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Research Article

Research on Grey Sliding Mode Control of Motor System of Fruit Harvesting Manipulator Joint

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Abstract: The sliding mode control algorithm based on grey prediction theory is proposed in this study, aiming at the uncertainties in the servo system of fruit harvesting robot and the external disturbances that may affect the control quality of conventional sliding mode control algorithm. The proposed algorithm uses the grey theory ability to unknown information data to establish the grey model to the uncertainty and real-time compensate the unmodeled dynamics and the interference signal of system. Meanwhile, an improved reaching law direction is proposed to resist chattering and improve control accuracy. The simulation results show that the proposed sliding mode control algorithm effectively predicts and compensates the unmodeled dynamics and disturbances signal in the DC motor servo system of the fruit harvesting robot and improves the control precision of controller which provides the theoretical basis for the industrial application based on the grey prediction theory of sliding mode control algorithm.

Keywords: Digital simulation, fruit harvesting robot, grey prediction, interference, noise, sliding mode control

INTRODUCTION

Fruit harvesting robot has been important research field of Agricultural Engineering in recent years, which is widely used for Picking tomatoes, cucumber, orange, apple, cherry, etc., (Zhang, 2010; Men *et al*., 2013; Qian *et al*., 2010; Yuan *et al*., 2009; Cai *et al*., 2009; Qinghua *et al*., 2009; Tanigaki *et al*., 2008; Liu *et al*., 2008). Tomato harvesting manipulator is seven degree of freedom manipulator consisting of 2 prismatic joints and 5 revolute joints (Liang *et al*., 2008, 2005; Liang and Wang, 2006) with a highly nonlinear system. It is an effective method for the nonlinear systems of sliding mode variable structure control. Sliding mode variable structure control appeared in twentieth Century 50 year. It has experienced 50 years of development and formed a relatively independent branch of study, becoming a general design method of automatic control system (Liu and Sun, 2007). Because of the time lag switch and spatial lag switch, the inertia of the system makes the sliding mode variable structure control add a zigzag trajectory on the sliding mode smooth in actual application, causing chattering. That is the reason for the exist of chattering. If we eliminate the chattering, the ability of anti disturbance and anti disturbance of eliminated variable structure control will be eliminated. So it is impossible to eliminate the chattering only to weaken it scope to a certain extent. The chattering problem becomes obvious obstacle to the application of variable structure control system in the actual. In order to solve this problem, the scholars have done a lot of research. The study Su *et al*. (1993) designs two kinds of filter: pre filter and post filter. The study Kim *et al*. (1996) design a disturbance observer based on the theory of two element control in the sliding mode control to feed-forward compensation for observed interference. The study Lin and Chou (2003) designs a real-time genetic algorithm realizing the online adaptive optimization of adaptive gain term in the sliding mode variable structure controller, which effectively reduces the chattering. Chinese scholar Gao (1996) proposes a method of eliminating chattering in variable structure control system with using the concept of reaching law. This study put forward an improved reaching law method to eliminate the chattering problem in sliding mode control. Taking into account uncertainties of the fruit harvesting robot servo system and quality control of traditional sliding mode control algorithm which is affected by the external disturbance, it proposes sliding mode control algorithm based on a gray prediction theory. The algorithm builds up the uncertainty of gray model using the gray theory ability to unknown information data and real-time compensate system un-modeled dynamics and interference signal to improve control accuracy.

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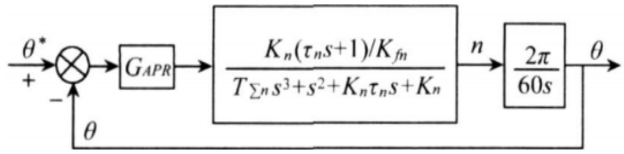

Fig. 1: Dynamic structure of position servo systems

MATHEMATICAL MODEL OF PERMANENT MAGNET SYNCHRONOUS MOTOR POSITION LOOP

This study has the joint motor fruit harvesting robot as an example to conduct in-depth research. The dynamic structure diagram of position servo system of PMSM is as shown in Fig. 1.

