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MICROCONTROLLER-BASED INTELLIGENT LIGHTING CONTROL SYSTEM WITH ADAPTATION TO ENVIRONMENTAL CONDITIONS

Abstract. Relevance. The growing need for energy-efficient lighting solutions and the development of smart home technologies create the need to develop intelligent lighting control systems. Modern systems must adapt to changing environmental conditions, ensure user comfort and significantly reduce energy consumption. **Research object:** intelligent lighting control systems based on microcontrollers with functions of adaptation to environmental conditions. **Purpose of the article:** conducting an analytical review of existing intelligent lighting control solutions, determining optimal technical solutions and identifying promising development directions. **Research results:** A comprehensive analysis of modern intelligent lighting control systems was conducted, key technologies of sensors, microcontrollers and adaptation algorithms were considered. The advantages and disadvantages of the main commercial solutions were identified, and optimal hardware and software platforms were identified. **Conclusions**. Intelligent lighting control systems demonstrate significant potential for energy savings (up to 60%) and increased user comfort. The most promising solutions are based on 32-bit ARM Cortex-M microcontrollers with integration of multiple sensors and machine learning algorithms.

Keywords: intelligent lighting; microcontroller; adaptive systems; energy efficiency; IoT; smart home; light sensors.

Introduction

Statement of the problem. Modern society faces increasing challenges in the field of energy consumption and environmental sustainability. According to the International Energy Agency, lighting accounts for about 15% of global electricity consumption [1]. In this context, the development of intelligent lighting control systems is becoming a critical task for achieving sustainable development goals. The development of Internet of Things (IoT) technologies, the availability of high-performance microcontrollers, and improvements in sensor technologies create unprecedented opportunities for the creation of adaptive lighting systems. Such systems are able to automatically adjust the intensity and spectral composition of light depending on the time of day, the presence of people, the level of natural light, and individual user preferences.

Analysis of recent research and publications. The issue of intelligent lighting control is being actively researched in various fields of science and technology.

Particular attention in the literature is paid to circadian lighting and its impact on human health [2]. Systems capable of adapting the color temperature of light according to natural biorhythms show significant improvements in sleep quality and overall well-being of users. Ukrainian researchers also make a significant contribution to the development of this field. The monograph by Kovalenko O.M. [3] presents the results of the development of microcontroller systems for building automation, including lighting control systems.

The purpose of the work is to conduct a comprehensive analysis of existing solutions for intelligent lighting control based on microcontrollers, determine the most effective technical approaches and identify promising areas for development in this industry.

Main part

Among the leading manufacturers of smart lighting systems, Philips stands out with its Hue system, which is rightly considered a pioneer in the field of consumer smart lighting. The Philips Hue system was first introduced in 2012 and has undergone significant evolution since then.

The technical architecture of the system is based on the Zigbee 3.0 protocol, which provides a reliable mesh network with the ability to control up to 50 light sources via the central Philips Hue Bridge. The bridge is equipped with a dual-core ARM Cortex-A9 processor with a frequency of 1 GHz and 512 MB of RAM, which ensures high command processing performance and minimal response latency. Philips Hue's ecosystem of compatibility is particularly noteworthy. The system integrates with over 1,000 third-party apps and supports voice assistants Amazon Alexa, Google Assistant, Apple HomeKit, and Samsung SmartThings.

Innovative features include Adaptive Lighting, which automatically adjusts color temperature throughout the day based on a person’s circadian rhythms. Geolocation-based control allows lighting to be automatically turned on and off based on the user’s location, as determined via a mobile app.

In terms of energy efficiency, Philips Hue bulbs consume 9.5 watts at the equivalent brightness of a 60-watt incandescent bulb, providing energy savings of up to 80% [4]. A key advantage of the Philips Hue ecosystem is the scalability and reliability of the Zigbee mesh network, which automatically creates alternative data transmission routes when individual nodes fail.

LIFX offers a fundamentally different technical solution that uses a direct connection to Wi-Fi without the need for an additional bridge. The technical core of LIFX lamps is based on a 32-bit ARM Cortex-M4 microcontroller with a frequency of 168 MHz, which provides significantly more computing power compared to competitors. Each lamp contains 6 types of LEDs: red, green, blue, warm white, cool white and infrared, which allows you to achieve a color coverage of 1000% sRGB - the widest in the industry. A unique feature of LIFX is the built-in a computer vision system implemented through machine learning algorithms in the lamp's microcontroller. This allows the lamps to automatically analyze the ambient light and adapt their parameters without external sensors [5]. The LIFX software platform is built on the FreeRTOS real-time operating system, which guarantees stable operation of multitasking processes and minimal response latency (less than 50 ms). The system API supports HTTP REST and WebSocket protocols, providing developers with flexible integration options with external systems.

A distinctive feature of LIFX is Polychrome technology, which uses multiple white LEDs of varying color temperatures to create a more natural white light [42]. The system also supports infrared light for specialized applications, including phototherapy and circadian rhythm support. The Lutron Caseta system represents a professional solution for the commercial and luxury residential segments, a key feature is the use of the patented Clear Connect RF protocol operating in the 434 MHz band, which provides exceptional communication reliability even in conditions of high radio frequency spectrum density [6].

