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Research on Mechatronic Control System Theory: Application Analysis of Electronic Circuits and Digital Encoders in Precision Motion Control of Industrial Robotic Arms

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Abstract. Mechatronic control systems serve as the core support for realizing precision motion control of industrial robotic arms. Adopting the literature analysis method, this paper conducts research from three dimensions namely electronic circuits, digital encoders and control circuit systems, sorts out the basic principles of each module, analyzes the cooperative operation mechanism of electronic control components, and clarifies the critical effect of closed-loop architecture on the positioning accuracy of robotic arms. The study reveals that traditional basic control schemes are restricted by measurement noise, dynamic coupling and hardware time delay, making it difficult to balance motion speed and trajectory tracking accuracy simultaneously. Based on theoretical sorting and literature review, this study clarifies the internal logic of how electronic control systems affect the operational accuracy of robotic arms, and can provide theoretical references for subsequent research such as optimization of error compensation algorithms and anti-interference hardware design.

Keywords: Mechatronics, Electronic Circuit, Digital Encoder, Industrial Robotic Arm, Precision Motion Control

1. Introduction

Industrial robotic arms are typical mechatronic equipment widely used in handling, assembly and other operations. They are extensively applied in various engineering fields including industry, national defense and aerospace, and the continuous development of these industries raises higher requirements for robotic arm performance. For instance, permanent magnet synchronous motors are the mainstream driving devices for industrial robotic arms. They rely on position sensing devices to continuously collect rotor position data, and the signals are transmitted back to the control circuit in real time to form closed-loop feedback for precise motor regulation. This closed-loop system lays the foundation for guaranteeing the operation accuracy of the robotic arm's end-effector [1]. Serial industrial robotic arms are mostly used for assembly and handling tasks, and the positioning accuracy of their end-effectors is limited by the characteristics of joint structures. At present, a large

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number of relevant studies focus on the identification of robotic arm structural parameters, stiffness modeling, prototype calibration and on-site debugging [2], whereas systematic theoretical sorting on the cooperative operation mechanism of electronic control components is relatively scarce. Therefore, this paper carries out a theoretical review via the literature analysis method.

This paper discusses three core issues: first, to clarify the respective basic control functions of electronic circuits, digital encoders and control circuits; second, to analyze how various electronic control components cooperate to constrain joint displacement and posture of robotic arms so as to complete high-precision operations; third, to explore the theoretical defects of traditional basic control systems when applied to industrial scenarios with high requirements.

This study attempts to break the theoretical barriers between electrical control and industrial robotics research directions, systematically sort out the underlying theoretical logic of the closed-loop control system for robotic arms, and provide theoretical preparation for mechanical majors to learn automatic control and robotics-related content.

2. Basic theory of core electronic control components

2.1. Basic theory of electronic circuits

As the most fundamental hardware carrier of the closed-loop control system for robotic arms, electronic circuits undertake two core functions: system power supply and transmission of control signals. Electronic control circuits are divided into power supply loops and signal transmission loops. The power supply loop converts external input voltage to provide stable and suitable direct current for the main control unit, sensors and driving devices; the signal loop realizes interaction between control commands and sensor feedback signals and completes level matching. Electromagnetic interference generated during the operation of robotic arm motors tends to cause signal distortion, so filter circuits and standardized grounding schemes are required to suppress noise. All upper-layer control strategies are ultimately realized by hardware circuits, and the operational stability of these circuits directly affects the performance of robotic arms.

2.2. Basic theory of digital encoders

As the core sensing elements in the closed-loop control system of robotic arms, digital encoders collect real-time information of joint rotation angles and rotational speeds, convert physical quantities of mechanical motion into electrical signals, and build motion feedback channels. Photoelectric encoders are widely applied to robotic arm joints. They generate pulse signals through gratings, and the control system calculates joint positions by counting pulses and distinguishes rotation directions with orthogonal pulses [3]. Open-loop systems without feedback links are vulnerable to positioning deviations caused by load fluctuations and transmission clearances. The resolution of encoders directly determines the accuracy of angle detection, and encoder output signals are also susceptible to electromagnetic interference. Such components build a data bridge between mechanical motion and electrical regulation.

2.3. Basic theory of control circuit systems

The control circuit system acts as the core hardware platform for closed-loop regulation of robotic arms. It receives feedback data from encoders, calculates motion errors and outputs adjustment commands to construct a complete negative feedback control logic. Centered on main control

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devices, the system sequentially completes collection of feedback signals, calculation of position deviations and output of driving commands, dynamically corrects the operating state of motors, and continuously reduces errors between actual positions and target trajectories. Problems such as slow response and operational vibration of robotic arms will occur if signal transmission delay or insufficient hardware computing capacity exist. This theory describes how power supply circuits and sensing encoders coordinate to realize autonomous regulation via hardware and feedback information, and helps form a comprehensive understanding of mechatronics.

