

# Eye Protection Device - Technical Documentation

## Project: VisionGuard

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## Executive Summary

The VisionGuard Device is an innovative IoT solution designed to promote safe viewing habits for children using televisions. The device combines advanced Time-of-Flight (ToF) sensing technology with intelligent behavior modification algorithms to automatically manage TV access based on viewer proximity. This technical document provides comprehensive circuit analysis and design rationale for electronics R&D teams.

## System Architecture Overview

### Core Functionality

- Multi-zone distance monitoring** using VL53L5CX ToF sensor
- Automated TV control** via IR transmission for input switching
- Wireless configuration** through WiFi/Bluetooth connectivity
- Matter protocol compatibility** for smart home integration
- Expandable I2C interface** for additional sensor modules
- USB-C connectivity** for power and programming

### Key Design Principles

- Low power consumption** optimized for continuous operation
- Robust signal integrity** with proper impedance control
- Thermal management** for reliable long-term operation
- Modular I2C expansion capability**

## Circuit Analysis

### 1. Main Processing Unit (U2: ESP32-C6-MINI-1-N4)

**Design Rationale:** The ESP32-C6 was selected for its unique combination of features:

- 802.11ax WiFi 6** and **Bluetooth 5 LE** connectivity
- Matter/Thread** protocol support for smart home integration
- High performance 32-bit RISC-V single-core processor** with low power consumption
- USB 2.0 FS OTG** for direct programming interface

### Power Supply Design:

- 3.3V rail** generated by ST1L05 low-dropout regulator

- **Decoupling network:** Multiple 100nF ceramics (C2, C3, C9, C10, C14) for high-frequency noise suppression
- **Bulk capacitors:** 1μF (C6, C7) for transient response
- **Power sequencing:** Proper enable control through R7 (10kΩ) pull-up

#### Reset and Boot Control:

- **SW1 (ENABLE):** Hardware reset with RC debouncing (R1=10kΩ, C5=1μF)
- **SW2 (GPIO12):** Boot mode selection for programming
- **Pull-up resistors:** R8 (2.2kΩ) on critical GPIO pins

## 2. Time-of-Flight Sensor (U6: VL53L5CXV0GC/1)

#### Multi-Zone Sensing Capability:

- **64-zone SPAD array** providing 8x8 resolution
- **Operating range:** 4mm to 4000mm with high accuracy
- **Field of View:** Configurable up to 63° diagonal

#### Interface Design:

- **I2C communication** at up to 1MHz
- **Dual power supply:** 2.8V analog (AVDD), 1.8V digital (IOVDD)
- **Interrupt capability** via INT pin to GPIO14
- **Reset control** through I2C\_RST signal

#### Power and Signal Integrity:

- **Pull-up resistors:** R4, R5 (2.2kΩ) on I2C lines for proper signaling
- **Decoupling:** Dedicated bypass capacitors for both supply domains
- **Thermal pad:** Efficient heat dissipation for stable operation

## 3. Power Management System (U3: ST1L05APU33R)

#### Power Distribution:

- Input filtering: C1 (22μF), C4 (4.7μF) for input stability
- Output filtering: C11 (4.7μF), C8 (4.7μF) for load transient response

#### USB-C Implementation:

- **Power delivery:** Supports standard 5V USB power
- **Data capability:** USB 2.0 FS differential pairs routed to ESP32-C6
- **Configuration resistors:** R13, R16 (5.1kΩ) on CC pins for UFP identification

#### Signal Integrity Measures:

- **Controlled impedance:** 90Ω differential pairs for USB signals
- **Length matching:** Minimized skew between D+/D- traces
- **EMI filtering:** Series termination resistors R9, R10 (22Ω)

## 4. Infrared Transmission System (U5, Q1, LED1)

**IR LED Driver Circuit:**

- **High-power IR LED:** 940nm wavelength for optimal TV receiver compatibility
- **NPN switching:** SS8050 transistor (Q1) for current amplification
- **Current limiting:** R14 (220Ω) for LED protection
- **Base drive:** R4 (2.2kΩ) for proper transistor saturation

**Modulation Capability:**

- **GPIO4 control:** Software PWM for IR protocol generation
- **Wide protocol support:** Compatible with NEC, RC5, RC6, Sony SIRC
- **Range optimization:** Focused beam pattern for reliable TV control

5. I2C Level Translation (U7: PCA9617ADPJR42)

**Bidirectional Level Shifting:**

- **Side A:** 3.3V logic (microcontroller domain)
- **Side B:** 5V logic (external sensor compatibility)
- **Buffer capability:** Increased current drive for longer I2C runs

**External Expansion Connector (CN4):**

- **4-pin JST PH connector:** Industry-standard for sensor modules
- **Pin assignment:** VCC (5V), GND, SCL, SDA

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# PCB Design and Layout Analysis

## PCB Form Factor and Mounting

The device utilizes a rectangular PCB form factor optimized for TV bezel mounting. The compact design measures approximately 16mm x 50mm, allowing discrete installation on most TV models without interfering with screen visibility or aesthetics.

