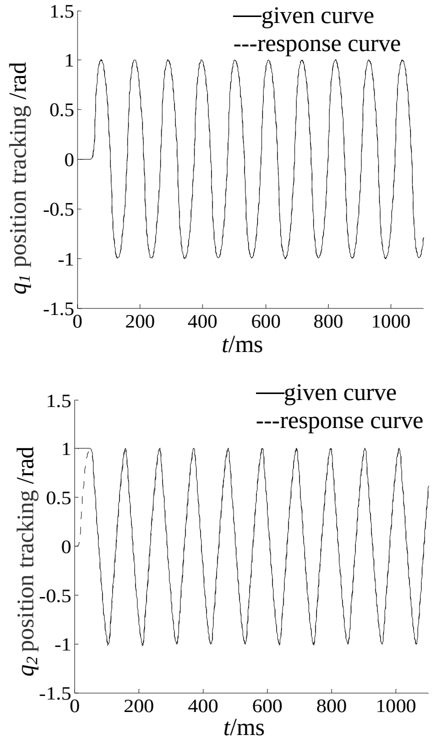


Fig. 15. The position tracking curve of joint 1 and joint 2.

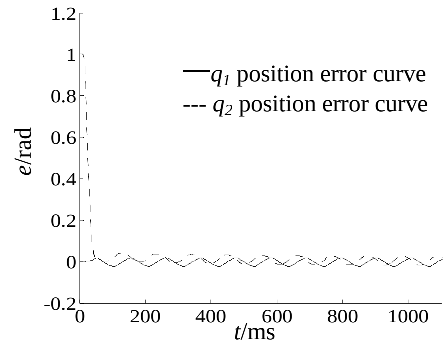


Fig. 16. The position tracking error curve of joint 1 and joint 2.

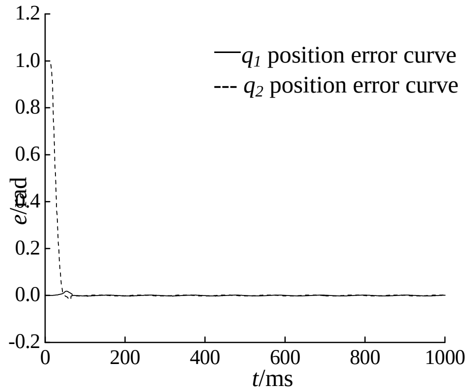


Fig. 17. The position tracking error curve of joint 1 and joint 2.

Using the improved reaching law sliding mode control algorithm in position tracking of the joint 1 and joint 2, by increasing ε_1, approach speed is fast but buffeting is increased; by decreasing α, buffeting is decreased but approach speed is slow. Joint 1 is close to the sliding surface and joint 2 is away from the sliding surface by this time. By increasing ε_2, approach speed is also fast but buffeting is increased; by decreasing β, buffeting is also decreased but approach speed is slow. Joint 1 is away from the sliding surface and joint 2 is close to the sliding surface by this time. By increasing γ, joint 1 and joint 2 are with fast convergence; by increasing *k*, joint 1 and joint 2 are close to the sliding surface and system dynamic quality is improved. Fig. 17 shows that the convergence of joint 1 is faster than joint 2 and the rapidity of joint 2 is improved, which is better than the former two reaching laws.

As previously mentioned, through three groups of simulation tests, experiments demonstrate that the improved algorithm is feasible and robust, which is better than the double power reaching law control algorithm and the double power adaptive reaching law control algorithm. Joint 1 and joint 2 are able to track the desired trajectory fast. So it can effectively improve the speed of the system in order to reduce the response time.

6. Conclusions

Aiming at previous algorithms in the real-time weak and fast difference, the sliding mode variable structure is improved. This paper proposes an improved reaching law and carries on the analysis. With the comparison test of two kinds of sliding mode control algorithms, experiments demonstrate that the control algorithm has good dynamic quality and can track the desired trajectory quickly. Therefore, it improves the performance of manipulator effectively. But because of the number of parameters and selection of randomness, it will consider introduce the neural network combined with improved reaching law control later.

References

[1]. Zhang Tie, Xie Cun-Xi, Robots, *South China University of Technology Press,* Guangzhou, 2001.

