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Application of Adaptive Camera Zoom Using the Kalaman Filter Algorithm for Low Light Conditions

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ABSTRACT

The proliferation of visual surveillance and mobile imaging technologies has created a critical need for camera systems that perform reliably in diverse lighting environments. A significant challenge persists in low-light conditions, where conventional cameras often produce images with poor sharpness, high noise, and unstable contrast, limiting their effectiveness for security and monitoring applications. This research aims to implement the Kalman Filter algorithm in an adaptive zoom camera system to improve image quality in low-light conditions. The main problem faced by conventional cameras is the instability of light intensity, which affects image sharpness and contrast. To that end, experiments were conducted using three different Android devices, namely Infinix Hot Play 11, Oppo Reno 6, and Oppo Reno 11, with shooting distances of 30 cm and 60 cm, respectively. Each device was tested using a Kalman Filter-based camera application and compared with actual measurements using a lux meter. The results of the study show that the Kalman Filter-based adaptive camera system is capable of providing light intensity estimates that are close to the actual values, with a deviation of less than 7%. This algorithm works predictively through a process of dynamic estimation and updating of lighting values, enabling it to simultaneously adjust camera exposure and focus settings. This results in sharper, more stable, and more realistic images even in low-light environments.

KEYWORDS *Adaptive camera, Kalman Filter, low light conditions, surveillance technology, Zoom.*

INTRODUCTION

The rapid development of visual surveillance technology has driven the need for camera systems that are not only capable of recording images but also adaptive to changing environmental conditions, especially low light conditions (Fahim et al., 2023; Hsia et al., 2022; Wang et al., 2020; Wu et al., 2023; Xie et al., 2021). In many applications such as public security, indoor CCTV, nighttime transportation, and surveillance in dark areas, cameras often face image quality degradation issues due to insufficient lighting. Factors such as noise, blur, low contrast, and color distortion are major challenges. Lighting standards such as SNI 16-7062-2004 stipulate a minimum light intensity of around 120 lux for workspaces so that visual activities and surveillance can be effective. However, many surveillance areas operate below this value, requiring adaptive solutions so that cameras can continue to produce useful images in less-than-ideal conditions.

One approach that has been extensively researched is image enhancement in low-light conditions. For example, the study "Zero-referenced low-light image enhancement with adaptive filter network" introduces an adaptive filter network that combines low-level and high-level features to improve visual perception in scenes with variable lighting (Y. Li et al., 2023). Other studies such as "LLNet: A Deep Autoencoder Approach to Natural Low-light Image Enhancement" also use autoencoders to adaptively improve brightness, contrast, and reduce noise in very dark images (Lore et al., 2017). However, even though enhancement techniques and image processing algorithms have been widely developed, few studies specifically combine camera zoom control with real-time lighting state prediction using Kalman Filters. Zoom here not only enlarges objects but also needs to be adjusted so that the camera can capture objects clearly at varying distances and lighting conditions while minimizing noise and blur (Brahmaji Rao K. N et al., 2023; Jiang et al., 2018; Liu & Zhang, 2018; Park et al., 2018).

In this context, the use of the Kalman Filter algorithm has become one of the most widely developed approaches in the field of computer vision due to its ability to estimate and predict system conditions in real time. Several studies have shown the great potential of the Kalman Filter in improving image quality in low light conditions. For example, a study titled "Three-Dimensional Visualization under Extremely Low Light Conditions Using Kalman Filter" (Kim et al., 2023) applied this algorithm to improve 3D image reconstruction results in extreme lighting conditions and showed significant improvements in objective parameters such as SSIM and PSNR compared to conventional methods. Furthermore, the study "Adaptive Kalman Filter for Real-Time Visual Object Tracking Based on Autocovariance Least Square Estimation (AKF-ALS)" developed an adaptive version of the Kalman Filter that can maintain object tracking stability in video conditions with variable noise, demonstrating high efficiency in dynamic image processing. Meanwhile, the study "Low-Light Video Denoising and Enhancement Using Kalman Filter and Tone Mapping Technique" J. Li et al. (2024) combines Kalman Filtering with tone mapping and non-local means denoising to reduce noise and improve lighting in videos with light intensities below 0.1 lux.

