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Design and Research of an Intelligent Classroom Device Control System based on Visual Monitoring Analysis

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Abstract: Given the current problems in university and primary/secondary school classrooms—low efficiency of manual operation for electrical equipment, significant energy waste, and non-standardised management—this paper proposes an intelligent classroom equipment control system based on visual analysis of surveillance cameras. Using the existing classroom surveillance network, deep learning-based visual algorithms are applied in the system for real-time analysis of surveillance video to accurately detect the presence of people, their numbers, locations, and environmental conditions in the classroom. According to the pre-set intelligent control logic, the system can automatically start or stop the operation of classroom lighting, fans, air conditioning devices, multimedia equipment, etc., and adjust their operating parameters. The architecture of the system and its hardware components are presented in this paper, along with the principles of the visual recognition algorithm, equipment control strategy and software implementation. The stability and energy-saving effects of the system are shown in practice through tests. Based on the test results, the recognition accuracy of the system for personnel exceeds 95%, it can adaptively regulate various electrical devices according to the actual usage conditions of classrooms, effectively reduces unnecessary energy consumption in classrooms, and significantly improves the intelligence and precision of equipment control. Therefore, this system has good practical application value and is likely to be widely used.

Keywords: Visual Monitoring Analysis; Smart Classroom; Intelligent Lighting Control; Automated Equipment Control; Deep Learning; Energy-saving Management.

1. Introduction

1.1. Research Background and Significance

With the all-round development of smart campus initiatives, intelligence and energy efficiency are now key goals for campus infrastructure construction. As necessary public teaching areas in the campus, classrooms have a high density and frequent use of electrical equipment, such as lighting fixtures, fans, air conditioners, multimedia teaching devices, etc. At present, most of the classrooms in China still use traditional manual control systems, and the start-up and shut-down of equipment, as well as adjustments to operating parameters, must all be done manually. Common problems include failure to turn off equipment promptly after class in the absence of users; failure to turn on lighting in response to low natural light on cloudy days; mismatched operation of air conditioners and fans with the number of people in the classroom; and equipment running at full load despite only occasional use by people. These behaviours lead to considerable waste of energy and increase the load on the campus energy management system, as well as the degradation of equipment [1].

Most traditional intelligent classroom management solutions are based on single-device sensing technology, such as infrared people-counting modules, light sensors, and temperature-humidity sensors, for data collection. However, the above solutions have serious detection blind spots, are easily interfered with, cannot accurately count the number of people, and are also affected by fluctuations in ambient temperature and light; thus, they are not suitable for the complex teaching environment of a classroom. However, the existing campus surveillance system does not cover all classrooms and is not available 24 hours a day. No large-scale additions of new hardware are required; these systems can be run on the existing infrastructure to achieve scene awareness and intelligent management, thus reducing retrofitting and operating expenses significantly.

The school has installed a classroom video surveillance system based on electronic examination rooms at present. During the renovation of smart classrooms, the system's image data has been used for various types of data analysis to collect and analyze key indicators, such as student attendance rates, front-row seating rates, head-up engagement rates of students during lectures, and overall classroom engagement status. Deep learning algorithms are used in the system for image processing to accurately identify the presence and behaviour of people in a classroom, precisely count the number of students, and address the shortcomings of older sensor-based detection technology. Thus, adaptive and eye-like visual-based fine-grained control of classroom electrical equipment is achieved. The application of this technology can help to address the problems of energy waste in classrooms, delayed monitoring, and poor management of campus operations, thus reducing both energy consumption and operating and maintenance costs. In line with the goals of constructing green and intelligent campuses, this initiative can promote the progress of sustainable and intelligent development for campuses in practice.

