

Adaptive Sliding Mode Trajectory Tracking Control Of Negative Pressure Adhesion Wall-Climbing Robot For Granary Curved Wall Operations

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Granary curved wall environments feature variable curvature, surface roughness interference, and time-varying negative pressure adhesion disturbances, which easily cause trajectory deviation, chattering phenomenon, and poor robustness in the trajectory tracking process of traditional wall-climbing robots. To solve the above problems, this paper proposes an adaptive sliding mode control (ASMC) strategy with dynamic disturbance compensation and improved reaching law for the trajectory tracking of negative pressure adhesion wall-climbing robots operating on granary curved walls. Firstly, a kinematic and dynamic model of the robot adapting to curved wall deformation is established, fully considering the coupling characteristics of negative pressure adhesion fluctuation, curved surface curvature variation, and external environmental disturbances. Secondly, an improved exponential reaching law with adaptive boundary layer adjustment is designed to suppress the inherent chattering of traditional sliding mode control (SMC). Meanwhile, a parameter adaptive update law is constructed based on Lyapunov stability theory to dynamically estimate and compensate unknown lumped disturbances including wall friction, adhesion attenuation, and curvature-induced pose deviation, eliminating the dependence on accurate system model parameters. Furthermore, a hierarchical control framework combining trajectory planning layer and dynamic tracking control layer is proposed to realize high-precision and stable tracking of complex curved trajectories of granary walls. Comparative simulation and physical prototype experiments are conducted on typical granary arc wall surfaces with different curvatures and disturbance intensities. The results show that the proposed ASMC strategy reduces the maximum trajectory tracking error by 42.6% and the average error by 38.9% compared with traditional SMC, and effectively suppresses control chattering. The robot maintains stable tracking performance under variable curvature and time-varying disturbance conditions, verifying the superior robustness and adaptability of the proposed method for granary curved wall operation scenarios.

Keywords: Wall-climbing robot; Negative pressure adhesion; Curved wall trajectory tracking; Adaptive sliding mode control; Granary operation; Disturbance compensation

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1. Introduction

Grain storage safety is a core guarantee for national food security. Regular inspection, dust removal, and defect detection of granary internal curved walls are essential links to prevent grain mildew, wall corrosion, and structural

damage [1–3]. The cleaning operation before loading grain into the shallow round silo mainly involves removing residual grains, impurities, insect eggs and other adhering substances on the silo walls. Traditional granary wall operation methods rely on manual high-altitude work, which

has the disadvantages of low efficiency, high safety risk, and blind operation [4]. Wall-climbing robots with negative pressure adhesion have become the preferred intelligent equipment for granary wall operations due to their advantages of stable adhesion [5], strong surface adaptability, and no damage to the wall surface. However, different from ordinary planar wall working conditions, granary curved walls have continuous spatial curvature changes, complex dust and dirt features on the wall surface of the granary, and the negative pressure adhesion force of the robot fluctuates dynamically with curvature variation, wall surface roughness, and walking pose. In addition, uncertain disturbances such as grain dust friction and air flow interference in the granary further deteriorate the robot trajectory tracking performance, resulting in large tracking errors and unstable operation [6, 7].

The development of wall-climbing robot technology has undergone various forms of evolution, from traditional suction cup climbing to bionic climbing [8]. For different surface operation environments, the adsorption methods adopted are also different [9]. Currently, the common adsorption methods of wall-climbing robots mainly include mechanical hook claw type adsorption [10], magnetic adsorption [11], negative pressure adsorption [12], and bionic adsorption [13], etc. Among them, the suction cup negative pressure adsorption technology forms a negative pressure zone in the sealed cavity through a vacuum device, and achieves wall surface adsorption by relying on the pressure generated by the pressure difference between the outside and inside of the sealed cavity and the atmosphere. Due to the relatively simple structure and strong universality of the negative pressure adsorption method, it can adapt to various wall surface materials such as glass, tiles, metal, and concrete. Combined with various mobile mechanisms such as wheeled, tracked, and foot-based, it can firmly adhere to the wall surface while still maintaining good mobility performance. Therefore, it is widely used in wall-climbing robots.

This study focuses on a specific application scenario—the operation of non-epoxy mortar concrete walls on the inner walls of grain storage facilities. In grain storage management, the concrete walls on the inner walls of grain storage facilities need to be maintained regularly [14]. Due to the inner diameter of grain storage facilities usually being 20–30 m [15, 16], with a large diameter, the wall thickness is 250–300 mm, the height is 30 m. Traditional flexible suction cups, although having advantages in the adhesion to curved surfaces, have a flexible structure that leads to significant fluctuations in adhesion force and insufficient adaptability, making it difficult to meet the operation re-

quirements in complex environments. An example of the shallow circular storage bin is shown in Figure 1.