The Caseta technical architecture is based on the Texas Instruments CC1310 central processor specially optimized for sub-GHz radio communication. The processor contains an ARM Cortex-M3 core with a frequency of 80 MHz and a built-in radio frequency module with a receiver sensitivity of -110 dBm, which provides a communication range of up to 18 meters through walls and up to 150 meters in open space [7].

Lutron's unique technology is an adaptive dimming algorithm that automatically calibrates to the type of connected load - from traditional incandescent lamps to modern LED panels. The system supports smooth dimming from 1% to 100% brightness without flickering thanks to the use of high-frequency PWM control (20 kHz) and algorithms for compensating for LED driver nonlinearities.

The system software includes an intelligent scenario planner with the ability to create up to 100 custom lighting programs, each of which can contain up to 16 sequential stages with configurable time intervals. The system integrates with leading building automation protocols, including KNX/EIB, BACnet and Modbus RTU. A feature of professional positioning is the support of the emergency protocol, which ensures automatic activation of emergency lighting when the main power is turned off via the built-in 1200 mAh backup battery. The battery life in emergency mode is up to 4 hours at 25% brightness.

The Lutron Caseta system also integrates predictive maintenance technology, which analyzes the operating parameters of each device and predicts the need for maintenance or component replacement before they actually fail.

Table 1 presents an analysis of technical characteristics, showing significant differences in the architectural solutions of leading manufacturers.

Table 1 – **Comparative characteristics of commercial intelligent lighting systems**

System	Communication Protocol	Max. Devices	Power Consumption	Lamp Price ($)	Response Time (ms)
Philips Hue	Zigbee 3.0	50	9.5	50	100
LIFX	Wi-Fi	Unlimited	11	35	200
Lutron Caseta	Clear Connect RF	75	8,5	60	50

Hardware platforms for smart lighting

Espressif Systems' ESP32 microcontroller (Fig.1) has become widely used in DIY projects due to its built-in Wi-Fi and Bluetooth support, low cost, and developed development ecosystem. The dual-core Xtensa LX6 processor with a frequency of up to 240 MHz provides sufficient performance for implementing complex lighting control algorithms.

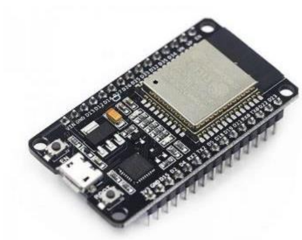

Fig. 1. ESP32

With 520 KB of internal SRAM and support for external flash memory up to 16 MB, the ESP32 easily handles storing complex lighting scenarios, web interfaces for remote control, and configurations of various lamps. The key advantage of the ESP32 in smart lighting projects is its 16 high-precision PWM channels with a resolution of up to 16 bits, providing smooth dimming and accurate color rendering of flicker-free RGB/RGBW LED strips. Its 18 channels of 12-bit ADC enable connection to light, motion, temperature, and humidity sensors to create adaptive systems that automatically adjust brightness and color temperature to environmental conditions and time of day. Multiple I2C and SPI interfaces simplify integration with ready-made sensor modules and LED drivers.

STMicroelectronics' STM32 series, based on ARM Cortex-M cores, demonstrate an optimal balance of performance and power consumption (Fig.2). The ultra-low-power STM32L4 microcontrollers are particularly suitable for autonomous lighting systems [8].

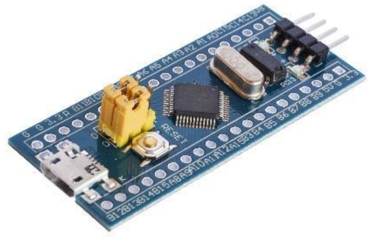

Fig. 2. STM32 Blue Pill

Nordic Semiconductor nRF52 series is specifically optimized for IoT applications with a focus on power efficiency and support for multiple wireless protocols including Bluetooth LE, Thread and Zigbee.

The ARM Cortex-M4 architecture with DSP instructions and a hardware FPU in the STM32L4 enables fast processing of complex color correction, spectral analysis, and adaptive lighting control algorithms in real time.

The key advantage of the STM32L4 for battery-powered lighting is its consumption of only 100 nA in shutdown mode and 420 nA in standby mode with RAM contents preserved, providing years of battery life. Multiple power-saving modes allow for optimization of consumption for specific scenarios, from emergency lighting with periodic activation to decorative lighting with night mode.

Sensor technologies

Modern smart lighting systems integrate numerous types of sensors:

Photodiode-based light sensors (e.g. BH1750) (Fig. 3) provide accurate measurement of natural light levels with a resolution of up to 1 lux. This allows the system to automatically adjust the brightness of artificial lighting to maintain a comfortable level of light.

