# OPTIMAL SLIDING MODE CONTROL PARAMETERS FOR MANIPULATOR ROBOT BASED ON BAT ALGORITHM

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**ABSTRACT**

*Tradition sliding mode controllers are commonly applied to a wide range of engineering systems, bay the control parameters are primarily selected based on the designer's experience and fine-tuned through experimentation. Swarm optimization algorithms have demonstrated their advantages in multi-variable and multi-objective problems, and the convergence to a global optimal point has been presented in numerous studies. This paper presents an optimal parameterization method for the sliding mode control using the BAT algorithm (a type of swarm optimization algorithms). Simulation results and comparisions conventional sliding mode control on a manipulator robot system demonstrate the effectiveness of this approach.*

## 1. INTRODUCTION

The field of robot manipulator Control is an area of significant interest, owing to the complex dynamics and ever-changing model parameters. Analyzing the dynamics of robot model involves studying the relationships of the forces acting on the robot arm's joints. Nonlinear dynamic models and complex relationships between the connecting joints are the reasons that make controlling a robot to follow a trajectory challenging in term of precision and sustainability. Therefore, designing control system using traditional control methods that depend on the robot system's dynamics is a highly challenging task. Many control synthesis methods have been implemented for this purpose. Error-based control methods, such as PID and their improvements, have been widely adopted. The disadvantage of these control systems is the difficulty in finding control parameters and the diminished control quality when the input magnitude varies significantly over time. Many studies utilize LQR and MPC controller, but they are all based on linear models, resulting in a rapid degradation in control quality when the system moves far from the operating point. Fuzzy controllers and controllers using neural networks have also been mentioned in numerous studies. Meeting the response time requirements is an issue that these methods have to confront. Evolutionary algorithms (Eas) used for optimizing control parameters for manipulator robot systems have also been subject of numerous research papers.

Sliding mode control is a control method suitable for non-linear systems like manipulator robots. The drawback of this control method is the occurrence of high-frequency chattering, which can sometime lead to suboptimal control quality. Numerous studies have presented techniques to reduce or eliminate this phenomenon [1]. In recent years, a technique for system turning known as swarm intelligence has seen significant development. The BAT algorithm learns from movement patterns of bats in foraging and obstacle avoidance to establish an optimization method for finding the global minimum of the objective function. This paper presents a method for designing a sliding mode controller an optimizing parameters using the BAT algorithm. The effectiveness of the proposed control law í demonstrated through simulations in MATLAB software, and its efficiency is showcased when compared to several traditional sliding mode control laws.

## 2. ROBOT MANIPULATOR MODEL AND SLIDING MODE CONTROL

### *2.1 Robot manipulator model*

The two-degree-of-freedom robot arm model is depicted in Figure 1. The robot consists of two rotational joints placed in the coordinate system as shown in the diagram. Joint $l_1$ can rotate around the z – axis using DC motor DC1. Joint $l_2$ rotates in a plane parallel to the z-axis, driven by DC motor DC2, with its center located at the endpoint of joint $l_1$. The purpose of the control system is to maintain the robot arm with an attached camera following a predefined or unknown trajectory. The values of the mases $m_1$ and $m_2$, as well as the lengths of joints $l_1$ and $l_2$, are provided in Table 1. These values will be used in the simulation and evaluation of system..

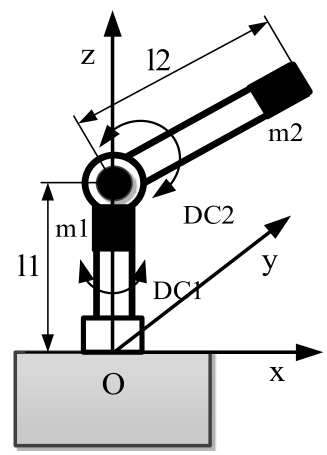


**Fig. 1.** *Model of a two-degree-of-freedom robot system with an attached camera*

**Table 1.** Robot arm model parameters

| Symbol | Description | Value | Unit |
|---|---|---|---|
| $m_1$ | Joint mass 1 | 30 | kg |
| $m_2$ | Joint mass 2 | 20 | kg |
| $l_1$ | Joint length 1 | 0.3 | m |
| $l_2$ | Joint length 2 | 0.4 | m |
| g | Gravitational acceleration | 9.81 | $m^2/s^2$ |

The dynamics of the camera-mounted robot arm are constructed based on Lagrange-Euler formula. The torques for joints 1 and 2 are denoted as $\boldsymbol{\tau}_1$ and $\boldsymbol{\tau}_2$ , respectively. These torques are generalted by the respective motors, DC1 and DC2.