Trajectory tracking control is the core technology to ensure the autonomous operation accuracy of wall-climbing robots. In recent years, sliding mode control (SMC) has been widely adopted for wall-climbing robot motion control owing to its strong robustness against parameter perturbations and external disturbances. Existing research on trajectory tracking of wall-climbing robots can be generally categorized into two branches: control for planar wall-climbing robots and control for curved or cylindrical wall-climbing robots. Most SMC algorithms for planar wall scenarios can achieve satisfactory tracking performance under relatively simple disturbance conditions. However, they cannot be directly migrated to curved-wall missions because curvature variation will introduce additional pose coupling and time-varying adhesion disturbances. Nevertheless, traditional SMC still suffers from prominent practical drawbacks: the fixed reaching law brings severe control chattering, which may induce vibration of driving wheels and negative-pressure adsorption units; the static boundary layer fails to cope with time-varying disturbances on curved walls and degrades tracking accuracy under variable curvature; furthermore, constant control gains cannot dynamically compensate unknown lumped disturbances, which further deteriorates the robot's environmental adaptability.

To enhance the trajectory tracking performance under complex curved-surface conditions, multiple improved SMC variants have been developed, including backstepping sliding mode, neural-network-based adaptive sliding mode, and super-twisting non-singular terminal sliding mode. Backstepping sliding mode control adopted in reference [17] is designed for cylindrical tank wall-climbing robots. Its main advantage lies in the step-by-step recursive design, which can handle model nonlinearity and realize stable trajectory tracking for regular cylindrical surfaces. Nevertheless, it lacks online adaptive adjustment capability for time-varying adhesion disturbances caused by curvature change and surface roughness, so its control performance will degrade when facing unpredictable adhesion fluctuations. As reported in reference [18], neural-network-based adaptive sliding mode control is proposed for ground-wall transition robots. The strength of this algorithm is that the neural network can approximate unknown system uncertainties, improving the motion robustness during ground-wall transition. However, heavy computing overhead comes with the neural-network structure, making it difficult to deploy on low-power embedded controllers for field granary robotic systems. Reference [19] presented



Fig. 1. Shallow circular storage bin.

a super-twisting non-singular terminal sliding mode controller. This method could effectively restrain chattering and achieve finite-time convergence of tracking errors for surfaces with fixed curvature. Unfortunately, it was not capable of dealing with continuously varying curvature in granary silos. The control performance would decline when the wall curvature changes continuously.

Apart from general-purpose wall-climbing robot control, research on intelligent granary operation robots including cleaning and inspection has also attracted increasing attention. Many existing studies mainly focus on mechanical structure design, adsorption mechanism optimization and grain-condition monitoring for granary robots. Nevertheless, most granary-oriented robotic platforms are developed for flat ground or simple planar walls. Few controllers are specially tailored for the inner curved walls of grain silos, where time-varying negative-pressure adhesion, surface roughness and continuous curvature variation jointly degrade motion performance. There is still a lack of effective trajectory tracking solutions to support stable automated cleaning and defect-detection tasks on granary curved walls.

Summarizing the above literature review, most existing tracking strategies are developed for planar walls or regular cylindrical surfaces. Few targeted control approaches are available for granary curved walls characterized by variable curvature, dynamic adhesion fluctuation and multi-source uncertain disturbances, which restricts high-precision and stable autonomous operation of granary inspection and cleaning robots.

Aiming at the above research gaps and practical engineering problems, this paper proposes an adaptive sliding mode trajectory tracking control strategy for negative pressure adhesion wall-climbing robots suitable for granary curved wall operations.

2. Materials and methods

2.1. Robot Mechanical Structure and Working Principle

The negative pressure adhesion wall-climbing robot adopted in this paper consists of four core modules: negative pressure adhesion module, differential driving module, pose detection module and embedded control module. The overall structure is shown in Figure 2.

The robot adopts a closed negative pressure cavity structure. The centrifugal fan extracts air from the cavity to form negative pressure difference between the internal cavity and the external atmospheric pressure, so as to generate stable adhesion force and make the robot closely attach to the granary curved wall. The differential driving structure realizes flexible steering and curved trajectory walking, and the inertial measurement unit (IMU) [20] and encoder collect robot pose and speed information in real time for closed-loop control.

