System Requirements Document (SRD) and Operations Manual

DILBOT Laboratory Automation System

Project: DILBOT (Devices and Interface Lab's Design and Development of Robotic System)

July 22, 2025

Document Control

Version	Date	Author(s)	Description of Changes
1.0	June 15, 2025	Project Lead	Initial draft of the SRD.
1.1	July 22, 2025	Project Lead	Added functional requirements and system architecture.

This document specifies the functional and non-functional requirements for the DILBOT Laboratory Automation System. It also serves as a high-level operations and integration manual.

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1 Introduction

1.1 Purpose

This System Requirements Document (SRD) specifies the functional and non-functional requirements for the DILBOT Laboratory Automation System. This system aims to integrate a Robot Arm, Spin Coater, Pipetting Module, a custom-designed gripper, UV ozone cleaner, nitrogen flushing area and other complimentary devices/equipment into a cohesive automated platform for advanced laboratory processes, specifically for material and device acceleration in emerging photovoltaics technologies.

1.2 Scope

The scope of this document covers the integrated control software, mechanical interfaces, electrical connections, and operational procedures for the automated system. It includes requirements for:

- Robot arm control and path planning/motion planning.
- Spin coater operation and recipe management.
- Pipetting module control and liquid handling.
- Custom gripper design, fabrication, and control.
- Control and operation of UV ozone cleaner, flushing station, heating tray and other complimentary equipment.
- Floor planning and management.
- Inter-module communication and synchronization.
- User interface for recipe creation and execution.
- Safety and error handling mechanisms.

Exclusions: This document does not cover the detailed design of individual components (e.g., internal mechanics of the robot arm or spin coater), nor does it cover the specific chemical processes or material science recipes beyond their programmatic control.

1.3 Definitions, Acronyms, and Abbreviations

DILBOT Devices and Interface Lab's Design and Development of AI assisted Robotic System

SRD System Requirements Document

UI User Interface

API Application Programming Interface

CAD Computer-Aided Design

PCB Printed Circuit Board

RPM Revolutions Per Minute

LLD Liquid Level Detection (Hamilton Pipette)

HMI Human-Machine Interface (often used interchangeably with UI in industrial contexts)

GUI Graphical User Interface

TCP Tool Center Point (Robot Arm)

1.4 References

1. Mitsubishi Industrial Robot RH-3CH-Sxx/RH-6CH-Sxx INSTRUCTION MANUAL (RH_6CH.pdf)
2. SCS G4 Spin Coater Series 0725 (43 SCS G4 Spin Coater Series 0725.pdf)
3. ZEUS X1 Integrator Manual (7624482_Manual_ZEUS_X_Pipetting_A5_COREII_R21.pdf)
4. ZEUS X1 - instructions (Instructions_ZEUS X1.pdf)
5. Project Proposal: Drona–Appendix_DILBOT_27-06.docx
6. Existing CAD models of the laboratory setup.
7. [**TO BE SPECIFIED:** Relevant industry safety standards, e.g., ISO 10218-1/2 for industrial robots, IEC 61010 for lab equipment][In consultation with Devices and Interfaces laboratory team, some standard operating procedures will be created to carry out the experiments in safe manners]

2 Overall Description

2.1 Product Perspective

The DILBOT system will be a standalone automated workstation integrated into a laboratory environment. It will receive high-level recipe commands from a user and execute them by orchestrating the actions of the robot arm, spin coater, pipette, hot plates, nitrogen flushing area and custom gripper. The system will provide feedback on its status and allow for manual intervention if necessary. The system will integrate with existing laboratory infrastructure and be capable of operating autonomously for defined periods in a controlled environment.

2.2 Product Functions

The primary functions of the DILBOT system include:

- Automated handling and transfer of substrates/samples between modules using the robot arm and custom gripper.
- Precise application of liquid materials via the pipette, including aspiration, dispensing, and tip management (two dispensing methods to be used).
- Controlled spin coating of substrates with programmable speed, ramp, and dwell times.
- Automated loading and unloading of consumables (e.g., pipette tips, well plates, substrates) from designated locations.
- Execution of complex, multi-step laboratory recipes defined by the user.
- Real-time monitoring of system status, progress, and error reporting.
- Logging of all operational data, sensor readings, and error events for traceability and debugging.
- Emergency stop and safety interlock mechanisms to ensure operator safety.

