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Design of 360° Dead-Angle-Free Smart Desk Lamp based on Visual Tracking

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Abstract

Objectives: This study aims to design a dead-angle-free smart desk lamp. *Methods:* The convolutional neural network (CNN) algorithm was used to realize the identification and positioning of objects. Then, the desk lamp arm was driven according to positioning to realize dead-angle-free illumination. In the subsequent testing, the designed desk lamp was compared with others driven by the support vector machine (SVM) and back-propagation neural network (BPNN) algorithms. *Findings:* The CNN algorithm implemented in the smart desk lamp demonstrated superior target recognition performance and positioning accuracy when compared to the other two algorithms. Moreover, with this algorithm, the smart desk lamp efficiently generated tracking responses for targets and displayed minimal positioning errors once tracking became stable. *Novelty:* The novelty of this article lies in the utilization of the CNN algorithm to achieve visual tracking for a smart desk lamp, which serves as the basis for its automatic adjustment.

Keywords: Smart Desk Lamp; Visual Tracking; Convolutional Neural Network; Image Recognition.

1. Introduction

The emergence of smart homes has significantly enhanced the convenience of people's lives. Within this context, lighting fixtures have evolved into products that can be adjusted and optimized through intelligent control [1]. Table lamps, which belong to the category of lighting equipment, usually provide illumination for specific areas like desktops. Traditional desk lamps do not change their lighting angle and intensity once they are set, but users' positions and postures can vary during the use of the lamp. Consequently, the initially appropriate fixed angle may no longer be suitable, and users are unable to adjust the desk lamp in real-time [2]. This has led to the emergence of smart desk lamps capable of autonomously adjusting the light angle or intensity [3].

The smart desk lamp proposed in this paper leverages vision tracking technology to facilitate autonomous light angle adjustment, aiming to provide comprehensive illumination coverage. Relevant studies in the field of smart lighting are as follows. Luo et al. [4] introduced a human location-based indoor smart lighting system to enhance the energy efficiency of existing indoor lighting systems. Experimental results demonstrated that this system enhanced indoor lighting energy efficiency by at least 15%, with an error rate of less than 2%, compared to conventional voice-controlled lighting systems. Hajjaj & Miki [5] proposed an innovative approach to enhance the performance of smart lighting systems by estimating individual illuminance levels and desired color temperatures in workplace environments.

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Experimental outcomes revealed that power consumption in workplaces could be reduced by using distributed luminance to meet each user's lighting preferences. Additionally, Sun & Yu [6] introduced an indoor smart lighting control approach based on a distributed multi-intelligent framework, which exhibited higher intelligence and efficiency. This approach contributes to the advancement of intelligent lighting technology.

Wojnicki et al. [7] proposed a coherent and formal method for generating lighting control systems from graph-based environmental descriptions. In a pilot deployment of over 3,500 lighting points in Krakow, Poland, the generated CAG reduced energy consumption by up to 34% when applied as the control system. Luo et al. [4] proposed a human position-centered indoor intelligent lighting system to enhance the energy efficiency of existing indoor lighting systems. Experimental results demonstrated that, compared to current voice-controlled lighting systems, this system can increase the energy efficiency of indoor lighting by at least 15% with an error rate below 2% [8].

Wang [9] designed an intelligent lighting control system based on wireless sensor networks and validated the effectiveness of this system through tests. Previous studies have focused mainly on large-scale illumination when discussing intelligent lighting. However, in practical life, there is also a need for small-scale lighting tools such as desk lamps.

Therefore, the objective of this study is to enhance desk lamps by integrating them with visual tracking algorithms, enabling them to function as smart desk lamps capable of automatically illuminating targets from all angles. This paper provides a concise introduction to the smart desk lamp, which is based on visual tracking, and outlines its regulatory and control strategies. Furthermore, it presents a case study of the smart desk lamp. Initially, the performance of the convolutional neural network (CNN) algorithm for target object recognition and localization within the smart desk lamp was tested. Then, it was compared with the support vector machine (SVM) and back-propagation neural network (BPNN) algorithms. Subsequently, the target object tracking capability of the smart desk lamp was tested. The overall structure of this article is "abstract - introduction - introduction to vision-based smart desk lamp - case study - discussion - conclusion".

2. Smart Desk Lamp based on Visual Tracking

2.1. The Basic Structure of the Smart Desk Lamp

A desk lamp is a type of lighting fixture designed to illuminate desktops and other small areas. Traditional desk lamps, while adjustable in terms of height and angle, require manual adjustments. Once set, their height and angle generally remain constant [10]. When users engage in long-term tasks under the illumination of a desk lamp, it can be difficult for them to maintain their position and posture [11]. This difficulty may result in blind spots in the lighting provided by the desk lamp, leading to shadows within the illuminated area. The severity of these shadows can vary and may have different effects on the user [12]. The limitations have been addressed by the emergence of smart desk lamps incorporating advanced control technology [13].

