Composite Integral Sliding Mode Control with Neural Network-based Friction Compensation for A Piezoelectric Ultrasonic Motor

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***Abstract*—In this paper, a neural network-based (NN-based) integral sliding mode control approach is presented for a piezoelectric ultrasonic motor. The precision motion performance of the motor can be adversely affected in the presence of nonlinearities including friction and disturbance, as well as parameters uncertainties. Integral sliding mode control is effective in dealing with uncertainties and disturbances. To achieve better performance on tracking desired motion trajectories, a neural network structure with modified jump basis functions are used to model and compensate the discontinuous friction in the motor control systems. This structure can approximate friction with high accuracy but require few NN nodes. Stability of the proposed control strategy is analyzed. The simulation studies are provided to demonstrate the precise tracking performance of the proposed control scheme.**

***Index Terms*—Integral sliding mode control, neural network, friction compensation, piezoelectric ultrasonic motor**

I. Introduction

Precision motion tracking performance is an essential requirement in various applications, such as robotic manipulators [1], [2], micro-operation platforms [3], [4], and especially surgical devices [5], [6]. As a versatile motion platform, piezo-actuated stages have been adopted to build different systems for specific purposes. In some microscopes for scanning imaging [7], the horizontal and vertical motions are driven by the piezoelectric component, which has merits of fast response, high precision, compact size, large driving force and so on [8].

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A piezoelectric ultrasonic motor is a kind of direct drive motor, which is composed of a mover and a stator. It is also driven by piezoelectric component and provides high precision and larger stroke compared with flexure-mechanism-based piezoelectric actuators. This is due to the special movement mode of the piezoelectric ultrasonic motor. Therefore, piezoelectric ultrasonic motor can be used for many applications, for example, the surgical device designed for assisting the medical practitioners in completing the surgery at eardrum [9].

However, the friction resulting from relative motion between the mover and stator produces adverse effects on the tracking performance of the motor. In a system driven by piezoelectric ultrasonic motor, high tracking performance can not be achieved by traditional control methods. To avoid friction modeling, usually a robust control method is preferred, such as proportional-integral-differential (PID) control, sliding mode control (SMC) [10], [11], and intelligent control [12]. In closed-loop control, sliding mode control (SMC) shows great robustness by making the tracking error reach the designed sliding mode surface quickly and then remain on it. To further improve the system performance, a strategy is to use the disturbance observer-based control, where the friction is observed and compensated by a disturbance observer. Remarkably, extended state observer (ESO) [13] and sliding mode observer [14] have been applied to achieve such compensation. However, observer can be limited by its bandwidth which make it only suitable for slow trajectory tracking. Besides that, various sliding mode functions have been proposed for the precision motion control, such as introducing integral term [15], terminal sliding mode [16], etc. It has been verified that PID-type sliding surface has fast transient response compared

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with the traditional PD-type one. And it has been used widely by many researchers in the control of nonlinear systems.

It should be also noted that better performance can be achieved with the consideration of the friction model. There are several models [17]–[19] that have been studied to capture frictional effects, but they are considerably complex. Moreover, the friction varies with temperature and mechanical wear. Generally, an accurate model includes static, Coulomb viscous and negative friction [20]. However, it is very difficult to build and identify an accurate model to realize the high precision model-based compensation [2]. An effective method is to use approximating models. In [21], the simplest Coulomb friction model is used, and the adaptive robust control (ARC) is proposed. Since neural networks (NNs) is powerful in approximating nonlinear functions [22], many NN-based friction compensation methods have been proposed [23]–[25]. The traditional NNs are based on smooth basis function but a large number of NN nodes are required to reconstruct piecewise continuous friction. To overcome this limitation, the standard NNs are augmented with extra nodes using jump basis functions to approximate non-smooth functions [23]. Significantly, the NNs consisting of jump basis functions can approximate any non-smooth functions with few nodes [2]. However, this type of jump basis is set as zero when the input is negative, which is not suitable for such systems that is moving back and forth.