2.3 User Classes and Characteristics

Laboratory Researchers/Scientists:
- **Characteristics:** Possess scientific domain knowledge, may have limited programming experience.
- **Needs:** Intuitive GUI for recipe creation and execution, clear status feedback, reliable and repeatable operation, easy data logging access.

Maintenance Personnel:
- **Characteristics:** Possess basic mechanical and electrical troubleshooting skills.
- **Needs:** Access to diagnostic tools, calibration procedures, detailed technical documentation, easy access to replaceable components.

Developers/Engineers (Team Members):
- **Characteristics:** Possess strong programming, mechanical, and electrical engineering skills.
- **Needs:** Access to source code, APIs, detailed system architecture documentation, debugging interfaces, ability to extend functionality.

2.4 Operating Environment

The system will operate in a controlled laboratory environment, potentially within a fume hood or glove box for certain processes.

- **Temperature:** To be specified
- **Humidity:** To be specified
- **Power Supply:** To be specified
- **Connectivity:** To be specified
- **Vibration:** To be specified
- **Cleanliness:** To be specified

2.5 General Constraints

- **Safety:** The system must comply with all relevant laboratory safety standards (e.g., chemical handling [to be given by lab], electrical safety) and robot safety guidelines (e.g., ISO 10218). Emergency stop mechanisms and safety interlocks.
- **Footprint:** The integrated system must fit within the existing laboratory space and adhere to the dimensions specified in the latest CAD model.
- **Modularity:** System components and software modules should be designed for high modularity to allow for independent development, testing, and future upgrades or replacements without requiring major system redesigns.
- **Maintainability:** The system should be designed for ease of maintenance, troubleshooting, and calibration. This includes clear labeling, accessible components, and comprehensive documentation.
- **Data Integrity:** All experimental data, recipe parameters, and system logs must be stored reliably and be easily retrievable.
- **Software Language:** Primary control software to be developed in [TO BE SPECIFIED: Preferred programming language, e.g., Python, C++].
- **CAD Software:** All mechanical designs to be created using SolidWorks and Fusion 360, and FEA and other checks will be done on custom components before final hand-off.

2.6 Use Cases

2.6.1 Use Case: Automated Perovskite Precursor Deposition

Actor: Laboratory Researcher

Preconditions:
- System is powered on and initialized.
- Robot arm is homed.
- Spin coater chuck is clean and ready.
- Pipette tips are loaded in the tip rack.
- Precursor solution is in a designated well plate.
- Substrates are loaded in a substrate holder accessible by the robot.

Flow of Events:
1. Researcher selects "Perovskite Precursor Deposition (example)" recipe from the UI.
2. System verifies all preconditions.
3. Robot arm picks up a fresh substrate from the holder using the custom gripper.
4. Robot arm transfers the substrate to the spin coater chuck and places it securely.
5. Spin coater program "Precursor_Spin" is initiated by the central control system.
6. While spin coater is ramping up, robot arm moves to the pipette tip rack.
7. Robot arm picks up a pipette tip.
8. Robot arm moves the Hamilton pipette to the precursor solution well plate.
9. Hamilton pipette aspirates [TO BE SPECIFIED: Volume] of precursor solution using LLD.
10. Robot arm moves the Hamilton pipette over the center of the spinning substrate.
11. Hamilton pipette dispenses the precursor solution onto the substrate.
12. Spin coater completes its program (including ramp-down and dwell times).
13. Another fluid is dispensed.
14. Hamilton pipette moves to the waste bin and ejects the used tip.
15. Robot arm picks up the coated substrate from the spin coater.
16. Robot arm transfers the coated substrate to a designated drying rack.
17. System logs successful completion and relevant parameters.

Postconditions:
- Substrate is coated and transferred to the drying rack.
- System is ready for the next operation.

Possible Error Conditions:
- Substrate drop during transfer -¿ Robot stops, alerts user, logs error.
- Liquid level too low in well plate -¿ Pipette stops, alerts user, logs error.
- Spin coater motor fault -¿ Spin coater stops, alerts user, logs error.
- Communication loss with any module -¿ System pauses, attempts re-establishment, alerts user.