1.2. Current State of Research Domestically and Internationally

Some foreign universities have applied classroom energy consumption management systems based on visual recognition. Intelligent classroom control technologies in overseas countries and regions have begun to develop earlier, and by using mature machine vision and IoT technologies, nations such as those in Europe, North America, Japan and

South Korea have already achieved intelligent, interconnected control of classroom equipment. Based on the analysis of camera images, these systems can determine the number of occupants and their activities to adjust classroom lighting and air conditioning power dynamically for energy-efficient supply according to actual requirements. However, the algorithms of these systems were originally developed for small-class teaching environments abroad and are not very suitable for the conditions in Chinese classrooms, such as large class sizes, high occupant density, and complex spatial structures; moreover, the high cost of equipment renovation also hinders their widespread application [2].

In recent years, research in this area in China has advanced rapidly, and many universities and research institutions have conducted extensive studies on intelligent energy-saving control for classrooms. Most of the existing research has used a single sensor or basic image recognition for control. Some existing solutions use face detection and head counting to estimate the number of people in a classroom, then control the on/off of lighting fixtures and enable zonal control; however, these solutions generally have problems such as low recognition accuracy, poor interference immunity, and simple device coordination logic, which prevent the realization of precise, multi-device cooperative control of lighting, fans, air conditioners, and multimedia equipment. Most of the current solutions also need to add separate data-acquisition devices and do not utilise the existing surveillance resources in the campus effectively; thus, resources are wasted and retrofitting costs are high. In short, there are still many deficiencies in the current full-scenario intelligent classroom equipment control systems based on existing surveillance vision technology in China; urgently needed is an intelligent solution with low cost, high accuracy and multi-device coordination capabilities.[3]

1.3. Main Research Content and Innovations

This study aims to achieve intelligent energy-saving control of multiple devices in classrooms. Build upon the existing surveillance camera network in the school to develop an intelligent classroom device control system based on machine vision. The main research goals are as follows: First, we will build a four-level system structure of "vision data collection → intelligent analysis → logical decision-making → device operation", which is compatible with the current classroom surveillance network and thus reduces the difficulty of system expansion; Second, we will optimise a lightweight YOLO deep learning algorithm to improve the precision of occupant detection in surveillance videos, accurately count heads, and identify unoccupied states; Third, we will establish a cooperative intelligent control plan for various scenarios and devices to adjust lighting intensity, fan speed, air conditioning temperature and operating conditions, as well as multimedia equipment activation, based on all-around data such as the number of people, light conditions and indoor temperature; Finally, we will complete the hardware and software design of the system and carry out actual tests to verify the detection accuracy, response speed and energy-saving effects of the system.

The main innovations of this study are as follows: First, it fully utilizes the existing surveillance hardware resources in the campus to avoid the need for large-scale sensor deployment, thus reducing the construction and operating costs of the system significantly and adapting to various scenarios of campus renovation. Second, it overcomes the limitation of single-device control by enabling multi-dimensional cooperative intelligent regulation of lighting, fans, air conditioning units, and multimedia devices, and dynamically adjusting the operating mode of devices according to real-time occupancy data.[3] Compared with the traditional on/off control method, this approach has achieved substantial improvements in energy efficiency and practical applicability.

2. Overall System Design Scheme

2.1. System Design Principles

To ensure stable operation, full functionality and suitability for the campus environment, the system design strictly adheres to the following principles: First, the low-cost reuse principle—fully utilizing the existing surveillance cameras and network transmission equipment in the classrooms to reduce the deployment of new hardware and lower renovation costs; Second, the high-precision and high-stability principle—optimizing visual recognition algorithms to handle various complex circumstances, such as fluctuations in classroom light, obstructions by personnel and debris, etc., to ensure high accuracy of personnel detection and status identification, and guarantee stable 24/7 operation of the system; Third, the intelligent and refined operation principle—avoiding a single-switch control mode and employing graded operational state adjustments for devices according to different scenario demands to balance user experience and energy efficiency; Fourth, the safety and reliability principle—adding overload and short-circuit protection functions to the electrical control module, and integrating data encryption and anomaly warning capabilities in the software to protect both device operation and campus electrical safety; Fifth, the scalability principle—leaving functional interfaces for the addition of other modules in the future, such as environmental monitoring, energy consumption statistics, and remote management.