The aim of this paper is to design a controller to make the piezoelectric ultrasonic motor to achieve high precision motion tracking. This paper modifies the jump basis function to make it symmetrical in forward and backward motions. The NNs consisting of the modified jump basis is used to deal with the friction and an integral siding mode control with NNs is then proposed. Following that, the design procedure is described in details and the stability is analyzed in this paper. The rest of this paper is organized as follows. In Section II, the model of a piezo-actuated motor (i.e., piezoelectric ultrasonic motor) is presented. Next, the controller design is given in detail in Section III. In Section IV, some simulations are carried out to verify the effectiveness of the control system. Finally, the conclusions are drawn in Section V.

II. Model of A Piezo-Actuated Motor

For a 1-DOF (degree-of-freedom) piezoelectric ultrasonic motor shown in Fig. 1, the piezo component is fixed on the stator, and the output platform is bonded on the mover which is moved along the linear guide. In this motor, the friction results in nonlinear system dynamics. Therefore, the dynamic model of the motor can be described as

$$\ddot{x}(t) + a_1\dot{x}(t) + a_0x(t) = b_0u(t) + F(t) + d(t), \qquad (1)$$

where u and X are the input voltage and output displacement, respectively. a_1, a_0, and b_0 are the model coefficients. F represents the friction and d is the disturbance.

A detailed phenomenon-based model usually adopted for industrial controller design [20], which is described as

$$F(\dot{x}) = [\alpha_0 + \alpha_1 e^{-\beta_1|\dot{x}|} + \alpha_2(1 - e^{-\beta_2|\dot{x}|})]\text{sign}(\dot{x}), \qquad (2)$$

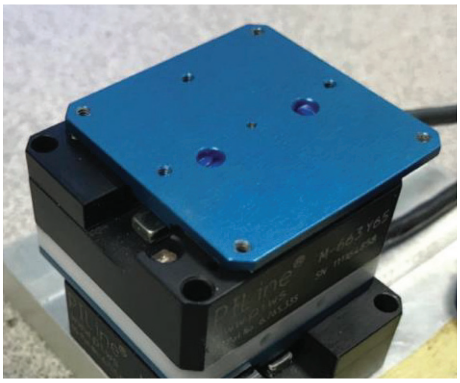

Fig. 1. A 1-DOF piezoelectric ultrasonic motor.

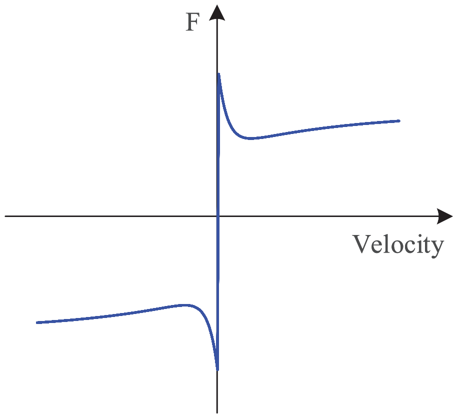

Fig. 2. Static, Coulomb and viscous friction model, with striback effect.

where α_0 provides Coulomb friction, static friction is given by $\alpha_0 + \alpha_1$, and α_2 captures the viscous friction effects.

The model (2) is suitable to model the friction and Fig. 2 shows the typical relationship between the friction force and the speed of movement.

It should be noted that the model (2) is highly nonlinear and discontinuous at zero because of the change in direction of movement. Therefore, identifying precise model parameters is extremely challenging and time-consuming. In this case, the NNs can be used to approximate this model.

III. Controller design

In the section, the design procedure of the proposed control scheme is to be introduced in detail. First, the jump basis functions is modified to be symmetrical. Then, the friction model is reconstructed by the NNs. Based on the replaced model with NNs, integral sliding mode control law is proposed and given with stability analysis.

A. Modified NNs

The common three-layer NN is used to approximate the friction model in the proposed control approach. Since the friction is related to the velocity, the velocity acts as the input of NNs. For non-smooth function, a sigmoid-jump approximation basis function [2], [20] is set as zero when the input is negative. Considering the friction exists whether the motor moves forward or backward, but in the opposite direction, the basis function can be modified as

$$\phi_i(v) = (1 - e^{-|v|})^{(i-1)}, \tag{3}$$

where i means the i-th neural network node.

