TOSCA Laser Control System - Architecture Overview

Document Version: 1.0 **Date:** 2025-10-26 **Status:** Phase 5 - Testing & Quality Assurance **Security Status:** WARNING: **Encryption NOT Implemented** (Planned Phase 6)

> **Note:** Current version does NOT include data encryption. See `08_security_architecture.md` for planned encryption implementation (Phase 6+). DO NOT use for clinical trials or production deployment until encryption is implemented.

Executive Summary

This document outlines the architecture for a laser control system. The system integrates laser control, linear actuator positioning, GPIO-based safety interlocks, camera-based alignment, and comprehensive subject/session tracking.

System Purpose

Control and monitor laser treatments with: - Precise power and timing control - Adjustable ring size via linear actuator - Real-time safety monitoring via photodiode and hotspot smoothing device - Camera-based alignment and focus verification - Complete treatment recording and audit trail - Longitudinal subject tracking across multiple sessions

Technology Stack

Core Technologies

- **Language:** Python 3.10+
- **GUI Framework:** PyQt6 (modern, cross-platform, feature-rich)
- **OS Platform:** Windows 10 (Mini PC)
- **Database:** SQLite (local, single-user)

Key Libraries

```
# UI & Visualization
PyQt6                     # Main GUI framework
pyqtgraph                # Real-time plotting (photodiode, power
        graphs)

# Image Processing & Computer Vision
opencv-python (cv2)      # Ring detection, focus measurement
```

~~~
numpy                   # Image array operations
pillow                  # Image saving/conversion

# Hardware Interfaces
pyserial               # Arroyo laser serial communication + Arduino
        Nano COM4
# pyfirmata            # REMOVED - replaced by custom serial
        protocol (Oct 2025)
# Xeryon library        # Linear actuator control (existing)
# VmbPy SDK            # Allied Vision camera interface (existing)

# Database & Data Management
sqlite3                # Built-in database
sqlalchemy             # ORM for cleaner database code
alembic                # Database migrations

# Logging & Utilities
logging                # Event logging
python-dateutil        # Timestamp handling
pydantic              # Configuration validation
jsonschema            # Protocol validation
```text

## High-Level Architecture
~~~

┌──
────────┐ │ User Interface (PyQt6) │ │ ┌────────┐ ┌────────┐
┌────────┐ ┌────────┐ │ │ │ Subject │ │ Live │ │Treatment │ │
Safety │ │ │ │Selection │ │ Video │ │ Control │ │ Status │ │ │ └────────┘
└────────┘ └────────┘ └────────┘ │
└──
────────┘ ↕
┌──
────────┐ │ Application Core (Business Logic) │ │ ┌────────────┐
┌──────────────┐ │ │ │ Session Manager │ │ Safety Manager │ │ │ │
- Subject select │ │ - Footpedal │ │ │ │ - Tech ID │ │ - Smoothing dev │ │ │ │ -
Recording │ │ - Photodiode │ │ │ └──────────────┘ │ - Interlocks │ │
│ ┌──────────────┐ └──────────────┘ │ │ │Treatment
Engine │ ┌──────────────┐ │ │ │ - Protocol exec │ │ Image
Processor │ │ │ │ - Power control │ │ - Ring detection │ │ │ │ - Ring sizing │
│ - Focus measure │ │ │ │ - Data logging │ │ - Video record │ │ │
└──────────────┘ └──────────────┘ │
└──
────────┘ ↕
┌──
────────┐ │ Hardware Abstraction Layer (HAL) │ │ ┌────────┐
┌────────┐ ┌────────┐ ┌────────┐ │ │ │ Laser │ │ Actuator │ │
Camera │ │ GPIO │ │ │ │ (Arroyo) │ │ (Xeryon) │ │ (VmbPy) │ │(Arduino) │
│ │ │ Serial │ │ API │ │ SDK │ │ Firmata │ │ │ │ │ │ │ │ │ │ Smoothing│ │ │ │
│ │ │ │ │ │Photodiode│ │ │ └────────┘ └────────┘ └────────┘
└────────┘ │
└──
────────┘ ↕
┌──
────────┐ │ Physical Hardware Layer │ │ [Laser] [Actuator] [Camera]

```
[Footpedal] [Smoothing] [Photodiode] │
└──────────────────────────────────────────────────────────────┘

## Hardware Components

### 1. Laser Controller
- **Device:** Arroyo Instruments TEC Controller
- **Interface:** Serial communication (RS-232/USB)
- **Library:** Custom Python class for Arroyo serial protocol
- **Control:** Power settings, on/off, status queries

### 2. Linear Actuator
- **Device:** Xeryon linear stage
- **Interface:** External API library
- **Function:** Controls laser ring size by adjusting optical position
- **Control:** Position commands → Ring diameter mapping

