

## Synthesize control signal to electric drive systems of 2-wheel autonomous robots using PA-BLDC actuator

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### ABSTRACT

*The paper studies the synthesis of a control signal generator for electric drive systems in 2-wheel autonomous robots using brushless DC motors (BLDC) with power amplifiers (PA). The mathematical and discrete structure of the PA input control signal generation block based on differential equations is proposed, ensuring the drive system tracks the guide element with high accuracy. Mathematical analysis has proven that the system is stable and converges to the desired value with small tracking errors. Simulations are performed in MATLAB Simulink with different guidance signals varying over time.*

**Keywords:** BLDC electric drive system; Power amplifier; Autonomous robot; Control signal generation.

### 1. INTRODUCTION

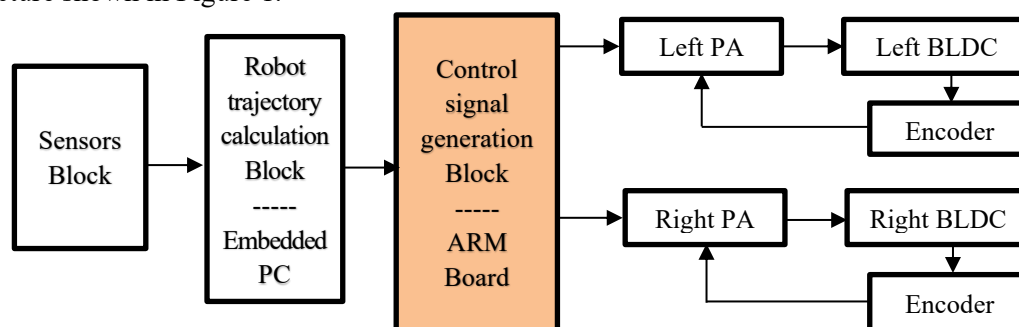
Electric drives play an important role in industrial applications and autonomous robots [1, 2], especially in tracking control systems. Among them, brushless DC motors (BLDC) and permanent magnet synchronous motors (PMSM) are two types of motors commonly used due to their high efficiency, high reliability, and precise control [4, 11-15]. Industrial autonomous robots require trajectory-tracking drives or guide elements from positioning and guidance systems. BLDC motor control systems involve electronic switching, often using Hall sensors to detect the rotor position [5, 10]. Speed control is achieved through PWM techniques and PID controllers [7, 9], providing simplicity and efficiency in low-noise environments. Several systems use isolated gate control methods via optocouplers to improve performance [3]. Sensorless control methods, such as back-EMF, are also being developed [8]. In addition, optimal control theory can be applied to BLDC motor drives to enhance stability and performance [6]. Optimum and adaptive control methods aim to adjust control parameters according to system changes, making the system operate more stably in complex environments. Recently, studies [9] and [10] have focused on developing compact, cost-effective, and high-performance control circuits and control strategies to meet the increasing demand for BLDC motors in various industries. Following that trend, several control algorithms have been integrated into the power amplifier (PA), making it easier to develop control systems using BLDC with a power amplifier (PA). Research [15] and [16] introduce the use of PA, which helps to synthesize the control loop of the electric drive system more accurately. In this way, BLDC and PA are considered actuators, and the designer only needs to adjust the open-loop system to achieve the best speed response. A controller will synthesize the position control loop to be suitable for each application requirement. In this integration direction, there is currently no research work that addresses the structure and mathematical guarantees for the input command generation system of PA.

From the above analysis, this paper proposes a structure of the control signal generator based on differential equations and discrete models, ensuring that the electric drive system using a BLDC motor and PA power amplifier tracks the input signal with high accuracy.

## 2. SYNTHESIS OF CONTROL SIGNAL GENERATION BLOCK

### 2.1. High-precision drive system

The drive control system of the 2-wheel autonomous robot [1] presented in this study is a drive system using BLDC motors accompanied by the PA. The electric drive control system has the structure shown in Figure 1.



**Figure 1.** The control diagram of the differential 2-wheel autonomous robot.

The controller consists of a central processor designed based on an Embedded PC (trajectory calculation block), a 2-channel control signal generator that usually uses ARM microcontroller boards with high processing speed and stability. The selection of motor power must meet the requirements of the system's dynamic parameters, such as maximum angular acceleration, maximum angular velocity under the condition of maximum resistive torque, and the determined moment of inertia of the transmission system. On the other hand, after selecting the motor power, it not only fully meets the required maximum parameters, but can also generate velocity and acceleration values greater than desired ones. Therefore, the digital control system must ensure the highest control quality while ensuring the allowable limits of the electromechanical system.

