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Performance Analysis of Self-Adjusting Aperture Optical Systems under Varied Atmospheric Conditions.

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Abstract - Contemporary optical instrumentation constitutes a fundamental strategic asset in military surveillance and tactical operations, necessitating high operational efficiency across a broad spectrum of irradiance conditions, from peak diurnal intensity to low-light regimes. A significant technical challenge involves maintaining invariant image fidelity amidst extreme dynamic ranges in ambient illumination. This study investigates an innovative adaptive iris system designed to autonomously modulate the entrance pupil, thereby optimizing radiant throughput and mitigating aberrations. Utilizing the ZEMAX design environment, an opto-mechanical system was synthesized featuring discrete pupil diameters Dm of 2.8 mm, 3.5 mm, and 4.0 mm, tailored for photopic, mesopic (twilight), and scotopic conditions, respectively. The system's optical integrity was rigorously verified against four primary criteria: Modulation Transfer Function (MTF), Longitudinal Aberration, Field Curvature, and Geometric Distortion. Numerical simulations confirm that the system exceeds all performance benchmarks: the MTF values surpassed 0.4 at the targeted spatial frequency (exceeding the 0.2 threshold), longitudinal aberration was constrained below 0.03 mm, field curvature remained within the 1.318 mm tolerance, and distortion was limited to within ±0.5%. These findings demonstrate that the self-adjusting aperture configuration provides a robust and effective solution for multi-environment reconnaissance missions.

Keywords - Self-adjusting aperture, opto-mechanical system, Modulation Transfer Function (MTF), ZEMAX.

I. INTRODUCTION

Optical instrumentation constitutes a critical component of modern military and surveillance technology, providing indispensable strategic assets for reconnaissance, target identification, and tactical support. These sophisticated systems—ranging from military-grade binoculars and night-vision devices to high-resolution imaging payloads on Unmanned Aerial Vehicles (UAVs)—integrate fundamental optical principles with advanced information technology to augment situational awareness and data processing. Operational environments are inherently dynamic, encompassing extreme low-light regimes, adverse meteorological conditions, and complex terrains. Consequently, ensuring performance reliability across these diverse scenarios necessitates a high degree of system adaptability and robustness.

A notable advancement in contemporary optical design is the integration of self-adjusting aperture lens mechanisms. This innovative system utilizes high-precision radiometric sensors to autonomously modulate the entrance pupil diameter. The primary objective of this feature is to regulate the radiant throughput, thereby ensuring invariant image fidelity across a vast dynamic range of ambient irradiance. Specifically, the aperture constricts in high-irradiance environments to mitigate veiling glare and extend the depth of field (DoF). Conversely, in low-light regimes—such as mesopic or scotopic conditions—the pupil dilates to maximize photon collection efficiency.

This dynamic adaptability is critical for maintaining operational robustness and superior optical performance in fluctuating field environments To ensure the operational efficacy and fidelity of the proposed optical configuration, a rigorous performance verification is imperative. This methodology encompasses a quantitative analysis of the system's performance against standardized optical benchmarks and industry-recognized metrics. By systematically evaluating parameters such as spatial frequency response and wavefront integrity, the study establishes a robust framework for validating the system's reliability under real-world operational scenarios.

Consequently, this research provides a comprehensive assessment of the optical performance and imaging fidelity of the proposed adaptive iris lens system across a spectrum of meteorological conditions. The investigation entails a rigorous analysis of the system's conformity to fundamental optical metrics—specifically the Modulation Transfer Function (MTF), longitudinal aberration, field curvature, and geometric distortion—to verify adherence to stringent military-grade performance specifications.

II. METHODOLOGY

The evaluation of the optical lens quality with a self-adjusting aperture consisted of two phases: System Design and Parameterization, and Performance Assessment using Standard Optical Criteria.

The self-adjusting aperture lens system was designed and simulated using optical design software, ZEMAX. The objective of this design stage was to model a system capable of optimizing image acquisition across a wide range of light conditions, which is crucial for military and surveillance applications.

The key parameters defining the simulated optical system are summarized below, corresponding to a high-resolution imaging capability.