The kinematical relations for each mass can be written easily:

$$\begin{cases} x_1 = 0 \\ y_1 = 0 \\ z_1 = l_1 \end{cases} \quad and \quad \begin{cases} x_2 = l_2\cos(\theta_2)\cos(\theta_1) \\ y_2 = l_2\cos(\theta_2)\sin(\theta_1) \\ z_2 = l_1 + l_2\sin(\theta_2) \end{cases} \qquad (1)$$

The potential and kinetic energies of the system are given by [18,19] :

$$\begin{aligned} V &= m_1 g l_1 + m_2 g(l_1 + l_2\cos(\theta_2)) \\ T &= \frac{1}{2}m_1(\dot{x}_1^2 + \dot{y}_1^2 + \dot{z}_1^2) + \frac{1}{2}m_2(\dot{x}_2^2 + \dot{y}_2^2 + \dot{z}_2^2) \end{aligned} \qquad (2)$$

By applying Lagrange’s equation [19]

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right) - \frac{\partial T}{\partial q_j} + \frac{\partial V}{\partial q_j} = \tau_j \qquad (3)$$

we get the following system of equations, after some manipulation

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{C}(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau} \qquad (4)$$

Where the state variable $\boldsymbol{q}, \boldsymbol{\tau}$ is defined by: $\boldsymbol{q}=[\theta_1\ \ \theta_2]^T$ , $\dot{\boldsymbol{q}} = [\dot{\theta}_1, \dot{\theta}_2]^T$ , $\ddot{\boldsymbol{q}} = [\ddot{\theta}_1, \ddot{\theta}_2]^T$ are vectors representing the position, velocity and angular acceleration of joints 1 and 2, $\boldsymbol{\tau}=[\tau_1,\tau_2]^T$ is the vector representing the torque acting on joints 1,2, and **M** represent the inertia matrix (symmetric positive definite) , **C** is the Coriolis and centrifugal matrix, gravity vector $\boldsymbol{g}=[g_{12},g_{21}]^T$ which is given by:

$$\mathbf{M} = \begin{bmatrix} m_2 l_2^2 \sin^2(\theta_2) & 0 \\ 0 & m_2 l_2^2 \end{bmatrix};$$

$$\mathbf{C} = \begin{bmatrix} m_2 l_2^2 \sin(2\theta_2)\dot{\theta}_2 & 0 \\ -m_2 l_2^2 \sin(2\theta_2)\dot{\theta}_1 & 0 \end{bmatrix};$$

$$\mathbf{g} = \begin{bmatrix} 0 \\ -m_2 g l_2 \sin(\theta_2) \end{bmatrix}$$

### *2.2 Principle of sliding mode control*

The essence of sliding mode control can be summarized in the diagram below:

