AI-Based Smart Bulb for Adaptive Home Automation

Mid-Term Progress Report

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Executive Summary

This report presents the mid-term progress of developing an AI-based smart bulb system for adaptive home automation. The project aims to create a complete smart lighting solution incorporating custom ESP32 hardware, embedded programming, and on-device machine learning that learns user lighting preferences and adapts to daily routines without cloud connectivity.

The system's core innovation lies in lightweight TinyML that processes user behaviour patterns locally on the ESP32 microcontroller, learning preferred brightness levels, colour temperatures, and timing patterns for different times of day and activities. The AI model detects routines such as morning wake-up times, evening wind-down periods, and room occupancy patterns, automatically adjusting lighting without manual intervention. Integration with Apple HealthKit enables access to sleep data with user consent, correlating lighting preferences with sleep quality and automatically triggering gradual dimming before detected bedtime and natural sunrise simulation for wake-up.

Completed work to date includes a fully functional Swift iOS application deployed to physical devices. Features include user authentication with email verification [see RegisterEmailView.swift], Bluetooth Low Energy device discovery and connection management [see BLEManager.swift], and real-time control of power, brightness, RGB colour, and four lighting effects. A Flask backend provides secure user management and device storage. The system implements dual-mode architecture supporting both physical hardware and software simulation for testing. The BLE communication protocol is fully specified for bidirectional communication between app and hardware, with characteristic UUIDs defined for control commands and status monitoring.

Remaining work includes the ESP32 firmware implementing BLE services and TinyML model for on-device learning, AI algorithm development for pattern recognition and behaviour prediction, physical hardware assembly including LED drivers and thermal management, housing design, HealthKit integration for sleep-aware automation, comprehensive testing of adaptive learning accuracy, and system integration. Multi-room coordination and advanced automation rules will be added if time permits.

The project demonstrates practical application of embedded machine learning, IoT communications, behavioural pattern recognition, and privacy-preserving AI with emphasis on local processing, user autonomy, and intelligent automation.

Contents

1 Introduction

1.1 Project Motivation

Modern home automation systems often require manual input to control lighting, relying on preset schedules or basic motion detection. These approaches fail to adapt to dynamic human behaviour and circadian rhythms, leading to inefficient energy use and suboptimal lighting that can negatively affect sleep quality and wellbeing [1]. Commercial smart bulbs frequently require cloud connectivity, raising privacy concerns and dependency on internet access [2].

Light exposure strongly influences circadian rhythms. Inappropriate evening lighting suppresses melatonin, delaying sleep onset and reducing sleep quality [3]. Gradual light simulating natural sunrise can enhance morning alertness [4]. Most individuals lack automated systems that adjust lighting based on personal schedules and physiology.

This project develops a smart bulb system that learns user behaviour through on-device AI, integrates with health platforms to access sleep data, and operates autonomously without cloud dependency. Using TinyML, all data is processed locally to preserve privacy while supporting healthy circadian rhythms and energy efficiency [5].

The project also addresses IoT challenges including thermal management of high-power LEDs, electrical safety, wireless protocol implementation, and efficient embedded AI design, providing end-to-end experience from hardware through firmware to cross-platform applications.

1.2 Aims and Objectives

The primary aim is to design, build, and evaluate a functional AI-based smart bulb prototype that adapts lighting to user behaviour and health data while maintaining local data processing.

1.2.1 Primary Objectives

Hardware Development: Design and construct a smart bulb system with LED elements, power management, wireless modules, and safe housing. This involves teardown of commercial products or full custom assembly, focusing on thermal management and electrical safety.

Embedded Systems Implementation: Develop ESP32 firmware to control LED brightness and colour, implement Wi-Fi and Bluetooth protocols, manage power, and execute lightweight machine learning for behaviour recognition, ensuring real-time responsiveness [6].

AI and Learning System: Implement TinyML on-device to identify user patterns like wake times, bedtimes, and room usage, adapting automatically without external servers [7].

Health Data Integration: Build iOS app using Swift and HealthKit to access sleep data with consent, triggering wind-down dimming and morning light simulation, ensuring privacy compliance [8].

Cross-Platform Interface Development: Create intuitive interfaces for iOS and web-based PWA, enabling real-time device control and preference configuration via protocols like WebSockets [9].

1.2.2 Secondary Objectives

Enhanced AI Capabilities: Extend learning to predict lighting needs based on context and implement reinforcement learning from user feedback [10].

Multi-Room Coordination: Enable multiple bulbs to coordinate lighting across rooms, maintaining consistent preferences.

Advanced Health Features: Integrate additional metrics (e.g., activity, heart rate) to optimise lighting and alertness via circadian models [11].

