Design and Optimization of Mechatronic Integrated Control System

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Abstract: This paper focuses on the design and optimization of electromechanical integrated control systems. Firstly, the basic principles and technologies of electromechanical integrated control systems were introduced, and their applications in industrial automation, intelligent robots, intelligent transportation, and agricultural automation were elaborated. Subsequently, the process and methods for designing an electromechanical integrated control system were proposed, including system requirements analysis and planning, system structure design and module division, selection and configuration of electromechanical components, control algorithm design and parameter optimization, and control system simulation and verification. In order to further explore optimization methods for system design, this article introduces optimization design theory and methods, and provides a detailed introduction to the optimization strategies and steps for the design of electromechanical integrated control systems. The effectiveness of the optimized design was verified through analysis of examples and evaluation. Finally, summarize the research results and propose existing problems and improvement suggestions. Through the research in this paper, reference and guidance will be provided for the design and optimization of electromechanical integrated control systems.

1. Introduction

The mechatronics integrated control system, as an advanced control system that integrates mechanical, electronic, and control technologies, is widely used in industrial production, transportation, agriculture, and other fields. Its design and optimization are key to improving system performance and efficiency. As shown in Figure 1 Mechatronics equipment. The design and optimization of electromechanical integrated control systems is a complex process that involves knowledge and technology from multiple disciplines. In the system design phase, it is necessary to clarify the system requirements, design the system structure, select suitable electromechanical components, and design reasonable control algorithms. In the system optimization stage, it is necessary to consider factors such as optimizing system performance indicators, minimizing costs, system stability and robustness. [1]With the rapid development of technologies such as artificial intelligence, the Internet of Things, and big data, electromechanical integrated control systems will become more intelligent and adaptive, and will be more closely integrated with other fields of technology, further improving the performance and application range of the system. Through research

on the design and optimization of mechatronics integrated control systems, it can promote the development and innovation of this field, improve the efficiency and reliability of the system, and contribute to the development of industrial production, transportation, and agriculture.

Figure 1: Mechatronics equipment

2. Basic Principles and Technologies of Electromechanical Integrated Control System

2.1. Concept and characteristics of mechatronics integration system

Mechatronics integration system refers to the organic integration of mechanical, electronic, and control technologies to form a complete control system. It combines traditional mechanical structures with electronic components, computers, and control algorithms to achieve close collaboration between machinery and electronics, achieving a higher level of automation control [2]

Mechatronics systems have a compact structure: Mechatronics systems tightly integrate mechanical structures, electronic components, and controllers, resulting in a small footprint and compact size for a wide range of application scenarios. Excellent interconnectivity: Effective information exchange and data transmission between mechanical, electronic, and control components in mechatronics systems. The mechanical components can be transmitted to the electronic system through the data collected by sensors, and the electronic system precisely controls the mechanical components through the controller. This interconnectivity enables mechatronics systems to achieve more efficient working modes. Flexibility and Scalability: Mechatronic systems have a high degree of flexibility and scalability. The various components of the system can be modular designed according to specific requirements, making it easy to replace, upgrade, and expand. This enables the system to adapt to the needs of different fields and application scenarios. Highly integrated control capability: The electromechanical integration system integrates modern control technology, including various sensors, actuators, and control algorithms. [3]Through the collaborative work of these control components, the system can achieve highly accurate motion control, position control, speed control, and other functions. Efficient energy utilization and energy-saving: The electromechanical integration system can achieve efficient energy utilization and energy-saving by optimizing control algorithms and energy management systems. For example, in the production line of mechatronics integration, reasonable control and scheduling can reduce energy consumption and improve production efficiency. As shown in Figure 2, mechatronics control system.
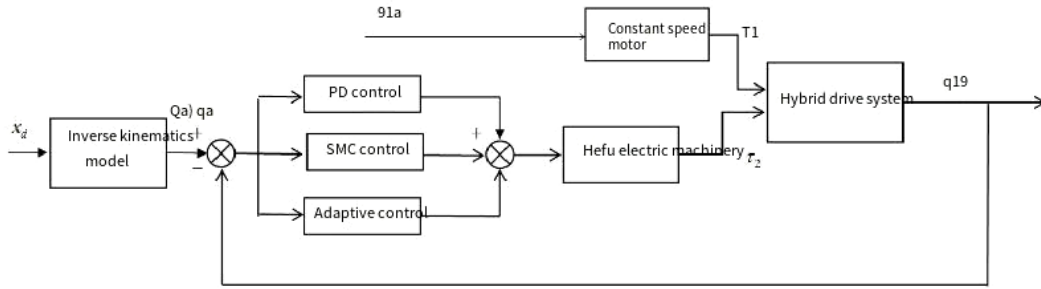
Figure 2: Mechatronics control system