2.2. Overall System Architecture

The four levels of the whole system from bottom to top are the video acquisition layer, the visual analysis layer, the intelligent decision-making layer, and the device execution layer; although they operate independently, they are coordinated to form an organized system and achieve high-efficiency operation [4].

The video acquisition module uses the existing high-definition surveillance cameras in the classroom as its main hardware to achieve 24/7 real-time acquisition of panoramic classroom images. The system will obtain scene information, such as people's activities, light conditions and equipment operating states, and then transmit a live video stream over the campus LAN to the analysis end of the back-end. The camera has high-definition video recording and real-time transmission capabilities, covers the whole area of the classroom, does not have any blind spots in the surveillance, and provides all-round, high-quality image data for the following visual analysis.

The core processing unit of the system is the Visual Analysis Layer, and an optimised lightweight YOLO deep learning algorithm is employed to perform frame-by-frame analysis of the incoming real-time video stream. Through the above processes of image preprocessing, feature extraction and object detection, this layer can accurately identify the presence of people in the classroom, count the number of people, and determine whether they are stationary or moving.

At the same time, it can detect light in the picture and provide necessary data for the intelligent module. This layer can reduce the impact of environmental noise, such as obstructions from curtains, changes in ambient light, and interference from furniture or other objects, thus improving detection accuracy.

The intelligent decision-making module of the system is used to apply predefined multi-scenario intelligent control logic and threshold parameters. Obtain personnel data and the output of environmental visual analysis from the visual analysis layer; integrate them with indoor temperature and humidity auxiliary data; perform all-around logical evaluations; and generate corresponding device control commands. Depending on the operating conditions of different times, such as empty classrooms, occasional use, full-class teaching, or break times, the lighting, fans and air-conditioning devices, etc., can be adjusted accordingly. In addition, there is a delayed control and anomaly correction function to avoid damage to the equipment caused by frequent start-stop operations.

Smart Relays, dimming modules, speed-regulating modules, air-conditioning control modules and other classroom terminal electrical devices are included in the device execution layer. It receives control instructions from the decision-making module, accurately executes functions such as starting/stopping devices, adjusting brightness, regulating airflow speed and temperature, etc., and at the same time sends real-time operating status data back to the backend system to build a closed-loop control system.

2.3. System Operation Flow

The entire operating process of the system is automated and runs in a closed-loop manner, as shown in the following steps: Surveillance cameras acquire real-time video images of the classroom and transmit them over a network to the backend processing unit; the backend processing unit performs preliminary processing on the video frames and applies deep learning analysis to extract essential data, such as the number of people in the classroom, their presence status, and ambient light conditions; based on the pre-set control strategy, the intelligent decision-making module determines the necessary operating mode for the equipment in the current environment and then sends control signals to the terminal control unit to regulate the operation of various electrical devices; at the same time, the system collects real-time operating status data from these devices, modifies the control logic dynamically, and promptly adjusts the operating conditions of the equipment upon detecting any changes in the environment; in the absence of personnel, all devices will be automatically turned off after a certain delay to achieve continuous intelligent control and management.[5]

3. System Hardware Design

The hardware of this system is a hybrid design consisting of "reuse of existing equipment plus the addition of a few modules". The core system will keep the original high-definition surveillance cameras and network transmission devices in the classrooms, and add new embedded main control modules, intelligent control modules, and environmental detection modules. This Design has a simple hardware structure, is low-cost, and simple to install.

3.1. Video Capture Hardware

The system can be connected to the existing 1080P HD network surveillance cameras in the classroom, supports real-time video transmission at 25fps, and has a horizontal field of view of 120°. The three areas in the classroom have all been covered by cameras to avoid any blind spots, and these cameras are equipped with day-and-night adaptive imaging that automatically switches to infrared imaging in low-light conditions to ensure high-definition image acquisition at night and provide a stable source of image data for visual algorithm-based detection. Cameras are connected to the campus LAN via RJ45 connectors and can upload real-time video streams over the network without special cables.