In the motor system dynamics, the unknown friction model can be replaced as

$$F(\dot{x}) = F_{NN}(\dot{x})\mathrm{sign}(\dot{x}) + \varepsilon, \tag{4}$$

and

$$F_{NN} = W^*\Phi. \tag{5}$$

where $W^* = [w_1^*, w_2^*, ..., w_n^*]$ is the weights, $\Phi = [\phi_1, \phi_2, ..., \phi_n]^T$ is the vector of basis functions, and n is the number of NN nodes. ε is the bounded approximation error, i.e., $|\varepsilon| < \varepsilon_m$.

B. Integral Sliding model control

With the NN-based friction model, the system dynamics can be rewritten as

$$\ddot{x} + a_1\dot{x} + a_0 x = b_0 u + F_{NN}\mathrm{sign}(\dot{x}) + \varepsilon + d. \tag{6}$$

Here, the time variable t is omitted for simplicity. The disturbance d is assumed to be bounded, namely, $|d| < d_m$.

Define the position error and integral sliding mode function with the given reference trajectory x_d as follows:

$$e = x - x_d, \tag{7}$$

$$\sigma = k_1 e + k_2 \int e, \tag{8}$$

where k_1 and k_2 are positive constants, σ is the sliding variable.

Then, the second-order state space model can be selected as

$$\sigma_1 = \sigma, \tag{9}$$

$$\sigma_2 = \dot{\sigma}_1 = k_1\dot{e} + k_2 e, \tag{10}$$

$$\dot{\sigma_2} = k_1\ddot{e} + k_2\dot{e}. \tag{11}$$

Remarkably, σ_{2d} is a virtual control which is chosen as

$$\sigma_{2d} = -\xi_1\sigma_1, \tag{12}$$

where ξ_1 is a positive constant.

Let's define a positive definite function V_1,

$$V_1 = \frac{1}{2}\sigma_1^2. \tag{13}$$

By differentiating V_1 with respect to time, we have

$$\begin{aligned} \dot{V}_1 &= \sigma_1\dot{\sigma}_1 = \sigma_1\sigma_2 \\ &= \sigma_1\sigma_{2d} + \sigma_1(\sigma_2 - \sigma_{2d}) \\ &= -\xi_1\sigma_1^2 + \sigma_1(\sigma_2 - \sigma_{2d}). \end{aligned} \tag{14}$$

Once $\sigma_2 = \sigma_{2d}$, it can be obtained that $\dot{V}_1 = -(\sigma_1)^2$ and thus σ_1 is guaranteed to be asymptotically stable.

Now, let $\theta = \sigma_2 - \sigma_{2d}$ and consider the following Lyapunov function,

$$V_2 = V_1 + \frac{1}{2}\theta^2. \tag{15}$$

By differentiating V_2 with respect to time and combining (11) and the NN-based system model (6), we have

$$\begin{aligned} \dot{V}_2 =& \dot{V}_1 + \theta\dot{\theta} \\ =& -\xi_1\sigma_1^2 + \sigma_1\theta + \theta(\dot{\sigma}_2 - \dot{\sigma}_{2d}) \\ =& -\xi_1\sigma_1^2 + \sigma_1\theta + \theta(k_1\ddot{e} + k_2\dot{e} - \dot{\sigma}_{2d}) \\ =& -\xi_1\sigma_1^2 + \sigma_1\theta + \theta[k_1(b_0 u + F_{NN}\mathrm{sign}(\dot{x}) + \varepsilon + d \\ & - a_1\dot{x} - a_0 x - \ddot{x}_d) + k_2\dot{e} - \dot{\sigma}_{2d}]. \end{aligned} \tag{16}$$

According to (16), the ideal control law can be chosen as

$$\begin{aligned} u_d =& -\frac{1}{b_0}(F_{NN}\mathrm{sign}(\dot{x}) + \varepsilon + d - a_1\dot{x} - a_0 x - \ddot{x}_d) \\ & - \frac{1}{b_0 k_1}(\sigma_1 + k_2\dot{e} - \dot{\sigma}_{2d} + \xi_2\theta). \end{aligned} \tag{17}$$

Substitute (17) into (16), $\dot{V}_2$ can be obtained as

$$\dot{V}_2 = -\xi_1\sigma_1^2 - \xi_2\theta^2. \tag{18}$$

However, the friction F_{NN} and the term $\varepsilon + d$ are unknown. Therefore, the following adaptive law is designed to estimate them.