The vision-tracking-based smart desk lamp proposed in this paper leverages machine vision provided by a camera to autonomously adjust its lighting height and angle. The basic structure of this smart desk lamp is depicted in Figure 1.

Figure 1. Basic structure of a smart desk lamp

The overall configuration of the smart desk lamp includes a base, a desk lamp arm, a desk lamp head, servos, a camera, and a rangefinder [14]. Among these components, the base, desk lamp arm, and desk lamp head adhere to conventional desk lamp design [15]. Four servos are employed to adjust the height and angle of the lamp head. As per the control strategy, Servo No. 1 controls the left and right movements of the light source, Servo No. 4 regulates the vertical movements of the light source, while Servo Nos. 2 and 3 govern the distance. The camera and rangefinder are integrated into the head of the desk lamp for capturing images and determining the distance between the lamp head and desktop. These captured images are essential for enabling visual tracking and providing the basis for servo adjustments [16].

2.2. Adjustment Strategy for the Smart Desk Lamp

This smart desk lamp utilizes image recognition technology [17] to identify and locate the target object under the desk lamp. It adjusts the motion of the servos based on identification and localization to keep the position of the target object in the image within a certain range, ensuring visual tracking and automatic adjustment [18]. Figure 2 shows the control strategy of the smart desk lamp based on visual tracking, and its control steps are described below.

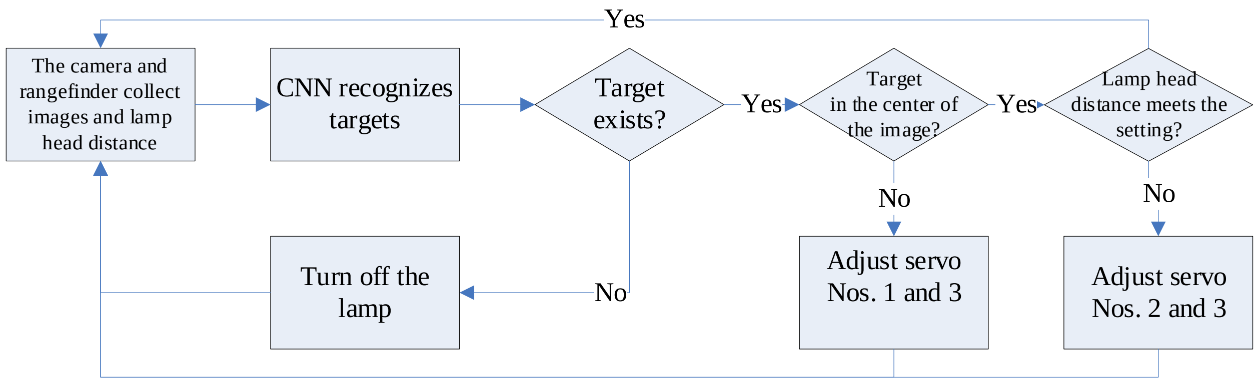

Figure 2. Control strategy for smart desk lamp based on visual tracking

- The camera and rangefinder mounted on the head of the desk lamp are used to capture images within the illumination range of the desk lamp and the distance between the head of the desk lamp and the desktop.
- The CNN algorithm [19] is used for target recognition and localization based on the captured images. The basic structure of the CNN algorithm consists of input and output layers, a convolutional layer, and a pooling layer. The captured images are input into the input layer, followed by convolutional feature extraction in the convolutional layer using a convolutional kernel [20]. The corresponding equation is:

$$H_i = \sigma(H_{i-1} \otimes \omega_i + b_j) \quad (1$$

Where H_i and H_{i-1} are the feature maps output from the i^{th} and $i-1^{th}$ layers [21], ω_i is the weight in the structure of the i^{th} layer, b_i the bias in the structure of the i^{th} layer, and $\sigma(0)$ is the activation function. After that, the pooling layer compresses the convolutional features. Mean pooling [22] is used, that is, the pooling box takes the mean value of the data inside the box when it slides on the convolutional feature map. Finally, the results are output in the output layer, i.e., recognize the target object in the target box (the marker to be tracked by the light source of the desk lamp) and give the coordinates of the target box in the image [23].