**Mounting Considerations:**

- **Thin profile design** (<10mm total thickness) for minimal visual impact
- **Component placement** concentrated to avoid TV frame interference
- **Cable routing** optimized for clean installation with USB-C power connection

## Physical Design Overview

The PCB layout demonstrates professional-grade design practices with strategic component placement optimized for both functionality and manufacturing efficiency. The compact form factor is achieved while maintaining proper isolation between critical circuit blocks.

## Component Placement Strategy

**Power Management Zone (Left Side):**

- **U3 (ST1L05 LDO)** positioned near USB-C connector (U4) for minimal input trace length

- **Power filtering capacitors** clustered around LDO for optimal decoupling effectiveness

#### Microcontroller Core (Center-Left):

- **U2 (ESP32-C6-MINI-1-N4)** centrally located for equidistant routing to peripherals
- **SW1 (ENABLE) and SW2 (BOOT)** positioned for easy access during development and testing

#### Sensor Interface (Upper Right):

- **U6 (VL53L5CX ToF sensor)** placed at PCB edge on the middle for unobstructed field-of-view
- **Optimal orientation** allows mounting at TV bezel edge with clear sensing path
- **I2C level translator U7** positioned between sensor and microcontroller domains

#### IR Transmission System (Lower Right):

- **U5 (IR LED) and LED1** positioned for maximum transmission efficiency
- **LED2 (status indicator)** placed for user visibility when device is mounted
- **Driver transistor** located close to IR LED for minimal switching loop area

#### Expansion Interface:

- **CN4 (I2C connector)** positioned at PCB right edge for external cable access
- **Connector orientation** facilitates neat cable routing in installation

#### Layer Stack-up Strategy

- **2-layer design** optimized for cost-effectiveness while maintaining signal integrity
- **Layer 1 (Top):** Primary component placement with signal routing and copper pour ground areas
- **Layer 2 (Bottom):** Secondary component placement, additional routing, and extensive ground copper pour for EMI suppression and thermal management

#### Ground Plane Implementation:

- **Copper pour ground areas** on both top and bottom layers provide effective EMI shielding
- **Via stitching** between layers ensures low-impedance ground connections
- **Strategic ground plane splits** only where necessary to maintain signal integrity
- **Thermal heat spreading** achieved through maximized copper area on both layers

#### Signal Integrity Considerations

##### High-Speed Signal Routing:

- **USB differential pairs** routed with controlled 90Ω impedance
- **Length matching** between D+ and D- within ±0.1mm
- **Guard traces** on adjacent layers to minimize crosstalk
- **Via optimization** to reduce discontinuities in critical paths

##### I2C Signal Integrity:

- **SCL/SDA traces** routed with consistent spacing and minimal via count
- **Pull-up resistor placement** optimized for signal rise time
- **Cross-plane isolation** between 3.3V and 5V I2C domains

## Power Distribution Network (PDN)

### 3.3V Rail Design:

- **Wide copper pours** for low resistance distribution
- **Multiple via connections** between layers for current sharing
- **Localized decoupling** at each IC with appropriate capacitor values

### 5V Rail Management:

- **Direct path** from USB-C to expansion connector
- **Ferrite bead isolation** where required for analog circuits
- **Current path optimization** for IR LED drive circuit

## Thermal Management

- **Ground plane heat spreading** utilizing full copper pour on Layer 2
- **Thermal vias** strategically placed under:
  - LDO regulator (U3) for heat dissipation
  - ESP32-C6 module for processor cooling
  - IR LED driver for power device cooling
- **Component spacing** optimized for natural convection cooling
- **Heat-sensitive component isolation** from high-power circuits

## EMI/EMC Compliance Design

### Electromagnetic Interference Mitigation:

- **Ground plane continuity** with minimal slots and careful via stitching
- **Crystal oscillator shielding** through local ground guard rings
- **Switching regulator layout** with tight current loops
- **Cable connector filtering** at expansion interface

### Electromagnetic Compatibility Features:

- **Ferrite bead placement** on sensitive analog supplies
- **Bypass capacitor positioning** for maximum effectiveness
- **Trace routing** to minimize loop areas in switching circuits
- **Shield-to-ground connections** where applicable

## Manufacturing and Assembly Considerations

### Assembly Process Optimization:

- **Component orientation** standardized where possible
- **Fiducial markers** (not shown but implied) for pick-and-place accuracy
- **Keep-out zones** maintained around connectors and mechanical features
- **Solder mask design** optimized for reliable solder joint formation