An important feature of the PA is that it has many types of input ports to provide the control value, such as pulse, communication, and voltage inputs. In the tracking control mode, the communication ports will not guarantee the working speed according to the velocity requirements of the objects to be tracked. In such cases, it is possible to use the methods of inputting the signal through the analog port or the pulse port. In the analog input mode, the PA will control the motor and the entire transmission system to operate in the angular velocity tracking mode, which is calculated in the digital signal processors. They are the digital controllers based on the tracking error between the transmission system and the external control signal. When PA operates in the pulse input mode, the controller can be set to work in the position or angular velocity tracking mode. The desired position and speed are generated by a 90°-phase shifted double pulse train or a single pulse train with a direction signal. Integrating this pulse train with the internal counters of the PA will produce the position value to be tracked by taking the rate of change of the tracked value, which essentially measures the frequency of the pulse train, and produce the angular velocity to be tracked.

In the case of a non-backlash system, the simple way to synthesize the control system is to install the PA and examine the system quality using traditional methods. However, this solution is only effective for the system operating in the steady state mode. It is ineffective and not good in tracking mode, because the system has to endure continuous transients. The drive system will operate in the continuous position change mode, which means that the input parameter for the system is the desired position. To create the set value for the system (the desired value), it is necessary to refer to the guide element (or the robot trajectory calculated by the calculation block). For the non-backlash system, the robot's direction angle can be referred to as the motor shaft angle.

In the practical implementation mentioned in the following part, we use the type of motor Oriental BLDC BLH2D50, the frequency range 1 – 25 kHz (the period: 40 – 1000 ms).

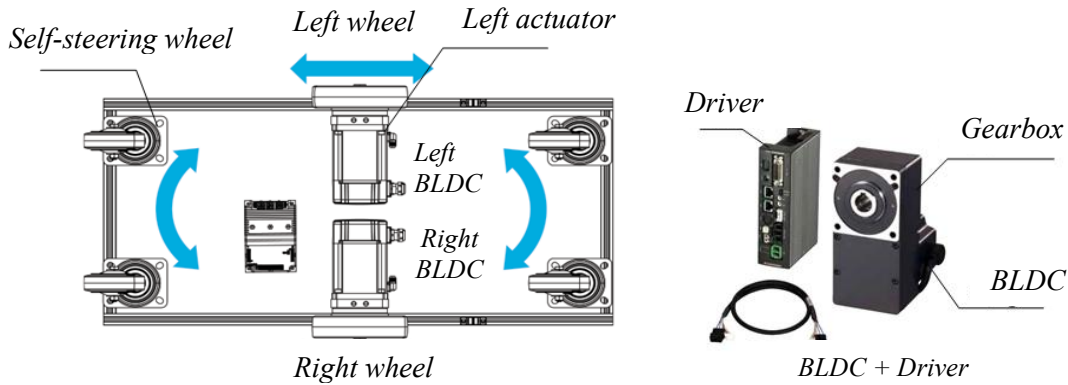


Figure 2. The drive system of a differential 2-wheel autonomous robot.

2.2. Synthesis of control signal generator

For the selected drive system, the angle value of the BLDC motor is measured directly in the power amplifier. In position tracking mode, the PA will control the motor to follow the input angle value, and there is no need to manage the motor angle with the outside controller. The controller structure diagram is shown in Figure 2.

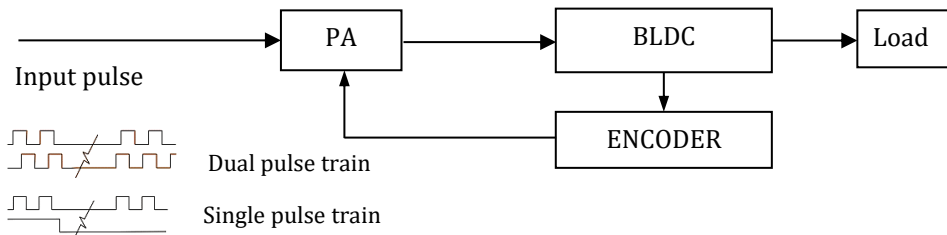


Figure 3. Structure diagram of motor - power amplifier drive unit.

