Analyze of Evolution and Cross-Era Difference of Autofocus Technology in Projectors

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Abstract. The evolution of image projection technology began with shadow play and the camera obscura in the 12th century. It has now led to the development of modern auto-focus (AF) projection systems. This paper analyzes the development and performance of autofocus technologies in three main types of projectors: lamp-based, Light-Emitting Diode (LED), and laser systems. After the commercialization of LED projectors in 2006 and laser projectors in 2010, AF capabilities became necessary for maintaining image quality in varied conditions. Projectors play a crucial role in education, culture, medicine, and industry. They greatly enhance understanding and accessibility. The accuracy and dependability of autofocus systems affect their overall efficiency. This study looks at the operating principles, technical methods, and performance limits of each AF mechanism. It focuses on precision errors and adaptive behaviors. The results show a consistent trade-off between cost, efficiency, and accuracy across the different technologies. This research emphasizes the need for ongoing innovation in AF design. This will help create smart, connected, and user-friendly projection solutions in a wide range of situations.

Keywords: AF, Projector, Performance, Precision, Commercialization

1 Introduction

For creating images by using light, this can be traced back to the shadow play and camera obscura in the 12^{th} century. Around 14th century, the concave mirrors were invented, and the possible 15^{th}-century image projector was created, though it's debated whether this was a true projector or a type of show box. In 1659, the first lamp-based projector, also the first projector, called Magic Lantern, was made with transparent plates, one or more lenses, and a light source. The first application of LED projector was commercialized in 2006. Samsung adopted Texas Instruments (TI)'s DLP chip and heat dissipation patent, and assembled the complete machine into the SP-P4008 [1]. The practical application of infrared laser projection technology began with the release of the XJ-A140 projector by Casio in 2010. This model used a blue-violet laser and a 940nm infrared laser to stimulate a phosphor wheel, marking the first commercialization of laser projection [2].

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Projectors have a wide range of applications in life, including education, cultural communication, medical care and public safety, and economic and industrial impact. Specifically, by dynamically visualizing abstract concepts (such as physical motion trajectories), projectors have increased the average class comprehension accuracy by 38% in the education aspect [3]. In some resource-poor areas, their portability has enabled teachers to increase the number of students they can teach in a single day by 200%. Furthermore, the costs are relatively low, at only 1/20 of that of electronic tablets.

As a vital tool for education and other aspects, the image quality of the projector directly affects the efficiency of knowledge transfer. However, the frequent movement of devices and the changes in environment may cause low efficiency.

This study offers a detailed look at the evolution of AF technology in projectors. It specifically focuses on lamp-based, LED, and laser projection systems. The study explores the basic operating principles behind each autofocus mechanism, emphasizing the different technical approaches and methods used. Additionally, the research includes a thorough comparison to highlight the key differences between these AF systems, especially regarding their performance, efficiency, and limitations. A main part of this investigation involves a careful evaluation of the accuracy errors found in each autofocus technology. The study aims to provide a clear understanding of how autofocus features have evolved alongside projector lighting technologies. It also offers valuable insights for future advancements in projection system design and control.

2 Theoretical basis analysis

AF technology functions as a closed-loop control system designed to drive the lens to its optimal focus position quickly and precisely. The core operational sequence involves: (1) the image sensor capturing image data; (2) the image signal processor (ISP) analyzing this data (e.g., calculating contrast levels or phase differences) to determine the current focus state and required lens movement direction/magnitude; (3) the lens controller/driver generating appropriate control signals; and (4) the lens actuator (motor) translating these signals into physical lens displacement [4]. Feedback from the newly captured image after each adjustment allows the system to iteratively converge on the sharpest focus. The closed-loop control system of projector is shown in Fig.1.

