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A novel UPSO-DSMC controller for two dimensional bridge crane

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Abstract. To improve the control performance of two-dimensional bridge crane, a novel dynamic sliding mode variable structure control algorithm is presented. The proposed controller can ensure global stability through improved design of sliding surface for the drive control force, and obtain the continuous driving control force in time domain, by using the Sigmoid function for switching function to suppress chattering. Meanwhile, the sliding mode control parameters are optimized using Uniform Search Particle Swarm Optimization (UPSO), and the rope length, swing angle and position are selected as independent variables of particle fitness function. Besides, the rope length, the swing angle and the position of load are adopted as the parameters of particle fitness function.Experimental results demonstrated that it is effective on chattering suppression, swing reduction, and robust with various load qualities and friction resistances.f

Key words. bridge crane, under-actuated system, dynamic sliding mode, chattering reduction
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1. Introduction

As a complex under-actuated nonlinear control system, the bridge crane system plays a vital role in modern industrial production. Due to its application values, many scholars focus on precisely control of position and oscillation angle on bridge cranes[1-2].Gao [3] proposed the concept of sliding mode approach rate. Layered sliding mode and time-varying sliding mode were used to implement bridge crane anti-set control in variable length [4]. Also sliding surface methods have proposed to improve the system performance [5-6]. Due to the time delay and the mechanical inertia of the system, the ordinary sliding mode control method could cause chattering on the sliding mode surface, resulting in adverse impact on the system. However,

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the controller designed is complicated and has chattering, but most of them do not consider variable length of rope.

In 1995, Wu [7] proposed a population-based parallel global optimization Particle Swarm Optimization (PSO) algorithm, which can be utilized to solve a large number of non-linear, non-differentiable and multi-peak complex problems [8]. In [9-10], the suggested values of parameters in PSO algorithm are proposed and the selection principle of parameters for the convergence of PSO algorithm is proved, experimentally.

To solve the problem that basic particle swarm optimization algorithm is easy to fall into local optimal solution, the concept of PSO particle search center is defined in this paper. Based on the calculation of the probability density between the global optimal solution and the local optimal solution at random state, a uniform search particle swarm optimization (UPSO) algorithm is proposed in which particle search center is uniformly distributed between two optimal solutions. The proposed algorithm could have faster convergence speed and better stability in optimization, especially in the optimization of non-uniform, multi-peak function.

2. Two-dimensional bridge crane system

Anti-swing positioning control for bridge crane has been extensively applied in the crane traveling. However, load swing may influence work efficiency and cause accidents easily. A suitable control method for a dynamic condition and nonlinearity model is the main difficulty. For simplicity, the quality and elastic deformation of the rope, and resistance of wind and air, as well as the sling trolley, and connecting parts of the friction are ignored in the system. Thus, rectangular coordinate system can be established as follow.

Firstly, setting positive X-axis and Y-axis as the force direction and the vertical ground-down respectively. Then the coordinates of the load and crane $(x_m,\ y_m)$, $(x_M,\ y_M)$ are evaluated. Generalized coordinates are selected in the system as load swing angle θ, lifting rope length l, horizontal position x.

According to the two-dimension crane, coordinates of crane and payload mass can be expressed as

$$\begin{cases} x_M = x \\ y_M = 0 \\ x_m = x - l\sin\theta \\ y_m = l\cos\theta \end{cases} \tag{1}$$

For simplify, the state equation of the two-dimension overhead crane system can be expressed as

$$\begin{cases} \ddot{x} = \frac{1}{M}\left(f_1 - D\dot{x} + f_2\sin\theta\right) \\ \ddot{l} = g\cos\theta + l\dot{\theta}^2 + \frac{(f_1 - D\dot{x})\sin\theta}{M} + \frac{f_2\left(M + m\sin^2\theta\right)}{Mm} \\ \ddot{\theta} = \frac{(f_1 - D\dot{x} + f_2\sin\theta)\cos\theta}{Ml} - 2\frac{\dot{l}\dot{\theta}}{l} - \frac{g\sin\theta}{l} \end{cases} \tag{2}$$

3. Design of a Novel Dynamic Sliding Mode Control

The design of control of anti-swing and positioning of variable rope length overhead cranes using hierarchical sliding mode and time-varying sliding mode is especially complicated but not sufficient for suppressing vibration. To solve the above problems, a novel dynamic sliding mode control method is presented in this paper. Firstly, the vibration is suppressed by adding differential inputs of control system into the sliding mode surface of ordinary dynamic sliding mode strategy to obtain control driving force which is continuous by integration. Secondly, since the vibration of sliding mode control is weakened by utilizing sigmoid equation as switch function, there is no need to switch the control structure within a certain neighborhood of switching surface.