3 Functional Requirements

This section details the functional requirements for each major component of the DILBOT system.

3.1 Robot Arm (Mitsubishi Electric RH-6CH-Sxx)

FR-RA-001 Communication Establishment: The system shall be able to establish and maintain a persistent communication link with the Mitsubishi Electric Robot Arm controller via Ethernet (TCP/IP).

- **Sub-FR-RA-001.1:** The system shall support automatic reconnection attempts in case of communication loss.
- **Sub-FR-RA-001.2:** The system shall provide a clear indication of the robot arm's connection status on the UI.

FR-RA-002 Precise Movement Control: The system shall be able to send commands to the robot arm for precise movement to specified X, Y, Z coordinates (position) and A, B, C angles (orientation) in Cartesian space.

- **Sub-FR-RA-002.1:** The system shall allow specification of movement speed and acceleration for each motion command.
- **Sub-FR-RA-002.2:** The system shall support linear and interpolated movements between points.

FR-RA-003 Joint and Cartesian Control: The system shall support both joint-space movements and Cartesian-space movements.

FR-RA-004 Status Feedback: The system shall be able to continuously read and display the current TCP position (X, Y, Z, A, B, C) and the robot's configuration flag.

FR-RA-005 Collision Avoidance: The system shall implement a software-based collision avoidance logic using the loaded CAD model of the workspace.

- **Sub-FR-RA-005.1:** The system shall allow definition of exclusion zones and keep-out areas.
- **Sub-FR-RA-005.2:** The system shall provide a warning or halt movement if a potential collision is detected.

FR-RA-006 Teach-in Functionality: The system shall allow users to manually jog the robot arm to desired positions and save them as named waypoints.

- **Sub-FR-RA-006.1:** Teach-in shall be possible via a joystick or software controls on the UI.
- **Sub-FR-RA-006.2:** Saved waypoints shall include position, orientation, and configuration flags.

FR-RA-007 Tool Management: The system shall support defining and switching between multiple tools by updating the robot's TCP offset.

3.1.1 Robot Arm - Installation and Operation

Installation Guide

[PLACEHOLDER: This section will contain detailed instructions for the physical and electrical installation of the Mitsubishi RH-6CH-Sxx robot arm. This includes mounting specifications, controller connections, power requirements, and network configuration for TCP/IP communication.]

Using RT Toolbox3

Install the RT Toolbox3 from the official website of Mitsubishi

Standard Operating Procedure (SOP)

This SOP outlines the routine procedures for operating the robot arm within the DILBOT system.

1. **System Startup:**
    - *[PLACEHOLDER: Step-by-step instructions on the correct power-up sequence for the robot arm controller and enabling servo power.]*
    - *[PLACEHOLDER: How to launch the DILBOT control software and establish a connection with the arm.]*
2. **Homing Procedure:**
    - *[PLACEHOLDER: Instructions for executing the robot's homing sequence, ensuring it starts from a known, calibrated position. Describe both automated homing from the UI and manual procedures if necessary.]*
3. **Manual Operation (Jogging):**
    - *[PLACEHOLDER: Guide on using the UI's teach-in/jogging controls. Detail how to switch between joint, Cartesian, and tool coordinate systems. Explain speed controls and safety precautions during manual movement.]*
4. **Defining and Saving Waypoints:**
    - *[PLACEHOLDER: How to move the robot to a specific location (e.g., above the spin coater) and save its coordinates and orientation as a named waypoint within the DILBOT software for use in recipes.]*
5. **System Shutdown:**
    - *[PLACEHOLDER: The correct sequence for parking the robot, disabling servo power, and shutting down the controller and software.]*

3.2 Spin Coater (SCS G4 Spin Coater Series)

FR-SC-001 Communication Establishment: The system shall be able to establish and maintain communication with the SCS G4 Spin Coater.

- **Sub-FR-SC-001.1:** [TO BE SPECIFIED: Determine exact communication interface (e.g., RS-232, USB, Ethernet) and protocol].
- **Sub-FR-SC-001.2:** The system shall provide a clear indication of the spin coater's connection status on the UI.

FR-SC-002 Program Execution: The system shall be able to program and execute spin coating cycles consisting of up to 20 steps.