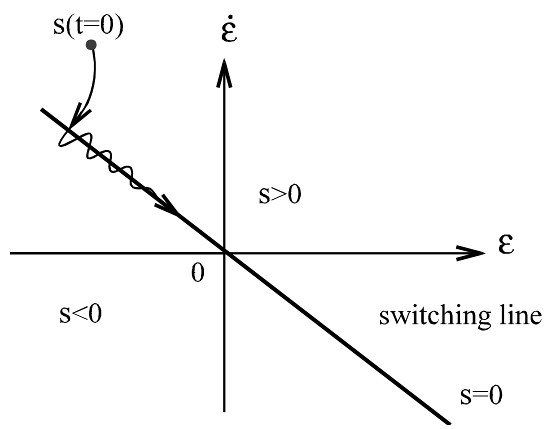


**Fig. 2.** *The sling surface on the plane* $\mathbf{e} - \dot{\mathbf{e}}$

Figure 2 represents oscillationans around the sliding sufare $\mathbf{s} = \mathbf{0}$ on the plane $\mathbf{e} - \dot{\mathbf{e}}$ , if the sliding condition $\mathbf{s}^T\dot{\mathbf{s}} < 0$ is met, then $\mathbf{s}$ is the sliding sufare, and the control system’s trajectory will oscillate around the sliding suface towards the origin of the coordinate system. Typically, the sliding plane is chosen in the form PID controller.

$$\mathbf{s}(t)=\dot{\mathbf{e}}+\mathbf{C}_1\mathbf{e}+\mathbf{C}_2\int_0^t \mathbf{e}\,dt \qquad (5)$$

$\mathbf{C_1}$, $\mathbf{C_2}$ are positive definite diagonal matrices and $\mathbf{s}=\left[s_1,s_2,.......s_n\right]^T$.

$\mathbf{e}=\mathbf{q}_d-\mathbf{q}$ is the control error at joints

According to the sliding mode control principle, when $t\to\infty$ will make $\mathbf{s}=\mathbf{0}$.

+

The system will be asymptotically stable with $\mathbf{e} = \mathbf{0}$, when $t\to\infty$ or $\mathbf{q}(t)\to\mathbf{q}_d(t)$ is the unique solution

For a robotic system with a dynamic equation described as equation (4), the essence of the sliding method for this system is to find an appropriate control signal such that systems (5) is asymptotically stable, meaning that **s(t) → 0**.

### *2.3 Simulating robot control using the traditinal sliding control method*

With the determined control signal [1]

$$\boldsymbol{\tau}=\mathbf{M}\ddot{\mathbf{q}}_d+\mathbf{B}\dot{\mathbf{q}}_d+\mathbf{g}\text{-}\mathbf{M}\mathbf{C}_1\dot{\mathbf{e}}\text{-}\mathbf{M}\mathbf{C}_2\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_1\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_2\int_0^t \mathbf{e}\,dt\text{-}\mathbf{K}\mathbf{s}\text{-}\gamma\mathbf{s}\left\|\mathbf{s}\right\|^{-1}$$

Torque $\boldsymbol{\tau}$ consists of two components: the nonlinear compensatory component

$$\boldsymbol{\tau}_{ff}=\mathbf{M}\ddot{\mathbf{q}}_d+\mathbf{B}\dot{\mathbf{q}}_d+\mathbf{g}\text{-}\mathbf{M}\mathbf{C}_1\dot{\mathbf{e}}\text{-}\mathbf{M}\mathbf{C}_2\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_1\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_2\int_0^t \mathbf{e}\,dt$$

And the sliding component $\boldsymbol{\tau}_s=\text{-}\mathbf{K}\mathbf{s}\text{-}\gamma\mathbf{s}\left\|\mathbf{s}\right\|^{-1}$

$\mathbf{K}=\mathbf{K}^T>\mathbf{0}$ is an n*n symmetric and positive definite matrix, $\gamma>0$

Control model

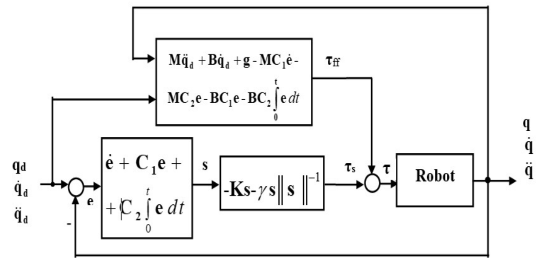


**Fig. 3.** *Control system struture diagram with PID sliding surface*

**Table 2.** Performance criteria

| Performance criteria | Limit value | Unit |
|---|---|---|
| Settling time (T) | 10 | sec |
| Rise time ($T_C$) | $\leq 3$ | sec |
| Overshoot ($O_C$) | $\leq$ 20% Setpoint ($Q_c$) | |
| Number of oscillations (N) | $\leq 2$ | |
| Limit torque on joint 1 | $-2,000.0\leq\tau_1\leq+2,000.0$ | N.m |

