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# A Novel Theoretical Framework for Early Myopia Detection Using Structured Light and Modulation Transfer Function Analysis

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***Abstract***

***Purpose:*** *To address the growing global prevalence of myopia by introducing a cost-effective, portable framework for early detection, with a focus on pediatric applications and underserved communities.*

***Methods:*** *The proposed method combines structured light projection, Modulation Transfer Function (MTF) analysis, and liquid lens adjustment to enable precise, non-invasive measurement of refractive error and axial elongation. Theoretical foundations, key equations, and simulation-based validations are presented.*

***Results:*** *Simulations demonstrate the feasibility of MTF-based refractive error analysis and axial length estimation using liquid lens adjustments. The proposed approach is sensitive to variations in refractive error and provides accurate estimations of myopia-related parameters.*

***Conclusion:*** *The framework has the potential to transform myopia screening by offering a scalable and accessible solution for early diagnosis and monitoring. Future work will focus on experimental validation and hardware optimization to translate this concept into a deployable device.*

***Translational Relevance:*** *This method represents a significant step toward democratizing access to precision ophthalmic diagnostics, particularly in resource-limited settings, and has implications for reducing the global burden of myopia.*

**Keywords:** Myopia, Structured Light, Modulation Transfer Function, Liquid Lens, Axial Length, Pediatric Screening, Portable Device, Telemedicine

## Introduction

### Background

Myopia, commonly known as nearsightedness, affects nearly 30% of the global population and is projected to rise to 50% by 2050. The condition is particularly prevalent among children, where unchecked progression can lead to severe visual impairments and complications such as retinal detachment or glaucoma in adulthood. Early detection and timely intervention are crucial for mitigating these risks, making myopia a significant public health priority [1-7].

Accurate measurement of refractive error and axial length, key indicators of myopia progression, is essential for early diagnosis. Existing diagnostic methods, including ultrasound biometry and optical coherence tomography (OCT), offer high precision but are costly, bulky, and largely inaccessible in resource-limited settings.

### Need for Innovation

The increasing prevalence of myopia, especially in pediatric populations, underscores the urgent need for portable, affordable, and accurate diagnostic tools. A solution that bridges the gap between clinical precision and accessibility could revolutionize early screening programs and improve global eye health outcomes [2].

**Proposed Approach**

This manuscript introduces a novel framework for myopia detection, leveraging structured light projection, Modulation Transfer Function (MTF) analysis, and liquid lens adjustment. This method enables precise and non-invasive measurement of refractive error and axial elongation, packaged in a cost-effective handheld device. By integrating advanced optical principles, the proposed approach offers a scalable alternative to current technologies, particularly for underserved communities.

## Objectives

The objectives of this work are:

1. To present the theoretical foundation of the proposed method, grounded in optical and physiological principles.
2. To demonstrate the potential of structured light and MTF analysis through numerical simulations and practical examples.
3. To outline pathways for experimental validation and future device development.

**Theoretical Framework**

**The Role of Axial Length and Refractive Error in Myopia**

Myopia is characterized by a mismatch between the axial length (L) of the eye and its refractive power (D). Axial elongation increases the eye's overall refractive power, causing light rays to focus in front of the retina, leading to blurred distance vision. Measuring L and D provides critical information for diagnosing and monitoring myopia progression.

The relationship between axial length, refractive error, and the optical components of the eye is governed by the Schematic Eye Model [3]. This model approximates the eye as a single optical system with contributions from the cornea (Pc) and lens (Pl):

$$D = P_c + P_l - \frac{1}{L}$$

Rearranging to estimate axial length:

$$L = \frac{1}{P_c + P_l - D}$$

Where:

- **D:** Refractive error (diopters)
- **Pc:** Corneal power (~43 diopters)
- **Pl:** Lens power (~17 diopters)

**Structured Light Projection**

Structured light projection involves emitting a polarized grid pattern onto the retina. This approach leverages the eye's optical system to create a sharp image of the grid on the retina. The reflected grid pattern is captured by a detector, where deviations in sharpness and deformation provide insights into the eye's refractive properties.

**Key aspects include**

- **Polarization Filtering:** A vertical polarizer suppresses reflections from the cornea and lens, isolating the retinal reflection.
- **Grid Design:** High-contrast, evenly spaced horizontal and vertical lines optimize pattern recognition.

**Modulation Transfer Function (MTF) Analysis**

The MTF quantifies the sharpness of the grid reflection by evaluating how well different spatial frequencies are preserved. The sharpness is highest when the liquid lens is optimally adjusted to compensate for refractive errors.

