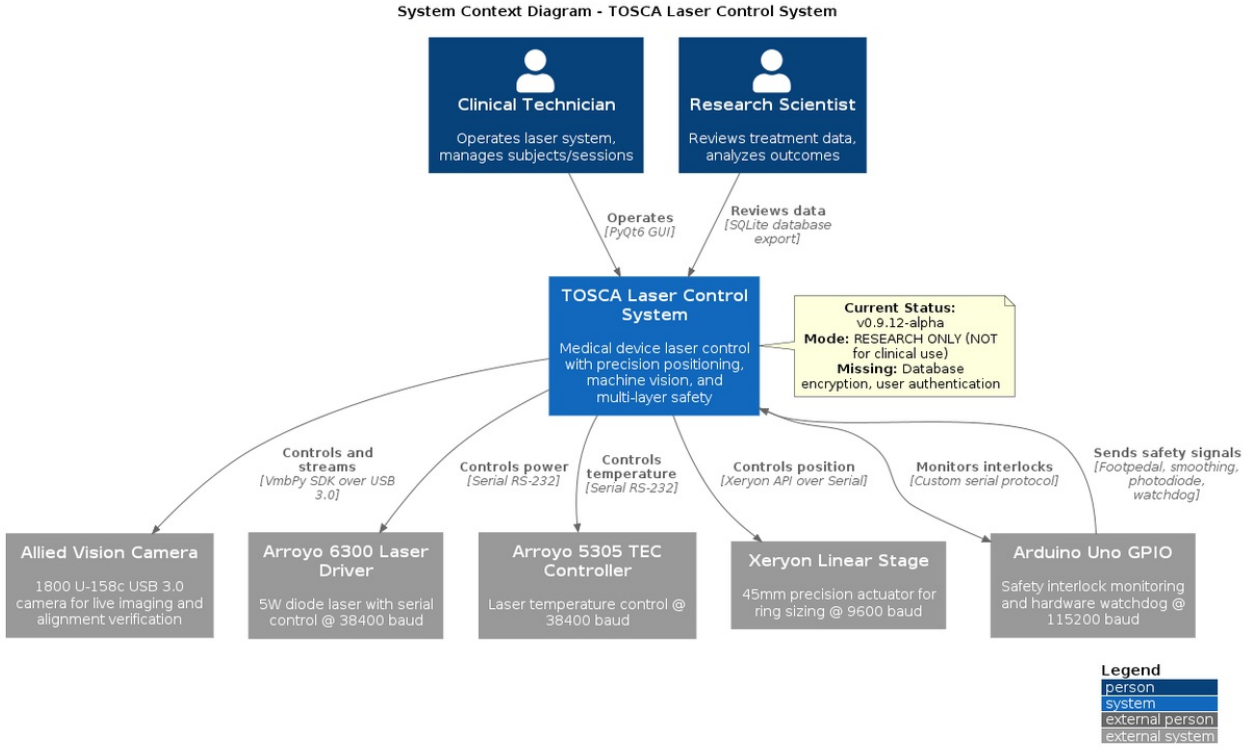
TOSCA Laser Control System - Architecture Overview