FR-SC-003 Step Parameter Definition: For each step, the system shall allow programmatic definition of: Rotational speed, Ramp time, and Dwell time.

FR-SC-004 Cycle Control: The system shall be able to initiate, pause, resume, and terminate a spin coating cycle programmatically.

FR-SC-005 Status Query: The system shall be able to query the current operational status of the spin coater.

FR-SC-006 Program Storage: The system shall be able to store and recall up to 30 spin coating programs.

3.3 Pipetting Module (Hamilton ZEUS X1)

FR-HP-001 Communication Establishment: The system shall be able to establish and maintain communication via USB/Serial connection.

FR-HP-002 Liquid Handling Commands: The system shall be able to send commands for aspiration, dispensing, and mixing cycles.

FR-HP-003 Volume Control: The system shall support precise volume control with a minimum increment of [TO BE SPECIFIED: e.g., 0.1 µL].

FR-HP-004 Liquid Level Detection (LLD): The system shall integrate and utilize the LLD functionality.

FR-HP-005 Tip Management: The system shall be able to control picking up new tips and ejecting used tips.

FR-HP-006 Deck Geometry Configuration: The system shall allow programmatic configuration of the Hamilton module's deck geometry.

FR-HP-007 Status and Error Reporting: The system shall be able to query the current status and receive specific error codes.

3.4 Custom Gripper

FR-GR-001 Substrate Grasping: The gripper shall be able to securely grasp and release various substrate sizes.

- **Sub-FR-GR-001.1:** Accommodate substrate sizes from [TO BE SPECIFIED: Min size] mm to [TO BE SPECIFIED: Max size] mm.
- **Sub-FR-GR-001.2:** Minimize contact area with the active surface of the substrate.

FR-GR-002 Controlled Gripping Force: The gripper shall have a controlled and adjustable gripping force.

- **Sub-FR-GR-002.1:** The gripping force shall be adjustable via the central control system.
- **Sub-FR-GR-002.2:** The gripper shall maintain a set gripping force within a tolerance of [TO BE SPECIFIED: e.g., ±5%].

FR-GR-003 Feedback Mechanisms: The gripper shall provide feedback on its current state (Open/Closed, force, grasp success).

FR-GR-004 Physical Compatibility: The gripper shall be lightweight ([TO BE SPECIFIED: Max weight, e.g., ¡ 500g]) and compatible with the robot arm's payload capacity.

FR-GR-005 Control Interface: The gripper's control electronics shall interface seamlessly with the central control system.

- **Sub-FR-GR-005.1:** The interface shall be [TO BE SPECIFIED: e.g., Digital I/O, Analog I/O, Serial (UART/SPI/I2C)].

FR-GR-006 Iterative Design: The gripper design process shall support multiple iterations based on testing and feedback.

3.4.1 Custom Gripper - Installation and Operation

Installation Guide

[PLACEHOLDER: This section will provide detailed instructions for mounting the custom gripper onto the robot arm's flange. It will include a mechanical assembly guide with diagrams, a bill of materials (BOM), and an electrical wiring diagram showing how to connect it to the control box or robot controller I/O.]

Standard Operating Procedure (SOP)

This SOP describes the routine use of the custom gripper.

1. **Tool Center Point (TCP) Calibration:**
    - *[PLACEHOLDER: Step-by-step guide on how to perform a TCP calibration for the gripper. This is critical for accurate positioning. This will involve defining the TCP relative to the robot's flange using a 4-point or 6-point method via the DILBOT UI.]*

2. **Gripping Operation:**
   - *[PLACEHOLDER: Instructions on how to use the 'Open Gripper' and 'Close Gripper' commands from the UI or within a recipe. Detail how to set parameters like gripping force and speed.]*
3. **Maintenance and Cleaning:**
   - *[PLACEHOLDER: Guidelines for regular inspection, cleaning of gripper fingers to prevent contamination, and checking for mechanical wear.]*

3.5 System Integration & Recipe Management

FR-SI-001 Centralized Control: The system shall provide a single, centralized control application.

FR-SI-002 Recipe Creation & Management: The system shall allow users to create, edit, save, load, and delete custom recipes.

