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Research on Distributed Energy Saving Control Method for Street Lights Based on ZigBee Network

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Abstract: With the acceleration of urbanisation, the energy consumption of urban public lighting system increases, and the traditional street light system not only wastes serious energy, but also lacks intelligent control, which makes it difficult to automatically adjust the lighting status according to the environmental changes. In order to solve this problem, intelligent street light control system comes into being. The distributed energy-saving control method of street lights based on ZigBee network can take advantage of the low power consumption, high reliability and self-organisation characteristics of ZigBee protocol to achieve intelligent regulation and control of street lights, thus significantly improving the efficiency of energy use. In this regard, this paper explores in detail the design scheme of distributed energy-saving control system for street lights based on ZigBee network, which combines wireless sensor technology to achieve the collection of environmental data and the transmission of control instructions through low-power wireless communication nodes, and ultimately achieves the goal of optimising street lighting management, energy saving and consumption reduction.

Keywords: street lighting; distributed energy saving control; ZigBee network; module design

Introduction

In urban construction, the development and application of intelligent lighting systems has become an important direction in the current urban infrastructure construction. Intelligent street light control system can intelligently adjust the brightness of street lights according to the environmental light intensity, surrounding traffic flow and weather changes, and thus achieve the goal of energy saving and prolonging the life of the equipment.ZigBee network is a kind of low-power, low-cost, scalable wireless communication protocol for large-scale distributed systems, and has significant technical advantages in the field of intelligent control. In terms of street light energy saving control, ZigBee network can be used to develop a distributed energy saving control method for street lights, to achieve efficient intelligent management of street lights, and to achieve accurate environmental monitoring and dynamic regulation through distributed sensor nodes, so as to optimise the energy use efficiency of the street light control system.

1. Advantages of ZigBee in Intelligent Control

ZigBee is a low-power, high-efficiency wireless communication protocol, which has the advantage of being widely used in intelligent control systems.ZigBee is able to provide wireless communication for a longer period of time while consuming very low power, which is suitable for devices that need to run for a long time and are battery-powered, such as smart street lights, sensor networks, etc. In intelligent control systems, especially in distributed control systems, ZigBee network can effectively extend the working cycle of devices. In intelligent control systems, especially distributed control systems, ZigBee's low power consumption can effectively extend the working cycle of devices.The self-organisation capability of ZigBee networks is another major advantage in intelligent control systems. It supports a variety of topologies, including star, tree and mesh structures, with high flexibility in system design. In practical applications, the number of nodes in the network is often huge, ZigBee can effectively organise the nodes to work together through wireless connections. Network nodes can spontaneously join or leave the

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network, reducing manual intervention and improving the adaptability and scalability of the system. Therefore, ZigBee is particularly suitable for intelligent control environments that require dynamic adjustment.The low-cost feature of ZigBee is also an important advantage in intelligent control. During the construction of large-scale intelligent control systems, the protocol stack can be simplified and the hardware design cost can be reduced. In addition, ZigBee has a strong anti-interference ability in intelligent control, and can maintain stable communication in complex environments.ZigBee's self-recovery ability and network redundancy design can ensure that when some nodes fail or communication problems occur, other nodes will quickly take over the task to avoid the collapse of the system.ZigBee also provides a variety of security mechanisms, including encryption, identity authentication, and data integrity verification, etc., which is helpful to guarantee the data security of the intelligent control system (Sun, 2024).

2. Distributed Energy Saving Control Hardware Design for Street Lights Based on ZigBee Networks

2.1. System hardware design

The core hardware of the system consists of several components, including the electronic chip, sensors, wireless communication module, power management module, and street light control terminal.G9338 electronic chip is the core component of the whole hardware system, responsible for receiving data from the sensors and generating control commands, which are transmitted to the street light terminal through the wireless communication module. This electronic chip supports complex signal processing and can dynamically adjust the switching state and brightness of the street light according to the environmental information fed back from the sensor. In the system design, the signal transmission between the sensor and the control chip adopts radar technology. When the sensor monitors the environmental changes, it can quickly collect data and transmit it to the control chip through the radar signal. The system can respond to changes in the external environment in real time, such as automatically adjusting the brightness of the street light according to the light intensity, or automatically turning off the street light when no one passes by. In the hardware design, the ZigBee network itself has the advantage of low power consumption, which can ensure the system to run stably for a long time under battery power. Each control node adopts a low-power design, which can still maintain low battery consumption after a long time of work. The modular hardware design makes the hardware components of the system relatively independent, which is convenient for later expansion and maintenance. Each street light control unit can be flexibly configured and adjusted according to actual needs without having to redesign the entire system architecture. Modularity also allows the system to be locally replaced and repaired in the event of a failure, reducing system downtime and maintenance costs (Chen, 2024). The power management module is also very important, in this system design, the intelligent power management scheme is used to monitor and manage the battery in real time, optimise the battery charging and discharging process, and be able to dynamically regulate the operating state of the street light according to the actual demand, avoiding excessive consumption of electricity, thus enhancing the overall energy-saving effect of the system.