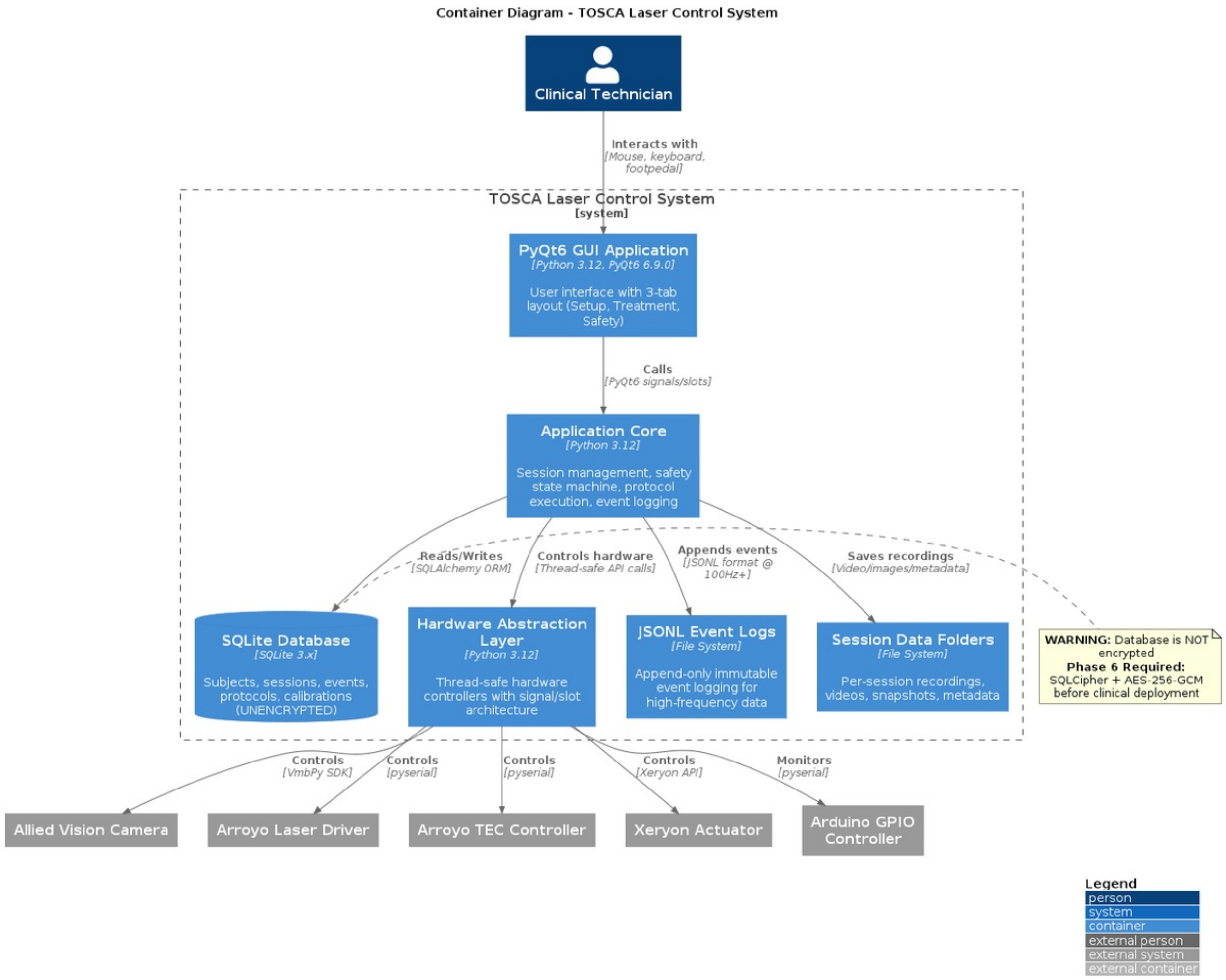
Architecture Diagrams

Figure 1: TOSCA System Context



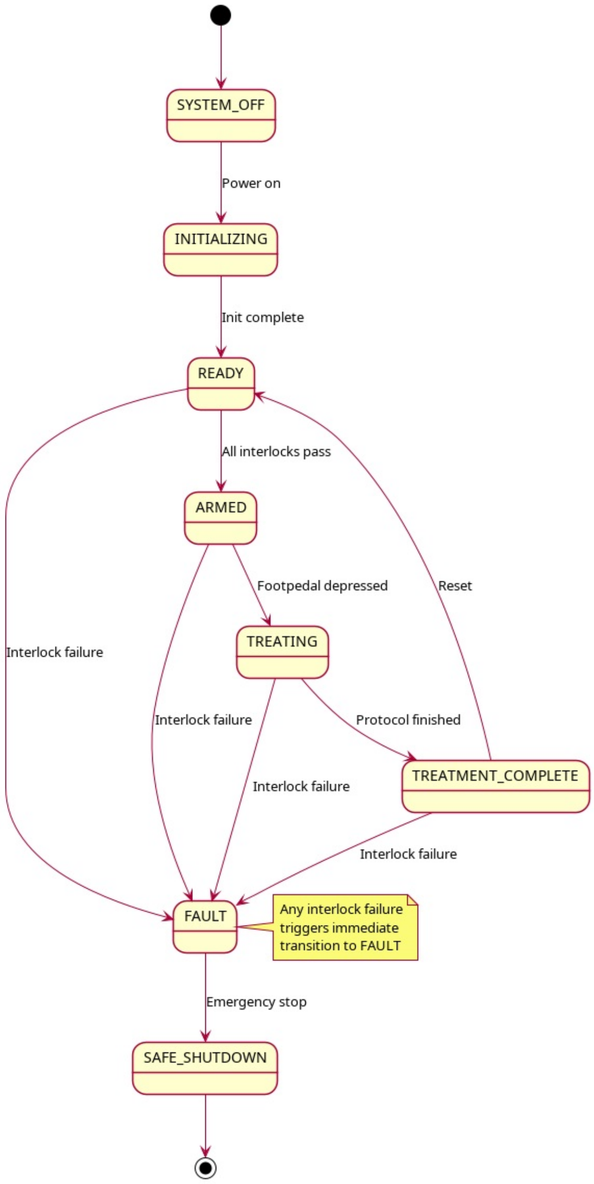
TOSCA System Context

Figure 2: TOSCA Container Diagram



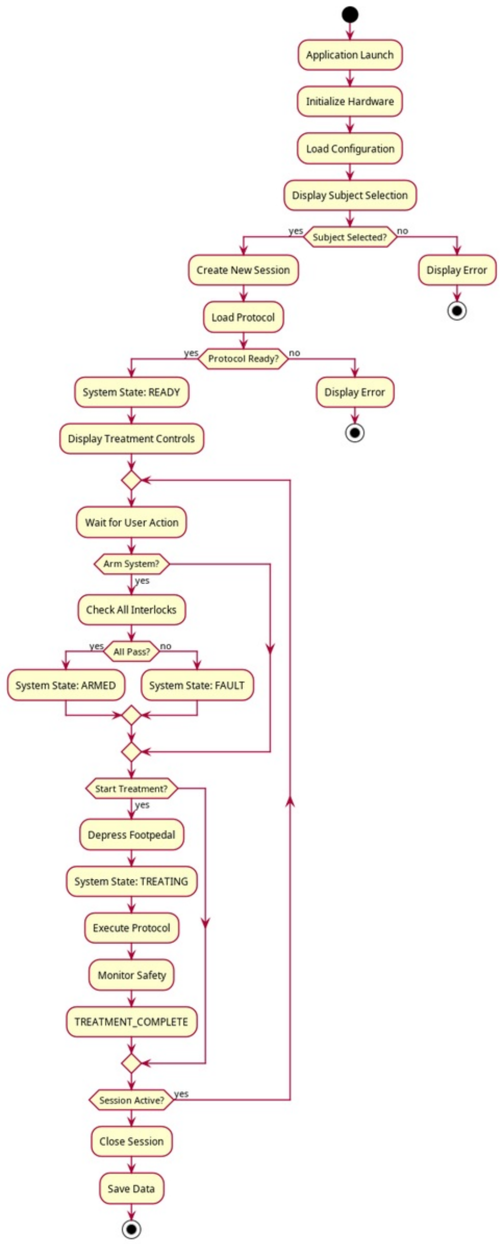
TOSCA Container Diagram

Figure 3: safety-state-machine



safety-state-machine

Figure 4: session-workflow



session-workflow

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

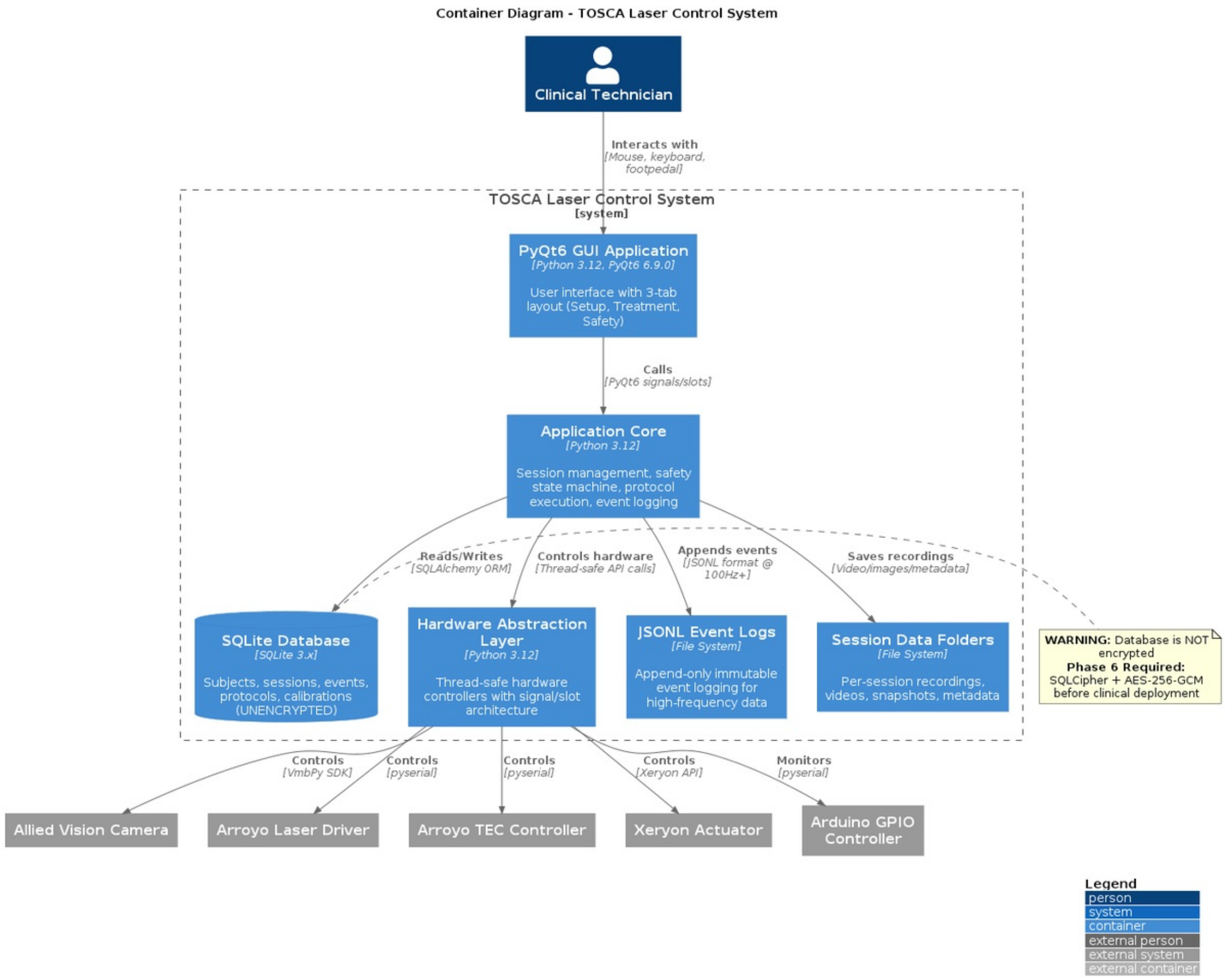
Core Technologies

- **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
```

High-Level Architecture



TOSCA System Architecture - Container View

Figure 1: High-level architecture showing the three-layer design - User Interface (PyQt6), Application Core (Business Logic), and Hardware Abstraction Layer (HAL). The diagram illustrates component relationships and data flow between layers.

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

```
*See diagram above for state machine visualization.*

**States:** **SYSTEM_OFF**, **INITIALIZING**, **READY**, **FAULT**, **ARMED**, **SAFE_SHUTDOWN**, **TREATING**, **TREATMENT_COMPLETE**

**Key Transitions:**
- [SYSTEM_OFF] [INITIALIZING] [READY]