### 3. Camera System
- **SDK:** VmbPy (Allied Vision Vimba Python SDK)
- **Interface:** USB/GigE
- **Functions:**
  - Live video feed display
  - Manual focus/alignment by operator
  - Ring detection (circle finding)
  - Focus quality measurement
  - Treatment recording

### 4. GPIO Controller - Safety Interlocks and Monitoring (Arduino Nano)
- **Device:** Arduino Nano (ATmega328P) on COM4
- **Migration Note:** Replaced FT232H GPIO expander in October 2025
- **Firmware:** Custom watchdog firmware with serial protocol
- **Communication:** USB serial (pyserial, 115200 baud)
- **Digital I/O:**
  - **Pin D2 (Output):** Smoothing device motor control
  - **Pin D3 (Input):** Smoothing device vibration sensor
  - **I2C Bus (A4/A5):** MCP4725 DAC control for SEMINEX aiming beam (via LDD200 driver)
- **Analog Input:**
  - **Pin A0 (ADC):** Photodiode voltage monitoring (0-5V, 10-bit)
- **Functions:**
  - Safety interlock monitoring (motor + vibration detection)
  - Real-time laser power measurement via photodiode
  - SEMINEX aiming beam control for alignment (12-bit DAC, 0-4095)
  - Hardware watchdog timer (1000ms timeout)
  - Cross-platform support (Windows/Linux/macOS)

## Safety Architecture

### Critical Safety Interlocks (All Must Pass for Laser Operation)

1. **Footpedal Deadman Switch** (GPIO-1)
   - Type: Active-high requirement
   - Behavior: Laser can only fire while footpedal is DEPRESSED
   - Fail-safe: Releasing pedal immediately disables laser
   - Poll rate: 100Hz minimum

2. **Hotspot Smoothing Device** (GPIO-1)
```

```
   - Type: Signal health monitoring
   - Behavior: Device must output valid signal
   - Fail-safe: Loss of signal triggers immediate laser shutdown
   - Validation: Signal presence + value within acceptable range

3. **Photodiode Feedback** (GPIO-2 ADC)
   - Type: Output power verification
   - Behavior: Measured power must match commanded power
   - Fail-safe: Deviation beyond threshold triggers shutdown
   - Monitoring: Continuous during treatment

4. **Software E-stop**
   - Type: UI button + keyboard shortcut (e.g., ESC key)
   - Behavior: Immediate treatment halt
   - Priority: Highest - bypasses all queues

5. **Session Active**
   - Type: Logical interlock
   - Behavior: Laser cannot fire outside active treatment session
   - Purpose: Ensures all actions are logged and attributed

6. **Image Valid**
   - Type: Camera feed health check
   - Behavior: Valid image frame received within timeout
   - Purpose: Ensures alignment/monitoring capability

### Safety State Machine
```

[SYSTEM_OFF] → [INITIALIZING] → [READY] ↓ [FAULT] ← ← ← ← ← ← ← ← [ARMED] ← ← (all interlocks pass) ↓ ↓ [SAFE_SHUTDOWN] [TREATING] ← (footpedal depressed) ↓ [TREATMENT_COMPLETE]

```
Any interlock failure → Immediate transition to FAULT state → Safe shutdown

## Session Workflow

### Session Initialization
```

1. Application Launch ↓
2. Hardware Connection & Self-Test ↓
3. Tech ID Entry (required for all operations) ↓
4. Subject Selection Screen ├─ Option A: Select Existing Subject (search by subject code) │ └─ Load subject history └─ Option B: Create New Subject └─ Generate subject code, enter demographics ↓
5. Session Creation └─ Log: Subject ID, Tech ID, Start Time

```
### Pre-Treatment Setup
```

1. Display Live Camera Feed ↓
2. Operator Manual Actions (outside software control): ├─ Adjust focus (physical optics) ├─ Align laser ring to treatment site └─ Position subject ↓
3. Software Assistance: ├─ Real-time focus quality indicator ├─ Ring detection overlay └─ Alignment guides ↓
4. Operator confirms ready

Treatment Execution

1. Select Treatment Protocol ├─ Load saved protocol, OR └─ Create/modify custom protocol ↓
2. Safety Pre-checks ├─ All hardware connected ├─ Interlocks in valid state ├─ Camera image valid └─ Session active ↓
3. Operator initiates FIRE trigger ↓
4. System transitions to ARMED state ↓
5. Treatment Loop (while footpedal depressed): ├─ Execute protocol step (power, ring size) ├─ Monitor photodiode ├─ Monitor smoothing device ├─ Capture camera frames ├─ Log all parameters (timestamp, power, position, voltage) └─ Check safety interlocks (every cycle) ↓
6. Treatment completion or pedal release ↓
7. Return to READY state

Session Recording

Continuous Recording During Treatment:
- Video: Full treatment video saved to session folder
- Event log: Every parameter change, every cycle
- Images: Periodic snapshots + key events
- Metadata: Timestamps, device states, operator actions

Data Storage Location:

data/ ├── sessions/ │ ├── session_YYYYMMDD_HHMMSS_/ │ │ ├── video.avi │ │ ├── events.json │ │ ├── snapshots/ │ │ │ ├── frame_001.png │ │ │ ├── frame_002.png │ │ └── metadata.json

Session Closure

1. Operator ends treatment ↓
2. Save final recordings ↓
3. Add session notes ↓
4. Mark session as complete in database ↓
5. Update subject last_modified timestamp ↓
6. Return to Subject Selection (for next subject)

Treatment Protocol Engine

> **Note:** This section describes the older step-based protocol model.
>
> **Current Implementation:** See `06_protocol_builder.md` for the action-based protocol engine (current design).
>
> The action-based model provides greater flexibility with event-driven actions, conditional logic, and real-time adjustments. The step-based model shown below is kept for historical context.

Protocol Structure (Legacy Step-Based Model)