$$\hat{F}_{NN} = \hat{W}\Phi, \tag{19}$$

$$\dot{\hat{W}} = L\Phi\mathrm{sign}(\dot{x})\theta, \tag{20}$$

where the diagonal matrix $L = diag(l_1, l_2, ..., l_n)$ is adaptation rate.

$$\dot{\hat{k}}_m = \gamma|\theta|, \tag{21}$$

where $k_m\mathrm{sign}(\theta)$ functions as a robust term to handle the disturbance and λ is its adaptation rate. It can be seen that the frictional force is estimated and compensated by the neural networks, so the residual nonlinearities is small and needs to be dealt with by the robust term, namely, the discontinuous sign function term $k_m\mathrm{sign}(\theta)$. In the proposed controller, k_m is obtained through adaption so that the chattering problem can be mitigated.

Then, the practical control law is given by

$$\begin{aligned} u =& -\frac{1}{b_0}(\hat{W}\Phi\mathrm{sign}(\dot{x}) + \hat{k}_m\mathrm{sign}(\theta) - a_1\dot{x} - a_0 x - \ddot{x}_d) \\ & - \frac{1}{b_0 k_1}(\sigma_1 + k_2\dot{e} - \dot{\sigma}_{2d} + \xi_2\theta), \end{aligned} \tag{22}$$

where ξ_2 is a constant.

In summary, the structure of the obtained control scheme is shown in Fig. 3

By giving the following conditions, $k_m \geq d_m + \varepsilon_m$, $\tilde{W} = \hat{W} - W^*$ and $\tilde{k}_m = \hat{k}_m - k_m$, the Lyapunov function is defined as

$$V_3 = V_2 + \frac{k_1}{2}\tilde{W}L^{-1}\tilde{W}^T + \frac{k_1}{2\gamma}\tilde{k}_m^2. \tag{23}$$

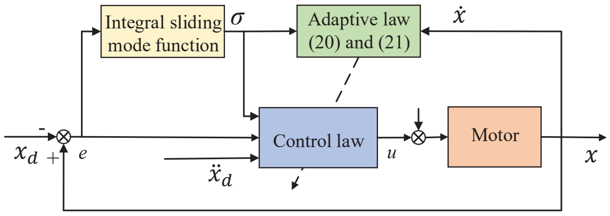

Fig. 3. Block diagram of the proposed control scheme.

Take the time derivative of (23), it yields

$$\begin{aligned}\dot{V}_3 &= \dot{V}_2 + k_1\tilde{W}L^{-1}\dot{\tilde{W}}^T + k_1\tilde{k}_m\dot{\tilde{k}}_m \\ &= -k_1\theta\tilde{W}\Phi\text{sign}(\dot{x}) + k_1\theta(-\hat{k}_m\text{sign}(\theta) + \varepsilon + d) \\ &+ k_1\tilde{W}L^{-1}\dot{\tilde{W}}^T + k_1\tilde{k}_m\dot{\tilde{k}}_m - \xi_1\sigma_1^2 - \xi_2\theta^2 \\ &\leq k_1\theta(-\hat{k}_m\text{sign}(\theta) + k_m) + k_1\tilde{k}_m\dot{\tilde{k}}_m - \xi_1\sigma_1^2 - \xi_2\theta^2 \\ &= -k_1\tilde{k}_m|\theta| + k_1\tilde{k}_m\dot{\tilde{k}}_m - \xi_1\sigma_1^2 - \xi_2\theta^2 \\ &= -\xi_1\sigma_1^2 - \xi_2\theta^2 < 0. \end{aligned} \tag{24}$$

It can be seen that (24) is negative, which implies that σ and θ will converge to zero. It can be also concluded that the proposed controller is stable with the NNs to deal with the adverse effects of the unknown friction.

Furthermore, it is shown in [26] that the adaptive law of weights can be augmented with modification term to improve robustness of the controlled system. Thus, the adaptive law is modified as,

$$\dot{\hat{W}} = L\Phi\text{sign}(\dot{x}) - \Lambda\hat{W}, \tag{25}$$

where the values are small constants in diagonal matrix $\Lambda = [\lambda_1, \lambda_2, ..., \lambda_n]$. Actually, the weights will go through low-pass filters to prevent sudden changes in control.