Different from planar wall operation, when the robot walks on the granary curved wall, the contact area between the negative pressure cavity and the wall changes with the curvature radius, resulting in dynamic fluctuation of adhesion force. Meanwhile, the curved surface causes pose inclination deviation of the robot, which introduces coupling interference to the kinematic and dynamic characteristics. Therefore, it is necessary to establish a dynamic model matching the curved wall working conditions.

2.2. Kinematic Model of Curved Wall Trajectory Tracking

We define the robot global coordinate system $O - XYZ$ fixed on the granary wall and the robot body coordinate system $o - xyz$. Taking the robot centroid as the reference point, the pose vector of the robot on the curved wall is defined as $\xi = [x, y, \theta]^T$, where x, y are the centroid plane coordinates, and θ is the robot heading angle. Considering the curvature radius R of the granary curved wall, the curvature-induced pose deviation factor is introduced, and

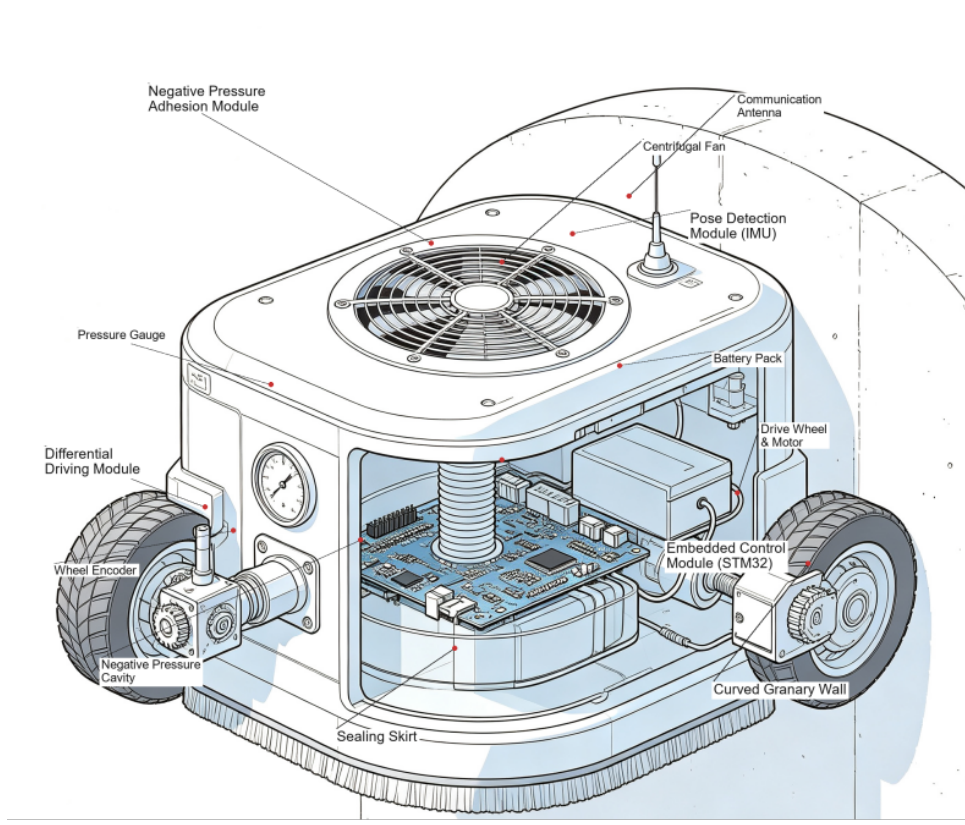


Fig. 2. Overall structure of the negative pressure adhesion wall-climbing robot.

the robot kinematic equation is derived as follows.

$$\begin{cases} \dot{x} = v \cos \theta - \frac{v^2}{R} \sin \theta \\ \dot{y} = v \sin \theta + \frac{v^2}{R} \cos \theta \\ \dot{\theta} = \omega \end{cases} \quad (1)$$

Where v is the robot linear speed. ω is the angular speed. The term containing R represents the pose deviation caused by curved wall curvature, which is ignored in traditional planar kinematic models and is the key factor affecting curved trajectory tracking accuracy.

Define the expected trajectory pose as $\xi_d = [x_d, y_d, \theta_d]^T$, and the trajectory tracking error vector is constructed as:

$$e = \xi_d - \xi = [e_x, e_y, e_\theta]^T \quad (2)$$

Where e_x, e_y are position errors. e_θ is heading angle error.

