PhD Research Proposal: AI-Driven Adaptive Optics for Personalized Amblyopia Therapy (R&D Prototype)

1. Candidate Information

- **Candidate Name:** Asadullah Rahoo
- **Email:** asadullahrahoo98@gmail.com
- **GitHub Repository:** https://github.com/AsadRahu60/Eye-Adaptive-Lens-System
- **Phone:** +49 176 47604330
- **Current Status:** M.Sc. Computer Science (University of Passau); B.Eng. Electronics

- **Keywords:** tunable lenses, LC occlusion, embedded systems, safety-critical control, vision therapy, ML assist

Executive Summary

Amblyopia therapies like patching are static, poorly personalized, and often face compliance challenges. This proposal outlines a supervised research platform that delivers per-eye optical modulation using electronically tunable lenses and liquid-crystal (LC) occlusion. This system enables graded, clinician-configured stimulation during near and everyday tasks. It integrates various sensors (distance, ambient light, IMU), a safety-first control stack (slew-rate limits, occlusion duty caps, watchdog fail-safe), complete telemetry, and an optional ML assist that only suggests mild changes under hard guardrails and falls back to rule-based logic. Phase 1 focuses on bench validation; later stages prepare a pilot protocol with a clinical partner. The aim is a reproducible, instrumented platform for testing hypotheses about adaptive amblyopia therapy—not a medical product. All experimental work will follow conservative safety limits and proceed only under appropriate supervision and ethics approval.

2. Background & Gap

2.1. Clinical Gap

Traditional amblyopia treatments, primarily patching, are often binary and difficult to tailor precisely to individual patient needs. Older children and adults frequently experience limited benefit, highlighting a significant need for more adaptable and personalized therapeutic approaches. The brain's underlying suppression of the amblyopic eye, and the importance of binocular interactions, are not adequately addressed by current static methods.

2.2. Scientific Opportunity

There is a compelling scientific opportunity to explore whether small, per-eye graded changes to focus, contrast, or occlusion can better promote binocular balance. Such dynamic adjustments, if delivered comfortably and imperceptibly, could enhance patient adherence and lead to improved outcomes by actively engaging neural plasticity. This moves beyond passive correction to active neuro-rehabilitation.

2.3. Technical Enablers

Recent advancements provide the necessary technical foundation for this research:

- **Compact Tunable Lenses:** Miniaturized optical components capable of rapid and precise focal adjustments.
- **Liquid Crystal (LC) Shutters:** Electronically controllable elements for dynamic occlusion or contrast modulation.
- **Low-Power Embedded Controllers:** Devices like the ESP32 enable complex logic and connectivity in a compact form factor.
- **BLE Connectivity:** Facilitates wireless communication for control and data logging.
- **Robust Logging and Telemetry:** Essential for capturing detailed session data, monitoring system performance, and ensuring safety.

These enablers allow for the development of a safe, configurable, in-situ optical manipulation system suitable for controlled research settings.

3. Research Aims

The overarching goal is to build, validate, and prepare for pilot studies an AI-assisted adaptive optics platform for personalized amblyopia therapy. The specific aims are:

1. **Develop a safety-first adaptive optics platform:** Design and construct a system with per-eye tunable focus and LC occlusion, incorporating complete telemetry and strong guardrails for safe operation.
2. **Develop and evaluate therapy policies:** Implement initial conservative rule-based modes, then integrate a guardrailed ML assist to suggest small, adaptive adjustments, always enforcing hard safety limits.
3. **Quantify system feasibility and performance:** Measure key metrics such as response latency, repeatability (targeting pm0.1 D), user comfort envelopes, and operator usability.
4. **Prepare for clinical studies with a partner:** Develop ethics-ready documentation, conduct safety testing, and outline a pilot protocol (including inclusion/exclusion criteria, endpoints, and a data plan) in collaboration with a clinical partner.

4. Approach & Work Packages (24 Months)

The research will be structured into four interconnected work packages, each with specific deliverables and exit criteria, spanning a 24-month period.

WP1 System Engineering (Months 0-6)

- **Objective:** Establish the core hardware and software infrastructure for the adaptive optics platform.

- **Activities:**
    - **Hardware:** Design and implement per-eye tunable lens drivers and an LC shutter AC drive with true AC (no DC bias). Integrate sensors including Time-of-Flight (ToF) distance, ambient light, and Inertial Measurement Unit (IMU).
    - **Firmware:** Develop ESP32 firmware for BLE communication, sensor fusion, watchdog functionality, and implementation of soft limits and safe defaults.
    - **Host Software:** Create Python-based host software for lens control, a context engine, comprehensive data logging, and report generation tooling.
- **Exit Criteria:** Dual-eye bench control demonstrated; safety clamps verified; deterministic logs captured; Continuous Integration (CI) pipeline green on hardware-independent tests.

WP2 Calibration & Safety Validation (Months 4-10)

- **Objective:** Calibrate all system components and rigorously validate safety mechanisms.
- **Activities:**
    - **Calibration:** Perform per-eye diopter mapping, establish slew-rate comfort curves, and map LC opacity against drive signals.
    - **Safety:** Verify AC drive on an oscilloscope, establish and test thermal/current limits, confirm watchdog behavior, and conduct comprehensive fault-injection tests.
    - **Data Integrity:** Define a session schema and execute reproducibility tests (e.g., 10 cycles within pm0.1 D).
- **Exit Criteria:** Complete calibration assets; comprehensive safety protocol report; documented repeatability and latency metrics; expanded automated test suite.