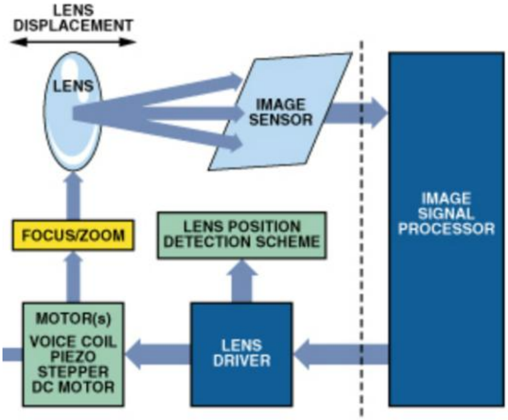

Fig. 1. The closed-loop control system of projector [4]

Modern systems use dynamic step-size control. They start with larger steps for rough positioning and switch to smaller adjustments when they approach focus. The shift happens when variations in the focus metric go beyond set limits. This ensures speed and precision. This method effectively manages lens nonlinearities while keeping stable performance in different scene conditions. To improve convergence efficiency and compensate for lens dynamics, modern autofocus systems use a hybrid search strategy. First, a rough global scan with 50-100μm steps quickly finds the potential focus area by detecting the rising edge of the focus metric curve. Then, a fine local search with 1-5μm micro steps accurately locks onto the peak position using gradient-assisted binary subdivision. This flexible method cuts total steps by 40-60% compared to fixed-step approaches while avoiding overshooting in low-contrast areas. The transition threshold adjusts in real time based on the signal-to-noise ratio (SNR) analysis of the focus metric [5].

3 Analyze of AF technologies of different projectors:

3.1 Lamp-based projector

The closed-loop control system in lamp-based projector includes image sensor (Photodiode array), image signal processor (Transimpedance amplifier + peak-hold circuit), lens driver (Analog comparator + step motor driver) and motors.

Photodiode array: detect changes in the clarity of the projected image. The photodiode in the image sensor converts the light signal into an electrical signal. When the photodiode absorbs more light, more free electrons and holes will appear to generate a larger current. This is because when light emits the semiconductor material of the photodiode, photons are absorbed, exciting electrons from the valence band to the conduction band and forming electron - hole pairs. The built - in electric field of the PN junction in the photodiode then separates these electron - hole pairs, causing electrons to move to the N - region and holes to the P - region, thus forming a measurable photocurrent [6].

Transimpedance amplifier + peak-hold circuit . In bulb projectors, photodiodes convert optical power P_{opt} from projected image sharpness detection into photocurrent I_{ph} following the relationship [7].

$$I_{ph} = R \cdot P_{opt},\ R=\eta e\lambda/hc \tag{1}$$

Where η as quantum efficiency, e as electron charge, λ as light wavelength, h as Planck constant, and c as speed of light. The transimpedance amplifier (TIA) then converts this weak current signal to a voltage with gain, expressed as

$$V_{\mathrm{TIA}} = -I_{\mathrm{ph}} \cdot Rf \tag{2}$$

Where Rf is feedback resistor, a critical step for amplifying faint signals. The peak-hold circuit subsequently retains the maximum value of this amplified voltage, $V_{\mathrm{peak}} = \max\ \{V\mathrm{TIA}(t)\}$, which corresponds to peak image sharpness. Together, these components process raw optical signals into stable peak indicators, enabling comparison with a reference threshold V_{ref} to determine focus completion, thus forming a critical signal processing stage for autofocus control [8].

Analog comparator + step motor driver. Analog comparator: In the autofocus of a projector, an image sensor or focus detection module first captures partial projected images and converts them into analog electrical signals (with signal strength positively correlated to sharpness). A preset reference threshold signal for clear focus is input. The comparator compares the real - time detection signal with the reference: a low level (fuzzy focus) is output if the detection signal is lower, and a high level (near clear focus) if not [9]. The result is fed back to the control chip, which drives the stepper motor to adjust the lens or stops based on the level.

