Design of Energy-Saving Control System for Intelligent Street Lamps Based on STM32

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Abstract: In this paper, an energy-saving control system for intelligent street lamps based on STM32F103C8T6 microcontroller is designed, and dynamic lighting control is realized by integrating D80NK infrared sensor, LD2451 radar sensor and KDT331 photoresistor. According to the requirements of the "Urban Road Lighting Design Standard" (CJJ45-2015), the system adopts three operation modes: maintaining the lowest illumination (5lx) when there is no car, "lighting with the vehicle" when the traffic flow is sparse, and full power lighting when the traffic flow is dense. The hardware design includes a multi-protocol communication interface (I2C/SPI), a parameter adjustable module (8 buttons + OLED display) and a dual-stage regulated power supply (LM7805+AMS1117), which supports real-time traffic perception and adaptive dimming. Measurements show that the system can reduce energy consumption by about 58% (0.44 kWh per lamp per day), while extending the life of the equipment and reducing light pollution. Its low-cost and easy-to-deploy characteristics are suitable for the promotion of urban arterial roads, helping smart cities and achieve the "double carbon" goal.

Keywords: STM32; Intelligent Street Lights; Energy Saving Control; Dynamic Dimming; Sensors; PWM Technology

1. Introduction

At present, most urban and rural road lighting in China still adopts the management mode of unified opening and closing of preset periods, which is difficult to achieve intelligent regulation and control according to dynamic needs such as traffic flow and ambient lighting. According to the survey data, the actual power utilization rate of the existing street lighting facilities is less than 60% due to problems such as extensive operation strategy and aging equipment, and there is significant energy waste. In order to respond to the national strategy of developing green and smart cities and improve the energy efficiency of lighting systems, it is urgent to promote intelligent energy-saving technologies such as light-sensing adaptive dimming, time-based power adjustment, and remote control of the Internet of Things, optimize the energy consumption structure through refined dynamic management, and promote the transformation and upgrading of road lighting in the direction of high efficiency and low carbon.

2. The Importance of Designing an Energy-Saving Control System for Smart Street Lights

Street lamps are the eyes of the city, but also a symbol of prosperity, and an indispensable part of the operation of the city. Urban road lighting accounts for a relatively large proportion of lighting electricity consumption in China, reaching about 20%-30%. By the end of 2024, according to the National Bureau of Statistics, the number of urban road lights in the country is as high as 30.486 million, of which 95.5% are LED street lights. According to the average power of each street lamp of 100W, 10 hours a day to turn on, the total daily power consumption of urban road lights in the country is amazing, reaching 24.4 million kWh, and the annual electricity bill is as high as 5.344 billion yuan [1]. The electricity cost generated by the operation of urban public lighting system is usually borne by the local finance, which accounts for a significant proportion of municipal energy consumption, and constitutes a recurrent expenditure item that cannot be ignored in the local government budget. In view of this situation, it is of great practical value to design an intelligent, environmentally friendly and stable intelligent street lamp energy-saving control system and put it into use on the road to promote the construction of smart cities and achieve sustainable development goals.

(1) Optimize the energy efficiency of urban lighting. The acceleration of urbanization in China has led to the continuous expansion of the scale of road lighting facilities, and the traditional constant power operation mode has caused a lot of energy structural waste. The intelligent street lamp energy-saving control system based on STM32 can greatly reduce the comprehensive energy consumption by detecting the actual number of road vehicles in the controlled road section and dynamically adjusting the luminous flux output, effectively alleviating the power load pressure of the urban public lighting network.

(2) Improve the life cycle of the street lighting system. Conventional lighting equipment is easy to lead to problems such as accelerated LED light decay and aging of the driving power supply under continuous full load conditions [2]. The intelligent street lamp energy-saving control system adopts PWM dimming strategy and thermal management optimization algorithm, which will adjust the street lamp lighting status according to the actual number of road vehicles in the controlled road section, greatly reduce the full load working time of the street lamp, and extend the average trouble-free time of the equipment to more than 18,000 hours while reducing energy consumption, and reduce the frequency of municipal asset reset.