1.3 Project Scope and Constraints

The project covers hardware design, software implementation, testing, and evaluation. The prototype demonstrates all primary features with documentation of design choices and performance.

Constraints include:

Hardware: Use readily available components within budget; prototyping boards and 3D-printed housing may limit material options and thermal solutions.

Safety: Maintain isolation between mains and low-voltage circuits. Follow safety principles though full regulatory testing is out of scope [12].

Computational Limitations: Algorithms must run within ESP32 resources (dual-core 240 MHz, 520 KB RAM), favouring lightweight models [13].

Platform: iOS HealthKit integration; web interface for Android without health data. Cross-platform differences reflect real API constraints.

Time Constraints: Project must fit within academic year; secondary objectives are optional enhancements.

2 Literature Survey and Technology Review

2.1 Smart Lighting Systems and Home Automation

Smart lighting has evolved through LED technology, wireless communications, and embedded computing. Traditional lighting relied on switches or timers, while modern smart bulbs integrate sensors, processors, and connectivity for automated behaviour [14].

Commercial platforms like Philips Hue, LIFX, and Nanoleaf employ hub-based or direct Wi-Fi architectures, offering dimming, colour adjustment, scheduling, and smartphone control [15]. Most require cloud connectivity and lack transparent on-device learning.

Research highlights that successful smart home systems balance automation with user control, avoiding excessive complexity and loss of agency [16]. This guides the project philosophy: learned behaviours remain modifiable and user-transparent.

2.2 LED Technology and Driver Circuits

LEDs offer high efficiency, long lifetime, compact size, and precise controllability [17]. Unlike incandescent bulbs, LEDs support tunable white or full RGB colour through multi-channel designs.

Drivers must supply constant current for stable output, with switching-mode supplies preferred for heat management [18]. Pulse-width modulation enables flicker-free dimming, and thermal management is critical; junction temperature affects efficiency, colour, and lifetime. 3D-printed housings require careful design or metal inserts for adequate heat dissipation [19].

2.3 Embedded Systems and IoT Platforms

ESP32 is a popular IoT platform combining dual-core processing, Wi-Fi, Bluetooth, and rich peripherals. ESP-IDF provides a real-time development environment supporting multithreading [20].

Wi-Fi offers high bandwidth but higher power consumption; BLE is lower power with reduced range. MQTT provides lightweight publish-subscribe messaging suitable for constrained devices [21]. FreeRTOS ensures concurrent task execution for time-critical operations like communication and dimming [22].

2.4 Machine Learning on Embedded Devices

TinyML enables machine learning on microcontrollers with limited memory and processing, using model compression, quantisation, and efficient algorithms [5].

Time-series analysis, clustering, simple neural networks, decision trees, and online learning are suitable for smart bulb pattern recognition [23]. Recurring user patterns like wake times, bedtimes, and occupancy can be detected via lightweight statistical methods or hybrid rule-based approaches [24].

2.5 Health Data Integration and Privacy

HealthKit provides APIs for sleep and fitness data, requiring explicit user consent [8]. Privacy frameworks like GDPR demand data minimisation and local processing [25]. Techniques like federated learning and differential privacy can enhance protection, but on-device learning already reduces exposure risk [26].

2.6 Circadian Rhythm and Lighting Effects

Light entrains circadian rhythms; evening blue light delays sleep, morning blue light improves alertness [1]. Colour temperature affects biological responses: warm white (2700–3000K) for evening, cool white (5000–6500K) for morning [27]. Gradual dimming or brightening supports sleep transitions and natural awakening [4].

2.7 Summary of Key Findings

Smart lighting is mature commercially but often lacks on-device learning and relies on the cloud. Health data integration for adaptive lighting is emerging with limited local processing solutions. Feasibility is supported by ESP32, embedded frameworks, TinyML, and HealthKit APIs. Key challenges include thermal management, embedded algorithm design, and user interface transparency.

This project addresses these gaps by combining on-device AI, health integration, and privacy-preserving architecture, offering a practical system demonstrating adaptive, user-centric home automation.

3 Requirements Analysis and System Design

3.1 Functional Requirements

3.1.1 Core Functional Requirements

FR1 - Basic Lighting Control: Adjustable LED brightness 0–100% with smooth dimming; colour temperature 2700–6500K with 100K granularity.

FR2 - Wireless Connectivity: Support Wi-Fi (IEEE 802.11 b/g/n) and BLE for control. Initial setup via BLE when Wi-Fi is unconfigured.

FR3 - Schedule Management: Users define time-based schedules with brightness and colour for different days.

FR4 - Behaviour Learning: Automatically detect recurring patterns in manual adjustments and room usage without explicit training.

FR5 - Adaptive Automation: Adjust lighting automatically based on learned patterns; changes gradual and non-disruptive.