WP3 Therapy Policies & ML Assist (Months 8-16)

- **Objective:** Develop and evaluate both rule-based and ML-assisted therapeutic policies.
- **Activities:**
    - **Rule-based Policies:** Implement intermittent occlusion (duty scheduling) and contrast-balancing strategies for the fellow eye, incorporating conservative ramps and hysteresis.
    - **ML Assist:** Train a small, interpretable model (e.g., logistic baseline) on session telemetry to suggest mild duty adjustments. Crucially, enforce hard clamps and implement a fallback to rule-based logic in cases of uncertainty or deviation from safety parameters.
    - **Evaluation:** Compare adherence proxies (e.g., comfort rating windows, tolerated duty) and stability against a rule-only baseline on defined bench tasks.
- **Exit Criteria:** ML assist demonstrably improves predefined proxies (e.g., comfort, tolerated duty) without violating safety envelopes; complete audit trail of inputs/outputs and model versioning.

WP4 Usability & Pilot Readiness (Months 14-24)

- **Objective:** Prepare the system for potential human pilot studies, focusing on usability and ethical considerations.
- **Activities:**
  - **Wearable Rig:** Develop a lightweight frame, optimize cable management, and create an operator checklist; implement comfort prompts for the user.
  - **Pilot Preparation:** Draft a comprehensive ethics package (including risk analysis, consent model, and data plan) in collaboration with a clinical partner. Define clinical endpoints (e.g., adherence, comfort, binocular function tests) in conjunction with clinicians.
- **Exit Criteria:** Complete pilot protocol outline; operator usability report; comprehensive documentation bundle ready for ethics submission.

5. Safety, Ethics, and Data

5.1. Non-Clinical R&D and Approvals

This project is defined as non-clinical Research & Development (R&D) by default. Any work involving human participants will proceed *only* under formal ethics approval from the relevant institutional review board and strict clinician supervision. This is an R&D prototype, not a medical device for patient use.

5.2. Safety Guardrails

The system will incorporate multiple layers of safety:

- **Per-eye Slew-Rate Limits:** To prevent sudden or uncomfortable optical changes.
- **Duty Caps:** Maximum limits on occlusion or contrast modulation.
- **Watchdog Fail-Safe:** A mechanism to revert to neutral focus and transparent shutters immediately upon detection of any system fault.
- **Conservative Defaults:** All operational parameters will default to the safest possible settings.

5.3. Optical Safety

Specific measures for optical safety include:

- **True AC for LC Shutters:** Ensuring no harmful DC bias is applied to liquid crystals.
- **Current/Thermal Limits:** Adherence to vendor specifications for component operation to prevent overheating or damage.
- **Emergency Stop Behavior:** Clear protocols for system shutdown in critical situations.

5.4. Data & Privacy

- **Anonymity:** No personal identifiers will be collected or stored with telemetry data.
- **Telemetry Only:** Data collection will focus solely on system performance and optical parameters.

- **Model Versioning:** All machine learning model versions, along with their inputs and outputs, will be logged for complete auditability.
- **Consent & Access Control:** Export of any data will be under explicit consent, and storage will be managed with robust access control mechanisms.

6. Expected Outcomes

Upon completion, this PhD research is expected to deliver:

- **A reproducible research platform:** For adaptive, per-eye optical stimulation, featuring full telemetry and robust safety guards.
- **Benchmark results:** Quantifying response latency, repeatability, comfort envelopes, and providing comparisons between different therapeutic policies; accompanied by reports and scripts for replication.
- **Open documentation:** Including architecture, a roadmap with exit criteria, a risk register, safety protocols, test procedures, and calibration procedures.
- **Pilot-ready materials:** To support a clinician-led feasibility study within the PhD timeframe (subject to partner and approvals).
- **Scholarly outputs:** 2-3 peer-reviewed papers published across biomedical optics, vision science, and embedded systems venues; provision of open datasets and code where appropriate.

7. Candidate Fit & Supervision Request

I bring a unique blend of embedded systems and host software development skills, coupled with a strong emphasis on safety-critical thinking derived from QA/test discipline. My personal motivation, stemming from an understanding of amblyopia, further fuels my dedication to this research. My GitHub repository, "AsadRahu60/Eye-Adaptive-Lens-System," demonstrates my practical capabilities in developing a functional prototype that integrates:

- **ESP32 firmware:** Handling BLE connectivity, sensor fusion, and LC drive control.
- **Python host software:** For sophisticated lens control, context management, and logging.
- **Guardrailed ML assist:** Demonstrating foundational work in intelligent, safety-constrained adaptive control.
- **Reproducibility:** Ensuring testability and reliability through CI and synthetic demos.

I seek supervision within ophthalmology/biomedical optics/vision science, ideally with co-supervision from instrumentation/engineering, to bridge the computational and clinical aspects effectively. I am confident that I can align the scope of this research with active grants focused on instrument development, clinical translation, or analytics.

Lab Alignment Paragraph (edit per email):

Your lab's work on <adaptive optics / ophthalmic imaging / binocular vision / biomedical instrumentation> is a natural fit for my research. I am prepared to contribute a ready, instrumented platform—building upon my existing "Eye-Adaptive-Lens-System" project—and further push it toward pilot-readiness. I am keen to align experiments with your ongoing projects and clinical collaborations, fostering a synergistic research environment.

8. Minimal Technical Appendix (from repo)

- **Stack:** ESP32 firmware (BLE + sensors + LC drive), Python host (lens control, context engine, logs), optional Flutter UI.
- **ML assist:** A guardrailed logistic model suggests small duty changes; hard clamps always enforce safe ranges; full fallback to rules on uncertainty.
- **Reproducibility:** CI is green (format/lint/tests/markdown/arduino-lint), and a one-click synthetic demo (train + tests) runs without hardware, ensuring robust development and verification.
- **Repository:** The README of [AsadRahu60/Eye-Adaptive-Lens-System] provides detailed insights into its architecture, roadmap, safety considerations, tests, ML overview, and demo commands.

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