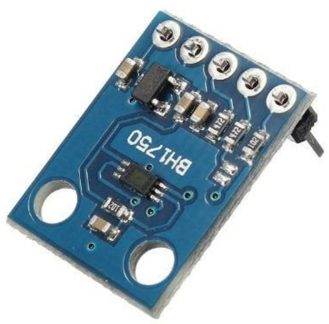

Fig. 3. Photodiode-based light sensors BH1750

PIR (passive infrared) motion sensors provide detection of human presence in a room. Modern models, such as the AM312 (Fig.4), are characterized by low power consumption (less than 15 µA) and high sensitivity.

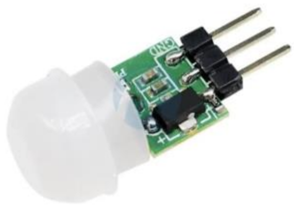

Fig. 4. PIR Motion Sensor AM312

Microwave sensors (e.g. RCWL-0516) are able to detect movement through obstacles and provide more accurate detection compared to PIR sensors.

A comparison of technical parameters of different types of sensors is presented in Table 2:

Adaptive control algorithms

Proportional-integral-derivative (PID) controllers are widely used for smooth changes in lighting brightness. Proper adjustment of PID coefficients ensures stable operation without overshoot and oscillations.

Machine learning algorithms, including neural networks and clustering techniques, are used to analyze user behavior patterns and automatically adapt lighting modes. Studies show that it is possible to reduce energy consumption by 30-40% when using predictive algorithms.

Circadian algorithms automatically adjust the color temperature of light throughout the day: from warm light (2700K) in the evening to cool (6500K) during the day, which helps maintain natural human biorhythms.

The data in Table 3 shows a wide range of available sensor solutions with different power consumption characteristics and functionality: PIR sensors exhibit minimal power consumption, making them preferable for stand-alone systems, while microwave sensors provide higher detection accuracy at the expense of increased power consumption.

Table 2 – **Comparative characteristics of sensors for lighting systems**

Sensor type	Model	Range (m)	Viewing angle (°)	Consumption (µA)	Response time (s)	Price ($)
Light	BH1750	-	-	120	0,12	2
PIR motion	AM312	7	110	15	2-3	1
Microwave	RCWL-0516	9	360	3000	0,5	3
Temperature	SHT30	-	-	2	0,15	4
Sound	INMP441	5	-	1100	0,01	6

Table 3 – **Efficiency of different lighting control algorithms**

Algorithm	Energy saving (%)	Adaptation time (min)	Regulation accuracy (%)	Implementation complexity
PID controller	35	0,5	95	Low
Neural network	45	5	98	High
Fuzzy logic	40	2	92	Medium
Circadian	25	30	85	Low
Hybrid	55	3	97	High

Conclusions

The study conducted a comprehensive analysis of modern microcontroller-based intelligent lighting control systems. Leading commercial solutions, hardware platforms, sensor technologies, and adaptive control algorithms were considered. Comparative analysis showed that intelligent lighting systems are able to provide:

– Reduced energy consumption compared to traditional systems

– Increasing user comfort through automatic adaptation to environmental conditions

– Improving sleep quality and overall well-being using circadian algorithms

– Integration with smart home ecosystems and remote control capabilities

The main areas of further development are: implementation of machine learning algorithms for predictive control, development of more energy-efficient wireless protocols, miniaturization of sensor systems and reduction of the overall cost of solutions.

A promising development direction is the integration of artificial intelligence technologies directly into lighting microcontrollers, which will enable local data processing without transmitting it to the cloud.

This is especially relevant in the context of growing demands for data privacy and reduced system latency.

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Інтелектуальна система керування освітленням на основі мікроконтролера з адаптацією до умов навколишнього середовища

А. Р. Сорокін, М. О. Чайкін

Анотація. Актуальність. Зростаюча потреба в енергоефективних рішеннях для освітлення та розвиток технологій розумного дому створюють потребу в розробці інтелектуальних систем керування освітленням. Сучасні системи повинні адаптуватися до змінних умов навколишнього середовища, забезпечувати комфорт користувача та значно знижувати споживання енергії. **Об'єкт дослідження:** інтелектуальні системи керування освітленням на базі мікроконтролерів з функціями адаптації до умов навколишнього середовища. **Мета статті:** проведення аналітичного огляду існуючих інтелектуальних рішень керування освітленням, визначення оптимальних технічних рішень та визначення перспективних напрямків розвитку. **Результати дослідження:** Було проведено комплексний аналіз сучасних інтелектуальних систем керування освітленням, розглянуто ключові технології датчиків, мікроконтролерів та алгоритмів адаптації. Визначено переваги та недоліки основних комерційних рішень, а також визначено оптимальні апаратні та програмні платформи. **Висновки.** Інтелектуальні системи керування освітленням демонструють значний потенціал для економії енергії (до 60%) та підвищення комфорту користувача. Найбільш перспективні рішення базуються на 32-бітних мікроконтролерах ARM Cortex-M з інтеграцією кількох датчиків та алгоритмів машинного навчання.

Ключові слова: інтелектуальне освітлення; мікроконтролер; адаптивні системи; енергоефективність; Інтернет речей; розумний дім; датчики освітлення.