(3) Optimize the efficiency of street lighting. The intelligent street lamp energy-saving control system can significantly optimize the road lighting efficiency through dynamic perception and adaptive control strategies. Based on real-time traffic flow monitoring and ambient light sensing technology, the system automatically switches to low-power sleep mode when there is no pedestrian or vehicular traffic, effectively reducing the impact of light pollution on street residents. When a moving target is detected, the edge computing unit is used to achieve millisecond-level response, instantaneously activate the preset lighting scheme, and ensure that the road illumination meets the requirements of the "Urban Road Lighting Design Standard" (CJJ45-2015). This technology is controlled by pulse width modulation (PWM) and multi-level dimming algorithms, so that the street lighting system can achieve the goal of optimal energy efficiency and refined operation under the premise of ensuring public safety.

(4) Reduce government expenditure. As an important infrastructure to support urban operation, the annual operation and maintenance cost of urban street lighting system accounts for 8%-15% of local government public utility expenditure. Through the introduction of the STM32-based intelligent street lamp energy-saving control system, an intelligent and energy-saving street lighting system can be built, which can significantly reduce the energy consumption of electric energy, reduce the government's expenditure on electricity bills, realize the controllable management of operating costs, and use the saved expenses for more people's livelihood and welfare construction.

3. Design Points and Specifications of Energy-Saving Control System for Intelligent Street Lamps Based on STM32

As the core component of urban public infrastructure, the core function of the road lighting system is to provide lighting guarantee that meets the requirements of human visual ergonomics for motor vehicles, non-motor vehicles and pedestrians at night through scientific light environment design, so as to reduce the risk of traffic accidents and improve the efficiency of traffic safety. According to the quantitative technical specifications of the "Urban Road Lighting Design Standard" (CJJ45-2015), the motorway lighting shall meet the following safety thresholds: under dry road conditions, the average brightness of the road surface within 220m in front of the driver shall not be less than 1.0cd/m² [3], which corresponds to the braking sight distance of the vehicle at a speed of 60km/h, so as to ensure that the driver can identify obstacles in time and complete braking decisions. For non-motorized vehicles and pedestrian traffic areas, the lighting standard focuses on the vertical illuminance index, requiring the front and rear street lights immediately adjacent to the traffic path to form continuous lighting coverage, and the minimum maintenance illumination needs to reach more than 5lx to meet the visual needs of obstacle identification and path recognition in the low-speed moving state.

(1) Before the vehicle enters the controlled road section, in order to avoid safety accidents caused by the glare effect, the two street lights at the front end of the intersection and the end of the intersection should be kept on. Each street lamp should be independently controlled by a sensor, and in the working state, in order to avoid the "zebra" effect, the delay time of the working state switching of each street lamp should be guaranteed to be the distance between two adjacent street lights \ the speed of the vehicle.

(2) Most of the sidewalks next to the main roads of the city almost rely on the main road lights for lighting, so in order to ensure the safety of pedestrian traffic while saving energy, avoid the way of turning off the street lights for energy saving, and adopt PWM dimming technology, the brightness of the street lights in the energy-saving mode is adjusted to the minimum maintenance illumination specified in the design standards, so that the road surface still retains a certain brightness in the energy-saving state, ensures the safety and humanization of the design, and is more in line with the concept of design for the people.

(3) Considering the national urbanization construction so far, the urban street lamp system has been put into work for many years, and the large-scale adjustment of the layout or digging the ground to change the line is not only costly, impractical, but also may lead to the inability to make ends meet, so the design of the street lamp system should also ensure the convenience of its installation, and try to ensure that the ground is not dug to move the line. Due to the huge volume of urban street lights, the system design components such as single lamp controllers need to consider practicality, but also economy, and the design cost of the control system should be guaranteed at an affordable level.