Choose: $\mathbf{K}=\begin{bmatrix}1000 & 0\\ 0 & 1000\end{bmatrix}$; $\gamma$ =20 ;

$$\mathbf{C}_1=\begin{bmatrix}15 & 0\\ 0 & 15\end{bmatrix};\mathbf{C}_2=\begin{bmatrix}20 & 0\\ 0 & 20\end{bmatrix}$$

The friction and disturbance componets are assumed to be:

$$\mathrm{d}(\mathrm{q},\dot{\mathrm{q}})=\mathrm{d}(\mathrm{t})=\begin{pmatrix}3\sin(20\boldsymbol{t})+1+5\dot{\boldsymbol{q}}_1\\ \cos(20\boldsymbol{t})+3\dot{\boldsymbol{q}}_2\end{pmatrix}$$

The robot's gripper will move in a circular path centered at coordinates (0.8, 0.8) with an angle of 3π/2 counterclockwise. With the robot's initial state being:

$$\begin{pmatrix}x_i\\ y_i\end{pmatrix}=\begin{pmatrix}0.8\\ 0.8\end{pmatrix}+0.7\begin{pmatrix}\cos\alpha\\ \sin\alpha\end{pmatrix},$$

Simulation results of the robot's operation using the traditional sliding control method are as follows :

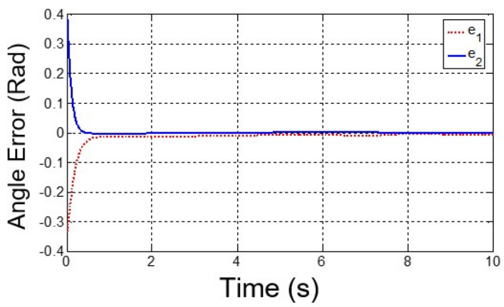


**Fig. 4a.** *Positional error of joints 1 and 2 in the coordinate space*

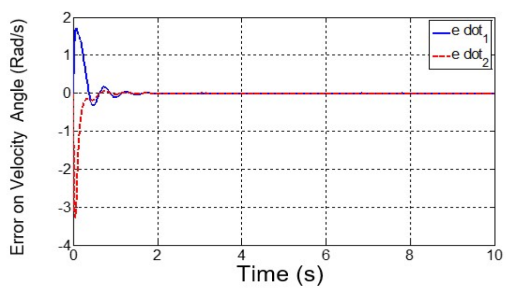


**Fig. 4b.** *Velocity error of joints 1 and 2 in the coordinate space*

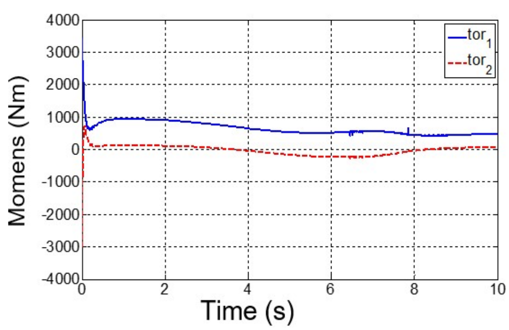


**Fig. 4c**. *Representation of the torque applied to joints 1 and 2*

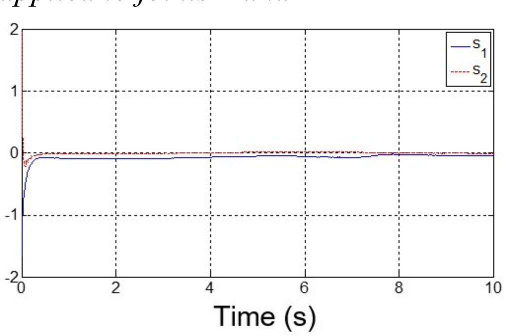


**Fig. 4d.** *Representation of the variation in the sliding surface* **s**

**Comments**: The system is stable, but there are remaining position and angular velocity errors due to chattering phenomena and static error components. This is slso evident in the graph in Figure 4d, where the sliding surface **s** and do not connverge to zero. The simulation results validate the author's arguments about the stability and robustness of the sliding control method, as well as the remaining drawbacks of this method.