Thus, to run the motor and get the desired rotation angle, it is necessary to generate a pulse train with the desired frequency and number of pulses and input it into the power amplifier PA. That pulse train has a frequency that tracks the change of the guide element  $\dot{\phi}_G$ , and the total number of pulses equaling the guide element  $\phi_G$ . To create such a pulse train, the guide element value will be provided to the control signal generator. The output of the generator is a pulse train with the desired frequency  $f$  (input pulse) and the total number of pulses  $S$ . Practically, the sum of the pulse is fed back from the output of the load. However, to facilitate stabilization analysis, ideally, we consider the controller that is integrated into the power amplifier to ensure that the BLDC rotates to the position where the sum of the pulses is  $S$ . With the assumption, the structure in Figure 3 is presented by an integral block in figure 4.

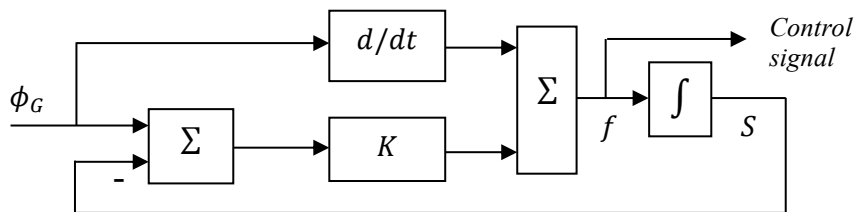


Figure 4. Structural diagram of the control signal generator for PA-BLDC.

The differential equation describing the system in figure 4 is shown in (1). Here,  $K$  is the parameter to adjust the converging,  $K > 0$ :

$$\begin{cases} f = \frac{dS}{dt} \\ \frac{dS}{dt} = \frac{d\phi_G}{dt} + K(\phi_G - S) \end{cases} \quad (1)$$

**Confirmation:** With  $K > 0$ , the system of equations (1) always ensures  $S \rightarrow \phi_G$  and  $f \rightarrow \dot{\phi}_G$

**Proof:**

The structure diagram of the control signal generator in Figure 4 is described mathematically with the differential equation system (1). From the second equation of the equation system (1), we have:

$$\frac{dS}{dt} - \frac{d\phi_G}{dt} = -K(S - \phi_G) \quad (2)$$

$$\frac{d(S - \phi_G)}{dt} = -K(S - \phi_G) \quad (3)$$

$$\frac{d(S - \phi_G)}{S - \phi_G} = -K dt \quad (4)$$

Integrating the two sides of (4), we get:

$$\ln|S - \phi_G| = -Kt + C \quad (5)$$

In (5),  $C$  is a constant depending on the initial conditions of the system (1).

Suppose at time  $t = 0$ , the difference between the guide element  $\phi_G$  and the total number of pulses  $S$  is  $\varepsilon_0 = |S - \phi_G|_0$ , at that time:

$$C = \ln \varepsilon_0 \quad (6)$$

Combine (5) and (6) to get:

$$S = \phi_G + \varepsilon_0 e^{-Kt} \quad (7)$$

Since  $K > 0$ , equation (7) presents that when  $t \rightarrow \infty$  then  $e^{-Kt} \rightarrow 0$ , therefore  $S \rightarrow \phi_G$ .

When  $S \rightarrow \phi_G$  then  $\dot{S} \rightarrow \dot{\phi}_G$ .

From the first equation of system (1), we also have  $f \rightarrow \dot{\phi}_G$ .

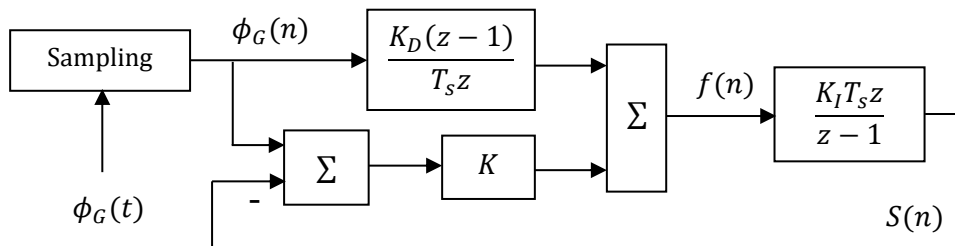
Confirmation has been proven. ■

**Remarks:**

- Equation (7) shows that the bigger  $K$  is, the faster  $S \rightarrow \phi_G$ .
- In practice, because the controller is a digital unit (e.g., an embedded PC), it operates in discrete mode. Therefore, the dynamic equation (1) needs to be represented as a discrete system of equations (8).

$$\begin{cases} f(n) = \Delta S(n) = S(n) - S(n-1) \\ \Delta S(n) = \phi_G(n) - \phi_G(n-1) + K[\phi_G(n) - S(n)] \end{cases} \quad (8)$$

The structure diagram of the signal generator in discrete mode is shown in Figure 5.