```python
```

~~~~
{
  "protocol_name": "Standard Treatment A",
  "description": "5W constant for 60s at 3mm ring",
  "steps": [
    {
      "step_number": 1,
      "duration_seconds": 60,
      "power_start_watts": 5.0,
      "power_end_watts": 5.0,  # Same as start = constant
      "ring_size_mm": 3.0,
      "ramp_type": "constant"  # or "linear", "logarithmic"
    }
  ]
}
```text

### Protocol Types

1. **Constant Power**
   - Fixed power for duration
   - Example: 5W for 60 seconds

2. **Linear Ramp**
   - Power increases/decreases linearly
   - Example: Ramp from 2W to 6W over 90 seconds

3. **Multi-Step**
   - Multiple sequential steps
   - Example: 3W for 30s, then 5W for 30s, then 3W for 30s

4. **Custom**
   - In-app protocol builder
   - Adjust any parameter on the fly

### Real-Time Protocol Adjustment

- Operator can pause treatment
- Modify power/ring size during pause
- Changes logged as protocol deviation
- Resume with modified parameters

## Image Processing Pipeline

### Pipeline Overview
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Camera Frame ↓ [Preprocessing] ├─ Grayscale conversion ├─ Noise reduction └─ Contrast enhancement ↓ [Ring Detection] ├─ Hough Circle Transform ├─ Edge detection refinement └─ Circle parameters (center, radius) ↓ [Focus Measurement] ├─ Laplacian variance (sharpness) ├─ Gradient magnitude └─ Focus score (0-100) ↓ [Display Overlay] ├─ Detected ring outline ├─ Focus indicator └─ Alignment guides ↓ [Recording] └─ Save annotated frames

~~~~
### Ring Detection Algorithm

```python
def detect_laser_ring(frame):
    """
~~~~

~~~~
    Detect circular laser ring in camera frame

    Returns:
        center (x, y), radius, confidence
    """
    # 1. Preprocess
    gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)
    blurred = cv2.GaussianBlur(gray, (9, 9), 2)

    # 2. Detect circles (Hough Transform)
    circles = cv2.HoughCircles(
        blurred,
        cv2.HOUGH_GRADIENT,
        dp=1,
        minDist=100,
        param1=50,
        param2=30,
        minRadius=20,
        maxRadius=200
    )

    # 3. Select best circle (brightest, most circular)
    # ... validation logic ...

    return center, radius, confidence
```text

### Focus Quality Measurement

```python
def calculate_focus_score(frame):
    """
    Calculate image sharpness/focus quality

    Returns:
        focus_score (0-100, higher = better focus)
    """
    gray = cv2.cvtColor(frame, cv2.COLOR_BGR2GRAY)

    # Laplacian variance method
    laplacian = cv2.Laplacian(gray, cv2.CV_64F)
    variance = laplacian.var()

    # Normalize to 0-100 scale
    focus_score = min(100, variance / 10)  # Calibrate threshold

    return focus_score
```text