The choice of parameters can affect the time **s**(t) **→ 0**, when **s**(t) **= 0**, chattering phenomenon will decrease rapidly if an appropriately powered motor is selected. Many studies have discussed the selection of the components of the matrix **C**. This paper introduces a method for parameter selection based on the BAT algorithm

## 3. OPTIMIZING THE PARAMETERS OF THE SLIDING CONTROL USING THE BAT ALGORITHM

### *3.1 BAT Algorithm*

The BAT algorithm, proposed by Xin She Yang, is based on some echolocation characteristics of bat [15]. In the agorithm, the followwing heuristic or idealization rules are used [16,17,18]

- All bats use echolocation to recognize distances, and they also distinguish between food, prey and obstacles;

- Bats fly randomly with a velocity $v_i$ at position $x_i$. They can autonomously adjust the frequency Q (or wavelength) of emitted pulses and adjust the pulse width $r \in [0,\ 1]$, depending on the distance to the target;

- While the magnitude of the echolocation sound can vary in many ways, it is assumed that the magnitude of the acholocation sound varies from a maximum value $A_0$ to a minimum value $A_{\min}$.

The algorithm optimizes the components of the matrix **C** as follows:

1. Initialize a population of bats (n) with random positions ($x_i$) and velocities ($v_i$) for both parameters $\mathbf{C_1}$, $\mathbf{C_2}$ ;

2. Evaluate the objective fuction values for all individuals of the bat population initialized in the previous step;

3. Compare the objective fuction values obtained to find the bat ($n_{best}$) with the corresponding position and velocity that achieves the best objective function value;

4. Update the pulse rate Q and velocity v of all bats according to ths following equation:

$$Q_{k+1} = Q_{\min} + (Q_{\min} - Q_{\max}) * rand;$$
$$v_{k+1} = v_k + (x_k - x_{best})Q_{k+1}$$

5. Update the position of all bats according to the following equation:

$$x_{k+1} = x_k + v_k$$

6. Update the position of a bat individual if the pulse width (r) is smaller than the pulse width of a randomly generated signal (ran);

$$\text{if}(rand > r)$$
$$x_{k+1}^{new} = x_{best} + \alpha.rand$$

7. Check the condition $(rand < A \,\&\, f(x_{k+1}^{new}) < f(x_{k+1}))$ accept the new population and increase the pulse width (r) while decreasing the loudness (A);

8. Check if the best valus of the new position in the bat populatin is smaller than the required value. If it is, and the algorithm; otherwise, repeat step 4.

The objective function of the BAT algorithm is chosen by the author's group is to be the ITAE (Intergral of Time-weighted Absolute Error) function:

$$ITAE: \quad F = \int t\left|e(t)\right|dt$$

***3.2 Simulating robot control using the sliding control method and optimizing the controller parameter with the BAT algorithm***

With the same simulation parameters and conditions as when the BAT algorithm was not used.

$$\boldsymbol{\tau} = \mathbf{M}\ddot{\mathbf{q}}_d + \mathbf{B}\dot{\mathbf{q}}_d + \mathbf{g}\text{-}\mathbf{M}\mathbf{C}_1\dot{\mathbf{e}}\text{-}\mathbf{M}\mathbf{C}_2\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_1\mathbf{e}\text{-}\mathbf{B}\mathbf{C}_2\int_0^t \mathbf{e}\,dt\text{-}\mathbf{K}\mathbf{s}\text{-}\gamma\mathbf{s}\left\|\mathbf{s}\right\|^{-1}$$

Choosen: $\mathbf{K} = \begin{bmatrix} 1000 & 0 \\ 0 & 1000 \end{bmatrix}$; $\gamma = 20$