**Figure 5.** Structure of the control signal generator for the drive system PA-BLDC.

In figure 5, we apply the standard of practical discrete integral and differential form with sampling time  $T_s$ , which is suitable for numerical simulation and digital control. The coefficient  $K_I, K_D$  are super parameters to adjust the response of practical differential and integral units. Normally, to improve the control quality, the feedback signal from the load side will be sent to the outside controller to synthesize the control command, then sent to the control signal generator proposed in figure 5. Thus, the electric drive control system of the industrial autonomous robot using the PA-BLDC drive system operating in position mode, as shown in Figure 5, will ensure that the output value of the system tracks the desired input value, ensuring the ability to follow the value of the guide element.

### 3. SIMULATION AND PRACTICAL RESULTS

#### 3.1. Simulation with $K = 100$

We choose  $K_D = K_I = 1; T_s = 10 \text{ ms}$ . The parameter  $K$  is assigned to different values to assess the effect of the proportional part on the tracking error of the system. The simulation is conducted with the left actuator of an Automated Guided Vehicle (AGV) under the assumption that the guide element has the step or sinusoidal form (figure 6).

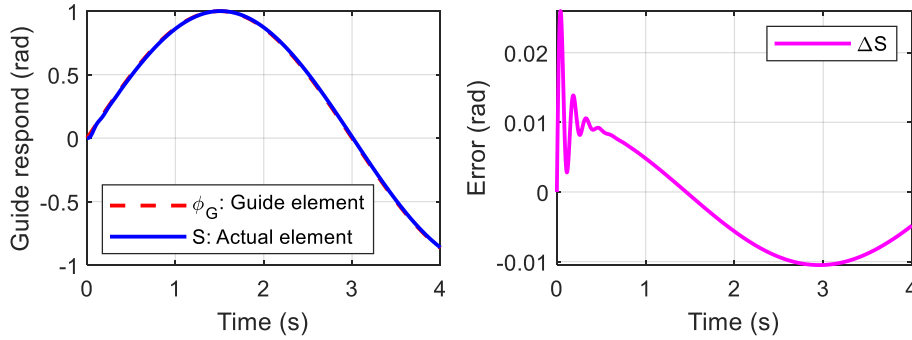


Figure 6. The response and error with the guide element  $\sin\left(\frac{2\pi}{6}t\right)$  and  $K=100$ .

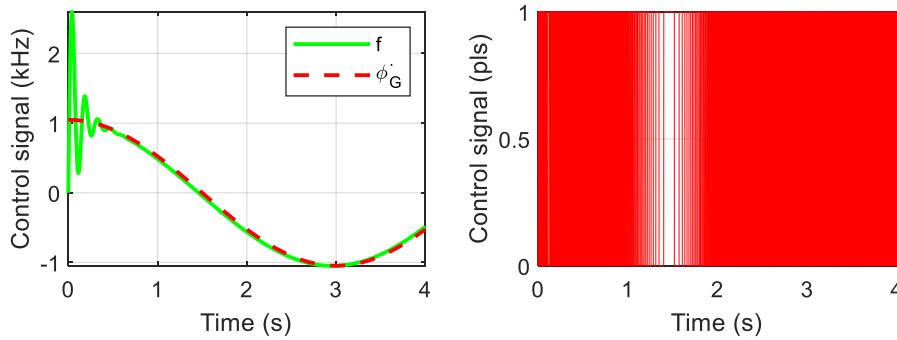


Figure 7. The control signal with the guide element  $\sin\left(\frac{2\pi}{6}t\right)$  and  $K = 100$ .

In figure 7, the guide element signal is the dashed red line, and the real element signal is the solid blue line. The simulation results show that  $S \rightarrow \varphi_G$  and  $f \rightarrow \dot{\varphi}_G$ .

#### 3.2. Simulation with $K = 200$

Figures 8 and 9 show the simulation results with the guide element of  $\sin\left(\frac{2\pi}{6}t\right)$  and  $K = 200$ . In figure 8, the guide element signal is the dashed red line, and the real element signal is the solid blue line. The simulation results show that  $S \rightarrow \varphi_G$  and  $f \rightarrow \dot{\varphi}_G$ . The convergence of the system is faster compared to the case  $K = 100$ .