- Whether there is a target object in the captured image is determined. If not, automatically turn off the lamp and return to step: if there is a target object, go to the next step.
- Whether the target object is in the center of the image is determined according to the target box coordinates. If not, Servo Nos. 1 and No. 3 adjust the position of the light source. For example, if the target object is positioned slightly higher in the image, Servo No. 3 will be used to move the lamp head upwards; if the target object is positioned slightly to the right in the image, Servo No. 1 will be used to move the lamp head towards the right. Simply speaking, Servo No. 1 and No. 3 will move the lamp head in the direction of the target object in the image, and then return to step: If the target object is in the center of the image, go to the next step.
- Whether the distance between the lamp head and the desktop meets the set conditions is determined. If it does, return to step: if it does not, adjust the height of the lamp head by Servo Nos. 2 and No. 3, and then return to step.

3. Case Study

3.1. Smart Desk Lamp Related Parameters

The desk lamp head was an LED lamp with a power of 11 W and an illumination of 564 Lx. The arm length of the desk lamp located below was 40 cm, while the arm length of the desk lamp located above was 30 cm. The base had dimensions of 30 cm × 30 cm × 30 cm. The servo model number was RC05P. The camera model number was HDQ15. The rangefinder model number was 4C96-HX8O-30m.

3.2. Experimental Setup

(1) Testing of target recognition algorithms

The target recognition algorithm used for visual tracking was first tested. The camera was utilized to capture 200 images containing the target object and 200 corresponding background images that do not contain the target object. 60% of them were used as the training set, and the remaining 40% were used as the test set. When preprocessing images, the image was firstly cropped or resized to a size of 500×400 pixels. Then, a Gaussian filter was applied to reduce noise in the image, followed by binarization.

The relevant parameters of the CNN algorithm were set as follows. The specification of the convolution kernel was 2×2. The activation function used was the sigmoid function. The specification of the pooling box was 3×3. The mean pooling was used in the box [24]. The stochastic gradient descent method was used for training. The learning rate was set as 0.1. The maximum iteration count was set as 200.

In order to further verify the effectiveness of the CNN algorithm, the SVM and BPNN algorithms were used for comparison. Both of the above algorithms extract scale invariant feature transform (SIFT) features here, from the image first. In the SVM algorithm, the sigmoid kernel function was used, and the penalty factor was set to 2. As to the relevant parameters of the BPNN algorithm, the number of nodes in the hidden layer was set to 30, the activation function was sigmoid, and the training was done by the stochastic gradient descent method [25]. The learning rate was set as 0.1. The maximum iteration count was set as 200.

(2) Testing of the smart desk lamp

The recognition and response of the smart desk lamp towards a target object were tested. Firstly, the camera was blocked, and an initial lamp arm posture was set. Then, a target object was randomly placed in the shooting range of the camera. Next, the block was removed, and the recognition and tracking behaviors of the desk lamp to the target object were observed. Moreover, the timing was started at the moment when the block was removed and ended when the lamp arm started to move. This period was defined as the response time for recognizing and tracking a target object with the designed smart desk lamp.

Afterwards, the effectiveness of the smart desk lamp in tracking the moving target object was tested. A target object was placed in an initial position. The target object was pulled in the set direction using the transparent thin line, and the change of the desk lamp was observed. The response time of the desk lamp to the moving target object, i.e., the time between the moments when the target object was pulled and the moment when the lamp arm started to move, and the following direction of the light source of the desk lamp, were recorded. The direction of pulling the target object was set as forward, backward, left, and right, and each direction was repeated five times. The target object was reset before each repetition.

3.3. Test Results

The partial recognition and localization results of the three target recognition algorithms for the desktop target object are shown in Figure 3. It can be seen that the recognition and localization results obtained using the CNN algorithm seems more accurate, and the localization and recognition box was just enough to frame the target; although the SVM and BPNN algorithms framed out the target object in the image, their localization boxes deviated from accurately enclosing the entire target.

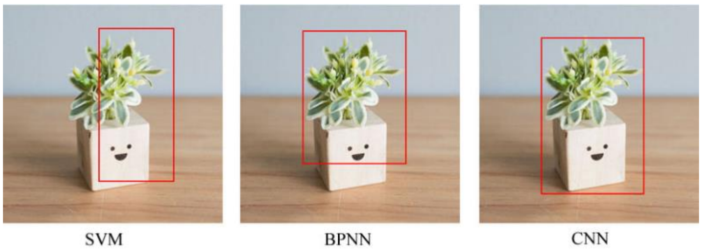

Figure 3. Some recognition and localization results of three target recognition algorithms

Firstly, the recognition and localization ability of the CNN algorithm for target objects was tested and compared with the SVM and BPNN algorithms, and the results are shown in Table 1. From the point of view of the recognition performance of the target object, the CNN algorithm had the best target object recognition performance, followed by the BPNN algorithm, and the SVM algorithm had the worst recognition performance; from the point of view of the localization performance of the target object, the SVM algorithm had the largest average error of localization, followed by the BPNN algorithm, and the CNN algorithm had the smallest average error.