To this end, the reaching law of controlling method is presented as follow

$$\dot{s}_i = -\varepsilon_i \phi(\lambda, s_i) - k_i s_i \quad i = 1\ \ 2 \tag{3}$$

where$\varepsilon_i$and k_i are positive constant. $\phi(\lambda, s_i)$is Sigmoid function which is defined as follow

$$\phi(\lambda, t) = 1 - e^{-\lambda t}/(1 + e^{-\lambda t}) \tag{4}$$

whereλ is a constant.

The equation (**??**)5) can be obtained from equation (**??**)2), s_1, $s_2$can be expressed as

$$\left\{\begin{array}{l} \dot{s}_1 = \frac{1}{M}\left(\dot{f}_1 - D\ddot{x} + \dot{f}_2 \sin\theta + f_2\dot{\theta}\cos\theta\right) + a\ddot{x} + b\dot{x} + c\ddot{\theta} + d\dot{\theta} \\ \dot{s}_2 = -g\dot{\theta}\sin\theta + \dot{l}\dot{\theta}^2 + 2l\dot{\theta}\ddot{\theta} + \frac{1}{M}\left[\left(\dot{f}_1 - D\ddot{x}\right)\sin\theta + (f_1 - D\dot{x})\,\dot{\theta}\cos\theta\right] \\ \quad + \frac{1}{Mm}\left[\dot{f}_2\left(M + m\sin^2\theta\right) + 2f_2 m\dot{\theta}\sin\theta\cos\theta\right] + a_1\ddot{l} + b_1\dot{l} \end{array}\right. \tag{5}$$

By substituting equation (**??**)2) and equation (**??**)3), f_1, $f_2$can be expressed as

$$\left\{\begin{array}{l} \dot{f}_1 = -\sin\theta\dot{f}_2 + \frac{D}{M}\left(f_1 - D\dot{x} + f_2\sin\theta\right) - \dot{\theta}\cos\theta f_2 \\ \qquad - M(a\ddot{x} + b\dot{x} + c\ddot{\theta} + d\dot{\theta} + \varepsilon_1\phi(\lambda, s_1) + k_1 s_1) \\ \dot{f}_2 = -\frac{m\sin\theta}{M + m\sin^2\theta}\dot{f}_1 - \frac{Mm}{M + m\sin^2\theta}\left[\frac{\dot{\theta}\sin 2\theta}{M}f_2 + \right. \\ \quad \frac{M(f_1 - D\dot{x})\dot{\theta}\cos\theta - D(f_1 - D\dot{x} + f_2\sin\theta)\sin\theta}{M^2} \\ \qquad \left. - g\dot{\theta}\sin\theta + \dot{l}\dot{\theta}^2 + 2l\dot{\theta}\ddot{\theta} + a_1\ddot{l} + b_1\dot{l} + \varepsilon_2\phi(\lambda, s_2) + k_2 s_2\right] \end{array}\right. \tag{6}$$

In sliding mode control system, there is vibration in sliding mode for time delay and space lag and system inertia in the switching of control structure. To restrain vibration, bipolar Sigmoid function in the new dynamic sliding mode control law can be represented as Sigmoid function $\mathrm{sgn}(S)$. Sigmoid function is more excessively smooth than saturation function and derivable which does not need to satisfy the sliding mode condition and specific switch control structure.

4. The proposed UPSO-DSMC Controller

The bridge cranes system is under-actuated and has strong nonlinear characteristics, the parameter selection in sliding mode control leads to difficulty in ensuring the accuracy of the swing angle detection and load positioning. Therefore, the evaluation indexes of two-dimensional bridge crane during movement are as follow: during the transportation process of bridge crane, the smaller the positioning error of the bridge cranes, the more sufficient suppression of swing angle, and the more coordinated the crane moves, there would be higher safety.