Key parameters of the Simulated Optical System:

- Focal Lengthe: $f' = 14$ mm

- Image Sensor: 1/1.2 SONY IMX 249 CMOS Sensor 1920x1200 resolution, with a pixel size $a_e = 5.86$ µm

- Field of view: 2ω = 50°

- Wavelength: λ = 0.486...0.656 µm

- Aperture Diameter: The aperture diameter is adjustable in three stages:

- $D_{m1} = 2.8$ mm (for clear sky, high light intensity)
- $D_{m2} = 3.5$ mm (for dawn and dusk conditions)
- $D_{m3} = 4$ mm (for overcast sky, low light intensity)

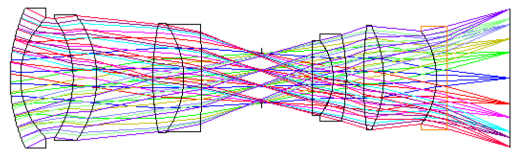

Figure 1: Adjustable aperture lens designed in ZEMAX software

The core feature of this system is the dynamic adjustment of the Entrance Pupil Diameter ( ), which is controlled by an integrated ambient light sensor. The sensor measures the light intensity and signals a processor to adjust the pupil across three distinct mechanical states, simulating adaptation to various real-world weather conditions.

Results

Criteria for the MTF function

Quantifying the Modulation Transfer Function (MTF) remains a cornerstone methodology for evaluating the imaging performance of an optical system. The MTF characterizes the system's efficiency in contrast reproduction as a function of spatial frequency, serving as a comprehensive metric to determine both spatial resolution and image fidelity. By analyzing the contrast attenuation across varying cycles per millimeter (lp/mm), the MTF provides a definitive assessment of the system's sharpness. Figure 2 illustrates the computed MTF curves for the synthesized optical configuration.

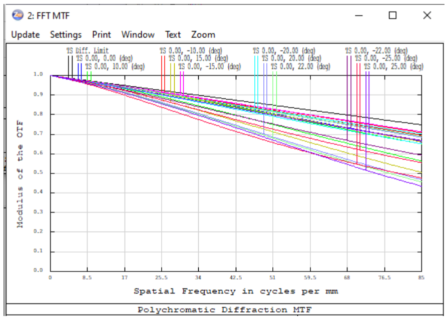

Figure 2: MTF curve

Within the MTF function analysis, image quality is assessed using two key parameters: the spatial frequency (on the x-axis) and the corresponding required MTF value (on the y-axis). The spatial frequency chosen for investigation must correspond to the resolution of the microdisplay and is calculated using the following formula:

Criteria for Longitudinal Aberration

Longitudinal Chromatic Aberration (LoCA) is a type of aberration caused by light rays of different wavelengths failing to converge at a single point on the optical axis. Figure 3 presents the longitudinal aberration plot of the optical system, where the horizontal axis represents the longitudinal aberration (in millimeters) and the vertical axis represents the aperture radius.

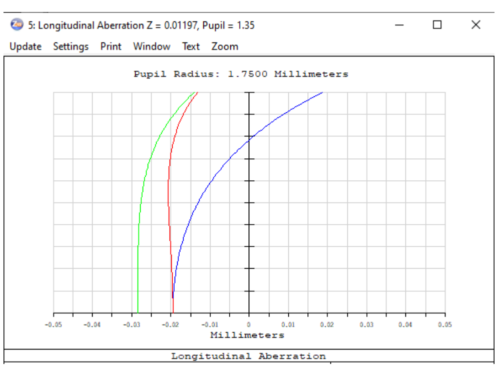

Figure 3: Longitudinal Aberration

The blue, green, and red curves correspond to their respective wavelengths λ = 0.486 µm; λ = 0.588 µm; λ = 0.656 µm. A larger deviation (along the horizontal axis) indicates a non-uniform convergence of light rays from the center to the edge of the aperture, which is particularly noticeable for the curve corresponding to the wavelength λ = 0.486 µm. Nevertheless, since the absolute value of the longitudinal aberration is less than 0.03 mm the optical system is considered to be well-designed and meets the quality criterion for longitudinal aberration.