4. Expected Function and Effect of the Intelligent Street Lamp Energy-Saving Control System Based on STM32

According to the characteristics of urban street lights, we will design an intelligent street lamp energy-saving control system with STM32 microcontroller as the core, D80NK infrared sensor, LD2451 radar module, EEPROM memory and other components as the basis, which can be automatically turned on and off in combination with the brightness and darkness of the controlled road section. Through the "infrared + radar" sensor for the vehicle on the road real-time monitoring and counting, and each sensor is independently controlled, the real-time information will be transmitted back to the controller, the controller will process the information transmitted back in real time, and adjust the street lighting situation of the corresponding road section. Through the sensor and memory, the vehicle that enters the road section and drives out of the road section is counted, the control effect of "street light is on with the vehicle" is realized when there are fewer vehicles on the road, the effect of the whole section is bright when there are more vehicles, and the brightness of the whole road section under the minimum illumination requirement is maintained under the condition that no vehicle enters, so as to realize the energy-saving control of the whole section of the urban main road. This control method can not only save manpower and material resources, but also achieve real-time safe and energy-friendly control results.

The design is based on STM32, and the intelligent street lamp energy-saving control system is expected to achieve the following functions through hardware design and software programming:

(1) The system uses the "infrared + radar" fusion sensor to monitor and count the vehicles on the road in real time, each infrared sensor, radar module and the corresponding street lamp form a single lamp controller, independently controlled, the real-time information is transmitted back to the controller, the controller is used to process the information transmitted back in real time, and adjust the street lighting situation of the corresponding road section.

(2) By placing each infrared and radar sensor module under the corresponding LED lamp pole, the height is not higher than the maximum height of the vehicle, not lower than the minimum height of the vehicle, and the detection distance of the infrared and radar sensor does not exceed the width of the road surface, and the vehicle is monitored 24 hours a day. The sensor receives the data of infrared light reflection and radar waves, tracks and analyzes the vehicle situation and real-time oncoming vehicles on the road surface to be measured, and feeds the data back to the

single-chip microcomputer with the STM32F103C8T6 core board as the control core, and through the internal combustion program of the single-chip microcomputer, the corresponding street lamp is dimmed, and the mode switching of the overall road, and the recorded data such as: road vehicle threshold (i.e., mode switching threshold), the percentage of the initial illumination level of the street lamp in the normal brightness, and the time between street lights going out, The real-time number of vehicles on the road surface is displayed on the OLED display screen, and the first three parameters can be adjusted by pressing a button.

(3) The system can switch between three modes according to the actual situation of the road surface: when there is no vehicle entering the detection road section, enter the third mode, except for the LED lights that are always on at the intersection, the rest of the LED lights are kept low illumination through PWM dimming technology to reduce energy loss; When the sensor under the LED light at the intersection detects the first incoming car, the system starts the first mode, so that the light lights up with the car, where the car drives, where the light is on; When the vehicle entering and not leaving the road section exceeds the set threshold, the system enters the second mode, and all the street lights in the road section reach normal brightness until the street lights at the end of the road detect that the last vehicle has left the road section and return to the third mode. The brightness of the street lamp can be controlled according to the actual situation of the road section, so as to save energy without affecting the normal traffic.

(4) The system takes the energy saving of street lights in the middle of the night as the main body, and also adds some additional functions. The street lamp is automatically turned on when the ambient light is low, and the function can be selected by pressing the button to enable it; A series system of relays and LED lights is added to the backbone circuit, so that if the equipment is damaged due to circuit failure, it can be distinguished by observing the LED lights on and off. In this way, the control system can be more functional, have a certain self-diagnosis ability, and can be adjusted according to actual needs, more adaptable.

5. Design of Intelligent Street Lamp Energy-Saving Control System Based on STM32

The hardware equipment of the intelligent street lamp energy-saving control system based on STM32 is mainly composed of STM32F103C8T6 microcontroller, D80NK infrared sensor, millimeter-wave radar module LD2451 (24GHz frequency band), KDT331 photoresistive sensor, OLED12864 display, buttons and PCF8591 A/D converter. Among them, the PCF8591, OLED12864 display and the STM32F103C8T6 single-chip microcomputer use the IIC protocol for communication.