2.2. Composition and structure of electromechanical integrated control system

Mechanical system: A mechanical system is the physical structural part of an electromechanical integrated control system, including various mechanical components, transmission mechanisms, and working devices. Mechanical components can be transmission devices (such as gears, belts, etc.), actuators (such as motors, cylinders, etc.), and sensors (such as position sensors, force sensors, etc.). The design of mechanical systems should consider factors such as working load, motion trajectory, and accuracy to meet the requirements of the control system.

Electronic system: An electronic system is an electronic component of an electromechanical integrated control system, including various sensors, actuators, electronic components, and circuit boards. Sensors are used to collect the motion status, working status, and environmental information of mechanical systems. The actuator is responsible for driving the movement of the mechanical system based on control signals, such as motor drive, cylinder control, etc. Electronic components and circuit boards are used for signal processing, data transmission, and control functions.

Control system: The control system is the core part of the electromechanical integrated control system, including control algorithms, controllers, and human-machine interfaces. The control algorithm is a control strategy and algorithm model designed based on the working principle and requirements of the system. The controller performs real-time control and coordination of mechanical and electronic systems based on control algorithms. The human-machine interface is used for users to interact with the system and configure parameters.

Mechanical systems, electronic systems, and control systems are connected and collaborated through signal transmission and data exchange. The motion status of the mechanical system is collected and transmitted to the electronic system through sensors. After processing the signal, the electronic system sends control instructions to the controller, which then transmits the instructions to the actuator to control the mechanical system. At the same time, the control system will make real-time adjustments based on feedback information from mechanical and electronic systems to achieve control objectives and optimize system performance.[4]

2.3. Technical requirements for electromechanical integrated control systems

The electromechanical integrated control system is a system that integrates mechanical and electrical control systems to achieve more efficient and precise control. When designing and optimizing electromechanical integrated control systems, a series of technical requirements need to be met. The electromechanical integrated control system needs to have stability and reliability. The system should be able to stably achieve predetermined functions during operation and maintain normal operation under various environmental conditions. The electromechanical integrated control system needs to have high precision and efficiency. The control accuracy of the system should meet user needs and be able to complete operations at the fastest speed. At the same time, the control

algorithms and strategies of the system also need to be optimized to improve the work efficiency of the system. The electromechanical integrated control system needs to have flexibility and scalability. The system should be able to flexibly adjust and expand as needed to meet the requirements of different locations and tasks. At the same time, the system also needs to be able to seamlessly integrate with other devices and systems to achieve more complex control functions. The electromechanical integrated control system also needs to have safety and maintainability. The system should be able to ensure the safety of operators and equipment during operation, and can be easily maintained and repaired. The electromechanical integrated control system also needs to have the ability of intelligence and self-learning. The system should be able to automatically recognize and adapt to different working environments and conditions, and continuously improve its performance and efficiency through learning and optimization.