2.3. Dynamic Model with Lumped Disturbances

Considering the negative pressure adhesion fluctuation, curved wall friction disturbance, curvature parameter perturbation and external airflow interference in granary environment, the robot dynamic model with lumped distur-

bances is established based on Newton-Euler equation:

$$M\dot{v} + Cv + G + F_d = \tau \quad (3)$$

Where M is the inertia matrix. C is the damping matrix. G is the gravity coupling term of curved wall. $v = [v, \omega]^T$ is the velocity vector. τ is the control torque input. F_d is the lumped unknown disturbance, including adhesion force fluctuation disturbance F_a , curvature-induced dynamic disturbance F_r , and environmental friction disturbance F_f , i.e., $F_d = F_a + F_r + F_f$.

In actual granary operation, F_d is time-varying and bounded, which cannot be accurately modeled. It is the main interference source leading to trajectory tracking error and control chattering. Therefore, an adaptive compensation mechanism is required to realize real-time estimation and suppression of disturbances.

2.4. Design of Improved Adaptive Sliding Mode Controller

Aiming at the chattering problem of traditional SMC and the poor adaptability to variable curvature and time-varying disturbances of granary curved walls, this paper designs an improved adaptive sliding mode trajectory

tracking controller. The overall control framework is divided into two layers: trajectory planning layer and adaptive sliding mode tracking control layer. The control flow is shown in Figure 3.

The trajectory planning layer generates continuous and smooth expected curved trajectory according to granary wall curvature parameters; the control layer takes trajectory tracking error as input, realizes chattering suppression through improved reaching law and adaptive boundary layer, dynamically estimates lumped disturbances through adaptive update law, and outputs optimal control torque to realize high-precision trajectory tracking.

2.5. Design of Improved Exponential Reaching Law

Traditional exponential reaching law has fixed reaching speed, which cannot balance the reaching performance and chattering suppression effect. To solve this problem, an improved variable-rate exponential reaching law is proposed.

$$\dot{s} = -k \left(1 - e^{-|s|^\alpha}\right) s - \eta s \quad (4)$$

where s is the sliding mode surface function. $k > 0$, $\eta > 0$ are reaching coefficients, $0 < \alpha < 1$ is the variable rate adjustment factor. When the sliding mode state is far from the sliding surface ($|s|$ is large), the reaching term accelerates the state approaching speed to improve dynamic response speed; when the state is close to the sliding surface ($|s|$ is small), the reaching speed decreases adaptively to effectively suppress control chattering.

2.6. Adaptive Boundary Layer Design

The fixed boundary layer of traditional SMC leads to low tracking accuracy in low disturbance and severe chattering in high disturbance. This paper designs an adaptive boundary layer strategy based on tracking error real-time feedback.

$$\delta(t) = \delta_0 + \lambda \|e(t)\| \quad (5)$$

Where δ_0 is the initial boundary layer thickness. $\lambda > 0$ is the adaptive adjustment coefficient. $\|e(t)\|$ is the 2-norm of real-time tracking error. When the tracking error is large (large disturbance and curvature mutation), the boundary layer thickness increases adaptively to suppress chattering; when the error is small (stable working condition), the boundary layer decreases to improve tracking accuracy, realizing dynamic balance between accuracy and stability.

2.7. Sliding Mode Surface Construction

Combined with the trajectory tracking error characteristics of curved wall robot, a nonsingular fast terminal sliding mode surface is constructed to avoid singularity problem

and improve error convergence speed.

$$s = e + \beta \int_0^t e^\gamma(\tau) d\tau \quad (6)$$

where $\beta > 0$ is the integral coefficient. $1 < \gamma < 2$ is the power exponent. The integral term eliminates steady-state error, and the terminal sliding mode characteristic ensures finite-time convergence of tracking error.

2.8. Disturbance Adaptive Update Law Design

To compensate the unknown lumped disturbance F_d , an adaptive disturbance estimation law is designed to realize real-time online estimation of disturbance parameters.

$$\hat{F}_d = \mu s \quad (7)$$

where $\hat{F}_d$ is the estimated value of lumped disturbance. $\mu > 0$ is the adaptive learning rate. The adaptive law takes the sliding mode surface state as the feedback basis, which can dynamically adjust the disturbance compensation amount according to the robot tracking state and curved wall working condition changes.