Step motor driver: A stepper motor driver serves as a crucial component for controlling stepper motors. Its operation is based on the conversion of electrical pulse signals into mechanical motion. When the driver receives a pulse signal from the control system, it energizes the corresponding coils of the stepper motor in a specific sequence. Mathematically, the relationship between the input pulse number N and the angular displacement θ of the motor can be expressed as

$$\Theta = N \times \alpha \tag{3}$$

Where α is the step angle determined by the motor's structure [10]. The driver also controls the direction of rotation by adjusting the sequence of coil energization. Additionally, the speed of the motor is proportional to the frequency f of the input pulse signals, following the formula

$$v = f \times \alpha / 2\pi \tag{4}$$

For angular speed in radians per unit time. Through these mechanisms, the stepper motor driver enables precise control over the motor's position and speed [11].

3.2 LED projector

The closed-loop control system in LED projector includes image sensor (CMOS image sensor), image signal processor (FPGA/DSP-based processing units + LED driver chips), lens driver (Digital comparators + stepper motor drivers) and motors.

CMOS image sensor. CMOS image sensors (CIS) operate via well-documented photoelectric conversion: incident light from projected images is received by pixel arrays, where photodiodes convert photons to electrical signals. On-chip circuits integrate these signals into voltages, digitized by ADCs to form grayscale matrices. CIS extracts focus metrics like contrast (via adjacent pixel intensity differences), with higher contrast indicating sharper focus, providing feedback for lens adjustment. This process leverages global shutter technology to avoid motion blur, critical for dynamic projection scenes, and on-chip noise reduction modules to enhance signal-to-noise ratio [12].

FPGA/DSP-based processing units + LED driver chips. FPGAs, consisting of configurable logic blocks (CLBs), programmable interconnects, and I/O blocks, enable real-time parallel processing of raw image data from sensors. They handle low-latency tasks like noise reduction via median filtering, format conversion, and pixel resampling, leveraging their reconfigurable architecture to adapt to diverse input signal standards [13]. DSPs, optimized for arithmetic-intensive operations, execute complex algorithms for image enhancement—such as edge sharpening using convolution kernels (e.g., Sobel operators) and contrast adjustment via histogram equalization [14]. Their specialized instruction sets (e.g., multiply-accumulate operations) accelerate computations critical for maintaining frame rates in projection systems. Together, FPGAs manage high-speed data flow and hardware-level processing, while DSPs perform advanced algorithmic tasks, forming a synergistic system validated in numerous projection and signal processing studies.

Digital comparators + stepper motor drivers. Digital comparators compare two binary numbers, with the input often being a digital value representing the current image sharpness metric (e.g., contrast value from CMOS sensor processing) and a pre - set reference value related to optimal focus. For single - bit digital comparators, when comparing two single - bit binary numbers A and B, if $A = 1$ and $B = 0$, the output indicating $A > B$ is high; if $A = 0$ and $B = 1$, the output for $A < B$ is high; and if $A = B$, the equality output is high. In multi - bit scenarios, like comparing two n - bit numbers $An-1A_{n-2}\cdots A_0$ and $B_{n-1}B_{n-2}\cdots B_0$, comparison starts from the most significant bit (An−1 and Bn−1). If An−1 > Bn−1, the overall result is A > B; if A_{n-1} < B_{n-1}, it's A < B. If An−1=Bn−1, the comparison moves to the next lower - order bit and so on. In LED projectors, digital comparators' outputs guide the stepper motor drivers. A high output for "image sharpness value < optimal value" might trigger the stepper motor to adjust the lens for better focus [15].

3.3 Laser projector

The closed-loop control system in laser projector includes image sensor Infrared (IR) image sensors or high-sensitivity CMOS sensors), image signal processor (FPGA-based processing units + laser speckle reduction modules), lens driver (Digital signal controllers (DSCs) + precision motor drivers) and motors.