- High MTF Values: Indicate minimal distortion, typically observed in emmetropic (normal) eyes.
- Reduced MTF Values: Suggest blurred reflections, common in myopic eyes due to axial elongation.

The liquid lens iteratively adjusts its focal position, and the MTF is calculated at each setting to identify the optimal focus corresponding to the refractive error.

**Combining MTF with Axial Length Calculation**

Once the refractive error (D) is determined via MTF and liquid lens adjustment, the axial length is estimated using the Schematic Eye Model:

$$L = \frac{1}{P_c + P_l - D}$$

Numerical Example:

For $D = -2$, $P_c = 43$, $P_l = 17$:

$$L = \frac{1}{43 + 17 - (-2)} = \frac{1}{62} = 0.01613\ m\ (16.13\ mm)$$

**Theoretical Sensitivity**

The sensitivity of the method is determined by the precision of MTF measurements and the resolution of liquid lens adjustments. Simulations indicate that a 0.1 diopter change in refractive error corresponds to a detectable change in axial length, sufficient for early myopia detection

## Proposed Methodology

**Projection and Capture**

The methodology begins with projecting a polarized grid pattern onto the retina and capturing its reflected image using a detector equipped with a vertical polarizer. Key steps include (Figures 1 and 2):

1. **Grid Projection**

- A grid pattern, comprising horizontal and vertical lines, is projected onto the retina using an infrared light source to ensure safety and minimize visible distractions.
- The grid is polarized horizontally to reduce interference from corneal and lens reflections.

2. **Image Capture**
3. The reflected grid is captured by an imaging sensor after passing through a vertical polarizer, which suppresses reflections from the cornea and lens while allowing the retinal reflection.

**Modulation Transfer Function (MTF) Analysis**

The captured grid image is analyzed to quantify its sharpness, with the MTF serving as the primary metric. This process involves:

1. **Spatial Frequency Assessment**

- The captured grid is analyzed at different spatial frequencies to evaluate how well the pattern's sharpness is preserved.

**2. Iterative Lens Adjustment**

- A liquid lens dynamically adjusts its focal position to maximize the MTF at high spatial frequencies.
- The lens position at which MTF is highest correlates with the eye's refractive error (D).

**Axial Length Estimation**

Once the refractive error (D) is determined, the axial length (L) is calculated using the Schematic Eye Model:

$$L = \frac{1}{P_c + P_l - D}$$

Numerical Example:

For $D = -3$, $P_c = 43$, $P_l = 17$:

$$L = \frac{1}{43 + 17 - (-3)} = \frac{1}{63} = 0.01587\ m\ (15.87\ mm)$$

**System Workflow**

**1. User Input**

- The operator initiates the measurement and adjusts the device's position to align the grid projection with the retina.

**2. Automated Capture and Analysis**

- The device automatically projects the grid, captures the reflected image, and calculates the MTF iteratively.

**3. Output Generation:**

- The device displays the measured refractive error (D) and estimated axial length (L) on a simple interface, along with a color-coded indicator of myopia risk.

**4. Potential Integration with AI**

To enhance performance, the system could incorporate AI algorithms for:

- Pattern Recognition: Automatically identifying grid distortions and optimizing MTF calculations.
- Population-Specific Calibration: Adjusting measurements based on demographic data, such as age and ethnicity.

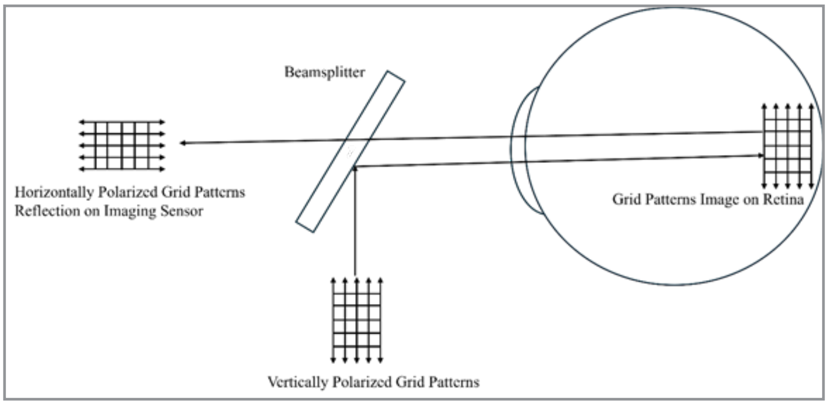


**Figure 1:** Conceptual illustration of the projection and reflection of structured light (grid patterns) onto the retina. This visually supports the methodology.