Table 1. Recognition and localization performance of three target recognition algorithms

	SVM	BPNN	CNN
Recognition accuracy/%	76.1	90.1	98.7
Recall rate/%	75.8	89.3	97.9
F-value/%	75.9	89.7	98.3
Average positioning error/mm	3.57	1.24	0.54

The average response time and the average tracking and localization error of the smart desk lamp for randomly placed target objects, as well as moving target objects, are shown in Table 2. When the target object was randomly placed and did not move, the smart desk lamp had an average response time of 0.33 s to track it, and the average positioning error was 0.53 mm after the light source was stabilized. Table 2 shows the average response time of the lamp to track the target object when it moves from its initial position in different directions, and the light source was able to move with the moving direction. After the target object stopped moving, the average error of localization when the desk lamp was stabilized was approximately 0.55 mm.

Table 2. Response time and tracking error of smart desk lamps for randomly placed as well as moving target objects

Target object state	Average response time/s	Light source mobility	Average tracking and positioning error/mm
Randomly placed	0.33	-	0.53
Move forward	0.35	Move forward	0.56
Move backward	0.34	Move backward	0.55
Move to the left	0.33	Move to the left	0.55
Move to the right	0.34	Move to the right	0.56

4. Discussion

A smart desk lamp is a type of desk lamp that possesses smart control capabilities, automatically adjusting brightness, color temperature, and lighting range by sensing ambient light and human activity to achieve comfortable lighting effects. Visual tracking technology is a computer vision-based technique that analyzes human activities and postures in images or videos for target tracking and behavior recognition. By combining smart desk lamps with visual tracking technology, these smart lamps are able to monitor human activities and postures in real-time using visual tracking technology, automatically adjusting brightness and lighting range based on this information. Additionally, leveraging visual tracking technology enables personalized lighting control, enhancing work efficiency and comfort.

The CNN algorithm was employed in the visual tracking technology used in the smart desk lamp. It first utilized the CNN algorithm to recognize and locate the target in the image and then adjusted the lamp arm based on the target's position to maintain it as closely as possible to the desired image location. Performance tests were conducted on the CNN algorithm during subsequent case analyses, followed by testing of the smart desk lamp's tracking responsiveness. Additionally, a comparison was made with the SVM and BPNN algorithms, and the obtained results are shown above.

The CNN algorithm, with the help of convolutional kernels, was able to extract local features from images. Moreover, the combination of local features extracted by multiple convolutional kernels formed overall features, which allowed the CNN algorithm to obtain more comprehensive and detailed features compared to the other two algorithms. As a result, it performed exceptionally well in object recognition and localization tasks. Additionally, this also led to smaller tracking errors when using the CNN algorithm for target tracking. The fast image processing capability of the CNN algorithm enabled it to respond quickly to changes in target positions.

The limitation of this article lies in solely using the CNN algorithm to enable the desk lamp to track targets. While it partially addresses the issue of lighting range, practical applications necessitate not only an appropriate lighting range but also suitable light intensity. Hence, a potential future research direction would involve incorporating automatic adjustment functionality for lighting intensity.

5. Conclusion

The article first introduced the structure of the smart desk lamp, then proposed a CNN-based adjustment control strategy, and finally conducted an example analysis of the smart desk lamp. During the analysis process, a comparison was made between the CNN, SVM, and BPNN algorithms. Finally, the tracking response and tracking error performance of the desk lamp were tested. The results demonstrated that, compared to the SVM and BPNN algorithms, the CNN algorithm possessed a greater advantage in recognizing and locating targets. Moreover, when confronted with changes in targets, the smart desk lamp equipped with the CNN algorithm was capable of responding faster and tracking more accurately.

The contribution of this article lies in the utilization of the CNN algorithm to achieve target recognition and positioning, thereby enabling control of the smart desk lamp to track and adjust targets. This paper provides a valuable reference for a fully adjustable, dead-angle-free smart desk lamp.

6. Declarations

6.1. Author Contributions

Conceptualization, J.S. and Y.L.; methodology, J.S.; software, J.S.; validation, J.S. and Y.L.; formal analysis, J.S.; resources, J.S.; data curation, J.S.; writing—original draft preparation, J.S.; writing—review and editing, J.S.; visualization, J.S.; supervision, J.S.; project administration, J.S.; funding acquisition, J.S. and Y.L. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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