In the analysis of the system, the speed loop is approximately equal to one order inertial link. The response time of unit speed step of servo system (Electric motor with no-load start to set the speed of response time in the setting of torque motor) is used as the equivalent inertia time constant T_m and speed loop magnification K_m, which represents the ratio of the actual motor speed and servo speed. When the speed loop is equivalent, position loop control objects are series connection of integral part and an inertia part. As the continuous tracking control, position servo system doesn't want overshoot and oscillation leading to the decrease of position control accuracy. Therefore, he position controller adapt proportion regulator in order to correct the position loop to a typical I system. Assume the proportion magnification of position regulator is K_{Pm}, the open-loop transfer function of the closed loop system is (Ji and Gu, 2006):

$$G_P(s)=\frac{2pK_{pm}K_m}{60s(T_m s+1)}=\frac{K_{pm}K_m/9155}{s(T_m s+1)}$$

Gray prediction theory: Grey theory was first proposed by Professor Deng (1990), the Huazhong University of Science and Technology's Theory (Liu, 2004). He builds the gray differential prediction model with a few and incomplete information. It helps that the system has the volume of gray whitening to improve the control performance and robustness.

Time series data gray prediction model GM (0, N):
GM (0, N) model building (Yan *et al.*, 2010): Assume $x_1 = \{x_1(1), x_1(2), x_1(3), \ldots, x_i(n)\}$ is the dependent variables, $x_i = \{x_i(1), x_i(2), x_i(3), \ldots, x_i(n)\}$, $i = \{1, 2, 3, \ldots, N\}$ is the independent variables, x_i are the time series data. A small amount of information which makes use of the gray forecasting model GM based on time series data (0, N). The steps that use a small amount of information to build time series data gray prediction model GM (0, N) are as follows:

Initializing time series data: After the initialization, the time series of dependent variables and independent variables are these (Yuan *et al.*, 2009):

$$x_i^{(0)}=x_i(k)/x_i(1) \tag{1}$$

In the formula, x_i (1) is a value of variable sequence.

The establishment of GM (0, N) model: It is assumed that $x_i^{(1)}$ is obtained by $x_i^{(0)}$ after AGO. We can get that the predication model of GM (0, N) is like that (Zhang, 2010):

$$x_1^{(1)}(k)=\sum_{i=2}^{N}b_i x_i^{(i)}(k)+a \tag{2}$$

In the formula, the parameter $\hat{b} = [b_2, b_3, \ldots, b_N, a]$. We can get $\hat{b}$ through the least square method:

$$\hat{b}=(B^T B)^{-1}B^T Y \tag{3}$$

In the formula:

$$B=\begin{bmatrix} x_2^{(1)}(2) & \cdots & x_N^{(1)}(2) & 1 \\ \vdots & & & \vdots \\ x_2^{(1)}(n) & \cdots & x_N^{(1)}(n) & 1 \end{bmatrix}, Y=\begin{bmatrix} x_1^{(1)}(2) \\ x_1^{(1)}(3) \\ \vdots \\ x_1^{(1)}(n) \end{bmatrix}$$

The approximate time response formula for solving is:

$$x_1^{(1)}(k)=\sum_{i=2}^{N}b_i x_i^{(i)}(k)+a \tag{4}$$

(4) on the reduction is obtained:

$$\hat{x}_1^{(0)}(k+1)=\hat{x}_1^{(1)}(k+1)-\hat{x}_i^{(1)}(k), k=1,2,3\cdots,n-1 \tag{5}$$

In it $\hat{x}_1^{(0)}(1)=\hat{x}_1^{(1)}(1)$

GM (0, N) model prediction flow: GM (0, N) model prediction flow is shown in Fig. 2 (Zhang, 2010).

THE DESIGN OF SLIDING MODE CONTROLLER

The design of sliding mode controller: The sliding surface is defined as:

$$s=c[R(k)-x(k)]=0 \tag{6}$$

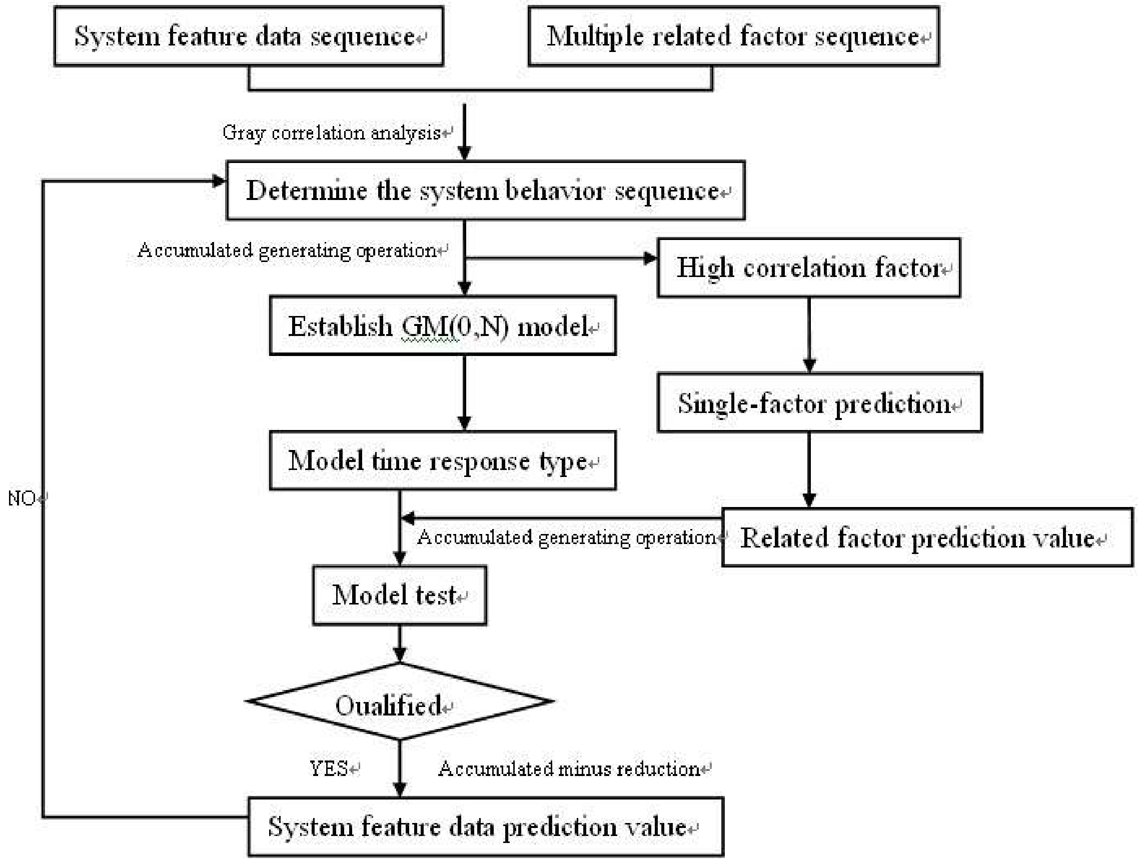

Fig. 2: GM (0, N) model prediction flow

The C conforms the stability condition of sliding mode $C=[C_1C_2\ldots C_n], C_n=1$.
Assume:

$$ds(k)=s(k+1)-s(k) \tag{7}$$

According to exponential reaching law:

$$\begin{gathered} ds(k)=-\varepsilon T\operatorname{sgn}(s(k))-qTs(k), \\ \varepsilon>0, q>0, 1-qT>0 \end{gathered} \tag{8}$$

So the sliding mode controller based on exponential approach law is as follows:

$$\begin{gathered} u(k)=(CB)^{-1}[C(R(k+1)-R(k)) \\ -C(A-1)x(k)-ds(k)] \end{gathered} \tag{9}$$

The improved approach law: Gao (1996) proposed the reaching law approach to inhibit the chattering problem which existed in sliding model control (Liu, 2009). And he also given reaching laws with four form, when we use the exponential reaching law method to reduce the chattering problem which existed in sliding model control (Deng, 1990; Yan *et al*., 2010), we can guarantee dynamic quality of the process of sliding mode reaching and weaken the chattering existed in the SMC method by adjusting the parameters of the exponential reaching law. In this study proposed a variable rate reaching law, it's discrete form as follows:

$$S(k+1)-S(k)=-\varepsilon T\|X\|_1\operatorname{sgn}(S(k)) \tag{10}$$

where, $\|X\|_1$-- 1 norm of x.