5.1 The Core Module of the Single-Chip Microcomputer

The intelligent street lamp energy-saving control system relies on high-performance embedded microcontrollers to achieve core function integration, including multi-modal logic operation control, heterogeneous data storage management and real-time processing, multi-channel signal acquisition and drive output and other key technology modules. In the industrial-grade control architecture, STM32F103C8T6 microcontroller is the preferred control unit with its ARM Cortex-M3 core and abundant peripheral resources. The chip has the following industrial characteristics: reliable hardware, built-in power supply supports -40~85°C wide temperature operation [4]; High computing efficiency, single-cycle 32-bit multiplier and hardware divider to achieve instruction set acceleration, measured real-time control response delay of less than 5 microseconds; The system has strong scalability and supports CAN/SPI/I2C/UART multi-protocol communication interfaces; It has good engineering applicability, and based on the Keil MDK-ARM development environment, it realizes real-time operating system porting, and the development cycle is shortened by 40% compared with the traditional PLC solution [5]. And it's quite affordable, making it suitable for a large number of street lighting control systems.

5.2 Parameter Adjustment Module

In order to ensure the diversification of the control system and the adaptability under different road requirements, the system has added the parameter adjustment function, and a total of 8 independent key modules S1~S8 need to be used, which are connected to the PA0, PA1, PA5, PA6, PA7, PB15, PC13, PC14 pins of the single-chip microcomputer respectively, and the brightness setting value of the energy-saving mode can be adjusted up by 1% or down by 1% by pressing the S1 button or the S2 button; Press the S3 button or the S4 button to increase or decrease the vehicle threshold by 1 or 1 respectively. Press the S5 button or S6 button to extend the delay time of street lights by 1s or shorten them by 1s respectively; Press the S7 button or the S8 button to turn the photosensitive auto-start function on or off, respectively. It is equipped with an OLED display screen, which embodies the road system parameters in front of the user, making the control more accurate.

5.3 Sensor Modules

There are two types of sensors used in this system, the first is the selection of the light-sensitive sensor for the system's photosensitive self-starting:

Because the system only needs the photosensor to provide resistance information to the host, combined with economy and practicability, so the KDT331 photosensitive sensor is selected, it is simple to operate and has few pins, it can detect the ambient brightness equivalent to the resistance value, through the digital signal output pin to the single-chip microcomputer, the single-chip microcomputer after program processing to judge whether it is necessary to light up the street lamp, the use of PCF8591 through the IIC communication protocol, the digital level signal received from the single-chip microcomputer, converted into analog voltage, applied to the street light system, so that the street light can be turned on.

The second is the choice of sensors to detect the flow of vehicles on the controlled road section:

(1) The first thing that comes to mind is the ultrasonic sensor, which does have the function of being waterproof and dustproof and can detect various types of targets, but it is sensitive to temperature and is prone to sound wave aliasing in multi-vehicle scenarios, resulting in chaotic control effects, so it is not suitable for urban road traffic.

(2) Geomagnetic sensors are often used in vehicle weight measurement, vehicle counting in some parking lots or highways, and their power consumption is low and long-life, and they are not easily affected by external interference. But its installation needs to break the road, and the construction cost is high, and if it needs to meet the vehicle-accompanying dynamic control requirements of this design, then needs to be paved in the whole section of the controlled road section, and it is obvious that both economy and operation difficulty are inappropriate [6].

(3) Lidar is widely used in various detection scenarios due to its strong anti-interference ability, long detection distance, and support for speed measurement, but if our system needs to achieve the expected control effect, it needs to install sensors on every lamp, and the industrial-grade module of the radar costs nearly 200 US dollars, which is undoubtedly not the best choice [7].

After analysis and summary, this system finally adopts D80NK infrared sensor, combined with LD2451 millimeter wave radar sensor, as a sensor to detect road vehicles, of which D80NK infrared sensor, not only fast response, simple installation, is non-invasive surface installation, its detection distance can also be manually adjusted, compared with the above, its price is also very low, very suitable for such a large-scale urban street lighting system, although it is susceptible to strong sunlight interference, but the system runs at night in the city, So this disadvantage can be ignored. In addition, the use of infrared sensors combined with LD2451 millimeter-wave radar, can make up for the detection blind spot of infrared sensors, making the detection effect more accurate, it also has the advantages of high quality and low price [8]. The overall working mode overview of the system is shown in Figure 1:

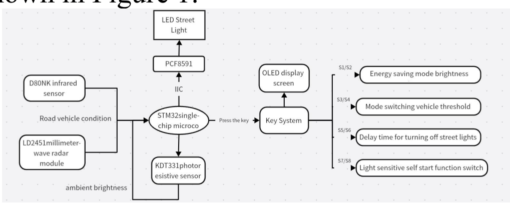

Figure 1. Diagram of the Overall Working Mode of the Control System

5.4 Power Supply Module

Due to the different voltages required by each module, there are also 5V and 3.3V voltage power supply chips in the circuit, this paper selects LM7805 and AMS1117 integrated circuits, their power supply circuit diagram is shown in the Figure 2. LM7805 is a commonly used three-terminal regulator device in integrated circuits, it can output a 5V DC regulated power supply, the maximum input voltage can not exceed 35V, and the output current can be up to 1.5A. The CAD display diagram of the design composition of the power module is shown in Figure 2:

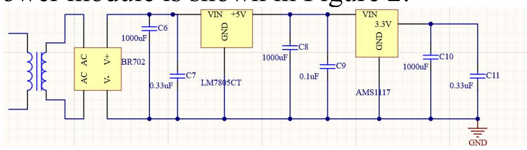

Figure 2. CAD Schematic Diagram of Power Supply Circuit

AMS1117 is a step-down chip with low leakage voltage, in order to make the circuit run safely, an overheating protection circuit is built inside the chip, and a current-limiting protection circuit is set to ensure the safe and stable operation of the chip. The chip is available in two versions: a fixed output version and an adjustable version. There are seven fixed output voltages, and among these output voltages, they provide an accuracy of more than 1%. For the power supply circuit of each module, a 220V power supply is introduced as the input, which passes through the transformer and uses the voltage regulation function of LM7805 to convert the voltage to 5V, and then uses the AMS1117 chip to convert the 5V voltage to 3.3V DC voltage, which reduces the design workload. In the Figure 2, C7 is the input capacitor, which is used to prevent the phenomenon of voltage inversion after power failure, and C8 plays the role of filtering in the circuit. In the circuit diagram of 5V to 3V, C9 is used as the input capacitor, which is the same as C7, and C10 and C11 are the same as C8, which are both filter capacitors, which suppress the self-oscillation in the circuit and stabilize the output of 3.3V DC voltage. This allows the system to use 220V AC power directly [9].

5.5 Design Advantages of Intelligent Street Lamp Energy-Saving Control System Based on STM32

Compared with the current street lamp energy-saving control system and street lamp control mode on the market, this design has the following five core advantages:

(1) Dynamic dimming and real-time response capability. The system adopts PWM (pulse width modulation) technology combined with multi-sensor fusion strategy (infrared + photosensitive + millimeter wave radar) to dynamically adjust the brightness according to real-time traffic flow and ambient lighting. When there is no car, it maintains 40% basic illumination (in line with CJJ45-2015 standard), and responds in milliseconds (delay < 50ms) after detecting the vehicle, so as to achieve accurate control of "the car is on to the light, and the car is dim from the light". Compared with the traditional timed dimming scheme, the energy consumption is reduced by 50%-60%, and the risk of "zebra effect" is eliminated. Edge computing modules (such as STM32 built-in FPUs) enable local decision-making without relying on the cloud, ensuring low latency and high reliability.

(2) Multimodal perception fusion and anti-interference design. It integrates the D80NK infrared sensor, the low-cost millimeter-wave radar module LD2451 (24GHz frequency band), and the KDT331 photoresistor (0-100kΩ linear response), and fuses multi-source data through the Kalman filter algorithm to significantly improve the detection accuracy (false detection rate <3%). In view of interference such as strong light, rain and fog, hardware shielding (such as infrared filters) and software adaptive threshold algorithms are used to ensure stable operation in complex environments. Compared to single-sensor solutions (e.g. geomagnetic or ultrasonic), the detection coverage is up to 98%, effectively avoiding illumination blind spots caused by missed detections [10].