As the switching gain and the proportional gain of the two sliding mode surfaces of the dynamic sliding mode respectively, ε_1, k_1, $\varepsilon_2$andk_2 determine the coordination and safety during the movement of the crane. In this paper, UPSO is utilized to search the optimal solution in global space. Simultaneously, to obtain the satisfactory dynamic characteristics of the transitional process, Integrated Time Absolute Error (ITAE) criterion function and the maximum swing angle are adopted as fitness function in the particle swarm optimization algorithm.

$$\tau = \tau_0 \left(1/2 - \xi\right) , \tag{7}$$

where is the integral of the product of time t and the absolute value of the difference of the cranes position prediction and its actual value. is the integral of time t and the absolute value of the difference of the rope length prediction and its actual value. $Max\{\theta\}$ is the maximum swing angle in control process. The proposed UPSO algorithm search process is as follows:

The proposed UPSO algorithm:
Randomly initialize particle swarm according to the initial range of particles, where particles are defined as: P=[ε_1, k_1, ε_2, k_2], V=[$V_{\varepsilon 1}$, V_{k1}, $V_{\varepsilon 2}$, V_{k2}], where $V_{\varepsilon 1}$, V_{k1}, $V_{\varepsilon 2}$, V_{k2} are the change rate of particles. Traversing particle swarm, do a jump test for each particle and calculate particle fitness according to the movement data. For each particle, its fitness value is compared with the best position p_{best} it passed, and if it is better, it is taken as the current best position p_{best}. For each particle, compare its fitness value with the best place g_{best}experienced globally, and if it is better, set it to the best global position g_{best}. Determine whether it's convergent according to J<0.5. if not, update particle based on UPSO and return to step 2; if it's convergent, searching end.

5. Stability Analysis

Theorem: State of two-dimensional overhead cranes nonlinear system is globally stable if the sliding mode surface is constructed equation (**??**)5), and equation (**??**)6) are utilized to ensure all the control parameters should be positive.

Certification: For sliding surface s_i, the derivation of Lyapunov energy function

V=(1/2)s$^2{}_i$ can be expressed as

$$\begin{aligned}\dot{V} &= s\dot{s} = s_i[-\varepsilon_i\phi(\lambda, s_i) - k_i s_i] \\ &= -\varepsilon_i s_i\phi(\lambda, s_i) - k_i s_i^2 \quad\quad i = 1, 2\end{aligned} \tag{8}$$

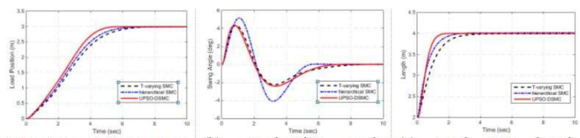
whereε_i, k_i, λ are positive constants. $s_i\phi(\lambda, s_i) \geq 0$, $k_i s_i^2 \geq 0$issatisfied, thus$\dot{V} = s\dot{s} \leq 0$.

The designed sliding mode could satisfy the condition under ss'<=0. In this case, points in the state trajectory space can reach the sliding switching plane s=0 for a finite time and all the state variables can reach the expected values after entering the sliding mode when the stability of sliding motion is guaranteed.

6. Experimental Results and Analysis

In order to verify the proposed crane controller, experiments are conducted with theoretical analysis here. Parameters of the proposed control algorithm are set as:*M=10kg, m=5kg, g=9.78 m/s*^{2}*, D=0.2,* the initial load rope length is 2m, and exceptive length is 4m.

To obtain a specific bridge crane system, a time-varying sliding mode, a hierarchical sliding mode and a novel dynamic sliding mode are adopted to simulate and control the anti-swing positioning respectively. Parameters of the proposed dynamic sliding mode (**??**)11) are set as: *a=20, b=8, c=7, d=140,* a_1*=15,* b_1*=36,* ε_1*=5,* k_1*=5,* ε_2*=0.03,* k_2*=28.* Experimental results of three kinds of sliding mode control for anti-load positioning with the same condition are shown in Figure 1.