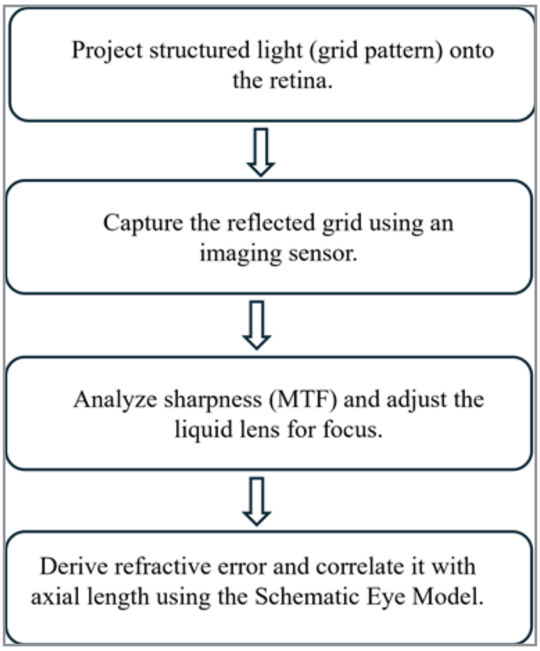


**Figure 2:** Flow diagram of the proposed method, which clearly explains the sequence of operations in your approach.

**Potential Applications**

**Early Myopia Detection**

The proposed method is particularly well-suited for early detection of myopia, especially in pediatric populations. By providing a portable and cost-effective solution, this approach can:

- Facilitate school-based screening programs.
- Enable parents and caregivers to identify myopia risks before symptoms worsen.
- Support early interventions such as orthokeratology lenses or pharmacological treatments to slow myopia progression.

**Resource-Limited Settings**

Traditional axial length measurement devices, such as OCT and ultrasound biometry, are expensive and require specialized training. The proposed device can bridge this gap by

- Offering a low-cost alternative for primary healthcare centers.
- Increasing access to refractive error diagnostics in underserved communities.
- Reducing the burden of preventable vision loss in low- and middle-income regions.

**Integration with Telemedicine**

Telemedicine is rapidly transforming healthcare delivery, and the proposed device aligns seamlessly with this trend. By integrating with telemedicine platforms, the device could:

- Allow non-specialists to capture diagnostic data, which can then be analyzed remotely by experts.
- Enable continuous monitoring of axial length and refractive error for patients in remote areas.
- Support large-scale public health initiatives by providing actionable data for population-based studies.

**Myopia Progression Monitoring**

The ability to measure refractive error and axial length accurately makes the device suitable for longitudinal monitoring of myopia progression. Potential applications include:

- Tracking changes in axial length in response to interventions.
- Providing personalized data for refining treatment plans.
- Supporting clinical research on the effectiveness of new therapies.

**Broader Ophthalmic Applications**

Although focused on myopia detection, the device's capability to measure refractive error and axial length can be extended to other ophthalmic conditions, such as:

- Hyperopia and astigmatism.
- Presbyopia management.
- Pre-surgical evaluations for cataract and refractive surgeries.

## Results and Discussion

This section presents the results of theoretical simulations designed to validate the feasibility of the proposed method. The simulations analyze the sensitivity and performance of Modulation Transfer Function (MTF) analysis and liquid lens adjustments for detecting refractive errors and estimating axial length [4].

**Simulation 1: MTF Analysis Across Refractive Errors**

To validate the sensitivity of MTF analysis to refractive errors, a structured light grid was projected onto the retina, and the reflected pattern was analyzed across various spatial frequencies. Three refractive conditions were simulated: emmetropic (D = 0), myopic (D = −2), and hyperopic (D = +2).

**Findings**

1. Emmetropic Eyes (D = 0):
- The MTF remains high across all spatial frequencies, indicating sharp and well-focused grid patterns.
- Example MTF values: 0.85 at low frequency (0.5 cycles/mm) and 0.75 at high frequency (5 cycles/mm).

2. Myopic Eyes (D = −2):
- The MTF exhibits significant degradation at higher spatial frequencies due to axial elongation and defocus.
- Example MTF values: 0.80 at low frequency and 0.6 at high frequency.

3. Hyperopic Eyes (D = +2):
- Moderate MTF degradation is observed, distinct from the myopic pattern.
- Example MTF values: 0.820.820.82 at low frequency and 0.650.650.65 at high frequency.