Criteria Field Curvature

Field curvature of an optical system is an aberration component calculated and displayed within the optical design software ZEMAX. Figure 4 illustrates the field curvature plot of the designed optical system.

The human visual system exhibits significant accommodative amplitude; however, this physiological capability undergoes progressive attenuation as a function of age, a process known as presbyopia. Consequently, the optical system's configuration must be meticulously optimized to ensure that the residual field curvature is constrained within the accommodative tolerance of the target demographic, specifically individuals in the 50–60-year age bracket. Empirical data indicates that the permissible longitudinal field curvature for this demographic is established at 1.318 mm.

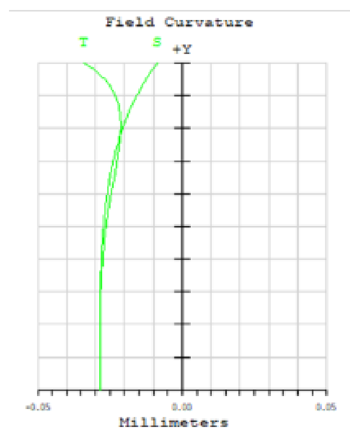

Figure 4: Field Curvature

By observing Chart 4, it is confirmed that the field curvature criterion for the designed optical system does not exceed 1.318mm. Thus, the optical system satisfies the criterion for field curvature.

Criteria for Optical Distortion

Geometric distortion is characterized by the displacement of image points relative to their predicted positions in a stigmatic (ideal) optical system. In a theoretical scenario where all monochromatic and chromatic aberrations are fully corrected, leaving only distortion, the image of a point source remains a point; however, its spatial coordinate is radially shifted from the paraxial image height. This phenomenon represents a mapping error rather than a loss of resolution. The magnitude of this displacement, typically expressed as a percentage of the ideal image height, quantifies the deviation from the object's true geometry.

According to references [1] and [2], the human eye cannot detect optical distortion within the range of 5% - 10% .For optical instrumentation, distortion that does not exceed this value is considered acceptable. Observing Figure 5, the Distortion Plot of the designed optical system, we note that the curve deviates to the left of the center, with the distortion value ranging from -0.5% - 0.5%. This indicates that the designed optical system satisfies the criterion for optical distortion.

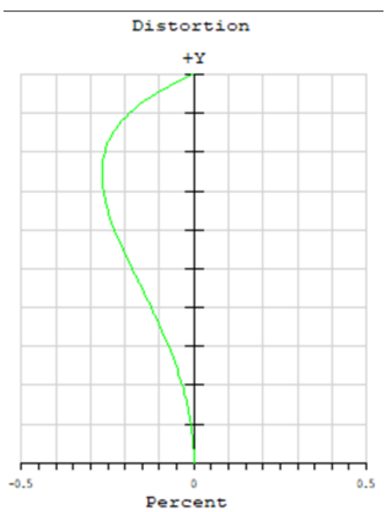

Figure 5: Distortion

III. CONCLUSION

This research has successfully demonstrated and empirically validated an adaptive iris optical system engineered to maintain invariant performance across dynamic and fluctuating observation environments. Through a comprehensive and systematic analysis, the system's imaging fidelity was quantitatively evaluated against four core optical benchmarks: the Modulation Transfer Function (MTF), longitudinal aberration, field curvature, and geometric distortion. The findings confirm that the integration of a self-adjusting aperture effectively mitigates environmental irradiance volatility while preserving high-resolution throughput.

The evaluation of the MTF function confirms high contrast and resolution across various spatial frequencies, while the analysis of longitudinal aberration and field curvature demonstrates the system's ability to maintain focus stability and image flatness. Furthermore, the minimal distortion levels recorded indicate that the integrity of the visual data is preserved. These findings validate the theoretical model and prove that the system can effectively suppress common optical aberrations. Ultimately, the results confirm that the designed optical instrument satisfies the stringent performance demands of modern surveillance technology, offering a versatile solution for high-precision monitoring in complex lighting scenarios.

Acknowledgements

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