- [FAULT] [ARMED] (all interlocks pass)
- [SAFE_SHUTDOWN] [TREATING] (footpedal depressed)
```

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**
5. **Option A** - Select Existing Subject (search by subject code)
6. **Load subject history**
7. **Option B** - Create New Subject
8. **Generate subject code, enter demographics**
9. **Session Creation**
10. **Log** - Subject ID, Tech ID, Start Time
```

Pre-Treatment Setup

```
1. **Display Live Camera Feed**
2. **Operator Manual Actions (outside software control)** -
3. **Adjust focus (physical optics)**
4. **Align laser ring to treatment site**
5. **Position subject**
6. **Software Assistance** -
7. **Real-time focus quality indicator**
8. **Ring detection overlay**
9. **Alignment guides**
10. **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_<session_id>/
            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)

```json
{
  "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"
    }
  ]
}
```

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

```
1. **Camera Frame**
2. **[Preprocessing]**
3. **Grayscale conversion**
4. **Noise reduction**
5. **Contrast enhancement**
6. **[Ring Detection]**
7. **Hough Circle Transform**
8. **Edge detection refinement**
9. **Circle parameters (center, radius)**
10. **[Focus Measurement]**
11. **Laplacian variance (sharpness)**
12. **Gradient magnitude**
13. **Focus score (0-100)**
14. **[Display Overlay]**
15. **Detected ring outline**
16. **Focus indicator**
17. **Alignment guides**
18. **[Recording]**
19. **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
```

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
```

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

```
**High-Level Structure:**

- **src/**
- **config/**
- **ui/**
- **core/**
- **hardware/**
- **image_processing/**
- **database/**
- **utils/**

**Key Files:**
- main.py                    # Application entry point
- settings.py              # User-configurable settings
- safety_limits.py         # Hard-coded safety parameters
- hardware_config.py       # Hardware connection parameters
- 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

*See full project structure in source repository*
```

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