**Discussion**

The MTF simulation results demonstrate that higher spatial frequencies are more sensitive to refractive errors, with distinct patterns for emmetropic, myopic, and hyperopic conditions. These findings validate the use of MTF analysis as a reliable metric for detecting refractive errors and distinguishing between different types of visual impairments.

**Simulation 2: Liquid Lens Adjustment**

To further validate the proposed method, we simulated the effect of liquid lens adjustment on the sharpness of the reflected grid pattern, quantified through MTF analysis. The liquid lens dynamically adjusts its focal position to optimize sharpness for different refractive errors (D = 0, −2, +2).

**Setup**

- Liquid lens focal range: −3D to +3D in 0.1D increments.
- MTF calculated at each lens position to identify the sharpest reflection corresponding to the optimal lens adjustment.

Findings

1. Emmetropic Eyes (D = 0):
- MTF peaks at 0D, reflecting the normal refractive state.
- Example MTF values: 0.85 at 0D, with degradation (<0.75) at −2D and +2D.

2. Myopic Eyes (D = −2):
- MTF peaks at −2D, consistent with the elongated axial length of myopic eyes.
- Example MTF values: 0.8 at −2D, with significant degradation (<0.60) at 0D and +2D.

3. Hyperopic Eyes (D = +2):
- MTF peaks at +2D, consistent with the shorter axial length of hyperopic eyes.
- Example MTF values: 0.82 at +2D, with noticeable degradation (<0.65) at −2D and 0D.

**Discussion**

The results demonstrate that the liquid lens adjustment effectively aligns the sharpness of the reflected grid with the refractive error. The lens positions corresponding to peak MTF values correlate directly with the refractive state of the eye. This confirms the feasibility of using liquid lens adjustments in tandem with MTF analysis for accurate refractive error detection.

**Simulation 3: Axial Length Calculation**

To validate the ability of the proposed method to estimate axial length (L) from refractive error (D), the Schematic Eye Model was applied using calculated refractive errors from Simulations 1 and 2.

**Setup**

The Schematic Eye Model equation:

$$L = \frac{1}{P_c + P_l - D}$$

Where:

- **Pc = 43:** Corneal power (diopters).
- **Pl = 17:** Lens power (diopters).
- **D:** Refractive error derived from MTF and liquid lens analysis.

Three refractive conditions were simulated:

- **D** = 0 (normal).
- **D** = −2 (myopic).
- **D** = +2 (hyperopic).

**Findings**

1. **Emmetropic Eyes (D = 0):**
- Axial length calculation:

$$L = \frac{1}{43 + 17 - 0} = \frac{1}{60} = 0.01667\, m\ (16.67\, mm)$$

2. **Myopic Eyes (D = −2):**
- Axial length calculation:
- 

$$L = \frac{1}{43 + 17 - (-2)} = \frac{1}{62} = 0.01613\, m\ (16.13\, mm)$$

3. **Hyperopic Eyes (D = +2):**
- Axial length calculation:
- 

$$L = \frac{1}{43 + 17 - (+2)} = \frac{1}{58} = 0.01724\, m\ (17.24\, mm)$$

**Discussion**

The calculated axial lengths align with expected physiological ranges for emmetropic, myopic, and hyperopic eyes. This simulation demonstrates that the proposed method, using refractive error derived from MTF and liquid lens analysis, can reliably estimate axial length. These results reinforce the applicability of the Schematic Eye Model in the proposed diagnostic framework.

**Simulation 4: Grid Pattern Deformation**

To explore the impact of refractive errors on the deformation of the projected grid pattern, we simulated the reflection of a structured light grid from the retina. Deformation metrics were analyzed for emmetropic, myopic, and hyperopic eyes.

**Setup**

- A 5x5 grid pattern (horizontal and vertical lines forming 16 squares) was projected onto the retina.
- Reflected grid images were simulated for:

1. D = 0 (normal).
2. D = −2 (myopic).
3. D = +2 (hyperopic).

- Deformation was quantified by measuring deviations in grid spacing (Δs) from the reference pattern.

**Findings**

1. Emmetropic Eyes (D = 0):
- The reflected grid closely matches the projected grid, with minimal deformation (Δs ≈ 0).
- Example spacing: 1.0 mm (horizontal and vertical).
2. Myopic Eyes (D = −2):
- The grid appears stretched, with increased horizontal and vertical spacing due to axial elongation.
- Example spacing: 1.1 mm (Δs = +0.1 mm).
3. Hyperopic Eyes (D = +2):
- The grid appears compressed, with reduced spacing due to shorter axial length.
- Example spacing: 0.9 mm (Δs = −0.1 mm)

**Discussion**

Grid pattern deformation provides a secondary metric for identifying refractive errors. While MTF analysis primarily determines sharpness and focal adjustment, deformation metrics offer additional validation by directly correlating changes in grid geometry with axial length variations. Combining these metrics could enhance diagnostic accuracy, particularly in borderline cases.