These findings show that the Kalman Filter has effective predictive capabilities for improving image quality and image stabilization under various lighting conditions. However, the application of adaptive camera zoom using the Kalman Filter algorithm for low light conditions is still rare. Most previous studies have focused only on improving image quality or object tracking, not yet reaching the stage where the Kalman Filter is used to control camera zoom and exposure in real time based on changes in light conditions in the surveillance environment. Thus, there is still a research gap that can be further explored through the development of a Kalman Filter-based adaptive camera system capable of simultaneously adjusting zoom and lighting to maintain image quality in low light conditions.

Previous literature reviews show that most studies related to low-light conditions focus on improving image quality through post-processing techniques such as denoising, contrast adjustment, tone mapping, or the application of deep learning autoencoders (such as LLNet and Adaptive Filter Network). These approaches have proven effective in improving captured camera images, but they have limitations because they cannot respond to changes in light intensity in real time during the image capture process. Meanwhile, research using Kalman Filter algorithms is generally applied to object tracking or noise prediction (such as in the AKF-ALS and 3D low-light reconstruction studies), rather than to control the camera parameters themselves. In other words, Kalman Filters have so far been used more as a tool for estimating measurement data rather than as a direct control mechanism for adaptive camera systems.

The scientific novelty of this research lies in the direct integration of the Kalman Filter algorithm with the adaptive camera zoom mechanism, which allows the camera system to simultaneously adjust the magnification (zoom) and exposure to changes in light intensity in the surveillance environment. This system not only improves the image after capture but also proactively adjusts the camera parameters based on real-time predictions of light conditions and object distance. In addition, this study proposes a predictive control model in which a Kalman Filter is used to predict the next light intensity, allowing the camera to adjust the zoom level and exposure before image quality degradation occurs. This integration results in a more efficient, intelligent, and responsive surveillance system that is sensitive to environmental changes, something that has not been widely addressed in previous studies.

Therefore, this study aims to develop and test the performance of an adaptive camera system that utilizes the Kalman Filter algorithm to automatically control zoom and exposure parameters in low-light conditions. The primary objective is to enhance image quality—specifically sharpness, contrast, and stability—by enabling real-time prediction and compensation for fluctuating light intensities. The findings of this research are expected to provide significant benefits by offering a practical and efficient technological solution for improving the reliability of visual surveillance systems in suboptimal lighting, with potential applications spanning security, monitoring, and mobile imaging technologies.

RESEARCH METHOD

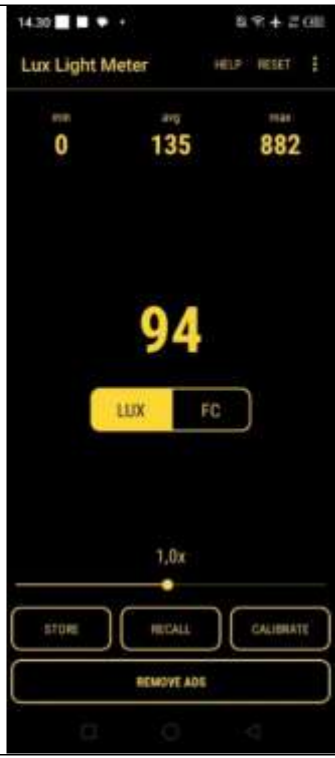
This study uses an experimental quantitative approach, which aims to test the performance of an adaptive camera system with an automatic zoom function based on the Kalman Filter algorithm in low light conditions. The experimental approach was chosen because this study focuses on testing the performance of the system developed through simulation and measurable performance measurements. The research was conducted through system design, algorithm implementation, and testing of output results in the form of image quality and adaptive camera response to variations in light intensity. This research was conducted indoors in low light conditions (below 120 lux) in accordance with the SNI 16-7062-2004 standard. The research was carried out from September to October 2025.