## Data Architecture

### Database: SQLite

**Location:** `data/laser_control.db`

**Key Tables:**
1. `subjects` - Subject records (anonymized)
2. `sessions` - Treatment sessions
3. `treatment_events` - Detailed event log (high frequency)
4. `protocols` - Saved treatment protocols
~~~~

5. `calibrations` - Device calibration data
6. `safety_log` - Safety events and faults
7. `tech_users` - Technician/operator accounts

See: `02_database_schema.md` for full schema

Event Logging Strategy

Two-tier logging:

1. **High-frequency data** (100Hz+): JSON files in session folder
   - Photodiode readings
   - Camera frame metadata
   - Real-time interlock states

2. **Event-based data**: SQLite database
   - Protocol steps
   - Power changes
   - Ring size adjustments
   - Safety triggers
   - User actions

Project Directory Structure

laser-control-system/ ├── src/ │ ├── main.py # Application entry point │ │ │ ├── config/ │ │ ├── settings.py # User-configurable settings │ │ ├── safety_limits.py # Hard-coded safety parameters │ │ └── hardware_config.py # Hardware connection parameters │ │ │ ├── ui/ │ │ ├── main_window.py # Main application window │ │ ├── subject_selection.py # Subject selection/creation dialog │ │ ├── treatment_control.py # Treatment control panel │ │ ├── video_display.py # Live camera feed widget │ │ ├── protocol_builder.py # Protocol creation/editing UI │ │ ├── safety_panel.py # Safety status indicators │ │ └── widgets/ # Reusable UI components │ │ │ ├── core/ │ │ ├── session_manager.py # Session lifecycle management │ │ ├── treatment_engine.py # Protocol execution engine │ │ ├── safety_manager.py # Safety interlock orchestration │ │ ├── recording_manager.py # Video/data recording │ │ └── calibration_manager.py # Calibration routines │ │ │ ├── hardware/ │ │ ├── base.py # Abstract hardware device class │ │ ├── laser_controller.py # Arroyo laser interface │ │ ├── actuator_controller.py # Xeryon actuator interface │ │ ├── camera_controller.py # VmbPy camera interface │ │ ├── gpio_interlocks.py # GPIO-1: Footpedal + Smoothing │ │ ├── gpio_photodiode.py # GPIO-2: Photodiode ADC │ │ └── hardware_manager.py # Unified hardware coordination │ │ │ ├── image_processing/ │ │ ├── ring_detector.py # Laser ring circle detection │ │ ├── focus_analyzer.py # Focus quality measurement │ │ ├── video_recorder.py # Video file writing │ │ └── frame_processor.py # Image preprocessing pipeline │ │ │ ├── database/ │ │ ├── models.py # SQLAlchemy ORM models │ │ ├── db_manager.py # Database operations │ │ ├── session_logger.py # High-frequency session logging │ │ └── migrations/ # Alembic migration scripts │ │ │ └── utils/ │ ├── logger.py # Application logging setup │ ├── validators.py # Input validation functions │ ├── exceptions.py # Custom exception classes │ └── constants.py # Systemwide constants │ ├── data/ │ ├── laser_control.db # SQLite database │ ├── sessions/ # Per-session data folders │ │ └── session__/ │ │ ├── video.avi │ │ ├── events.json │ │ ├── photodiode_log.csv │ │ ├── snapshots/ │ │ └── metadata.json │ └── logs/ # Application logs │ ├── app_YYYYMMDD.log │ └── errors_YYYYMMDD.log │ ├── docs/ │ ├── architecture/ │ │ ├── 01_system_overview.md # This file │ │ ├── 02_database_schema.md │ │ ├── 03_safety_system.md │ │ ├── 04_treatment_protocols.md │ │ └── 05_image_processing.md │ ├── user_manual.md │ └── installation.md │ ├── tests/ │ ├── test_hardware/ │ ├── test_core/ │ ├── test_safety/ │ └── test_integration/ │ ├── requirements.txt ├── setup.py └── README.md ```

Development Phases

Phase 1: Foundation (Hardware + Safety)

- [ ] Hardware abstraction layer for all devices
- [ ] Safety interlock system
- [ ] Basic GUI shell (PyQt6)
- [ ] Database schema and basic CRUD operations

Phase 2: Core Treatment Features

- [ ] Subject selection and session management
- [ ] Treatment protocol engine
- [ ] Manual treatment control (constant power)
- [ ] Basic event logging

Phase 3: Advanced Features

- [ ] Ring detection and focus measurement
- [ ] Video recording
- [ ] Protocol builder UI
- [ ] Advanced ramping protocols

Phase 4: Polish & Validation

- [ ] Comprehensive testing
- [ ] User manual
- [ ] Calibration procedures
- [ ] Performance optimization

Key Design Principles

1. **Safety First**: Multiple redundant interlocks, fail-safe design
2. **Audit Trail**: Every action logged, immutable records
3. **User Workflow**: Match clinical workflow, minimize clicks
4. **Hardware Abstraction**: Easy to swap/upgrade devices
5. **Modularity**: Loosely coupled components

6. **Testability**: Unit tests for critical paths
7. **Documentation**: Code + user docs maintained together

Next Documentation Files

1. `02_database_schema.md` - Complete SQL schema with indexes and constraints
2. `03_safety_system.md` - Detailed safety architecture and fault handling
3. `04_treatment_protocols.md` - Protocol format, execution engine, validation
4. `05_image_processing.md` - Computer vision algorithms and calibration

Document Owner: System Architect **Last Updated:** 2025-10-26 **Review Frequency:** Weekly during development