(a)Position change curve of crane. (b) Load-swing angle change curve (c) Load rope length change curve

Fig. 1. Results of three sliding mode control anti-swing Positioning Control

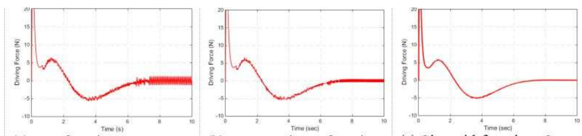
Figure 1 illustrates various sliding mode, which is capable of achieving load anti-swing position control requirement rapidly, and obtaining the displacement from 0 to 3 and yielding the rope length from 2 to 4. Compared with other methods response of displacement of the new dynamic sliding mode control crane is much faster to achieve load position control about 5s, as show in Figure 1a. From Figure 1b, we can conclude that fast hierarchical sliding mode control of cyclonic angle is significantly higher than that of dynamic sliding mode and hierarchical sliding mode control. Figure 1c shows that the dynamic sliding mode control of load rope has fast convergence time about 2s.

From Table 1, we can conclude that dynamic sliding mode control has obvious advantages in rope length control and cycloidal angle response. The amplitude of swing angle is no more than 4 degree and it can achieve anti-swing positioning for crane in 6s.

Table 1. Results of anti-swing positioning of bridge crane

	Car position t1(s)	Load line length t2(s)	Angular amplitude (?)	Angular convergence time t3(s)
Time-varying sliding mode	6.1	3.5	4.1	8.2
Layered sliding mode	6.2	3.0	5.3	8.2
Dynamic sliding mode	5.0	2.0	4.1	8

Based on the UPSO-DSMC control law, driving force is simulated by Sgn function, Saturation function and Sigmoid function respectively. Experimental results are shown in Fig. 2. Saturation function boundary layer thickness d is set as 0.02, and sigmoid function λ is set as 2.

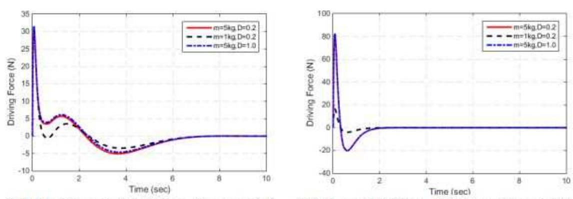


(a) Sgn function (b) Saturation function, (c) Sigmoid function=2

Fig. 2. Results under different horizontal driving force

From Figure 2, we can conclude that the jitter of the horizontal driving force $f_1$of the crane can be greatly suppressed when the Sgn function is replaced by the Sigmoid function. The driving force tends to be stable about 7s, which proves the feasibility of suppressing the chattering.

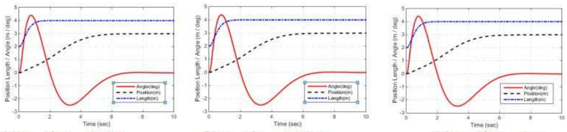
With the UPSO-DSMC control, a control experiment is performed on a bridge crane system as the load mass m is changed from 5kg to 1kg and the damper coefficient varies from 0.2 to 1. Results of control and motor driving force are shown in Figure 3 and Fig. 4 respectively.



(a) Horizontal driving force of f_1 (b) Load lifting driving force of f_2

Fig. 3. Variation of motor driving force change curve

Figure 4 illustrates that the viable driving force as load mass m reduced is that, the horizontal driving force $f_1$and load lifting driving force f_2 are relatively small, while the result is basically unchanged. As damping D and f_1 slightly increased, the driving force of $f_2$had no obvious variation, it is the same as control results.



(a) m=5kg, D=0.2 (b) m=1kg, D=0.2 (c) m=5kg, D=1

Fig. 4. Control results under various load mass m and damping D

7. Conclusion

A novel UPSO-DSMC method is presented in this paper. The dynamic model of bridge crane is obtained by Lagrangianequations, and three sliding mode controllers are proposed for a crane to transport the payload along a predefined trajectory. One sliding mode controller is also designed to hoist and lower the payload to track the predefined trajectory, and another are used to control the trolley position and payload swing angle. Extensive experiments show that the proposed controller is effective and less affected by the initial conditions, external disturbance and parameters uncertainty. Also, experiments on different load mass and friction damping have shown that the proposed method has strong robustness and great potential for high performance control on overhead crane.

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