The variable rate reaching law's reaching speed is $\varepsilon\|X\|_1$. However, $\|X\|_1$ gets a large value and the SMC has a big chattering. In order overcome the problem of the variable rate reaching law and exponential approach law, we have proposed an improved reaching law:

$$S(k+1)=(1-Tq)S(k)-\varepsilon T\tan sig(\|X\|_1)\operatorname{sgn}(S(k)) \tag{11}$$

where, $\tan sig(\|X\|_1)=2sig(\|X\|_1)-1=\dfrac{1-e^{-\|X\|_1}}{1+e^{-\|X\|_1}}$

Stability analysis: Define the Lyapunov function is:

$$V(k)=\frac{1}{2}[S(k)]^2 \tag{12}$$

So,

$$\begin{aligned} &V(k)=\frac{1}{2}[S(k)]^2\\ &V(k+1)=\frac{1}{2}[S(k+1)]^2\\ &V(k+1)-V(k)\\ &=\frac{1}{2}[S(k+1)]^2-\frac{1}{2}[S(k)]^2\\ &=\frac{1}{2}\{[S(k+1)-S(k)][S(k+1)+S(k)]\}\end{aligned} \tag{13}$$

$$\begin{aligned} &V(k)=\frac{1}{2}[S(k)]^2\\ &V(k+1)=\frac{1}{2}[S(k+1)]^2\\ &\because [S(k+1)+S(k)]\operatorname{sgn}(S(k))\\ &=[-qTS(k)-\frac{|S(k)|}{2}T\tan sig(\|x\|)\operatorname{sgn}(S(k))]\operatorname{sgn}(S(k))\\ &=-(q+0.5\tan sig(\|x\|))T|S(k)|<0\\ &\because [S(k+1)-S(k)]\operatorname{sgn}(S(k))\\ &=(2-qTS(k)-\frac{|S(k)|}{2}T\tan sig(\|x\|)\operatorname{sgn}(S(k))]\operatorname{sgn}(S(k))\\ &=(2-qT-0.5T\tan sig(\|x\|))(S(k))\\ &=(2-qT-0.5T)|S(k)|>0\end{aligned} \tag{14}$$

For the former case, the following equation can be obtained:

$$\begin{aligned} &V(k+1)-V(k)\\ &=\frac{1}{2}\{[(S(k+1)]-S(k))\operatorname{sgn}(S(k))]\\ &[S(k+1)+S(k))\operatorname{sgn}(S(k))]\}\\ &\therefore V(k+1)-V(k)<0\\ &\therefore V(k+1)<V(k)\end{aligned} \tag{15}$$

Therefore, the system is stable.

GRAY SLIDING MODE CONTROLLER

Grey Sliding mode control includes grey prediction and grey sliding mode compensation in two stages.

Grey prediction: One of the research method of grey system is to process the original data, known as the "generation of number". The cumulative generation can weaken the randomness and strengthen the regularity, so it has a special status in the gray system modeling. According to the grey system theory and the accumulation generation method, the grey prediction model can be established to realize the prediction of the unknown parameters and external interference.

Let $x^{(0)}$ be a primitive discrete sequence:

$$x^{(0)}=(x^{(0)}(1)x^{(0)}(2)\cdots x^{(0)}(n)) \tag{16}$$

$$x^{(0)}(k_1)=\sum_{m=1}^{n}x^{(0)}(m) \tag{17}$$

Then $x^{(1)}(k_1)$ is called the cumulative generation of $x^{(0)}(k_1)$.

Using $x(k)=\begin{bmatrix}x_1(k)\\x_2(k)\end{bmatrix}$ can get $x^{(0)}(k_1)$ and using the Eq. (8) can get the cumulative generation $x^{(0)}(k_1)$ of $x^{(1)}(k_1)$, the i = 1, 2, …, n, k = 1, 2, …, N, k_1 = 1, 2, …, N - 2, n is the system order.
Assume:

$$D(x,k)=(B)^{-1}(x(k+1)-Ax(k)-Bu(k)) \tag{18}$$

The u (k) is the sliding mode control of exponential reaching law, Namely.
Using the Eq. (18) can get the discrete series data $D^{(0)}(k)$ for D (x, k). Thus according to $D^{(1)}(k_1)=\sum_{m=1}^{n}D^{(0)}(m)$, the cumulative generation $D^{(1)}(k_1)$, $i=1,2,\cdots,n, k=1,2,\cdots,N, k_1=1,2,\cdots,N-2$ can be obtained.

According to the method of least squares, if (BB^T BB) is reversible, the identification results are:

$$V^T=(BB^TBB)^{-1}BB^TD^{(1)} \tag{19}$$

The $V=(V_1,V_2\cdots V_N,d)^T$:

$$BB=\begin{bmatrix}x_1^{(1)}(2) & \cdots & x_n^{(1)}(2) & 1\\ x_1^{(1)}(3) & \cdots & x_n^{(1)}(3) & 2\\ \vdots & \vdots & \vdots & \vdots\\ x_1^{(1)}(N) & \cdots & x_n^{(1)}(N) & N-2\end{bmatrix} \tag{20}$$

The $\{\det(BB^TBB)\}>\varsigma>0$, $X^{(1)}$ (k_1) is the cumulative generation of $X^{(1)}$ (*k*), then i = 1, 2, … , n, k = 1, 2, … , N, k_1 = 1, 2, …, N- 2 n is the system order.