Using the BAT algorithm, we determined

$$\mathbf{C}_1 = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}; \mathbf{C}_2 = \begin{bmatrix} 25 & 0 \\ 0 & 25 \end{bmatrix}.$$

The simulation results are as follows:

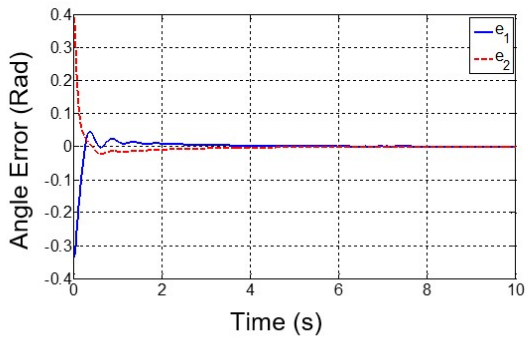


**Fig. 5a.** *Positional error of joints 1 and 2 in the coordinate space*

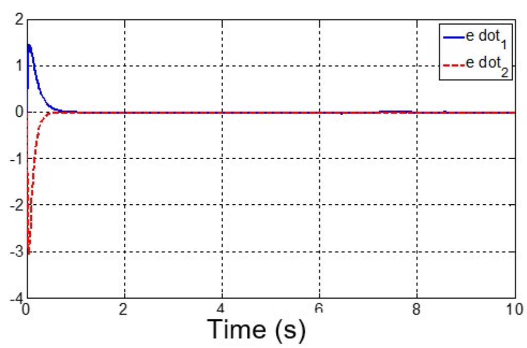


**Fig. 5b.** *Velocity error of joints 1 and 2 in the coordinate space*

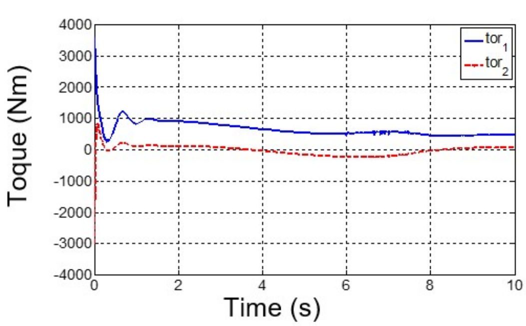


**Fig. 5c.** *Representation of the torque applied to joints 1 and 2, the matrix C has been optimized*

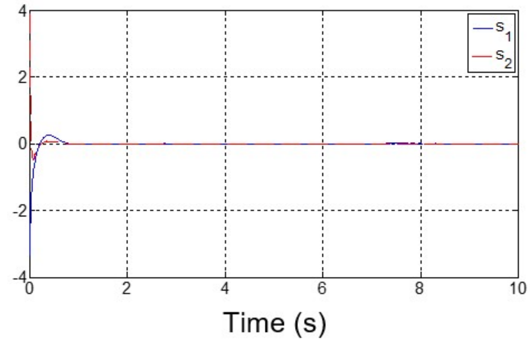


**Fig. 5d.** *The change in the sliding surface* **s** *with the optimied matrix* **C**

**Comments:** The system reaches stability, and initial values of the torques on joints 1 and 2 decrease significantly compared to traditional sliding control. The system will no longer have static errors, and the torque on the system will have a narrower range of variation. However, when the integral component is introduced into the sliding surface, it can result in larger overshoot during the transient process, leading to oscillations. Therefore, depending on the requirements and parameters of the robot system for each specific problem, we can choose between a PD or PID sliding surfaces that best suits the situation.

## CONCLUSION

Sliding control offers many advantages, especially robustness against noise and uncertainty in the parameters of robot model. Based on this method, the paper proposed a sliding control moden using the BAT slgorithm to optimize the control parameters. The robot controller uses sliding control with the sliding surface parameters optimized by the BAT algorithm, ensuring that the sliding surface **s** approaches zero, meets real-time requirements, and significatly reduces chattering. The sliding control system still maitains global stability, as demonstrated mathematically. With these proven results, depending on the control requiments, we cam design optimal sliding control systems using either PD or PID silding surfaces that suit the robot's parameters.

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