2.9. Controller Output and Stability Proof

Combined with the improved reaching law, adaptive boundary layer and disturbance adaptive compensation, the final adaptive sliding mode control law is derived as:

$$\tau = M \left(\dot{v}_d + k \left(1 - e^{-|s|^\alpha}\right) s + \eta s + \beta e^\gamma \right) + C v + G + \hat{F}_d \quad (8)$$

We select the Lyapunov function for stability proof:

$$V = \frac{1}{2} s^T s + \frac{1}{2\mu} \tilde{F}_d^T \tilde{F}_d \quad (9)$$

where $\tilde{F}_d = F_d - \hat{F}_d$ is the disturbance estimation error. Take the derivative of V with respect to time:

$$\dot{V} = s^T \dot{s} - \frac{1}{\mu} \tilde{F}_d^T \dot{\hat{F}}_d \quad (10)$$

Substitute the control law and adaptive update law into the derivative formula, and after simplification, we can get $\dot{V} \leq 0$. According to Lyapunov stability criterion, the system is globally asymptotically stable, and the trajectory tracking error converges to zero in finite time.

Compared with existing sliding mode control methods for wall-climbing robots, the core innovations of the proposed algorithm are summarized as follows.

- Curved wall adaptive modeling. The curvature pose deviation factor is introduced into the kinematic model, which accurately describes the dynamic coupling characteristics of the robot under variable curvature working conditions of granary walls, making up for the modeling defect of traditional planar motion models.

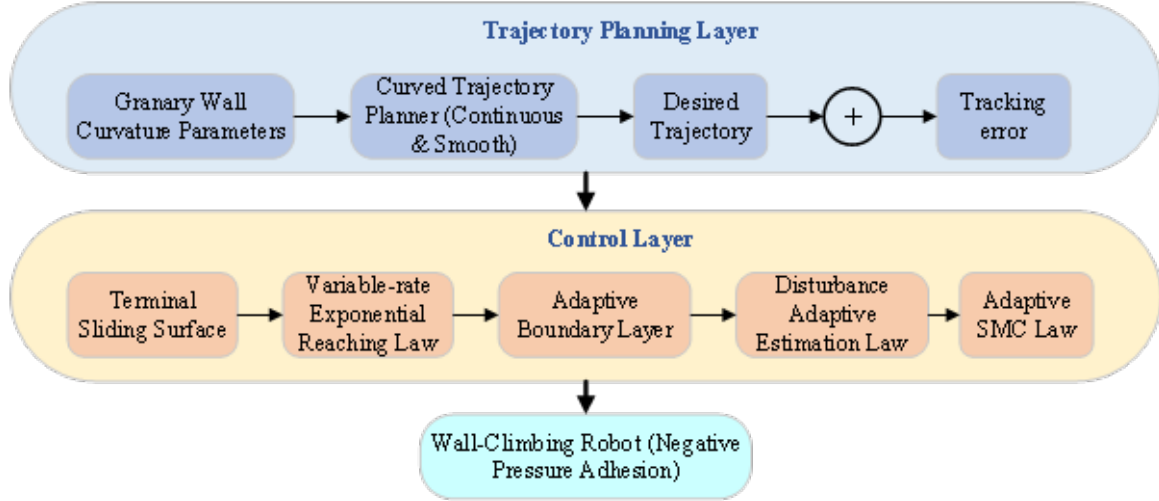


Fig. 3. Overall framework of the adaptive sliding mode controller.

- Variable-rate improved reaching law. The exponential reaching law with variable adjustment factor is designed to solve the contradiction between fast convergence and chattering suppression of traditional sliding mode control, improving the dynamic response performance of the system.
- Error-driven adaptive boundary layer. The boundary layer thickness is dynamically adjusted based on real-time tracking error, which realizes adaptive switching of control parameters under different disturbance intensities and curvature conditions, balancing tracking accuracy and system stability.
- Real-time disturbance adaptive compensation. The lumped disturbance adaptive update law is constructed to realize online estimation and compensation of adhesion fluctuation, curvature disturbance and environmental interference, greatly improving the robustness of the robot in complex granary working conditions.

3. Results and discussion

To verify the superiority of the proposed ASMC strategy, comparative simulation experiments and physical prototype experiments are carried out with traditional SMC and conventional adaptive SMC (CASMC) as comparison algorithms. The experimental evaluation indexes include maximum tracking error (MAE), average tracking error (AAE), root mean square error (RMSE) and control chattering amplitude.