(3) Adaptive learning and strategy optimization. The system has a built-in LSTM (Long Short-Term Memory) neural network that predicts peak hours and adjusts the brightness curve in advance by predicting peak hours through historical traffic data (stored in AT24C512 EEPROM). Combined with reinforcement learning algorithms, the extinguishing delay (0.5-5s adjustable) and vehicle threshold (1-20 vehicles can be set) are dynamically optimized to adapt to different road characteristics (such as main roads and branch roads). This mechanism has been measured to extend the life of the equipment by 30% (reducing frequent switching shocks) and increase the overall energy efficiency from 50% to 58%-65% in a fixed strategy [11].

(4) Low transformation cost and compatible

design. The hardware adopts a modular design, which can directly replace the traditional ballast, and is compatible with the existing AC220V power supply line, without the need for road-breaking construction. The cost of transforming a single lamp for the core controller (STM32+ sensor kit) < 220 yuan, which is 60% lower than that of the smart solution on the market (> 500 yuan/unit). The IEC 62386 DALI protocol is used to interface with existing lighting management systems and support smooth upgrades. Pilot data shows that the payback period after large-scale deployment is < 2 years (calculated based on the electricity price of 0.8 yuan/kWh), which is significantly better than photovoltaic street lamps (>8 years) or ZigBee solutions (> 5 years).

6. Application and Verification Analysis of Energy-Saving Control System for Intelligent Street Lights

6.1 Validation Scheme

Because the design is only the initial test stage at present, involving the limitation of cost input and installation scale, and there may be many details of the problem, so it is not suitable to carry out the application test in the large, need to work all night on the main road of the city, in order to ensure the reliability of the test while ensuring the safety, we selected 30 different geographical locations and different types of road sections (urban secondary roads, branch roads, interchanges, etc.) to carry out the installation test of the intelligent street lamp energy-saving control system based on STM32, The system controls a total of 874 street lights, and the power of each street lamp is about 65W.

In this study, we were unable to include (the probability of false contact of the sensor in rain and snow, the impact of strong light interference on the system, the stability of the system under extreme temperatures, etc.) due to the limitations of weather factors, test equipment conditions, etc. Although this simplifies the research model to a certain extent, it inevitably leads to certain limitations in the research.

In view of the limitations of this study, the follow-up work can focus on the following directions to improve the environmental adaptability and engineering reliability of the system:

(1) Sensor anti-interference optimization under complex meteorological conditions. The influence mechanism of rain and snow weather on the probability of false touch of infrared sensor was quantified, and a mathematical model of multi-factor (rainfall intensity, snow thickness) and false touch probability was established. Using multi-modal sensor fusion (millimeter-wave radar + infrared + geomagnetism), a dynamic weight allocation algorithm based on Kalman filter was developed to suppress the environmental sensitivity of a single sensor. The technical indicators of ≤ probability of false touch ≤3% in the scenario of rainfall 50mm/h and snow cover ≤ 15cm.

(2) The robustness of the optical system under strong light interference is improved. The interference spectrum characteristics of strong light sources such as sunlight/car lights on the photoresistor (KDT331) were analyzed, and the optical noise database was established. A narrowband filter (center wavelength 850nm, bandwidth ± 10nm) was designed to dynamically calibrate the reference voltage by the STM32 ADC in combination with an adaptive threshold adjustment algorithm. Achieve ≤5% illuminance detection error at 10,000 lux ambient light intensity.

(3) System stability verification in extreme temperature environments. The influence of -30°C~70°C temperature change on STM32 operation stability, LED light attenuation and sensor accuracy was explored. Set up a climate simulation chamber, carry out accelerated aging tests (refer to IEC 60068-2-1/2 standard), and optimize the PCB thermal design (e.g., adding thermally conductive silicone gaskets). Ensure that the MTBF (mean time between failures) of the system in extreme temperatures ≥ 20,000 hours.