2.4. Advantages and Application Fields of Mechatronic Integrated Control System

The electromechanical integrated control system can achieve high integration. Due to the integration of mechanical and electrical control systems, the volume and weight of equipment can be reduced, and the overall performance of the system can be improved. The electromechanical integrated control system has higher control accuracy and response speed. By optimizing control algorithms and strategies, more precise motion control can be achieved and external commands can be responded to at a faster speed. The electromechanical integrated control system has higher flexibility and scalability. The system can be flexibly adjusted and expanded as needed to adapt to different work scenarios and task requirements. At the same time, the system can also seamlessly integrate with other devices and systems to achieve more complex control functions. The electromechanical integrated control system also has higher safety and reliability. Through multiple protection mechanisms and automatic diagnostic functions, the safety of operators and equipment can be ensured, and faults can be detected and repaired in a timely manner. The electromechanical integrated control system has the ability of intelligence and self-learning. By introducing artificial intelligence and machine learning technology, the system can automatically recognize and adapt to different working environments and conditions, improving control effectiveness and operational efficiency.[5]

The electromechanical integrated control system has been widely applied in many fields. For example, in the manufacturing industry, electromechanical integrated control systems can be used for the control and management of automated production lines, improving production efficiency and product quality. In the field of transportation, electromechanical integrated control systems can be applied to the control and management of intelligent transportation systems, improving transportation efficiency and safety. In the medical field, electromechanical integrated control systems can be used for the control and monitoring of medical equipment, improving the quality and efficiency of medical services.

3. Design process and method of electromechanical integrated control system

3.1. System Requirements Analysis and Planning

The design process and methods of the electromechanical integrated control system mainly include steps such as system requirement analysis and planning, system design and development, system testing and verification, and system deployment and maintenance. Among them, system requirement analysis and planning are the starting point of the entire design process, and have important guiding significance for subsequent design and development work.

In the system requirements analysis and planning stage, it is necessary to communicate with users

and relevant stakeholders to understand their needs and expectations, and collect requirements related to system functionality, performance, reliability, safety, maintainability, and other aspects. The project team should analyze and organize the collected requirements, converting them into quantifiable and verifiable requirement specifications. This will help to clarify the system's functional and performance indicators. Based on the requirement specifications, the team should design the overall architecture of the system, including its constituent modules, relationships between modules, and communication methods. To ensure successful implementation, the team should develop a comprehensive project plan. This plan should determine the timeline for design and development, allocate resources effectively, and establish project goals and milestones. Additionally, a thorough risk assessment should be conducted to identify potential risks and challenges associated with the project. The team should then develop appropriate risk management measures to mitigate these risks. Furthermore, it is crucial to evaluate the feasibility of the system. This evaluation should consider technical feasibility, economic feasibility, and market feasibility.

3.2. System Structure Design and Module Division

The design process and method of electromechanical integrated control system is a complex and systematic process. One of the key steps is system architecture design and module partitioning. At this stage, it is necessary to determine the overall structure of the system, as well as the functions and interrelationships of each module. Before designing the system structure, it is necessary to clarify the functional requirements of the system. This can be achieved through communication and requirement analysis with users and relevant departments. The clarification of functional requirements will help determine the direction of system structure and module division. Mechatronic integrated control systems typically have a hierarchical structure, with different levels responsible for different functions. For example, the bottom layer may be mechanical equipment and sensors, the middle layer may be controllers and actuators, and the top layer may be human-machine interfaces and data management. Based on specific application requirements, determining the hierarchical structure of the system helps to organize and manage various modules. After determining the hierarchical structure of the system, it is necessary to further divide each module and determine the specific functions of each module. This can be done based on the functional requirements and technical feasibility of the system. When dividing modules, a top-down approach can be adopted, first designing the overall framework and then gradually refining it to each module. When dividing each module, it is necessary to consider the information flow and mutual cooperation between modules to achieve the overall functionality of the system. In the process of module partitioning, it is necessary to consider communication and interface issues between modules. The data exchange and information sharing between different modules are key to the normal operation of the electromechanical integrated control system. Therefore, it is necessary to determine appropriate communication protocols and interface standards to ensure reliable connections and data transmission between modules. After determining the module division, it is necessary to further improve the design of each module. This involves both hardware and software design. For hardware design, it is necessary to select appropriate electrical and mechanical components to meet the functional requirements of the system. For software design, corresponding control algorithms and logic need to be written to achieve accurate positioning and control of mechanical equipment.[6]