Infrared (IR) image sensors or high-sensitivity CMOS sensors. Infrared (IR) image sensors detect the unique patterns of infrared radiation linked to laser-projected images. Based on the photoelectric effect, IR sensors use materials like InGaAs or InSb. When infrared photons from the laser projection strike the sensor, they excite electrons in the material and create an electric current. This current is amplified and processed to form an image. High-sensitivity CMOS sensors are designed to capture the faint visible light from the laser-illuminated scene. They can adjust to the high contrast and high intensity of laser light, allowing their pixels to quickly respond to changes in light [16].

FPGA-based processing units + laser speckle reduction modules. Laser speckle reduction modules are important for reducing the negative effects of laser speckle. One common method is spatial modulation. For example, a diffuser can change the path of the laser beam. By vibrating or rotating the diffuser, different speckle patterns appear over time. Mathematically, the speckle contrast C, which is the ratio of the standard deviation of light intensity to the average light intensity, can be lowered. If C_0 is the initial contrast and C is the reduced contrast, continually changing the diffuser's state can significantly decrease C. Another method is temporal modulation. By quickly switching the wavelength or using pulsed lasers, the temporal coherence of the laser light is disrupted. This causes the speckle patterns to change so rapidly that the human eye cannot tell them apart, effectively lowering the perceived speckle [17, 18].

Digital signal controllers (DSCs) + precision motor drivers. Digital Signal Controllers (DSCs) and precision motor drivers operate synergistically to enable high-precision lens adjustments, a mechanism well-supported by extensive literature. DSCs serve as the control core, receiving real-time focus metrics (e.g., speckle contrast, edge sharpness) from image sensors. They process these signals using embedded algorithms—most commonly proportional-integral-derivative (PID) control, where the output signal

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d\, dt/de(t) \tag{5}$$

Where e(t) as the error between current and target focus, K_p/ K_i /K_d as gains—to calculate required lens displacement and generate pulsed or PWM control signals. Precision motor drivers act as the interface between DSCs and motors (e.g., stepper motors, voice coil motors). They convert DSCs' low-power signals into precise current/voltage outputs, leveraging techniques like micro stepping (for steppers) or closed-loop current control (for VCMs) to minimize step error and vibration. For instance, drivers with 1/256 micro stepping reduce angular error to <0.014°, while current feedback loops stabilize drive currents to ±1% tolerance, ensuring consistent lens movement. This DSC-driver synergy enables sub-micron displacement accuracy: DSCs' millisecond-level algorithm execution ensures rapid response, while drivers' high-resolution control eliminates overshoot, critical for maintaining focus stability in dynamic laser projection scenes [19].

3.4 Comparative analysis

Cost. Lamp-based Projectors: Bulb projectors are relatively inexpensive initially, with some models available for as low as \$100 - \$300. However, their long - term cost is high due to frequent bulb replacements. A bulb typically costs \$50 - \$200 and may need replacement every 1000 - 2000 hours of use.

LED Projectors: LED projectors usually have a mid - range initial cost, generally ranging from \$300 - \$1000 for consumer - grade models. Their long - term cost is low because the LED light source has a lifespan of up to 20000 - 30000 hours, reducing component replacement needs.

Laser Projectors: Laser projectors are the most expensive upfront, with prices starting around \$1000 for basic models and reaching well over \$5000 for high - end models. But they offer long - term cost - effectiveness with a lifespan of 20000 - 50000 hours and lower maintenance requirements [20].

Efficiency. Lamp-based Projectors: Bulb projectors have low energy efficiency. A 200 - watt bulb in a projector may only produce 1000 - 2000 lumens of brightness, with a large portion of energy wasted as heat.

LED Projectors: LED projectors are more energy - efficient. They can produce 500 - 3000 lumens of brightness with lower power consumption, typically around 50 - 150 watts, as stated in energy - consumption reports by multiple sources [21].

Laser Projectors: Laser projectors are highly energy - efficient, capable of producing high brightness levels (3000 - 10000+ lumens) with a relatively lower power - to - brightness ratio compared to bulb projectors. For example, a 300 - watt laser projector can output 5000 lumens, as demonstrated in comparisons [22].