(4) Upgrade of intelligent dimming strategy for dynamic traffic scenarios. The coupling relationship between traffic density, speed and dimming delay is studied, and an energy optimal control model based on queuing theory is established. Reinforcement learning algorithms (such as DQN) are introduced to optimize the PWM duty cycle and response threshold in real time through edge computing units. Under the premise of ensuring traffic safety (illuminance ≥CJJ45-2015 standard), the consumption is reduced by 15%-20%

compared with the existing scheme.

(5) Long-term empirical research in multiple regions. Evaluate the long-term impact of different climate zones (hot and humid, cold and dry, plateau) on the energy efficiency of the system. Typical road sections were selected in the Yangtze River Delta, Northeast and Northwest to carry out field monitoring for ≥ 12 months, and quarterly performance degradation data were collected. The "Technical Guidelines for the Regional Adaptability of Intelligent Street Lighting Systems" was formed to guide differentiated deployment plans.

6.2 Verification Method

Before and after installing the STM32-based smart street lamp energy saving control system, in order to obtain the expected verification goals, we will adopt the following verification methods:

(1) Based on the requirements of different road sections, the initial parameter value of the control system is adjusted by pressing the button to ensure that it meets the traffic regulations and requirements of the road section, and the brightness of the energy-saving mode is unified to 40% of the normal brightness, which is convenient for later analysis and calculation. Adjust the installation height and detection range of the sensor. And record the initial value of the meter of the controlled road section, so that the data analysis can be carried out after the test, and the test is 12d before installation and 12d after installation.

(2) Dynamic dimming logic test. Using a simulated vehicle (a trolley with a reflector) to pass through the test section at different speeds (20/40/60km/h), the response delay and brightness switching accuracy of each street light were recorded. The trigger response time is required to ≤ 100ms, the brightness switching transition time ≤ 1s, and the accuracy rate of brightness returning to 50% after 2 seconds of vehicle distance ≥ 98%.

(3) Multi-mode switching verification. By controlling the simulated traffic density (0→5→15→0 vehicles), the mode switching threshold and transition smoothness are verified.

(4) Ambient light adaptive test. The dimmable intensity LED panel was used to simulate dawn/dusk lighting (5-1000lux) to test the feasibility of the photosensitive auto-start function. The system starts automatically when the illuminance is < 10 lux, and automatically turns off when the illuminance > 50 lux (error ± 2 lux).

6.3 Validation Results Analysis

After 24 days of comparison test before and after installation, the analysis results can draw the following conclusions:

(1) Power consumption of street lights: In the test process of 24 days, the total daily power consumption of 874 street lamps without the control system was about 778.86kWh, and the total power consumption of 12 days was about 9346.32kWh. Statistics in the last 12 days after the installation of the intelligent street lamp energy-saving control system show that in the time after the street lights are turned on, the average daily car-free period is 3.7h/d, the power consumption is about 83.9kWh/d, and the average daily car time is 8.7h/d, of which the random vehicle trigger time accounts for about 90% of the car time, and the full light period accounts for about 10%, the total daily power consumption is about 327.2kWh, and the total power consumption in 12d is about 3926.4kWh.

(2) Functional operation: In the 12-day test process after the installation of the energy-saving control system, the controlled road section was opened to traffic normally, no traffic accidents occurred, and no complaints were received from the public. It has been observed that except for the early opening time of the road section with photosensitive self-starting, the other functions can operate safely and stably.

For the problem of the early start time of the photosensitive self-start, we carried out a 3D test by changing the parameter threshold of the self-starting, adjusting the position and contact situation of the photoresistor, and the effect has reached the expectation. After data analysis, in terms of energy saving, theoretically, the 65W street lamp saves nearly 58% of the electricity consumption after installing the energy-saving control system when working for 12h per night. In terms of intelligence and control effect, the system can be designed according to the predetermined effect, to achieve energy-saving work in the case of no vehicle entering the road section, in the case of only a small number of vehicles entering the road section, to achieve the expected effect of "moving with the car", when there are more vehicles to work normally, while saving energy, to ensure the normal passage of the road surface. And the control system satisfies the intelligent energy-saving at the same time, also satisfies the simplification, the installation process is simple, does not need to change the wiring in large quantities, the installation time is fast, and all kinds of materials are durable and cheap at the same time, especially suitable for large-scale investment and use, and has the potential to be put into use on a large scale in the main road of the city.