3. Theoretical mechanism of realizing precision motion of robotic arms through coordination of electronic control components

3.1. Electronic control hardware circuits and power

Electronic control hardware circuits serve as the physical basis for the operation of the entire robotic arm control system, performing dual tasks of energy supply and signal transmission. The power supply unit converts commercial alternating current into direct current matching the rated parameters of servo motors, encoders and main control chips to ensure stable operation of all types of components [4]. Signal transmission branches are responsible for two-way information interaction: on the one hand, they transmit motion commands generated by the controller downward; on the other hand, they forward real-time status data collected by sensors upward. Electromagnetic disturbance generated by motor startup and shutdown will interfere with weak electrical signals, so filtering and grounding noise reduction schemes must be integrated into circuit design [4]. Power supply fluctuations and signal distortion will directly trigger motor operation faults and greatly reduce the stability of closed-loop control systems. A reliable circuit architecture ensures the orderly coordination of all electronic control units.

3.2. Digital encoders and position/speed feedback

As built-in sensing units of robotic arms, digital encoders continuously monitor the rotation angles and movement speeds of each joint, convert mechanical displacement into standard level electrical signals, and build data transmission channels between mechanical bodies and controllers. Photoelectric encoders output pulse signals through grating structures. The controller acquires real-time joint positions by counting pulses and judges the rotation direction of rotating shafts via orthogonal pulse signals [5]. If the system adopts open-loop control without encoder feedback, error sources such as transmission deformation and external load disturbance cannot be perceived or compensated by the controller. Position data collected by encoders forms the foundation of closed-loop regulation, and the resolution of sensors directly affects the trajectory tracking effect of robotic arms.

3.3. Control circuit systems and closed-loop regulation

Control circuits undertake the functions of closed-loop operation and regulation. They receive actual joint motion data transmitted from encoders, compare the data with pre-planned target trajectories, calculate position deviations and output adjustment commands. The operational accuracy of industrial robots is jointly constrained by multiple structural and environmental coupling factors [6]. Relying on the negative feedback mechanism, control circuits dynamically adjust the output state of motors, continuously correct the rotation amplitude of joints and weaken the negative impacts of

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various non-linear errors. Gear transmission clearances commonly exist inside reducers of industrial robotic arms. Such non-linear factors will greatly reduce the repeat positioning accuracy of end-effectors, and such errors can be suppressed through model strategies [6]. This regulation mechanism is applicable to scenarios including material handling and parts assembly, and guarantees stable operational accuracy of robotic arm end-effectors.

4. Theoretical limitations of traditional basic control schemes applied to robotic arm control

4.1. Theoretical limitations of traditional basic control schemes applied to robotic arm control

Industrial robotic arms rely on encoders to collect joint angles and feed position signals back to controllers through closed-loop circuits to guarantee end-effector positioning accuracy. Electromagnetic noise generated by drivers and motors in actual industrial sites will couple into signal lines and interfere with encoder output. Encoder quantization effects, electrical noise, and mechanical vibration will all induce joint angle measurement errors [7]. Mechanical vibration and temperature changes will further amplify measurement deviations, leading to offsets between joint positions acquired by controllers and real physical positions. Once distortion occurs in the position feedback link, the closed-loop control system will output control commands based on incorrect signals and directly increase positioning deviations of robotic arm end-effectors. Traditional basic control architectures lack complete noise suppression mechanisms and cannot fundamentally eliminate the negative impacts caused by electromagnetic interference and sampling errors.

4.2. Dynamic coupling and hardware time delay

When multi-degree-of-freedom robotic arms perform high-speed linkage, inherent dynamic coupling effects exist among all joints. In grabbing operations, the weight and center of gravity of loads fluctuate dynamically, putting stringent requirements on the command update rate of control circuits. Restricted by inherent hardware bandwidth, traditional basic control circuits have inherent transmission delays in signal sampling, operation and output links. When robotic arms conduct multi-axis high-speed coordinated movement or work under frequent load change conditions, response lag will lead to delayed tracking of joint commands, triggering trajectory jitter and motion offset. Conventional basic control circuits alone cannot make up for response defects at the hardware level. In scenarios with drastic dynamic fluctuations of working conditions, it is hard to balance motion speed and trajectory tracking accuracy simultaneously, restricting the operating performance of robotic arms under complex working conditions.

5. Conclusion

This paper systematically explores the internal mechanism through which electronic control components cooperate to realize precision motion of industrial robotic arms, thus bridging the theoretical gap between electrical control and robotics research. By sorting out the basic theories of electronic circuits, digital encoders and closed-loop control systems, this study elaborates how power supply units, position sensors and control circuits cooperate to build a complete closed-loop control architecture. Analysis shows that stable voltage conversion, high-precision encoder feedback and real-time control operation jointly form the theoretical foundation for guaranteeing the positioning accuracy and operational stability of robotic arms. Meanwhile, this study identifies two core theoretical limitations of traditional basic control schemes applied to robotic arm systems. First,

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measurement errors induced by encoder quantization effects, electrical noise and mechanical vibration will create deviations between position information collected by controllers and real physical states of joints, which cannot be fundamentally eliminated by traditional control architectures. Second, inherent dynamic coupling effects among multi-degree-of-freedom joints, coupled with hardware bandwidth limitations and signal transmission delays, make it difficult for basic control circuits to balance motion speed and trajectory tracking accuracy under scenarios with dynamically fluctuating working conditions.

This study only carries out theoretical sorting and literature review analysis without experimental verification based on physical prototypes. Subsequent research can explore advanced error compensation algorithms and high-speed hardware control architectures to further improve the motion accuracy of industrial robotic arms under complex dynamic working conditions.

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