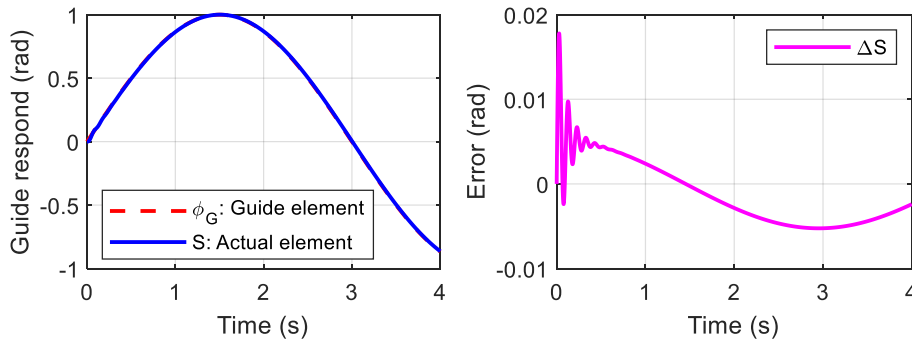


Figure 8. The response and error with the guide element  $\sin\left(\frac{2\pi}{6}t\right)$  and  $K = 200$ .

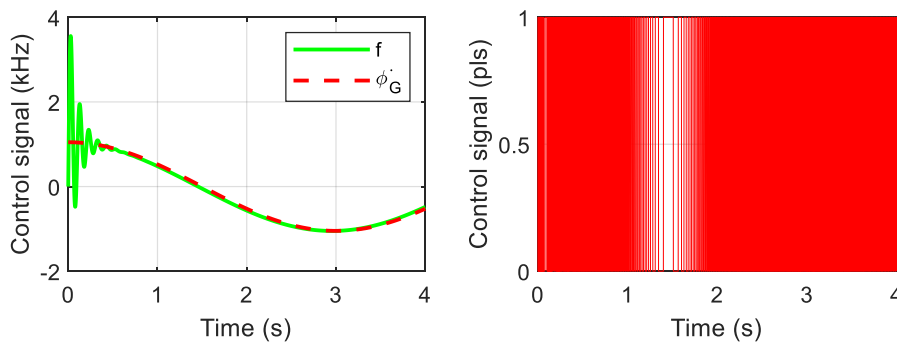


Figure 9. The control signal with guide element  $\sin\left(\frac{2\pi}{6}t\right)$  and  $K = 200$ .

3.3. Simulation with the guide element 1(t)

Figures 10 and 11 present the simulation results with the input of the guide element 1(t).

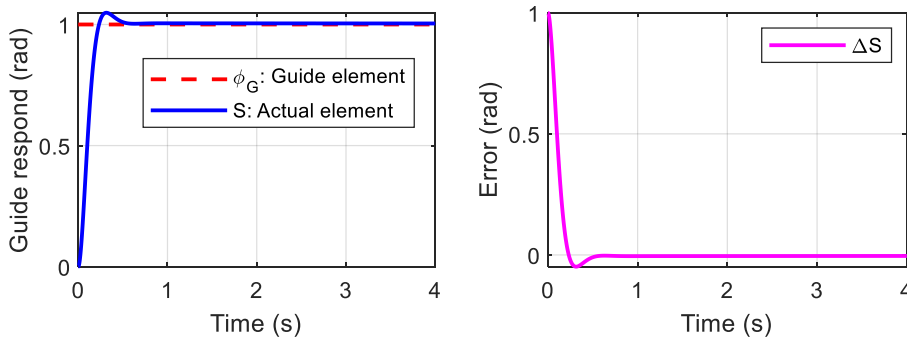


Figure 10. The response and guiding error with guide element 1(t).

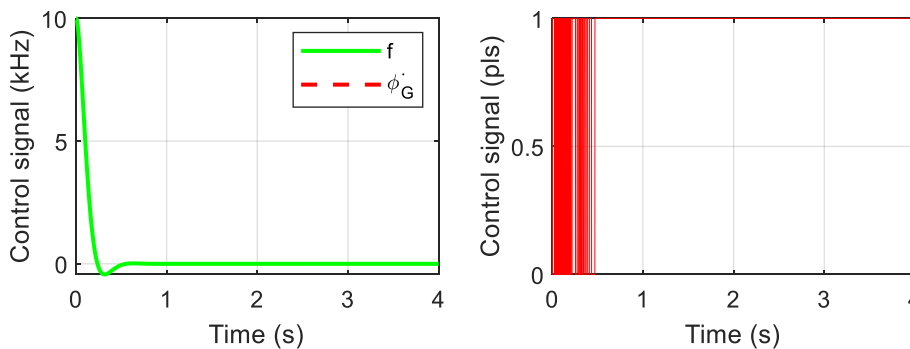


Figure 11. The control signal with guide element 1(t) and  $K=100$ .