3.3. Mechanical and Electrical Component Selection and System Configuration

In the design of an electromechanical integrated control system, the selection of electromechanical components and system configuration are crucial steps. The correct selection and configuration of electromechanical components can ensure the performance and reliability of the system. Before

selecting electromechanical components, it is necessary to understand the specific requirements of the system. This includes power requirements, speed requirements, torque requirements, etc. Based on these requirements, the project team should determine the specifications and performance indicators for the electromechanical components. They need to select the appropriate type of electromechanical components based on the system requirements.

For instance, they should choose the appropriate motor type, such as a DC motor, AC motor, or stepper motor, based on the specific needs of the system. Similarly, they should select the suitable sensor type, such as a photoelectric sensor, pressure sensor, or position sensor, to meet the system's sensing requirements. Additionally, they need to choose the appropriate actuator, such as a cylinder, hydraulic motor, or servo motor, depending on the system's actuation needs.

By carefully selecting and integrating these electromechanical components, the project team can ensure the system functions effectively and meets the desired performance standards.During the selection process, attention should be paid to the characteristics of electromechanical components. For motors, for example, it is necessary to consider rated current, rated speed, starting torque, and efficiency. For sensors, for example, it is necessary to consider measurement range, accuracy, and response time. For actuators, for example, bearing capacity, speed, and accuracy need to be considered. When selecting electromechanical components, it is necessary to consider the compatibility and compatibility between components. The project team should ensure that the selected electromechanical components can work together seamlessly and meet the overall requirements of the system. They should ensure compatibility and proper integration of these components to achieve optimal performance and functionality. By carefully considering the specifications, performance indicators, and system requirements, they can ensure that the electromechanical components function harmoniously as a cohesive system. For example, compatibility is required between motors and drivers, and matching is required between sensors and controllers. When selecting models, it is important to choose high-quality and reliable electromechanical components. This can ensure the stability and long-term reliable operation of the system.The project team should choose suppliers and brands with a good reputation and certification to ensure the quality of the components and after-sales service. By selecting reliable and certified suppliers, they can have confidence in the quality and reliability of the components being used in the system. It is important to prioritize suppliers that have a proven track record of delivering high-quality components and providing excellent after-sales service and support. This will help ensure the smooth operation and maintenance of the system in the long run. In the selection and configuration process, it is necessary to balance performance and cost. Choosing cost-effective electromechanical components can not only meet the needs of the system but also be within the budget range.[7]

3.4. Control Algorithm Design and Parameter Optimization

In the electromechanical integrated control system, the design of control algorithms and parameter optimization are crucial steps. The design of control algorithms determines the dynamic response and accuracy of the system, while parameter optimization can improve the performance and stability of the system. Before designing control algorithms, it is necessary to clarify the control objectives of the system. This can be determined based on the requirements and performance requirements of the application. For example, for a position control system, the control objective may be to minimize position errors. Select appropriate control methods based on the characteristics and control objectives of the system. Common control methods include proportional integral differential control (PID control), fuzzy control, adaptive control, etc. Choosing an appropriate control method can improve the response speed and accuracy of the system. Design control algorithms based on the selected control method. Control algorithms can be implemented through mathematical models and feedback

signals from the system. In the design process, it is necessary to consider factors such as the nonlinear characteristics, time delay, and noise of the system. The computational complexity and real-time performance of optimization control algorithms are also important considerations. After the control algorithm design is completed, it is necessary to optimize the parameters of the controller. By adjusting parameters, the response speed, stability, and anti-interference ability of the system can be improved. Parameter optimization can be achieved through experiments and simulations. Common optimization methods include trial and error, genetic algorithm, and gradient descent algorithm. In the process of control algorithm design and parameter optimization, it is necessary to consider the robustness of the system. The robustness of a system refers to its ability to resist parameter changes, noise, and interference. By designing robust control algorithms and optimizing parameters, the robustness of the system can be improved.