According to the grey theory and the grey identification of N = n + 3 step, the identification of the interference parameters can be realized.

Grey sliding mode compensation: The effective compensation for interference can realized by the interference parameters. The grey compensation controller is:

$$u_c=-(\sum_{i=1}^{n}V_ix_i+d) \tag{21}$$

At this time, the total sliding mode controller is as follows:

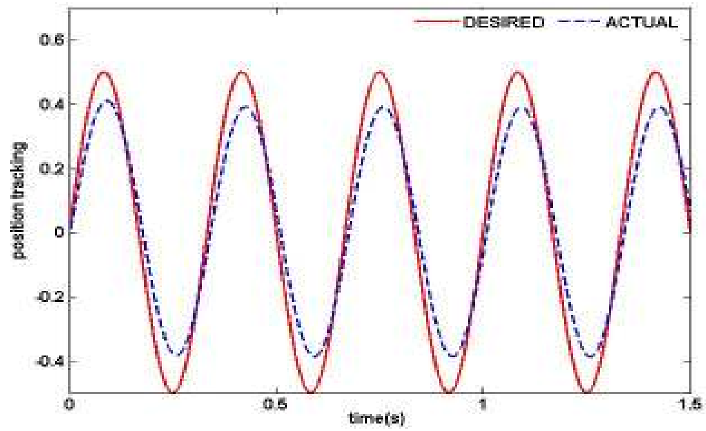

Fig. 3: Traditional sliding mode position tracking

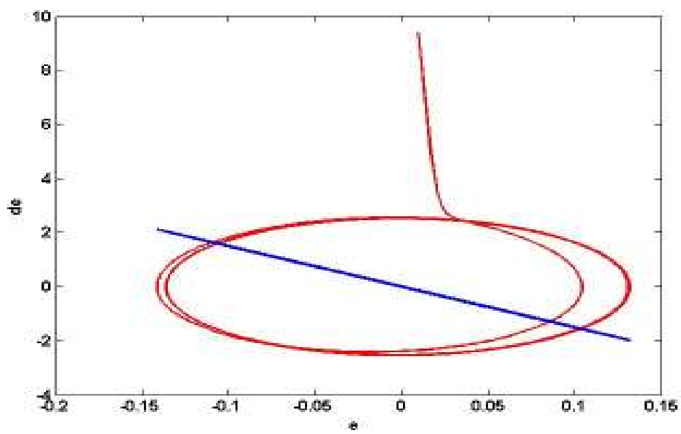

Fig. 4: Traditional sliding mode trajectories

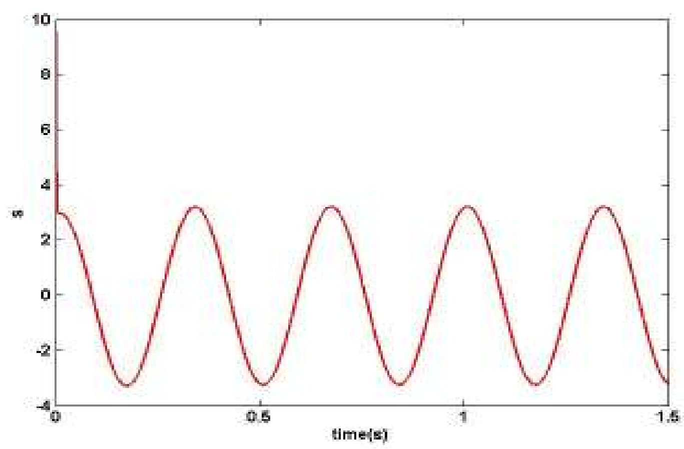

Fig. 5: Traditional sliding surface

$$u = u_s + u_c \tag{22}$$

NUMERICAL SIMULATION

In order to verify the validity of the algorithm, joint servo system of the fruit harvesting robot is studied by numerical simulation using MATLAB (omitted parameters), the simulation results shown in Fig. 3 to 8.