In figure 10, the guide element signal is the dashed red line, and the real element signal is the solid blue line. The simulation results show  $S \rightarrow \varphi_G = 1$  and  $f \rightarrow \dot{\varphi}_G = 0$ . Figure 10 also shows the settling time at time 0.5 s. When increasing parameter  $K$ , the quality of tracking the guide element will be better. This simulation result is completely consistent with the theory proven in the Confirmation in sub-section 2.2.

### 3.4. Practical results

The diameter of the AGV is 0.18 m, so the circumference of the wheel is 0.565 m. The velocity of AGV is 0.5 m/s. The distance between the two wheels is 0.53 m. The ratio of transactions is 30:1. Drive system: Oriental BLDC BLH2D50. The angular speed of AGV:

$$\omega_{wheel} = \frac{0.5}{0.09} = 5.556 \frac{rad}{s} \quad (9)$$

$$\omega_{motor} = \omega_{wheel} \times 30 = 166.667 \text{ rad/s} \quad (10)$$

According to simulation results, when  $K = 100$ , guide error at the wheel is about  $\pm 0.01 \text{ rad}$ , or approximately  $\pm 100 \text{ mm}$ , corresponding to path tracking error of  $\pm 38 \text{ mm}$ ; when  $K = 200$ , guide error at the wheel is about  $\pm 0.005 \text{ rad}$ , corresponding to path tracking error of  $\pm 19 \text{ mm}$ .

In the experiment result on the site (figure 12), we get the path tracking error of  $\pm 30 \text{ mm}$ .

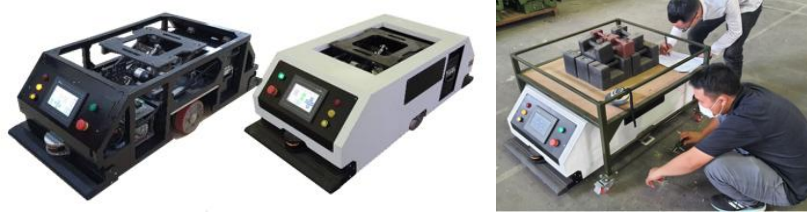


Figure 12. The practical testing images of the AVG.

## 4. CONCLUSIONS

The paper proposed a method of synthesizing input signals to control the drive system based on the integration of a BLDC motor and power amplifier (PA). This creates a pulse train to be fed into the PA with the frequency and total number of pulses corresponding to the position and velocity values of the autonomous robot, which are calculated in the previous blocks. The control signal generator is mathematically synthesized, ensuring the system accurately tracks the guide element. The research results also show that the tracking control system for BLDC motors using PA is a popular trend in the industry and mobile robots. With this signal generator, the PA is set in pulse input mode, meeting the requirements for speed and position of the guide element in the tracking control system for robots. In the following studies, the authors tend to propose intelligent control methods, considering the impact of load disturbance and the energy optimization problem.

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### TÓM TẮT

#### **Tổng hợp khối tạo tín hiệu điều khiển hệ truyền động điện cho robot tự hành 2 bánh vi sai sử dụng cơ cấu chấp hành PA-BLDC**

*Bài báo nghiên cứu tổng hợp khối tạo tín hiệu điều khiển cho hệ truyền động điện trong robot tự hành 2 bánh vi sai sử dụng động cơ một chiều không chổi than (Brushless Direct Current - BLDC) đi kèm bộ khuếch đại công suất (Power Amplifier - PA). Đề xuất cấu trúc và mô tả toán học của khối tạo tín hiệu điều khiển đầu vào PA dựa trên phương trình vi phân, đảm bảo hệ điều khiển truyền động bám theo phân tử dẫn đường với độ chính xác cao. Giải tích toán học đã chứng minh hệ thống ổn định và hội tụ đến giá trị mong muốn với sai số bám nhỏ. Mô phỏng được thực hiện trong MATLAB Simulink với các tín hiệu dẫn đường khác nhau biến đổi theo thời gian.*

**Từ khoá:** Hệ truyền động điện BLDC; Khuếch đại công suất; Robot tự hành; Tạo tín hiệu điều khiển.