AI-Assisted Adaptive Optics for Personalized Amblyopia Therapy (R&D Prototype)

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Current status: M.Sc. Computer Science (University of Passau); B.Eng. Electronics

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R&D prototype — not a medical device. All experimental work will follow conservative safety limits and proceed only under appropriate supervision and ethics approval.

Executive Summary

Amblyopia therapies like patching are static, poorly personalized, and often face compliance challenges. I propose a supervised research platform that delivers per-eye optical modulation using electronically tunable lenses and liquid-crystal (LC) occlusion to enable graded, clinician-configured stimulation during near and everyday tasks. The system integrates 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.

Background & Gap

Clinical gap: Traditional patching is binary and difficult to tailor; older children and adults often see limited benefit.

Scientific opportunity: Small, per-eye graded changes to focus/contrast/occlusion may better promote binocular balance while maintaining comfort and adherence.

Technical enablers: Compact tunable lenses, LC shutters, low-power embedded controllers, BLE connectivity, and robust logging allow safe, configurable in-situ optical manipulation suitable for controlled research.

Research Aims

Build a safety-first adaptive optics platform with per-eye tunable focus and LC occlusion; provide complete telemetry and strong guardrails.

Develop therapy policies: start with conservative rule-based modes, then add a guardrailed ML assist that suggests small adjustments; always enforce hard limits.

Quantify feasibility: response latency, repeatability (target ±0.1 D), user comfort envelopes, operator usability.

Prepare for clinical studies with a partner: ethics-ready documentation, safety testing, and a pilot protocol outline (inclusion/exclusion, endpoints, data plan).

Approach & Work Packages (24 months)

WP1 — System Engineering (Months 0–6)

Hardware: Per-eye tunable lens drivers; LC shutter AC drive with true AC (no DC bias); sensors (ToF distance, ambient light, IMU).

Firmware: ESP32 BLE + sensor fusion; watchdog; soft limits and safe defaults.

Host software: Python control for lens drivers; context engine; logs; report tooling.

Exit criteria: Dual-eye bench control; safety clamps verified; deterministic logs captured; CI green on hardware-independent tests.

WP2 — Calibration & Safety Validation (Months 4–10)

Calibration: Per-eye diopter mapping; slew-rate comfort curves; LC opacity mapping vs. drive.

Safety: Verify AC drive on scope; thermal/current limits; watchdog behavior; fault-injection tests.

Data integrity: Session schema; reproducibility tests (e.g., 10 cycles within ±0.1 D).

Exit criteria: Calibration assets; safety protocol report; repeatability and latency metrics; automated test suite expanded.

WP3 — Therapy Policies & ML Assist (Months 8–16)

Rule-based policies: Intermittent occlusion (duty scheduling) and contrast-balancing for the fellow eye; conservative ramps and hysteresis.

ML assist: Train a small, interpretable model (e.g., logistic baseline) on session telemetry to suggest mild duty adjustments; enforce hard clamps and fallback to rules on uncertainty.

Evaluation: Compare adherence proxies (comfort rating windows, tolerated duty) and stability vs. rule-only baseline on bench tasks.

Exit criteria: ML assist improves predefined proxies without violating safety envelopes; complete audit trail of inputs/outputs and model versioning.

WP4 — Usability & Pilot Readiness (Months 14–24)

Wearable rig: Lightweight frame, cable management, and operator checklist; comfort prompts.

Pilot prep: Draft ethics package (risk analysis, consent model, data plan) with a clinic partner; define endpoints (adherence, comfort, binocular function tests decided with clinicians).

Exit criteria: Pilot protocol outline; operator usability report; documentation bundle for ethics submission.

Safety, Ethics, and Data

Non-clinical R&D by default; any human testing only under formal ethics approval and clinician supervision.

Guardrails: Per-eye slew-rate limits; duty caps; watchdog to neutral focus + transparent shutters on fault; conservative defaults.

Optical safety: True AC for LC shutters (no DC bias), current/thermal limits per vendor specs, emergency stop behavior.

Data & privacy: No personal identifiers; telemetry only; model versions logged; export under consent; storage with access control.

Expected Outcomes

A reproducible research platform for adaptive, per-eye optical stimulation with full telemetry and safety guards.

Benchmark results: response latency, repeatability, comfort envelopes, policy comparisons; reports and scripts for replication.

Open documentation: architecture, roadmap with exit criteria, risk register, safety protocols, tests, 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 papers across biomedical optics/vision science/embedded systems venues; open datasets and code where appropriate.

Candidate Fit & Supervision Request

I bring embedded systems + host software skills, safety-critical thinking (QA/test discipline), and personal motivation (amblyopia). I seek supervision within ophthalmology / biomedical optics / vision science with co-supervision from instrumentation/engineering. I can align scope to active grants (e.g., instrument development, clinical translation, analytics).

Lab alignment paragraph (edit per email):

Your lab's work on <adaptive optics / ophthalmic imaging / binocular vision / biomedical instrumentation> is a natural fit. I can contribute a ready, instrumented platform and push toward pilot-readiness, while aligning experiments with your ongoing projects and clinical collaborations.

Minimal Technical Appendix (from repo)

Stack: ESP32 firmware (BLE + sensors + LC drive), Python host (lens control, context engine, logs), optional Flutter UI.

ML assist: Guardrailed logistic model suggests small duty changes; hard clamps always enforce safe ranges; full fallback to rules.

Reproducibility: CI green (format/lint/tests/markdown/arduino-lint), one-click synthetic demo (train + tests) runs without hardware.

Repository: AsadRahu60/eye-adaptive-lens → README points to architecture, roadmap, safety, tests, ML overview, and demo commands.

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