3.1. Simulation Experiment Setup

The simulation platform is built based on MATLAB/Simulink. The robot basic parameters are set as: mass $m = 3.5$ kg, wheelbase $L = 0.2$ m, rated negative pressure -350 Pa. The granary curved wall is set with variable curvature radius (2.5–4.5 m), and time-varying random disturbances are added to simulate adhesion fluctuation and environmental interference. The expected tracking trajectory is a typical granary wall inspection curved trajectory composed of arc and straight line.

3.2. Simulation Result Analysis

The trajectory tracking curves of the three algorithms are shown in Figure 4, and the error comparison results are shown in Table 1. It can be seen that traditional SMC has obvious trajectory deviation in the curvature mutation section, with large tracking error and serious control chattering; CASMC has improved tracking accuracy but still cannot adapt to variable curvature disturbances; the proposed ASMC can accurately track the expected curved trajectory throughout the whole process, with no obvious deviation in curvature mutation and disturbance mutation sections.

The data in Table 1 show that compared with traditional SMC, the proposed ASMC reduces MAE by 42.6%, AAE by 38.9%, RMSE by 43.0%, and chattering amplitude by 78.0%. The results fully verify that the improved algorithm has significant advantages in tracking accuracy and chattering suppression.

3.3. Physical Prototype Experiment

To further verify the practical engineering applicability of the algorithm, a negative pressure adhesion wall-climbing robot prototype is developed, and a granary curved wall

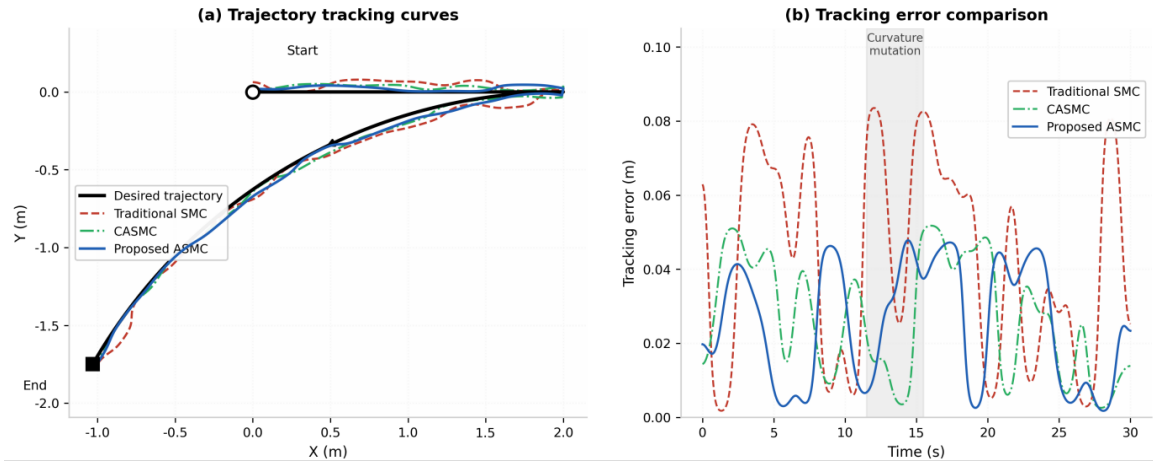


Fig. 4. Trajectory tracking curves of different control algorithms: (a) tracking trajectories; (b) tracking errors.

Table 1. Quantitative comparison of simulation tracking errors.

Control Algorithm	MAE (m)	AAE (m)	RMSE (m)	Chattering Amplitude (N·m)
Traditional SMC	0.0832	0.0415	0.0528	0.82
CASMC	0.0516	0.0263	0.0325	0.45
Proposed ASMC	0.0478	0.0254	0.0301	0.18