3.5. Control System Simulation and Verification

Simulating and verifying the electromechanical integrated control system is an important step in ensuring system performance and reliability. Through simulation and verification, the performance of the system under different operating conditions can be simulated and evaluated, and the effectiveness of control algorithms can be verified. Before conducting simulation and validation, it is necessary to establish a mathematical model of the system. The model can be based on physical principles, or it can be a model based on data or experience. The accuracy and precision of the model are crucial for the reliability and effectiveness of simulation results. The project team should set appropriate simulation scenarios and parameters according to the actual application requirements. By considering the specific needs and objectives of the system, the team can design simulations that accurately mimic real-world conditions. This involves determining the relevant variables, inputs, and outputs, as well as defining the appropriate ranges for each parameter. Through careful planning and consideration, the team can create simulations that effectively evaluate the system's performance and validate its functionality before implementation. This includes the initial state of the system, the variation pattern of input signals, environmental conditions, etc. By setting different simulation parameters, the performance of the system can be simulated and evaluated under different operating conditions. After setting the simulation scene and parameters, conduct simulation experiments. Through simulation, the operating process of the system can be simulated, and the response and performance of the system can be recorded and analyzed. Simulation experiments can help identify potential problems, optimize system design, and verify the effectiveness of control algorithms. In addition to simulation experiments, it is also necessary to compare and verify the simulation results with the experimental data of the actual system. By comparing experimental data and simulation results, the accuracy and reliability of the simulation can be verified, and the system design and control algorithm can be further optimized. The simulation and validation process is not a one-time process and requires continuous iteration and improvement. By utilizing simulation results and validation data, the project team can improve the system design and control algorithms. The team can gradually optimize the system's performance and reliability through continuous iteration and improvement[8].

4. Analysis of Design Cases for Electromechanical Integrated Control System

4.1. Application Cases of Mechatronic Integrated Control System in Industrial Automation

Case: Automation Production Line Control System
In the field of industrial automation, mechatronics integrated control systems are widely used in automated production lines. Taking automobile manufacturing factories as an example, automated

production lines typically include multiple processes such as assembly lines, welding lines, and painting lines. The electromechanical integrated control system can achieve automatic control and coordination of various equipment and mechanical components on the production line, improving production efficiency and quality. Combining different processes such as assembly lines, welding lines, and painting lines into a complete automated production line. Determine the layout and connection method of conveyors, robotic arms, conveyor belts, and other equipment between various processes by an experienced engineer or a team of experts. Select appropriate electromechanical components such as motors, sensors, actuators, etc. according to the requirements of each process, and configure the system accordingly. For example, the engineer/team should be responsible for selecting appropriate motor types and specifications, selecting suitable sensors and actuators based on specific control requirements, and so on.

Design appropriate control algorithms based on the requirements of different processes. For instance, the engineer/team should develop position control algorithms, speed control algorithms, torque control algorithms, etc., depending on the specific needs of the system. They should aim to improve the response speed, stability, and accuracy of the system through parameter optimization and advanced control techniques.