IV. Simulation Results

The numerical studies is conducted in MATLAB on the basis of the given nominal transfer function (see (26)) presented in a previous publication [27].

$$\ddot{x}(t) + 202\dot{x}(t) + 248.4x(t) = 4940u(t) + F(t) + d(t), \tag{26}$$

where the model parameters can be obtained $a_1 = 202, a_0 = 248.4, b_0 = 4940$. In the simulation, parameters in the friction model are set as $\alpha_0 = 1$, $\alpha_1 = 1.1$, $\alpha_2 = 0.5$, $\beta_1 = 20$ and $\beta_2 = 1.5$.

A. NN Approximation

In the numerical studies, the ability of NNs based on jump basis function to approximate the unknown friction model is tested firstly. The nodes is chosen as $n = 3$, and the weight matrix is $W = [2, -2.68, 2.05]$. With the same input $v = sin(2\pi t)$, the friction model and NNs outputs are shown in Fig. 4. It can be seen that the specific NNs can approximate the non-smooth friction accurately with only few nodes.

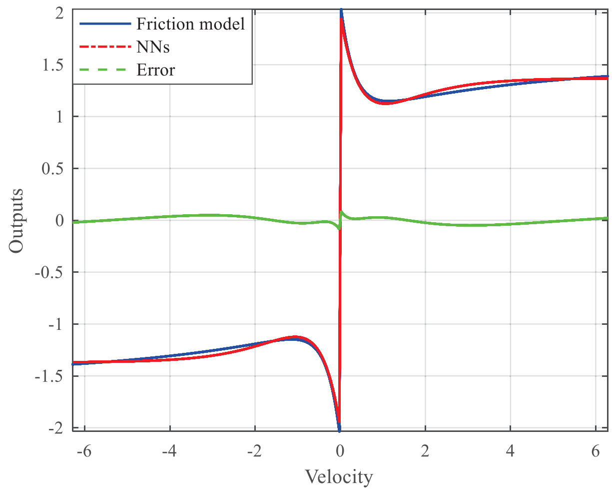

Fig. 4. Comparison of friction model and NNs Outputs.

B. Tracking Results

To apply the designed controller, the control parameters are chosen as $k_1 = 10$, $k_2 = 2000$, $\xi_1 = 800$ and $\xi_2 = 700$. The weights used in NNs are adjusted online with initial value of zero. The corresponding adaptive rates are set as $L = diag[100, 200, 200]$ and $\gamma = 0.1$.

For comparison purpose, the integral sliding mode controller (ISMC) without NNs is conducted in the simulation as well. The shared parameters are the same but the weights adaption rate L is set to be zero.

With the designed controller, the tracking results with a sine reference signal of the system is shown in Fig. 5. As can be

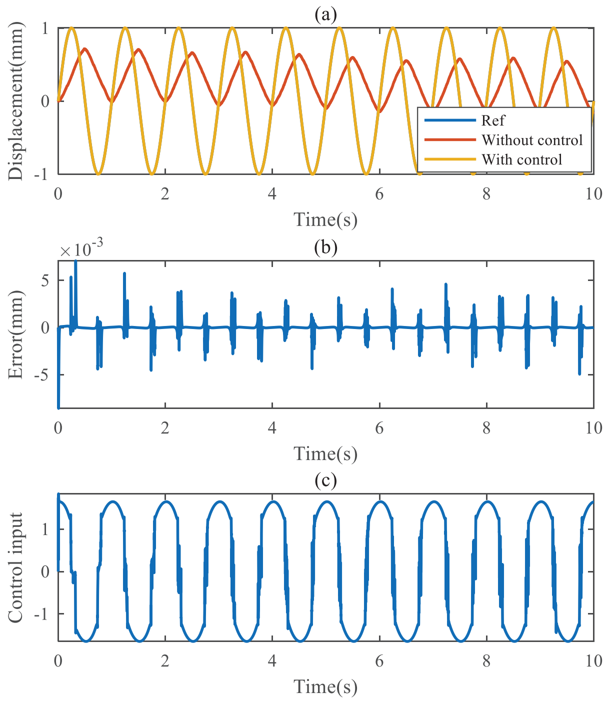

Fig. 5. Tracking performance of the integral sliding model control with NNs.