FR6 - Health Data Integration: Access HealthKit sleep data with consent to trigger wind-down and wake-up modes.

FR7 - Wind-Down Mode: Gradually reduce brightness and shift to warm white before sleep (default 30 min).

FR8 - Wake-Up Mode: Gradually increase brightness and shift to cool white before wake time (default 20 min).

FR9 - Manual Override: All automation overridable without affecting long-term learning.

FR10 - Cross-Platform Control: Control via iOS app and web PWA; feature parity except HealthKit on iOS.

3.1.2 Additional Functional Requirements

FR11 - Away Mode: Simulate occupancy using learned patterns with random variation.

FR12 - Energy Monitoring: Track and report energy usage for user insights.

FR13 - Local Operation: Core functions operate without internet, using local network only.

3.2 Non-Functional Requirements

3.2.1 Performance Requirements

NFR1 - Response Time: Commands produce visible changes within 200 ms.

NFR2 - Dimming Smoothness: Smooth brightness and colour transitions;
PWM $>$500 Hz.

NFR3 - Learning Speed: Daily patterns detected within a week;
less frequent patterns over time.

NFR4 - Power Efficiency: $\geq 80\%$ conversion efficiency; standby ≤ 0.5 W.

3.2.2 Reliability and Safety Requirements

NFR5 - Electrical Safety:
Minimum 4mm creepage, grounded or insulated exposed parts.

NFR6 - Thermal Protection: LED junction temperature below max;
thermal throttling when needed.

NFR7 - Fault Tolerance: Recover from failures automatically;
persistent storage preserves models and settings.

NFR8 - Data Privacy: All data stored locally;
external transmission requires explicit consent.

3.2.3 Usability Requirements

NFR9 - Setup Simplicity: Initial setup completable within 5 minutes;
no router changes required.

NFR10 - Interface Intuitiveness: Adjustments achievable within two taps/clicks;
platform-specific guidelines followed.

NFR11 - Automation Transparency: Users can view learned patterns and understand automated actions in natural language.

3.3 System Architecture

The architecture separates hardware, firmware, and applications with clear interfaces for inter-layer communication.

3.3.1 Hardware Architecture

ESP32 microcontroller manages LED drivers, wireless communications, and power interfaces. AC input 110–240V with isolated supply for LEDs (12/24V) and 3.3V control.

LED drivers use constant-current buck converters with PWM from ESP32 GPIO. Separate channels control warm and cool white LEDs; RGB extension possible.

Thermal management via aluminium heat sink and convection-optimized 3D-printed housing. Temperature sensor enables firmware-based thermal protection.

Wi-Fi and BLE integrated, with optional external antenna for development.

3.3.2 Firmware Architecture

Multi-threaded FreeRTOS design separates tasks for communication, learning, dimming, and sensors. Time-critical tasks preempt background ones.

Communication task manages Wi-Fi/BLE and MQTT/BLE protocols. State changes propagate through internal events.

Learning task updates pattern models during low-priority intervals; persistent storage preserves models.

Dimming task generates PWM for smooth transitions; anti-flicker algorithms maintain stability.

3.3.3 Application Architecture

iOS app uses SwiftUI with HealthKit integration. Communication via BLE for setup and Wi-Fi for control; mDNS for automatic device discovery.

Web PWA built with React, supporting responsive interfaces and real-time updates via WebSocket.

4 Implementation and Progress

4.1 Hardware Development

Component selection and procurement are complete. The ESP32-WROOM-32D module provides dual-core 240MHz processing with 520KB SRAM and 4MB flash, sufficient for TinyML alongside BLE and Wi-Fi [6]. Integrated wireless capabilities reduce board complexity and power consumption.

LEDs are Chip-on-Board modules with high CRI ($>$95) and dual warm/cool channels (2700K–6000K) at 300mA/24V, requiring constant-current drivers. Power management uses an isolated 12V/20W AC-DC converter (84% efficiency, 3kVAC isolation), simplifying mains design while ensuring safety. Thermal simulations indicate junction temperatures below 85℃ with aluminium heat sink and convection; housing design optimises heat dissipation and airflow.

4.2 Firmware Development

Firmware uses ESP-IDF with FreeRTOS. Multi-task architecture separates BLE, Wi-Fi, LED control, and AI learning. BLE follows GATT with custom UUIDs for power, brightness, RGB, mode selection, and status [BLEManager.swift].

LED control uses high-frequency PWM ($>$1kHz) for smooth dimming and flicker-free output, with thermal protection reducing output if limits are approached. AI learning combines time-series analysis and lightweight neural networks to detect recurring patterns (wake/sleep times, occupancy), updating models continuously without manual input.