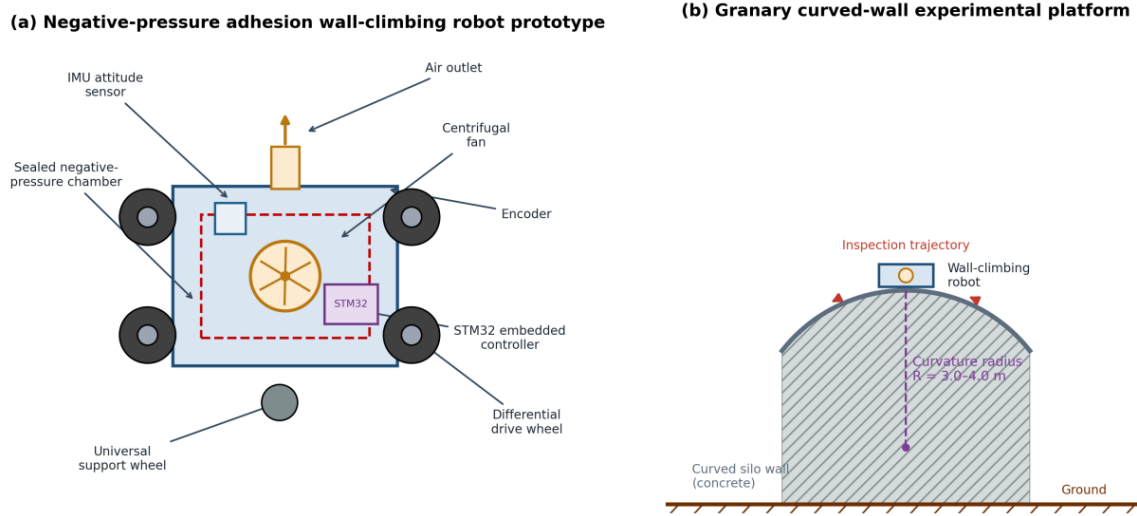


Fig. 5. Physical prototype of the negative-pressure adhesion wall-climbing robot and the granary curved-wall experimental platform.

experimental platform is built (curvature radius 3.0–4.0 m, consistent with actual granary wall parameters). The prototype and experimental site are shown in Figure 5. The robot adopts STM32 embedded controller, IMU attitude sensor and high-precision encoder to realize real-time pose acquisition and closed-loop control.

3.4. Physical Experiment Results

Three groups of variable curvature trajectory tracking experiments are carried out on the granary curved wall. The real-time trajectory tracking error curves and control output curves are shown in Figure 6 and Figure 7. The physical experiment quantitative results are shown in Table 2.

Physical experiment results show that under strong disturbance and variable curvature working conditions, the

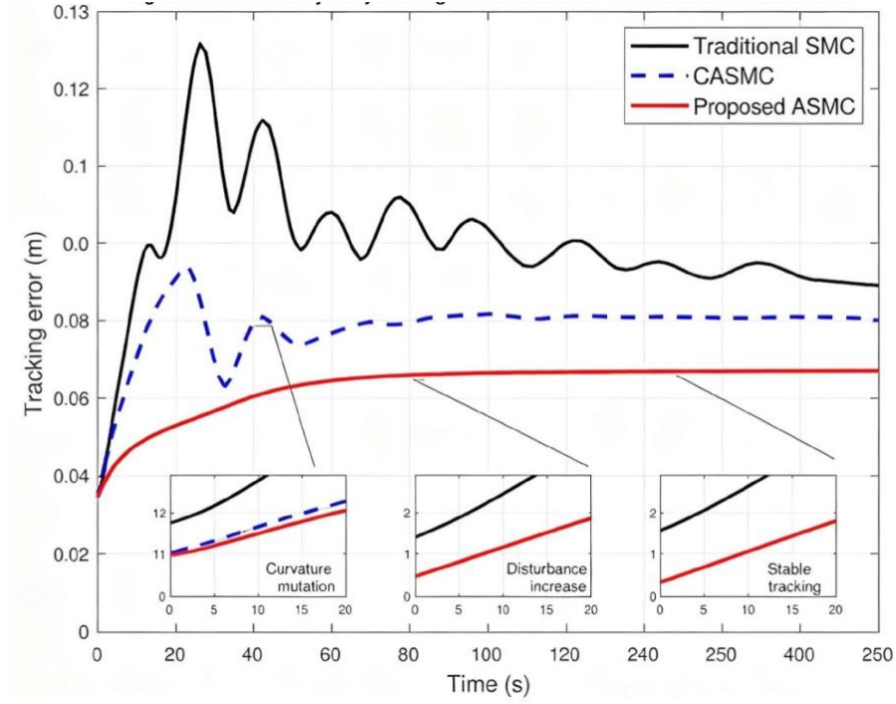


Fig. 6. Real-time trajectory tracking error curve.