FR-SI-003 Recipe Definition: Recipes shall be defined as a sequence of discrete operations. Examples:

```
    Robot.MoveTo(Waypoint_Name)
    Robot.PickUp(Substrate_Type, Source_Location)
    SpinCoater.RunProgram(Program_ID)
    Pipette.Aspirate(Volume, Source_Well_ID)
    Gripper.Close(Force_Level)

```

FR-SI-004 Conditional Logic: The system shall support conditional logic within recipes.

FR-SI-005 Real-time Status: The system shall provide real-time status updates.

FR-SI-006 Data Logging: The system shall automatically log all executed actions to persistent storage.

FR-SI-007 Error Handling & Recovery: The system shall implement robust error handling mechanisms.

FR-SI-008 Calibration Routines: The system shall include software routines to assist with calibration of robot arm waypoints.

3.6 User Interface (UI)

FR-UI-001 Intuitive Recipe Editor: The UI shall provide a graphical recipe editor.

FR-UI-002 System Status Display: The UI shall display the current status of each module.

FR-UI-003 Visual Feedback: The UI shall provide visual feedback on robot position, gripper state, etc.

FR-UI-004 Emergency Stop Access: A prominent software emergency stop button shall be present on the UI.

FR-UI-005 Manual Control: The UI shall allow for manual control of individual modules.

FR-UI-006 Log Viewer: The UI shall include a dedicated section for viewing system logs.

FR-UI-007 User Authentication: The UI shall implement a basic user authentication system.

4 Non-Functional Requirements

4.1 Performance Requirements

NFR-PER-001 Robot Arm Positional Accuracy: ±0.1 mm and angular accuracy of ±0.1°.

NFR-PER-002 Spin Coater Speed Tolerance: ±1 RPM tolerance.

NFR-PER-003 Pipetting Volume Accuracy: ±1% for volumes > [10 µL], and ± [Absolute error] for smaller volumes.

NFR-PER-004 Recipe Execution Time: Execute typical recipe within 15 minutes.

NFR-PER-005 Communication Latency: Shall not exceed 100 ms for critical cycles.

NFR-PER-006 Throughput: Capable of processing [Number] substrates per hour.

4.2 Safety Requirements

NFR-SAF-001 Physical Emergency Stop: At least one physical E-stop button.

NFR-SAF-002 Software Safety Interlocks: Prevent robot movement into exclusion zones, conflicting operations, etc.

NFR-SAF-003 Physical Guarding: All moving parts shall be physically guarded.

NFR-SAF-004 Visual Status Indicators: Clear visual indicators for system status.

NFR-SAF-005 Error State Handling: System shall transition to a safe, halted state on critical error.

NFR-SAF-006 Chemical Safety: System design shall consider compatibility with chemicals used.

4.3 Reliability Requirements

NFR-REL-001 Continuous Operation: At least 8 hours without manual intervention.

NFR-REL-002 Mean Time Between Failures (MTBF): At least 200 hours.

NFR-REL-003 Communication Robustness: Gracefully handle temporary communication loss.

NFR-REL-004 Recipe Repeatability: Execute the same recipe 100 times consecutively without system failure.

4.4 Maintainability Requirements

NFR-MNT-001 Modular Software Design: Highly modular software with well-defined APIs.

NFR-MNT-002 Component Accessibility: Custom hardware designed for easy assembly/disassembly.

NFR-MNT-003 Diagnostic Tools: Provide built-in diagnostic tools and detailed logs.

NFR-MNT-004 Calibration Procedures: Comprehensive and clear documentation shall be provided.

NFR-MNT-005 Software Updates: Support easy software updates and patches.

4.5 Usability Requirements

NFR-US-001 Recipe Creation Time: A new user can create a basic recipe within 30 minutes after 1-hour training.

NFR-US-002 Clear Error Messages: Error messages shall be clear, concise, and provide actionable information.

NFR-US-003 Feedback Consistency: Provide consistent visual and auditory feedback.

NFR-US-004 Intuitive Navigation: The UI navigation shall be intuitive.

NFR-US-005 Language Support: The UI shall primarily be in English.

4.6 Security Requirements

NFR-SEC-001 Access Control: Access protected by a multi-level user authentication system.

NFR-SEC-002 Software Updates: Third-party libraries shall be regularly updated.