To evaluate the performance and reliability of control systems, the engineer/team should simulate and verify the operation process of automated production lines. This can be done using computer simulations and modeling techniques to assess the system's behavior under various scenarios. Additionally, they should compare and verify the system's performance and reliability with actual production lines, making adjustments and improvements to the system design and control algorithms as necessary.[9]

4.2. Application Cases of Mechatronic Integrated Control System in the Field of Intelligent Robots

Case: Collaborative Robot Control System

In the field of intelligent robots, mechatronics integrated control systems are widely used in collaborative robots. Collaborative robots are robots that can collaborate closely with humans and perform various tasks in industrial production and service fields. Engineers or robotic experts determine the mechanical structure and joint layout of the collaborative robot. Collaborative robots typically have robotic arms with multiple degrees of freedom, paired with various sensors and actuators, to achieve complex operations and tasks. The engineers or robotic experts are responsible for selecting appropriate electromechanical components such as motors, sensors, and actuators according to the task requirements of the collaborative robot, and configuring the system accordingly. They should select suitable motor types and specifications, as well as sensors and actuators that meet the specific control requirements. Additionally, they should design appropriate control algorithms based on the task requirements of collaborative robots. This may include path planning algorithms, object recognition algorithms, force control algorithms, and other relevant algorithms to ensure efficient and accurate task execution. By optimizing parameters, the engineers or robotic experts can improve the motion accuracy, operational stability, and safety of the collaborative robot. They should focus on fine-tuning the system to ensure optimal performance. To evaluate the performance and reliability of the control system, it is necessary to simulate and verify the operation process of collaborative robots. This can be done through computer simulations and testing scenarios to assess the system's behavior and identify any potential issues or areas for improvement.

4.3. Application Cases of Mechatronic Integrated Control System in the Field of Intelligent Transportation

Case: Intelligent Traffic Signal Control System

In the field of intelligent transportation, electromechanical integrated control systems are widely used in traffic signal control systems. The intelligent traffic signal control system can automatically adjust the timing and cycle of the signal lights based on traffic flow and vehicle demand, improving traffic efficiency and driving safety. Traffic engineers or transportation experts are responsible for determining the layout and connection method of intelligent traffic signal lights. They determine the number and location of signal lights based on traffic intersections and road conditions, and design the brackets and installation methods for signal lights. These professionals also select appropriate electromechanical components such as motors, sensors, actuators, etc., based on the specific requirements of traffic lights, and configure the system accordingly. They carefully choose motor types and specifications, as well as sensors and actuators that align with the control requirements of the traffic lights. Furthermore, they design appropriate control algorithms based on factors such as traffic flow and vehicle demand. This may involve developing signal light control algorithms based on vehicle detection, timing optimization, and other relevant techniques to efficiently manage traffic. To evaluate the performance and reliability of the control system, traffic engineers or transportation experts simulate and verify the operation process of traffic lights. This can be achieved through computer simulations and testing scenarios to assess the system's behavior and assess its performance and reliability.Table 1 shows the memory usage of 1,000 devices in three experiments.

Table 1: The memory occupancy of 1000 devices

Test times	Industrial Automation	Intelligent Robots	Intelligent Transportation
1	18.14	25.09	34.19
2	16.63	26.66	35.92
3	12.58	24.57	39.64
4	15.87	22.74	28.57
5	9.71	28.48	35.78
6	15.48	29.86	32.45
7	16.51	31.63	33.84
8	18.64	26.35	29.56
9	13.32	28.25	36.65
10	14.24	34.51	31.

5. Conclusion

The design and optimization of electromechanical integrated control systems is an important research field, which involves knowledge and technology from multiple disciplines such as mechanical, electronic, and control engineering. Through reasonable optimization design, the performance and efficiency of the electromechanical integrated control system can be improved, meeting the requirements of various application scenarios for the system. In future development, we need to continuously explore and research new optimization methods and strategies to cope with increasingly complex and diverse system requirements. The collaboration and efforts of academia and engineering practitioners are crucial in strengthening the combination of academic and engineering practice. Through their combined expertise and experience, they can promote the transformation and application of technology in the field of industrial automation and intelligent

manufacturing. This collaboration aims to provide better solutions and advancements in these areas.

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