Precision Error. Lamp-based Projectors: In terms of autofocus precision, bulb projectors often have a relatively large precision error. Traditional autofocus mechanisms in bulb projectors may take longer to adjust and may not achieve the same level of sharpness as more advanced technologies. Some older model bulb projectors may have a focus error of up to 5 - 10 pixels in certain conditions.

LED Projectors: LED projectors equipped with modern auto - focus technologies, such as time-of -flight (ToF) sensors, offer better precision. The focus adjustment can be faster and more accurate, with a typical focus error of around 1 - 3 pixels.

Laser Projectors: Laser projectors, especially those with advanced auto - focus systems, can achieve extremely high precision. Some high-end laser projectors can maintain a focus error of less than 1 pixel, ensuring sharp and clear images even in complex projection scenarios.

Tabular Analysis. The key metrics of three mainstream projector types were compared, and the results are summarized in the following table 1.

Table 1. Comparison of Cost, Efficiency, and Precision Error Across Different Projector Types

Projector Type	Cost	Efficiency (Power consumption vs. Brightness)	Precision Error
Lamp-based Projectors	Low – initial; High – long term	Low	High
LED Projectors	Mid – initial; Low – long term	Medium	Medium
Laser Projectors	High – initial; Low – long term	High	Low

4 Challenges and prospects

4.1 Typical Challenges:

Despite the remarkable progress in autofocus technology across lamp-based, LED, and laser projectors, several challenges lie ahead for its future development.

Firstly, the demand for higher precision in various projection scenarios remains unmet. As users' requirements for image quality increase, achieving pinpoint-accurate focus in complex environments such as large - scale projection for theaters or high-resolution business presentations become crucial. Current autofocus systems may struggle to maintain consistent precision when dealing with fast-moving objects in projected content or in situations with significant ambient light interference.

Secondly, the balance between cost-effectiveness and advanced auto - focus features is a continuous challenge. While laser projectors offer high-end autofocus capabilities, their high-cost limits widespread adoption. Manufacturers need to find innovative ways to reduce the cost of implementing advanced auto - focus technologies, such as developing more cost-efficient sensors and algorithms, without sacrificing performance. This is especially important for the mass-market consumer segment, where price is a significant factor in purchasing decisions.

Finally, the integration of autofocus technology with emerging projection technologies and smart home ecosystems poses difficulties. As projectors become more connected and integrated with other devices, autofocus systems must be able to communicate and collaborate effectively. For example, in a smart home setup with multiple projection devices, seamless autofocus adjustment based on the overall environment and user preferences needs to be achieved.

4.2 Future Development

The future of auto-focus technology in projectors is promising. With advancing AI and machine learning, systems will better perceive environments, enabling faster, more precise adjustments when users switch content, as in education.

Integration with IoT will let projectors connect with smart devices, adjusting focus via voice commands in home theaters. New sensors and efficient motors will boost performance and stability.

5 Conclusion

In conclusion, the evolution of auto-focus (AF) technology in projectors shows a lively mix of technical progress and practical demand. From its basic principles to its use in lamp-based, LED, and laser projectors, AF systems have consistently improved user experience by focusing on precision, efficiency, and flexibility. Each type of projector has its own strengths and weaknesses in AF performance, shaped by their light sources, designs, and costs. Together, they reflect the broader industry goal of improving focus accuracy in different environments. Future challenges include balancing advanced features with affordability and integrating with new smart technologies, highlighting the need for ongoing innovation. Looking ahead, the path of AF technology in projectors will likely move closer to intelligent and connected trends, keeping clarity and convenience at the center of advancements in projection technology. These improvements will further establish projectors as flexible tools in education, entertainment, and professional settings.