### Quality Control Features:

- **Visual inspection areas** clear of components
- **Electrical test access** through dedicated test points
- **Component polarity indicators** clearly marked
- **Critical dimension callouts** for mechanical interfaces

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## Firmware Architecture

### ESPHome Integration

- **YAML configuration** for easy customization
- **OTA updates** via WiFi for field deployment
- **Home Assistant** native integration

### Matter Protocol Stack

- **Thread networking** for mesh topology
- **Standard clusters:** On/Off, Level Control
- **Security:** Device attestation and encrypted communication

### Algorithm Framework

- **Multi-zone processing:** Parallel distance calculations
- **Temporal filtering:** Moving average and outlier rejection
- **State machine:** Robust behavioral control logic
- **Configurable thresholds:** Age-appropriate distance settings

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## Configuration Parameters

### Distance Monitoring

Parameter	Range	Default	Description
Safe Distance	50-500cm	200cm	Minimum viewing distance
Warning Time	5-60s	15s	Alert before action
Compliance Time	10-300s	60s	Time to maintain safe distance
Detection Zones	1-64	16	Active sensing regions

### IR Remote Control

- **Protocol Selection:** NEC, RC5, RC6, Sony, Samsung
- **Device Codes:** Manufacturer-specific TV codes
- **Action Sequence:** Input switch → delay → restore
- **Retry Logic:** Multiple transmission attempts

### Connectivity Options

- **WiFi Provisioning:** WPS, SmartConfig, AP mode

- **Bluetooth Pairing:** Simple pairing for mobile configuration
  - **Matter Commissioning:** QR code and manual pairing codes
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## Performance Specifications

### Electrical Characteristics

- **Supply Voltage:** 5V  $\pm$ 10% (USB-C input)
- **Power Consumption:**
  - Active monitoring: 150mA typical
  - Standby mode: 25mA typical
- **Operating Temperature:** -10°C to +60°C
- **Storage Temperature:** -40°C to +85°C

### Sensing Performance

- **Detection Range:** 0.1m to 4.0m
- **Accuracy:**  $\pm$ 3% or  $\pm$ 10mm (whichever is greater)
- **Response Time:** <100ms for distance changes
- **Angular Resolution:** 8° per zone (8x8 array)

### Communication Range

- **WiFi:** Up to 50m (indoor, line of sight)
  - **Bluetooth:** Up to 10m (Class 2 device)
  - **IR Transmission:** Up to 8m (direct line of sight)
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## Quality Assurance Features

### Self-Diagnostics

- **Sensor health monitoring:** Automatic calibration verification
- **Communication integrity:** Link quality assessment
- **Power supply monitoring:** Voltage and current measurement
- **Temperature monitoring:** Thermal protection algorithms

### Fail-Safe Operations

- **Watchdog timer:** System reset on firmware hang
  - **Brownout detection:** Graceful shutdown on power loss
  - **Error logging:** Persistent storage of fault conditions
  - **Recovery modes:** Automatic and manual recovery options
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## Manufacturing Considerations

### Component Selection Rationale

- **Industrial temperature grade** components where critical
- **JEDEC standard packages** for reliable assembly
- **RoHS compliance** for environmental requirements
- **Long-term availability** from tier-1 suppliers

## Assembly Requirements

- **Lead-free soldering** process compatible
- **Reflow profile:** Standard SAC305 alloy
- **Test points:** Accessible for automated testing
- **Programming interface:** Tag-Connect footprint for production

## Quality Control

- **In-circuit testing** capability
- **Functional test fixtures** for calibration
- **Burn-in procedures** for high-reliability applications
- **Statistical process control** for yield optimization

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# Regulatory Compliance

## Safety Standards

- **IEC 62368-1:** Audio/video equipment safety
- **UL 2089:** Health/wellness devices
- **FCC Part 15:** Unintentional radiators

## Wireless Certifications

- **FCC ID:** Part 15.247 for 2.4GHz operation
- **IC certification:** Industry Canada approval
- **CE marking:** European conformity declaration
- **WiFi Alliance:** 802.11ax certification

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# Conclusion

The VisionGuard Device represents a sophisticated integration of modern sensing technology, wireless connectivity, and intelligent control algorithms. The circuit design demonstrates adherence to industry best practices in power management, signal integrity, and EMI control. The modular architecture allows for future expansion while maintaining robust core functionality.

The device addresses a genuine need for promoting healthy viewing habits in children while providing parents with a non-intrusive technological solution. The Matter protocol compatibility ensures future-proof integration into smart home ecosystems, while the ESPHome framework provides flexibility for customization and updates.

This technical foundation provides a solid platform for successful commercialization and field deployment of the Eye Protection Device.



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