**Summary of Results and Discussion**

1. Simulation 1 validated MTF analysis as a sensitive metric for refractive errors.
2. Simulation 2 demonstrated the feasibility of liquid lens adjustments for aligning focus and determining refractive power.
3. Simulation 3 connected refractive power to axial length using the Schematic Eye Model.
4. Simulation 4 highlighted the utility of grid deformation as a secondary validation metric.

**Challenges and Future Directions**

**Challenges**

Despite its potential, the proposed method faces several challenges that must be addressed to ensure successful implementation and adoption:

1. Calibration and Validation:
- Accurate axial length and refractive error measurements depend on precise calibration. The lack of clinical validation for the method poses an immediate challenge.
- Proposed Solution: Collaborate with research institutions to validate the system against gold-standard methods like OCT or ultrasound biometry.
2. Hardware and Cost Optimization:
- Integrating high-grade components, such as liquid lenses and polarization filters, while maintaining affordability is a key challenge.
- Proposed Solution: Explore cost-effective alternatives, such as digitally controlled lenses and off-the-shelf optical components.
3. Complexity of Pediatric Measurements:
- Younger patients may exhibit greater variability in measurements due to eye movement or lack of cooperation.

- Proposed Solution: Incorporate stabilization algorithms and user-friendly guidance systems to ensure reliable measurements.

4. Regulatory and Ethical Considerations:
- Compliance with medical device regulations and ethical considerations, especially for pediatric use, is critical.
- Proposed Solution: Initiate early engagement with regulatory bodies like the FDA and international equivalents to align with their requirements.

**Future Directions**

The proposed method lays the foundation for a transformative diagnostic tool. Several pathways for future research and development include:

1. Experimental Validation:
- Conduct controlled clinical studies to validate the theoretical model and establish the device's accuracy.
- Simulate and refine the method across diverse populations and refractive conditions.

2. AI Integration:
- Incorporate artificial intelligence algorithms to enhance pattern recognition, optimize MTF analysis, and provide real-time feedback.
- Develop population-specific calibration models that adjust for factors such as age, ethnicity, and gender.

3. Miniaturization and Portability:
- Focus on reducing the device's size and weight for seamless integration into handheld systems.
- Explore battery-efficient designs to improve usability in remote settings.

4. Expanded Use Cases:
- Investigate additional ophthalmic applications, such as hyperopia screening and presbyopia management.
- Extend the technology to preoperative and postoperative assessments for cataract and refractive surgeries.

5. Global Outreach:
- Collaborate with non-profit organizations and governments to deploy the device in underserved regions.
- Advocate for inclusion in school-based and community healthcare programs [12].

**Long-Term Vision**

The proposed method represents a step toward democratizing access to precision diagnostics in ophthalmology. By addressing these challenges and pursuing the outlined directions, this innovation has the potential to revolutionize early myopia detection and broader eye care [7-10, 11, 13, 14].

## Conclusion

Myopia, particularly in children, represents a growing global health challenge, requiring innovative approaches to early detection and management. This manuscript introduces a novel theoretical framework for myopia detection, combining structured light projection, Modulation Transfer Function (MTF) analysis, and liquid lens adjustment. By leveraging these advanced optical principles, the proposed method offers a cost-effective, portable alternative to traditional diagnostic tools such as OCT and ultrasound biometry.

The integration of axial length estimation with refractive error measurement provides a comprehensive approach to diagnosing and monitoring myopia progression. This framework has significant potential for applications in pediatric screening programs, resource-limited settings, and telemedicine platforms.

While challenges such as calibration, cost optimization, and regulatory compliance remain, the proposed method lays a strong foundation for transformative innovation in ophthalmic diagnostics. Future work will focus on experimental validation, hardware miniaturization, and the incorporation of AI to enhance performance and accessibility.

By addressing the limitations of current technologies, this framework has the potential to democratize access to accurate, early myopia diagnostics, ultimately improving global eye health outcomes.


## Conflict of Interest Disclosure

The author, Mohsen Sharifzadeh, has filed a provisional patent application (US Patent Application Number: 63/734,181) related to the method described in this manuscript. This potential financial interest has been disclosed in accordance with the journal's policy on conflicts of interest.


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