References

1. Huibers, A.: Projection display device with thermal compensation. U.S. Patent US7434946B2 (2008).
2. Shibasaki, M., Konno, H., Iwata, T.: Light source device and projector. U.S. Patent US20110075106A1 (2011).
3. UNESCO: Global education monitoring report: Technology in education: A tool on whose terms? (2023).
4. Qing, Y., Lu, B., Rong, J.: Process for automatic focusing. Chinese Patent CN1184502C (2005).

5. Dinh, V.H., Hoang, L.P., Vu, Y.N.T., Cao, X.B.: Auto-focus methods in laser systems for use in high precision materials processing: A review. Optics and Lasers in Engineering (2023).
6. Liu, J., Liu, P., Shi, T., Ke, M., Xiong, K., Liu, Y., Chen, L., Zhang, L., Liang, X., Li, H., Lu, S., Lan, X., Niu, G., Zhang, J., Fei, P., Gao, L., Tang, J.: Flexible and broadband colloidal quantum dots photodiode array for pixel-level X-ray to near-infrared image fusion. Nature Communications (2023).
7. Wilson, J., Hawkes, J.F.B.: Optoelectronics: An Introduction. Prentice Hall (1983).
8. Brownell, M.: Optical signal processing gets organized. OE Magazine (2022).
9. Pai, C.-W., Uchida, K., Tada, M., Ishikuro, H.: Design and analysis of a high-speed low-power comparator with regeneration enhancement and through current suppression techniques from 4K to 300K in 65-nm Cryo-CMOS (2023).
10. Kuo, B.C.: Step motors and control systems. SRL Pub. Co., Champaign (1979).
11. Krause, P.C., Wasynczuk, O., Sudhoff, S.D.: Analysis of electric machinery and drive systems. Wiley-IEEE Press, Hoboken (2002).
12. Takayanagi, I., Kuroda, R.: HDR CMOS image sensors for automotive applications. IEEE Transactions on Electron Devices 69(6), 2815–2823 (2022).
13. Phani, T.S.S., Arumalla, A., Prakash, M.D.: Partial dynamic reconfiguration framework for FPGA: A survey with concepts, constraints and trends. Materials Today: Proceedings (2021).
14. Pykse, E.: Performance comparison of GPU, DSP and FPGA implementations of image processing and computer vision algorithms in embedded systems. Master's thesis, Norwegian University of Science and Technology, NTNU Open (2018).
15. Silva, P.A., Louro, R.B., Grellert, M., Meinhardt, C.: Power-efficient design of approximate parallel-tree digital comparators. In: Proc. 2025 IEEE 16th Latin America Symposium on Circuits and Systems (LASCAS), pp. 1–4. IEEE, Puerto Varas (2025).
16. Li, X., Gong, H., Fang, J., Shao, X., Tang, H., Huang, S., Li, T., Huang, Z.: The development of InGaAs short wavelength infrared focal plane arrays with high performance (2017).
17. Evered, C., Li, K., Fan, Y., Zhong, B., Roula, A.: A review of light sources used for laser speckle reduction in display and imaging applications. Optics and Laser Technology (2024).
18. Redding, B., Choma, M.A., Cao, H.: Speckle-free laser imaging using random laser illumination. Nat. Photonics 6, 355–359 (2012).
19. Zhao, X., Ren, W., Chen, T., Duan, C., Guo, H., Liu, H.: Design of high-speed and high-precision scanning galvanometer control system based on FPGA+DSP architecture. In: Proc. 2021 IEEE Sustainable Power and Energy Conference (iSPEC), pp. 1404–1409. IEEE, Nanjing (2021).
20. IOP Publishing: Rays, waves and photons: A compendium of foundations and emerging technologies of pure and applied optics (2020).
21. U.S. Department of Energy: Energy savings potential of solid-state lighting in general illumination applications (2021).
22. Zhang, D., Xiao, W., Liu, C., Liu, X., Ren, J., Xu, B., Qiu, J.: Highly efficient phosphor-glass composites by pressureless sintering. Nature Communications (2020).