NFR-SEC-003 Network Security: Network interfaces shall be configured to minimize exposure.

NFR-SEC-004 Data Protection: All logged data and recipes shall be stored securely.

5 System Architecture (High-Level)

5.1 Software Architecture

The software will follow a modular, layered architecture to ensure maintainability, scalability, and reusability.

Layer 1: Hardware Abstraction Layer (HAL)
- **Purpose:** Provides a standardized interface to interact with each specific hardware module.
- **Components:** Robot Driver, Spin Coater Driver, Hamilton Pipette Driver, Gripper Driver.

Layer 2: Module Control Layer
- **Purpose:** Exposes high-level, human-readable control functions for each module.
- **Components:** `RobotController`, `SpinCoaterController`, `PipetteController`, `GripperController`.

Layer 3: Recipe Execution Engine
- **Purpose:** Interprets and executes user-defined recipes.
- **Components:** Recipe Parser, Sequence Manager, State Machine.

Layer 4: User Interface (UI) / HMI
- **Purpose:** Provides the graphical interface for user interaction.
- **Components:** Recipe Editor, System Status Dashboard, Manual Control Panel, Log Viewer.

Cross-Cutting Concerns
- **Data Logging System:** Centralized service for recording all system events.
- **Error Management System:** Centralized system for detecting and responding to errors.
- **Configuration Management:** Stores and manages system-wide settings.

5.2 Hardware Architecture

The hardware architecture consists of a central control unit connected to various laboratory automation modules.

Central Control PC

Robot Arm: Mitsubishi Electric RH-6CH-Sxx

Spin Coater: SCS G4 Spin Coater Series

Pipetting Module: Hamilton ZEUS X1

Custom Gripper

Safety System

Complementary Attachments & Labware

Power Distribution Unit

6 Verification Requirements

VR-001 Functional Requirements Verification: All functional requirements (Section 3) shall be verified through a combination of Unit Testing, Integration Testing, System-Level Testing, and Test Cases.

VR-002 Performance Requirements Verification: Verified through Quantitative Measurements, Repeated Trials, and Benchmarking.

VR-003 Safety Requirements Verification: Verified through Safety Audits, Failure Mode and Effects Analysis (FMEA), Simulated Faults, and Emergency Stop Activation Tests.

VR-004 Reliability Requirements Verification: Verified through Endurance Testing, Stress Testing, and Error Log Analysis.

VR-005 Maintainability Requirements Verification: Verified through Code Reviews, Maintenance Drills, and Documentation Review.

VR-006 Usability Requirements Verification: Verified through User Acceptance Testing (UAT), Time-on-Task Measurements, and User Feedback Surveys.

VR-007 Security Requirements Verification: Verified through Access Control Testing and Vulnerability Scanning.

A Appendices

A.1 Appendix A: Detailed Communication Protocols

[PLACEHOLDER: This appendix will contain a comprehensive document outlining the specific commands, data formats, and expected responses for each integrated device (Mitsubishi Robot, SCS Spin Coater, Hamilton Pipette, Custom Gripper). It will include examples of command sequences and data parsing logic.]

A.2 Appendix B: CAD Drawings and Mechanical Schematics

[PLACEHOLDER: This appendix will contain detailed 2D and 3D CAD drawings of the integrated system layout, mechanical schematics for the custom gripper (including BOM and assembly instructions), and drawings for all complementary attachments.]

A.3 Appendix C: Electrical Schematics

[PLACEHOLDER: This appendix will provide detailed electrical schematics for the custom gripper's control board and wiring diagrams for power distribution and inter-module connections.]

A.4 Appendix D: Test Plans

[PLACEHOLDER: This appendix will house specific test plans for unit, integration, system, safety, and performance testing. It will include detailed test cases, expected results, and criteria for success for each verification requirement.]

A.5 Appendix E: Glossary

[PLACEHOLDER: This appendix will contain an expanded list of terms and definitions specific to the DILBOT project, beyond the abbreviations listed in the introduction.]

[Placeholder for Hardware Architecture Diagram]

Figure 1: High-level diagram of the DILBOT hardware components.

[Placeholder for System Layout CAD Drawing]

Figure 2: Example CAD drawing of the integrated system.