2.2. Sensor and control module design

The sensor module is mainly responsible for collecting environmental data, including light intensity, motion signals and other external factors that may affect the control of street lights. The system carries out environmental monitoring through high-precision radar sensors and collects data in time according to environmental changes. The collected signals are transmitted to the control terminal through the wireless communication module, and the control module makes real-time adjustments to the street light according to these data. Radar sensors with high sensitivity and strong anti-interference ability are selected to accurately detect changes in the environment and cope with signal attenuation under strong light or extreme weather. In addition, the

sensor module also needs to have a strong adaptive ability, able to automatically adjust the parameters to adapt to different light intensity and environmental changes in the course of daily use, for example, in the daytime to automatically reduce the sensitivity of the motion signal, and at night to increase the ability to monitor the motion signal. Real-time wireless communication between the sensor and other sensor nodes needs to be maintained. In this regard, a low-power and stable ZigBee wireless communication module is used, enabling the sensor nodes to autonomously form a network in the network, and ensuring the timely delivery of information and data integrity through self-organisation and self-healing capabilities. At the same time, the ZigBee network can support a larger scale of sensor node arrangement, forming a dense network coverage among multiple street lights. The control module in the system is responsible for regulating the working state of the street light according to the data fed back from the sensors. The control module includes the functions of voltage regulation, current adjustment and lighting intensity control, etc., and determines whether it is necessary to turn on or adjust the brightness of the street light through the information transmitted from the sensors. In order to ensure the efficient operation of the system, the design requires the sensor module to have strong processing capability and stability, and to be able to respond quickly and accurately transmit information; the control module needs to respond quickly according to the data provided by the sensors and automatically adjust the working mode of the street lamp according to the needs of the system (Chai & Shao, 2024).

2.3. Wireless communication protocol and data transmission design

ZigBee protocol adopts distributed architecture, each street light node not only acts as a terminal for data transmission, but also acts as a routing node in the network, and participates in the topology adjustment and data forwarding of the network. The communication coordination node in the system is responsible for managing the connection status of the whole street light network, and automatically selects the best transmission path according to the real-time network condition through the dynamic routing algorithm at the network protocol layer. When some nodes fail or malfunction, the ZigBee network can re-route or adjust the data transmission path to ensure that the system can still operate stably. In addition, the ZigBee protocol also adopts a low-power mechanism in data transmission, using a low-power communication mode that enables the streetlight nodes to maintain low power consumption even in a long-time standby state, extending the work cycle of the device. Each street light node and the control terminal transmit data through the ZigBee protocol and achieve real-time monitoring. The communication nodes in the system are not only able to transmit the status information of the street lights, but also receive control commands to automatically adjust the switch and brightness of the street lights. The real-time and accuracy of data transmission is crucial to the effectiveness of the street light control system, and the ZigBee protocol ensures that the system can be adjusted in real time according to changes in the external environment by means of a precise signal transmission and fast response mechanism (Kou, 2024).

2.4. Lighting control terminal and power management design

The lighting control terminal design includes power management, relay control and wireless communication module. The power management module is responsible for adjusting the brightness and switching of the street lamps according to the instructions of the control terminal to ensure optimal energy use of the street lamps. The relays are controlled by voltage to ensure flexible and precise switching operation of the street light system. In the system design, the power management module is able to automatically switch to energy-saving mode when the power is low to extend the service life of the battery. In addition, the lighting terminal is designed with a wireless communication module for real-time data transmission with sensors and the control centre to ensure dynamic adjustment of the

street light system. The key to the design of the lighting control terminal lies in the precise control through the power management system and relays, and the realisation of intelligent adjustment functions. Each street light control unit is equipped with a battery management system, which can automatically enter the energy-saving mode when the power is low, reducing unnecessary power consumption. The relay system accurately controls the switching state of the street light under the voltage signal to ensure that the street light can respond in time according to the environmental changes (Liu et al., 2023).

3. Distributed Energy-saving Control Software Design for Street Lights Based on ZigBee Network

3.1. Design of ZigBee network module

ZigBee network module is mainly responsible for efficient data transmission and coordination between the nodes of the street light system in the distributed energy saving control system. In the design, the core advantage of ZigBee protocol lies in its low power consumption, high efficiency and high reliability. The design of the network module firstly takes into account the multi-node cooperative work, and realises the data transmission, signal detection and dynamic adjustment of the street light system through the network coordination nodes. In the initialisation phase, the host computer control module will issue an initial command through the network coordination node, instructing all street lights to start working. According to the real-time data fed back from the sensors, such as light intensity, battery power, etc., the host computer will determine whether it is necessary to adjust the brightness or switching state of the street lights, so as to achieve intelligent adjustment under different environmental conditions. In the design, the feedback mechanism between the sensor and the street light is extremely important. The sensor monitors the data in real time according to the environmental changes and transmits it to the control terminal through the wireless module to ensure that the system can be dynamically adjusted according to the actual demand. The system also includes the design of self-recovery ability, when part of the node malfunction or failure, the system can adaptive adjustment through the network coordination node, select the optimal node path for data transmission, to maintain the stability of the network and the continuity of data transmission. In addition, the network coordination nodes in the system need to support complex routing algorithms, which can dynamically select the optimal path for data transmission according to the real-time network topology and node status, thus ensuring that the street light system can operate stably under any environmental conditions (Zheng & Wu, 2022).