3.2. Main Control Processing Module

The central control chip of the system is a Raspberry Pi 4B development board. This device has a small size, is low-power, has good computing performance, and can run light-weight deployment of deep learning models. It has the functions of real-time video and image analysis, logical operations and command distribution. A Linux operating system is used by the control module to ensure stable operation of the visual recognition algorithm and control software. It can also be used to remotely debug and collect data from a network in several classrooms for distributed control.

3.3. Intelligent Equipment Control Module

The Control Module is relatively simple and can be connected to various devices in a classroom. Lighting devices are connected to intelligent dimming relay modules for continuous 0-100% brightness adjustment, as well as tiered dimming and on/off control; fan devices have stepless speed regulation modules to achieve multi-level wind speed adjustment and start/stop control; air conditioning devices are equipped with infrared intelligent control modules that simulate manual remote operation for air conditioning start/stop, temperature adjustment and mode switching; multimedia devices are connected to high-power intelligent relay modules for reliable start/stop control of projectors, audio systems and teaching computers. All control modules can perform low-voltage control of the high-voltage circuit and have built-in overload, short-circuit and lightning protection devices for electrical safety.

3.4. Auxiliary Environmental Monitoring Module

To improve the accuracy of equipment control, high-precision temperature and humidity sensors have been added to collect real-time data on the temperature and humidity in classrooms. Combine this data with the results of visual analysis to optimise the control logic for air conditioning and ventilation systems. Real-time transmission of sensor data via a serial port to the main control module is used to ensure a fast response speed and high detection accuracy. This way can solve the problem of only using visual detection and not obtaining environmental temperature and humidity information; thus, integrated control is achieved through the cooperation of visual and environmental sensing capabilities.[7]

4. System Software and Algorithm Design

4.1. Image Preprocessing Design

Raw video frames from surveillance cameras are usually

noisy and unevenly lit, etc., and their recognition accuracy is relatively low when used directly for object detection. Therefore, preprocessing operations need to be carried out on the video frames. The four steps of the preprocessing pipeline are: Grayscale Conversion, Gaussian Filtering for Denoising, Contrast Enhancement, and Size Normalisation. First, reduce the amount of computation and improve processing speed by converting the colour video frame to a grayscale image. Next, a Gaussian filter is used to reduce salt-and-pepper noise and Gaussian noise in the frames and eliminate distracting artifacts. Histogram equalization is then applied to increase the contrast of low-light and backlighting images, and the contours of people are enhanced. Finally, the size of the image is uniformly scaled to 640x640 pixels to meet the input requirements of deep learning models, and then object detection can be carried out.

4.2. Optimization of Lightweight YOLO Detection Algorithm

The YOLOv5 model with a small size is used as the foundation of this research for classroom detection. Given that the original YOLO model has a large number of parameters, is computationally expensive and difficult to deploy on embedded devices, this paper has reduced the network by removing some convolutional layers and optimising the feature fusion module. These modifications reduce both the number of model parameters and computational overhead, increase the speed of video frame processing, and achieve a real-time detection frame rate of 20 frames/s or higher to meet the requirements of real-time control.

To solve the problems of occlusion by people, dense distribution of individuals and variations in lighting in the classroom environment, we have optimised the model's loss function, strengthened its ability to extract human figures and key human body features, and eliminated interference from irrelevant background features. By training on a large number of real-world classroom scene samples, the model has learned to capture the features of people in different light conditions, various numbers of individuals, and various sitting and standing postures. Therefore, the model can distinguish between real people and interfering objects, such as desks, chairs, teaching aids, and human shadows, and reliably detect people for accurate counting of the number of people. A dynamic background update mechanism has also been introduced to address the problem of a changing environment, such as moving curtains and gradual light changes, and thus enhanced the stability and accuracy of detection.

4.3. Design of Intelligent Device Control Strategies

Based on the characteristics of the classroom teaching environment, this system integrates visual recognition results with ambient temperature and humidity data to develop multi-scenario adaptive intelligent control strategies. The four main scenarios of the above strategies are: idle time, occasional use, regular class hours and breaks, etc.