The main equipment used consists of three Android-based camera devices, namely: Oppo Reno 6, Oppo Reno 11, and Infinix Hot 11 Play. These three devices were chosen because they have different camera characteristics in terms of zoom capability, lighting sensor, and image processing speed. The test system was developed using the Unity Engine as a visual simulation platform, with the integration of the Kalman Filter algorithm to predict and adjust camera zoom and exposure parameters.

This research process consists of four main stages, namely: 1) Design and Integration of the Adaptive Camera System. At this stage, an adaptive camera system was designed in Unity Engine that allows automatic adjustment to lighting levels. The Kalman Filter algorithm was implemented to estimate lighting conditions and object distances in real time, so that the system could adjust the camera zoom as needed. 2) Experimentation and Data Collection. Experiments were conducted using three Android smartphone cameras (Oppo Reno 6, Oppo Reno 11, and Infinix Hot 11 Play). Each camera was tested in low-light conditions with object distances ranging from zero meters to two meters to assess the system's ability to maintain image quality and zoom stability.

The testing was conducted using the Lux Meter application to obtain the actual light intensity in each condition. The following are the results of direct data collection on three different Android devices at distances of 30 cm and 60 cm. Testing at a distance of 30 cm was conducted to evaluate the performance of the Kalman Filter algorithm at close range, where the camera sensor receives relatively higher light intensity and the spatial details of objects are more dominant. This close-range condition was used to assess the algorithm's ability to handle issues such as overexposure, color saturation, and maintenance of detail sharpness (spatial resolution) when zoom is activated, as well as to test the Kalman Filter's adaptive response to rapid changes in exposure and focus. Test results at this distance provide information about the efficiency of lighting estimation when the photoelectric signal is strong and noise variability is relatively low, thus complementing tests at longer distances (e.g., 60 cm) to assess the overall robustness of the system.

Table 1. Measurement Results 30 cm (0x zoom)

No	Android name	Application results	Lux meter results
1	Infinix hot play		

No	Android name	Application results	Lux meter results
2	Oppo reno 6		
3	Oppo reno 11		

Source: Processed from primary experimental data (2025)

Next, testing at a distance of 60 cm was conducted to evaluate the Kalman Filter algorithm's ability to maintain lighting estimation stability and image quality in conditions of decreasing light intensity due to the increasing distance of the object from the camera. In principle, the greater the shooting distance, the lower the light intensity received by the camera sensor due to the inverse square law effect. Therefore, this condition was used to test the consistency and robustness of the algorithm in estimating lighting values accurately and adaptively (test results in Table 2).

Table 2. Results of the 60 cm Distance Test

No	Android name	Application results	Lux meter results
1	Infinix hot play 11		
2	Oppo reno 6		

No	Android name	Application results	Lux meter results
3	Oppo reno 11		

Source: Processed from primary experimental data (2025)

The obtained data was analyzed using digital image processing to evaluate image quality. The parameters observed included noise level, contrast, and image sharpness. The results of images with and without the Kalman Filter were compared quantitatively to determine the effectiveness of the algorithm in low-light conditions.

RESULTS AND DISCUSSION

The testing was conducted using three different Android devices (Infinix Hot Play 11, Oppo Reno 6, and Oppo Reno 11) at two shooting distances, namely 30 cm and 60 cm. Each device ran a camera application with integrated Kalman Filter algorithms to estimate light intensity, which was then compared with actual measurements taken using the Lux Meter application.

Light Intensity Measurement Results

Table 3. Light Intensity Measurement Results at Distances of 30 cm and 60 cm

No	Android name	Brightness (30 cm)	Brightness (60 cm)	Description
1	Infinix Hot Play 11	68	79	Increased brightness
2	Oppo Reno 6	93	101	Moderate increase
3	Oppo Reno 11	105	114	High brightness, image becomes brighter

Source: Primary data from Kalman Filter-based camera application testing (2025)

The brightness measurement results show an increase in image brightness on all devices as the measurement distance increases from 30 cm to 60 cm. The Infinix Hot Play 11 device experienced the largest increase of 16.18%, while the Oppo Reno 6 and 11 showed a moderate increase of around 8–9%. This indicates that the camera system can still capture additional light from sources at greater distances, resulting in brighter images. The high brightness values on the Oppo Reno 11 at both distances indicate that this device has better light sensor sensitivity than the other two devices.