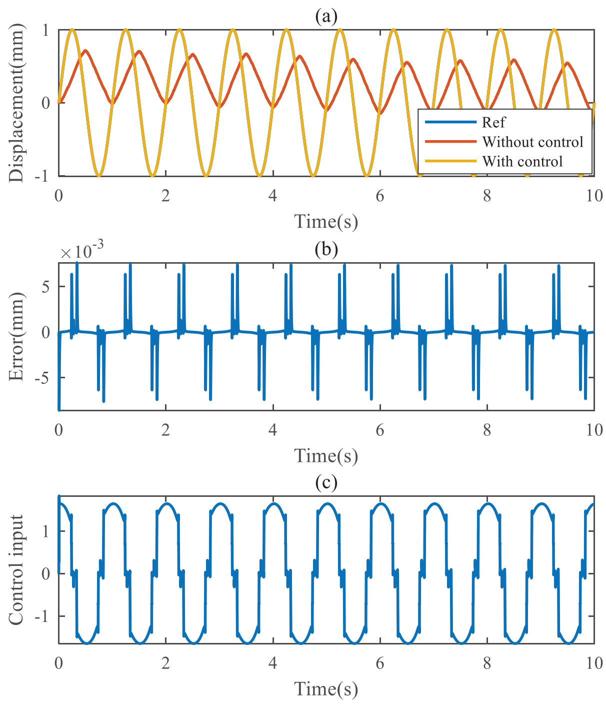

Fig. 6. Tracking performance of the integral sliding model.

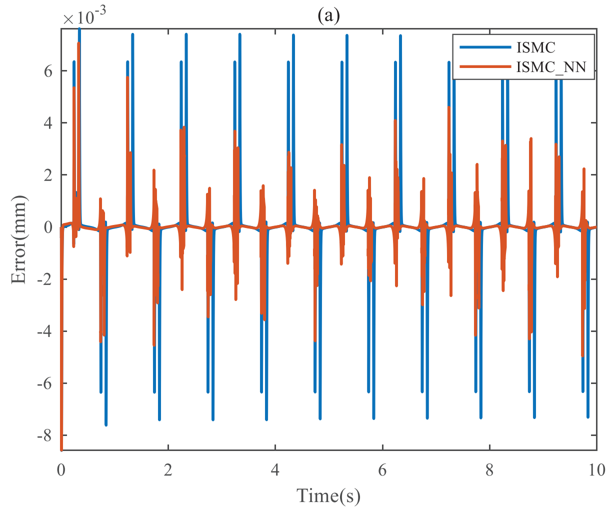

Fig. 7. Tacking error comparison of the two methods.

seen, the error converges quickly and reaches a stable range of 0.005 mm, which conforms the convergence and effectiveness of the proposed controller.

Without considering friction model-based compensation, ISMC treats the unknown friction as a part of disturbance. The tracking performance of using only ISMC is shown in Fig. 6. As can be seen the steady-state error with the ISMC can also reach a small range of 0.007 mm. However, the steady-state error by using only ISMC is larger than using ISMC_NN controller. The simulation results of ISMC are robust to deal with disturbance and uncertainties.

By comparing the errors of the two controllers as shown in Fig. 7, it can be observed that the proposed controller can track the desired trajectory more accurately and faster, which mainly results from NNs compensation for friction.

V. Conclusion

This paper proposed a NN-based integral sliding mode controller to track desired trajectories. To address the friction effects in the piezoelectric ultrasonic motor, neural networks is used to approximate the unknown friction model. The common NNs based on smooth basis functions need large number of nodes to capture non-smooth functions and may not ensure the accuracy. In this paper, an augmented NN consisting of jump basis functions can achieve accurate approximation for discontinuous functions using few nodes. Then, an integral sliding mode control is designed based on the system model with NN-based friction model. The sliding surface is a simple proportional-integral function of the position error and the control law is obtained through the backstepping method. The controller structure and design procedure are then presented in detail in this paper. The control strategy is analyzed using a Lyapunov theory for theoretical proof of its stability. The tracking performance of the designed controller is studied and analyzed via numerical studies. From the simulation results, great tracking performance can be achieved and the proposed method can be easily extend to applied to other similar nonlinear systems with the effects of discontinuous functions.

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