[2]. Mei Hong, Wang Yong, Fast Convergent Sliding Mode Variable Structure Control of Robot, *Information and Control*, Vol. 38, Issue 5, 2009, pp. 552-557.

[3]. Lin Lei, Wang Hong-Rui et al., Decentralized Control for Robot with Uncertainties Based on Double Saturated Function, *Control Engineering of China*, Vol. 15, Issue 2, 2008, pp. 213-216.

[4]. T. C. Kuo, Y. J. Huang, Neural Network Global Sliding Mode PID Control for Robot Manipulators [C], in *Proceedings of the World Congress on Engineering*, London, UK, January 2007, pp. 470-474.

[5]. Xi Lei-Ping, Guo Hui et al., Design of fuzzy trending law based on saturation function in sliding mode control for robotic manipulators, *Journal of Hebei University of Science and Technology*, Vol. 32, Issue 5, 2011, pp. 482-487.

[6]. Liu Jin-kun, MATLAB Simulation for Sliding mode control, *Tsinghua University Press,* Beijing, 2005.

[7]. Jin Hong-Zhang, Luo Yan-Ming et al, Investigation of a novel method of saturation function for chattering reduction of sliding mode control, *Journal of Harbin Engineering University,* Vol. 28, Issue 3, 2007, pp. 287-291.

[8]. Xi Lei-Ping, He Hui et al, Method of Chattering Elimination in Sliding Mode Tracking Control of Robotic Manipulators, *Computer Simulation*, Vol. 29, Issue 5, 2012, pp. 188-191.

[9]. V. I. Utkin, Sliding mode control design principles and applications to electric drives, *IEEE Transaction on Industrial Electronics,* Vol. 140, Issue 1, 1993, pp. 23-26.

[10]. Zhu Jian, Zhang Chang-Fan et al, The Sliding Mode Control Method Based on Improved Reaching Law and Its Application, *Journal of Hunan University of Technology*, Vol. 26, Issue 2, 2012, pp. 60-63.

Aims and Scope

Sensors & Transducers is a peer reviewed international, interdisciplinary journal that provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes original research articles, timely state-of-the-art reviews and application specific articles with the following devices areas:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing and interfacing;
- Frequency (period, duty-cycle)-to-code converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Further information on this journal is available from the Publisher's web site:
http://www.sensorsportal.com/HTML/DIGEST/Submission.htm

Subscriptions

An annual subscription includes 12 regular issues and some special issues. Annual subscription rates for 2013 are the following:

Electronic version (in printable pdf format): 400.00 EUR
Printed with b/w illustrations: 640.00 EUR
Printed full color version: 760.00 EUR

40 % discount is available for IFSA Members.

Prices include shipping costs by mail. Further information about subscription is available through IFSA Publishing's web site: http://www.sensorsportal.com/HTML/DIGEST/Journal_Subscription.htm

Advertising Information

If you are interested in advertising or other commercial opportunities please e-mail sales@sensorsportal.com and your enquiry will be passed to the correct person who will respond to you within 24 hours. Please download also our Media Planner 2013: http://www.sensorsportal.com/DOWNLOADS/Media_Planner_2013.pdf

Books for Review

Publications should be sent to the IFSA Publishing Office: Ronda de Ramon Otero Pedrayo, 42C, 1-5, 08860, Castelldefels, Barcelona, Spain.

Abstracting Services

This journal is cited, indexed and abstracted by Chemical Abstracts, EBSCO Publishing, IndexCopernicus Journals Master List, ProQuest Science Journals, CAS Source Index (CASSI), Ulrich's Periodicals Directory, Scirus, Google Scholar, etc. Since 2011 *Sensors & Transducers* journal is covered and indexed by EI Compendex index (including a Scopus, Embase, Engineering Village and Reaxys) in *Elsevier* products.

Instructions for Authors

Please visit the journal web page http://www.sensorsportal.com/HTML/DIGEST/Submission.htm Authors must follow the instructions very carefully when submitting their manuscripts. Manuscript must be send electronically in both: MS Word 2003 for Windows (doc) and Acrobat (pdf) formats by e-mail: editor@sensorsportal.com