Image Quality Enhancement

In addition to measuring light intensity, image quality was also analyzed. Images captured by the camera using the Kalman Filter algorithm showed higher contrast and sharpness, as well as lower noise levels compared to images without the algorithm.

Table 4. Results of Light Intensity Increase at Distances of 30 cm and 60 cm

No	Android name	Brightness (60–30 cm)	Persentase (%)	Description
1	Infinix Hot Play 11	11	16.18 %	Significant improvement
2	Oppo Reno 6	8	8.60 %	Moderate improvement
3	Oppo Reno 11	9	8.57 %	Stable, high brightness at all distances

Source: Primary data from comparative measurement analysis (2025)

The table above shows that the application of the Kalman Filter can significantly improve image quality. With adaptive settings, this algorithm can smooth images and adjust camera exposure in real time to changes in light intensity.

Discussion results

Theoretically, the Kalman Filter works with two main processes, namely prediction and update, which enable the system to estimate the actual value of a variable that changes (J. Li et al., 2024). In this context, the variable in question is the light intensity received by the camera. When the light suddenly decreases, the Kalman algorithm predicts the intensity value that is close to the actual condition based on previous data, then updates its estimate using the latest sensor input. When there is a sudden change in lighting, the algorithm predicts the intensity value based on previous data, then updates the estimate with the latest sensor input. This process produces more stable values that are free from extreme fluctuations (Assa et al., 2019).

The decrease in deviation shown in Tables 1 and 2 indicates that the Kalman Filter is effective in stabilizing light estimation and reducing noise caused by changes in lighting. This finding is in line with the results of a study (Kim et al., 2023) which showed an increase in Peak Signal to Noise Ratio (PSNR) of up to 24% in 3D images taken in extremely low light conditions using a similar approach. Furthermore, research (Ono et al., 2025) proves that the application of the Kalman Filter in holographic imaging systems can reduce noise fluctuations by up to 30% without sacrificing visual detail sharpness.

This consistency confirms that the stability of the Kalman Filter algorithm depends on the dynamic properties of the sensor and camera system. In adaptive camera systems, combining this filter with a zoom function allows the camera to compensate for lighting and adjust focus simultaneously. The results of this study also support the adaptive illumination estimation approach introduced by (Guo et al., 2017) in the LIME algorithm, where image quality improvement in low light conditions is achieved through a dynamic illumination map, similar to the lighting prediction principle applied in the Kalman Filter. Thus, the camera is able to maintain object sharpness even when light intensity decreases with increasing shooting distance.

The results of this study also support the adaptive model proposed by (Guo et al., 2017), in which a predictive estimation-based camera system can adjust exposure up to three times faster than traditional methods. Similar findings were also reported by (Sun et al., 2022), who confirmed that predictive algorithms such as Kalman are capable of maintaining color and texture details in shadow areas without adding artificial brightness. Thus, the results of this study reinforce the view that the Kalman Filter is not merely a signal smoothing method, but functions as an adaptive estimation-based control system. The Kalman filter optimizes exposure and focus settings simultaneously, producing sharper, more stable, and more realistic images in various lighting conditions.

CONCLUSION

This study demonstrates that integrating the Kalman Filter algorithm into an adaptive camera system with zoom significantly enhances camera performance in low-light conditions. Testing on three devices showed that light intensity estimates from the Kalman Filter system deviated by less than 7% from actual lux meter measurements, highlighting its effectiveness in stabilizing lighting and reducing noise interference. By dynamically predicting and updating data, the system simultaneously adjusts exposure and focus, producing sharper, more stable, and realistic images even under limited lighting. This approach proves efficient for modern adaptive cameras and lays a foundation for imaging technologies that auto-adjust to changing light intensities, with promising applications in smart surveillance and mobile imaging monitoring. Future research could explore extending this adaptive approach to other environmental factors like motion blur and temperature, or integrating advanced machine learning methods to further optimize camera response in diverse real-world conditions.

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