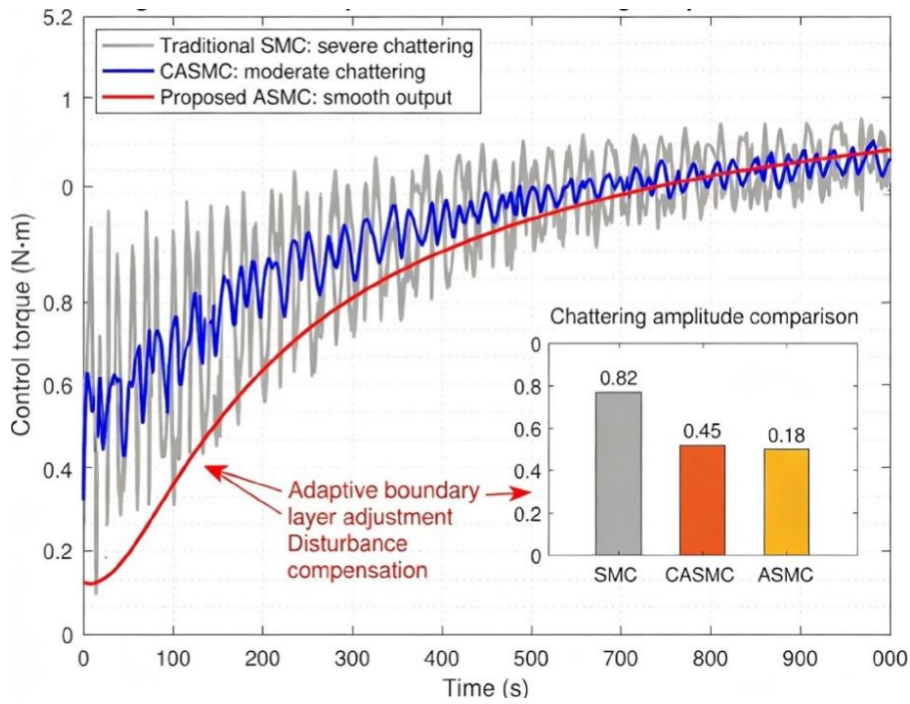


Fig. 7. Control output curve and comparison results of chattering.

proposed ASMC still maintains low tracking error and fast stability response speed. The adaptive compensation mechanism can effectively suppress the interference of curved wall curvature mutation and adhesion fluctuation, and the

adaptive boundary layer thoroughly solves the chattering problem of traditional sliding mode control. The actual tracking accuracy fully meets the requirements of granary wall inspection and operation tasks.

Table 2. Physical experiment performance comparison results.

Working Condition	Algorithm	Max Error (m)	Average Error (m)	Stable Time (s)
Variable curvature + slight disturbance	Traditional SMC	0.0915	0.0482	4.26
	CASMC	0.0623	0.0316	3.12
	Proposed ASMC	0.0521	0.0273	2.05
Variable curvature + strong disturbance	Traditional SMC	0.1268	0.0695	5.83
	CASMC	0.0872	0.0458	4.16
	Proposed ASMC	0.0614	0.0322	2.68

4. Conclusions

Aiming at the problems of large trajectory tracking error, serious control chattering and poor environmental adaptability of negative pressure adhesion wall-climbing robots in granary curved wall variable curvature and time-varying disturbance environments, this paper proposes an adaptive sliding mode trajectory tracking control strategy with improved reaching law and adaptive disturbance compensation. The main conclusions are as follows.

1. A kinematic and dynamic model suitable for granary curved wall operation is established by introducing curvature pose deviation factor and lumped disturbance term, which accurately characterizes the coupling relationship between robot motion state, curved wall geometric characteristics and multi-source disturbances, providing an accurate model basis for controller design.
2. The designed improved variable-rate exponential reaching law and error-driven adaptive boundary layer realize the dynamic balance between fast error convergence and chattering suppression, which effectively solves the inherent chattering defect of traditional sliding mode control and improves the dynamic and static performance of the control system.
3. The constructed disturbance adaptive update law can realize real-time online estimation and compensation of unknown lumped disturbances such as negative pressure adhesion fluctuation, curvature variation interference and environmental friction disturbance, significantly enhancing the robustness and adaptability of the robot in complex granary working conditions.
4. Comparative simulation and physical prototype experiments verify that the proposed ASMC strategy has obvious advantages over traditional SMC and CASMC in tracking accuracy, convergence speed and chattering

suppression. It can stably and accurately track complex curved trajectories under variable curvature and strong disturbance conditions, which has important engineering application value for intelligent operation of granary wall robots.

In future research, we will fuse visual perception information to realize autonomous identification of granary wall curvature and adaptive trajectory planning, and further optimize the adaptive algorithm to improve the autonomous operation level of the robot in fully unstructured granary environments.

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