3.2. Upper computer control module design

The upper computer control module is the management and monitoring centre of the street light system, and the upper computer can obtain key information such as the working status, light intensity, battery power, and fault conditions of all street light nodes in real time. The data transmission between the host computer and the street light control nodes is carried out through ZigBee protocol to ensure the real-time and accuracy of the data. In order to improve the management efficiency and operation security, the design incorporates the permission management function. Users with different identities have different operating privileges, such as managers, technicians, maintenance personnel and so on. The system automatically identifies the scope of authority according to the user's identity and opens the corresponding management authority, which can guarantee the stable operation of the system and prevent unnecessary failures or security problems caused by improper operation. The upper computer design focuses on user-friendliness, and its operation interface is simple and intuitive, easy to operate, and has real-time feedback function. Managers can monitor the operation of all street light nodes through the graphical interface, find abnormalities in time and make a quick response. In addition, the host computer also has a variety of alarm mechanisms, when the system is abnormal, it can promptly notify the relevant personnel to take remedial measures to reduce system downtime and energy waste. The data transmission between the host computer module and

the street light system must ensure a high degree of security to prevent the data from being stolen, tampered with or forged. For this reason, encrypted communication and identity authentication mechanisms are used in the design. In addition, the system supports remote control and diagnostic functions, which enable users to manage and maintain the street light system through remote connection, improving the convenience and flexibility of operation (Lai et al., 2022).

3.3. Design of distributed lighting terminal management module

The distributed lighting terminal management module is crucial in the distributed energy-saving control system for street lights. The module is optimised using neural network technology to improve the efficiency and accuracy of signal processing. Each lighting terminal node is connected to other nodes through the activation function of the neural network to form an adaptive control network. In the design, after the lighting terminal receives various information from the environment, it processes and analyses the data through a multi-layer neural network to automatically adjust the brightness and switching state of the street light. Specifically, the system intelligently adjusts the lighting scheme through real-time sensing of factors such as ambient light intensity, traffic conditions, and climate change, in order to achieve the best energy-saving effect and a comfortable lighting environment. The advantage of the neural network model lies in its adaptive capability. When the environmental conditions change, the system is able to adjust the control strategy based on real-time data. For example, if there is insufficient light intensity or a surge in traffic, the street lighting system will automatically increase the brightness and vice versa, thus maximising energy savings while ensuring road safety. The neural network is able to optimise the control strategy of the street light and ensure efficient operation of the system through its hierarchical structure and weight adjustment capability. In addition, the neural network can continuously optimise the control strategy through continuous learning, so that the system can gradually improve the energy-saving effect and reduce energy consumption in long-term operation.

3.4. Data encryption and security design

With the popularity of intelligent technology, data security has become an important issue that cannot be ignored in system design. For this reason, a strict data encryption and authentication mechanism is added to the software design to ensure the security and reliability of the system. The data transmission of each communication node in the system is encrypted, and modern encryption algorithms are used, so that even if the communication data is intercepted by malicious attackers, it cannot be cracked and utilised, which can protect the security of the system. In addition, in order to avoid unauthorised devices from accessing the network and carrying out malicious operations, an authentication mechanism is added to the system design. In the communication process between each node and the control centre, authentication must be performed first. Each communication node is authenticated with the control centre before sending data, and only authenticated devices can participate in data transmission and information exchange (Deng et al., 2021).

3.5. System self-recovery and scalability design

The self-recovery function is introduced in the software design, and each communication node is equipped with self-recovery capability, in the case of node failure or failure, the system can automatically detect the failure and re-select other available nodes for data transmission. When a node fails, the system will dynamically adjust the routing path through the network coordination node to direct the data flow to a healthy node, which can avoid the problem of paralysis of the whole system due to a single point of failure. In addition, the scalability design of the system also facilitates the future expansion of streetlights. As the city continues to grow and the number of streetlights increases, the system is able to support the addition of new streetlight nodes without affecting the stability of the existing network. In order to achieve this, the design adopts a flexible

network structure that can dynamically adjust and optimise the network topology to adapt to the distributed control of street lights of different sizes. When a new streetlight node joins the system, the network structure is automatically reconfigured and ensures smooth communication between the new node and the existing nodes.

Conclusion

In conclusion, this study focuses on the system design and analysis of a distributed energy-saving control method for street lights based on ZigBee networks, and explores the advantages of its application in intelligent lighting systems. Through the in-depth study of ZigBee protocol, hardware module and software architecture, we design an intelligent control system with high efficiency, low power consumption and easy expansion, which can dynamically adjust the street light brightness according to the real-time environmental changes and minimise energy consumption. The ZigBee-based distributed energy-saving control system for street lights shows good results in improving energy use efficiency, reducing operation and maintenance costs and enhancing system reliability, which is worth promoting and applying.

Conflict of Interest

The author declares that she has no conflicts of interest to this work.

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