Unoccupied Scenario: The system uses visual detection to confirm that no personnel are in the classroom; after continuously monitoring for 30 seconds without any human activity, it immediately turns off the multimedia equipment, lighting fixtures and fans, and then delays the shutdown of the air conditioning unit by one minute to prevent accidental shutdown due to a brief departure of occupants. When not in use, all electrical equipment will be turned off to save electricity.

Scenarios with sparse occupancy: When 1-5 people are detected in the classroom, only the basic operating requirements need to be met. Adjust the brightness of the light automatically according to the light in the video; if it is too dark outside, increase the brightness to 50%, and if it is too bright outside, turn off the light. If the temperature inside the house is higher than 28°C, a slow-speed fan will be turned on; if it exceeds 30°C, then the air conditioner will be used to keep the temperature at 26°C. Extra lighting and high-power devices are turned off; only the necessary ventilation and light functions will be used to save energy.

Standard teaching scenario: When the number of people in the classroom exceeds half of the total capacity, the system will consider it a normal teaching environment. All multimedia teaching devices are automatically turned on, and the lighting equipment is set to 100% brightness to meet the requirements for instructional lighting; the system then adapts its operating parameters according to the indoor temperature and humidity, maintains a low-speed operation of the ventilation fan in the range of 24–26 °C, and activates the air conditioning system automatically when the temperature exceeds 26 °C to balance user comfort and energy-saving control.

Break-time scenario: If there is frequent movement of personnel and no fixed sitting position has been occupied, the system will determine that it is a break time. The basic lighting will remain on, but the multimedia teaching equipment will be turned off; according to the ambient temperature, the operation of fans and air conditioners will be adjusted to avoid energy waste from continuous full-load operation of equipment, and after students take their seats, the system will automatically switch back to lecture mode.

At the same time, a manual-priority mode has been added to the system for manual operation by teachers and students. Manually intervene at this time to switch the operating mode; otherwise, the system will revert to automatic mode after 10 minutes and continue working normally.

4.4. Software Program Flow Design

The system software is a module-based programming system with the following core workflow: After the system starts up, it automatically obtains the camera's video stream and sensor data; then, it preprocesses the video frame and runs deep learning detection to output the number of people and whether they are present; by integrating ambient temperature and humidity data, an intelligent control strategy library is used to perform logical judgment; next, corresponding device control commands are generated and sent to the terminal control module; at the same time, real-time feedback on the operating status of devices is provided to achieve closed-loop control; this whole process is repeatedly carried out to respond dynamically to any changes in the environment, and device operating and energy consumption data are also recorded for later statistical analysis.

5. System Testing and Result Analysis

5.1. Test Environment and Test Plan

A representative multimedia classroom at a particular university was employed as the experimental environment for this study. The classroom is fully equipped with lighting, fans, air conditioning, multimedia devices, etc., and the intelligent

control system introduced in this paper has been applied. The three Stages of the tests are: Algorithm Accuracy Test, Device Control Function Test and Energy-Saving Performance Test. A large number of test cases were set up in various circumstances, such as bright daylight, cloudy weather, low light conditions, night time, high-occupancy periods, low-occupancy periods and empty states, and continuously for 72 hours.

Algorithm Accuracy Testing: Quantify the detection accuracy rate and counting error rate of personnel by the system in various scenarios; Device Functionality Testing: Verify the accuracy and stability of lighting dimming, fan speed regulation, air conditioning temperature control, and multimedia device startup/stop operations under all conditions; Energy Efficiency Testing: Compare the daily average electricity consumption of classrooms with and without the automated system in traditional manual operation to determine energy-saving effects.

5.2. Test Results and Analysis

According to the precision test results of the algorithm, in a normal light environment without obstructions from people, the detection accuracy rate is 98.2%; under low-light conditions and in crowded or obstructed areas, it drops to 95.1%, and the overall average recognition accuracy rate is 96.5%. The error rate of personnel counting is less than 3%, and the response speed for scene-state recognition is ≤0.5 seconds. High detection accuracy and a fast response speed are required for real-time control of classrooms; otherwise, equipment abnormal start-up or shut-down due to misclassification or failure to detect will occur.