Figure 3 and 6 use position tracking system based on the gray prediction theory in joint servo system of fruit harvesting robot. We can see that the system has good position tracking, small tracking error and fine

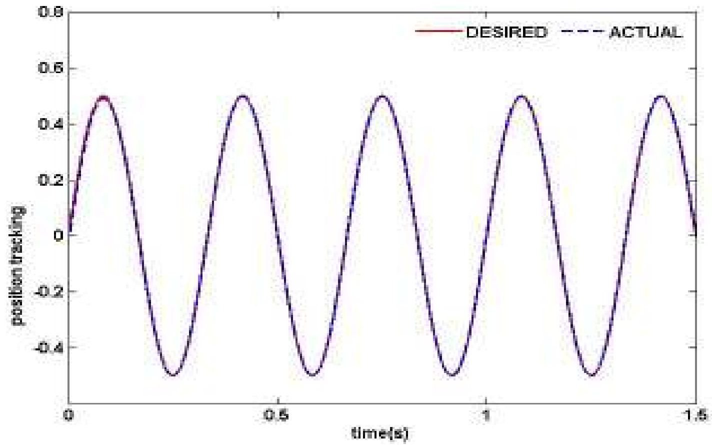

Fig. 6: Grey sliding mode sliding position tracking

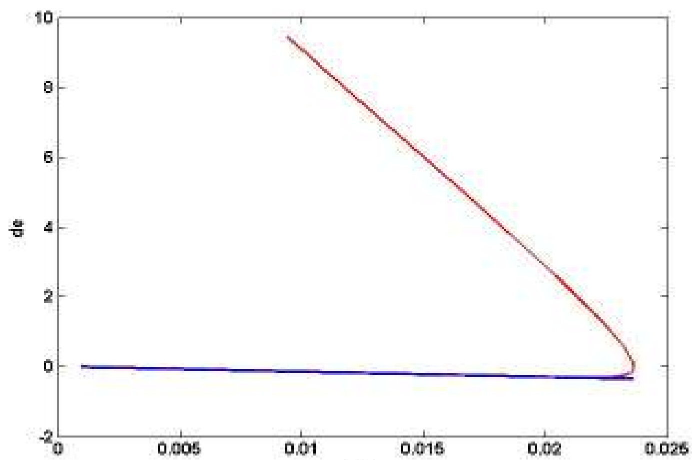

Fig. 7: Grey sliding mode sliding phase trajectory

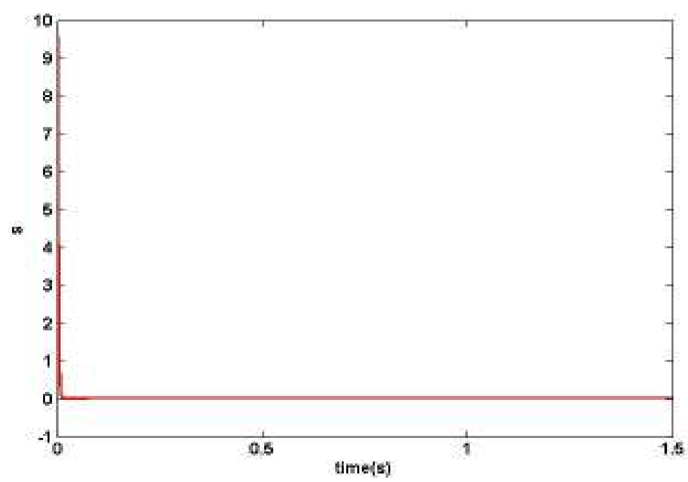

Fig. 8: Grey sliding mode sliding surface

repeatability after using the gray theory prediction and compensation.

Figure 5 and 8 are sliding model in joint servo system of fruit harvesting robot for the use of gray prediction theory. Using the gray theory prediction and compensation, not only is the chattering problem in sliding mode well controlled but also did not affect the robustness of the system.

CONCLUSION

The thesis draws a variable structure control algorithm based on the gray prediction theory and the improved sliding mode reaching law. It is applied in joint servo control system of fruit harvesting robot. We can make a conclusion by simulation results:

- The variable structure control algorithm of sliding mode based on gray prediction theory and the improved reaching law can forecast uncertainty component in a system.
- The variable structure control algorithm of sliding mode based on gray prediction theory and the improved reaching law can effectively resist the chattering problem in system, so as to lay the foundation of the application of the sliding mode structure.

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