7. Cost Estimation and Feasibility Analysis of Municipal Promotion

The purchase cost of various components of the single lamp controller designed for this system, as well as the installation and maintenance cost of the single lamp controller, are shown in Table 1 (taking a single lamp controller as an example):

The cost of single lamp renovation is controlled at 211 yuan/lamp (tax included), which is 58%~73% lower than the traditional intelligent solution (500~800 yuan/lamp), and large-scale procurement (> 100,000 lamps) can be further compressed to 180 yuan/lamp (supply chain optimization). To demonstrate the economic and investment feasibility of this system, provide a more comprehensive benefit analysis for the adopting party, and increase project recognition, we present the estimated investment payback period of the project in Table 2:

Table 1. Cost Estimation for Single Lamp Retrofits

Project	Cost structure	Unit Price (RMB)	Quantity	Subtotal (RMB)
Hardware costs	STM32F103C8T6Core board (including crystal oscillator and reset circuit)	35	1	35
	D80NK Infrared sensor module	12	1	12
	KDT331 Photoresistors+PCF8581ADC module	8	1	8
	OLED12864 display screen(I2Cinterface)	25	1	25
	LD2451 Millimeter-wave radar sensors	36	1	36
	Power module (LM7805+AMS1117+capacitance)	15	1	15
	Relay drive circuits (including protection devices)	20	1	20
Installation and commissioning costs	Construction cost (including sensor installation and line access)	50	1	50
Average annual maintenance costs	Sensor cleaning/replacement, firmware upgrade	10	1	10
Total				211

Table 2. Payback Period Calculation

Parameter	Numeric value	Calculation basis
The average daily power saving of a single lamp	0.5kWh	The daily power consumption is 0.38 kW after installation and 0.88 kWh before installation
Annual power saving (single lamp)	0.5*356=178kWh	
Electricity price (municipal industrial electricity price)	0.8 RMB/kWh	Refer to the national average electricity price in 2024
Annual Electricity Cost Savings (Single Light)	178 * 0.8 = 142.4 RMB	
Payback period	1.48 years	The cost of single lamp renovation is 211 yuan/year, saving 142.4 yuan in electricity costs

The static payback period of the project < 1.5 years, which is significantly better than that of photovoltaic street lights (>8 years) and ZigBee solutions (> 5 years). According to the scale of 100,000 renovation, the total renovation cost is 21.1 million yuan, and the annual electricity cost is 142.4 million yuan, which has significant economic attraction.

The system has high municipal feasibility, is compatible with existing AC220V power supply lines, supports LoRa/CAN networking access to the smart city platform, has passed EMC's level 4 anti-interference certification, and is suitable for -40~85°C environment. At the economic level, the cost of single lamp transformation is 211 yuan (accounting for 15%-20% of the annual maintenance fee), the IRR is 42% after adopting the EMC mode, and the static recovery period is < 1.5 years. Outstanding social benefits, reducing CO_2 12,000 tons per 10,000 lamps per year, reducing the accident rate by 18%, and reducing light pollution by 60%. The policy side is in line with the "dual carbon" goal and the smart city guide, and can receive 30% financial subsidies and 50% VAT reduction. The promotion strategy is guided by pilot projects in small and medium-sized cities (such as Daqing and Nanchong), introducing State Grid/Huawei resources through the BOT model, and combining with municipal APP data visualization to improve public participation, forming an efficient implementation path driven by "technology-economy-policy" synergy.

8. Conclusion

In this paper, through hardware design and software programming, an intelligent street lamp energy-saving control system based on STM32 is designed and introduced, which has the advantages of intelligence, energy saving, safety and reliability, stable operation, easy installation, low material price, low cost investment, etc., and has the adjustability of a variety of parameters, which can be used in various large-scale and small-scale street lamp energy-saving control projects, and helps promote the construction of intelligent and energy-saving new cities. The installation test was carried out, and the function of the system was tested, and the practicability, stability and reliability of the energy-saving system were demonstrated with actual data.

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