Functional test results of the equipment show that the system can accurately recognize various classroom scenarios and precisely coordinate the control of multiple devices according to the pre-set control strategy. Accuracy of device shutdown in unattended mode is 100%. In the event of a shortage of personnel, classroom teaching, or other circumstances during off-peak hours, there are no problems with light dimming, fan speed adjustment, air conditioner temperature regulation, or multimedia-device-start-stop functions in the system. The equipment operates normally and does not frequently start and stop or malfunction. The switch from manual operation to automatic operation is smooth and can be used in many different teaching scenarios.

Energy-saving test data show that in the traditional manual control mode, the average daily electricity consumption of the test classrooms was around 18.6 kWh; there was considerable energy waste due to idle operation of unattended equipment after class, excessive lighting during the day, and inefficient cooling or heating systems. After the application of this intelligent control system, the average daily electricity consumption of the classrooms dropped to 11.2 kWh; thus, a daily electricity saving of 7.4 kWh and a total energy-saving rate of 39.7% were achieved. Prolonged operation will reduce the energy consumption of classrooms in the school and save energy.

5.3. System Advantages and Existing Limitations

According to the test analysis, this system has several advantages over the old classroom management system: First, it can achieve a high resource reuse rate by using the existing surveillance equipment for intelligent control and thus avoid the cost of deploying many new sensors; Second, the accuracy of detection is relatively high; Deep-learning-based visual detection has overcome the limitations of traditional sensors, removed detection blind spots, and is very resistant to interference; Third, it has better energy-saving performance through hierarchical and coordinated regulation of multiple devices, rather than the simple on/off control of the old system; Fourth, it is very stable in various complex classroom environments, supports round-the-clock unattended operation, and has reduced maintenance and operation costs.

At the same time, the system still has some deficiencies: first, in cases of extremely low ambient light or severe crowding of people, the detection accuracy for individuals may be slightly reduced; second, at present, only basic equipment linkage control has been implemented, and extended functions such as energy consumption data tracking, remote early-warning mechanisms, and mobile-based control have not yet been added. In the future, to improve the detection accuracy of extreme cases further, we will expand the training data and optimise the algorithm model; at the same time, additional functional modules will be added to increase the intelligence and integrated management capabilities of the system.

6. Conclusion and Outlook

6.1. Research Conclusion

Given the deficiencies of traditional classroom equipment management, such as a lack of intelligent control, considerable energy waste and low intelligence levels, this paper introduces an intelligent classroom equipment control system based on visual analysis of surveillance cameras. Utilise the existing campus surveillance network and add a lightweight deep learning algorithm to the system for fine-grained monitoring of people and environments in classrooms. Multi-scenario intelligent control strategies can be employed to achieve adaptive and coordinated management of lighting, fans, air conditioners and multimedia devices.

According to the field test results, the system can correctly identify personnel, respond promptly and operate stably in practice. It can be customised to various situations in classroom teaching, and problems such as idle equipment and excessive energy consumption are effectively solved; as a result, the whole-school energy-saving rate is close to 40%. It will improve the intelligence and accuracy of classroom equipment management. Additionally, the system uses the existing hardware resources of the environment to reduce retrofitting costs and ensure stable operation. It can be used in many different classroom settings of primary and secondary schools and universities, and has good practical and expandable application.

6.2. Future Outlook

In the future, the system will be optimised and improved in three ways. First, algorithm optimisation: Introduce multi-feature fusion recognition technology to further improve the detection accuracy of complex scenarios by integrating personnel posture and behaviour characteristics, and at the same time, optimise algorithm computational efficiency for deployment on embedded devices with lower hardware specifications. Second, functional expansion: Add functions for energy consumption statistics, fault early warning, remote backend management and mobile app control to build a comprehensive "perception-control-statistics-management" system for classroom equipment. Third, scenario expansion:

Extend the system's control logic to campus public areas, such as laboratories, conference rooms and offices, to build an all-encompassing smart campus energy management system and provide stronger technical support for the development of green and intelligent campuses.

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