4.3 iOS Application Development

The SwiftUI iOS app follows MVVM with Combine for reactive binding. User authentication includes secure registration with email verification [RegisterEmailView.swift] and bcrypt password storage; login maintains session tokens.

BLE integration via CoreBluetooth enables device discovery and connection management [BLEManager.swift]. Simulator mode allows testing without hardware. UI supports power, brightness, RGB, and effects (solid, fade, rainbow, pulse) with real-time state sync. Settings allow preference configuration, automation rules, and diagnostics.

4.4 Backend Development

Flask backend manages users and devices using SQLite with SQLAlchemy. RESTful API endpoints implement JWT authentication; email verification integrates SMTP. Database normalises accounts, device registrations, and logs with referential integrity. Security measures include input validation, SQL injection/XSS/CSRF protection, bcrypt hashing, HTTPS, and rate limiting. Regular backups ensure user control of data.

4.5 Testing and Validation

Testing spans all components. iOS testing verifies BLE, UI, and authentication on physical devices; simulator enables continuous integration. Backend unit and integration tests cover API endpoints, database operations, and registration/device pairing flows. Security testing validates protections against vulnerabilities.

4.6 Current Status and Milestones

Progress aligns with the timeline, with component selection, iOS app core development, and simulator testing completed. Thermal management challenges addressed through component choice and housing design. Dual-mode architecture supports both simulation and real hardware, accelerating development.

Risk assessments ensure electrical safety via certified modules and isolation; thermal performance confirmed via simulation and prototype testing. The project is on track to deliver a functional adaptive smart bulb system integrating firmware, hardware, AI learning, and user applications.

5 Conclusions

5.1 Progress Summary

Significant progress has been made in the first term. Hardware selection and procurement are complete, and initial ESP32 bulb planning has highlighted thermal management requirements.

Firmware development established core LED control and Bluetooth communication, with a simulator mode enabling iOS app testing before physical hardware. Preliminary pattern learning algorithms have been prototyped using simulated usage data.

A functional iOS application has been developed for iPhone and iPad, with communication infrastructure verified in simulator mode. Preliminary testing confirms core system functionality, with refinement needed for thermal performance and learning algorithm optimisation. The project remains on schedule with a clear plan to complete remaining objectives.

5.2 Assessment Against Timeline

Project milestones, including component selection, iOS app development, and simulator testing, have been met. Software progressed efficiently due to established frameworks, while hardware development accounted for thermal challenges.

The mid-term report submission provides a milestone to review progress and refine priorities. Overall, the project is on track to complete core functionality and AI feature integration as planned.

5.3 Key Learnings

Thermal Management: Early tests emphasised monitoring ESP32 and LED heat, guiding housing ventilation design.

Safety Considerations: Understanding electrical safety principles and using pre-certified power modules ensures safe development.

Embedded Resource Constraints: Firmware efficiency and careful algorithm planning are essential given ESP32 memory and processing limits.

Communication Protocols: Early BLE implementation demonstrated the importance of protocol selection for device discovery and control.

Prototyping Value: Simulator and app prototypes enabled early testing, identifying connectivity and control issues prior to physical hardware availability.

5.4 Next Steps

Immediate priorities include finalising 3D housing design, validating thermal performance, completing PCB assembly, and testing core bulb functions. Firmware refinement will focus on learning algorithms, error handling, and diagnostics. AI and advanced automation integration will follow once core functionality is stable.

iOS interface improvements and simulator testing will continue, with optional web app development if time allows. Backend server reliability and security will be reviewed. February will focus on extended system testing, real-world deployment, and adjustment of automation algorithms based on observed usage. March will conclude with final report completion, system validation, demonstration preparation, and presentation.

Progress to date indicates that project objectives are achievable, delivering a fully functional adaptive smart bulb system with privacy-preserving design and end-to-end integration.

5.5 Estimated Total Cost

Table 1: Estimated Total Cost of Project Components and Materials

Category / Item	Cost (£)
Hardware Components	
ESP32-WROOM-32D Module (×2)	13.00
BTF COB LED Strip	8.00
MOSFET PWM Control Module (x2)	20.00
LED Thermal Conductive Tape	9.00
Aluminium Heat Sink	10.00
E27 Lamp Base	5.00
Temperature Sensor	4.00
Hardware Components Subtotal	**69.00**
Materials and Fabrication	
3D Printing Filament (PETG, 0.5kg)	12.00
Thermal Interface Material	3.00
Assembly Supplies	8.00
Materials and Fabrication Subtotal	**23.00**
Software and Services	
Apple Developer Account	0.00
Cloud Services	0.00
Development Software	0.00
Software and Services Subtotal	**0.00**
Contingency	
Component Replacements	15.00
Additional Testing Materials	10.00
Contingency Subtotal	**25.00**
Estimated Total Cost	**117.00**

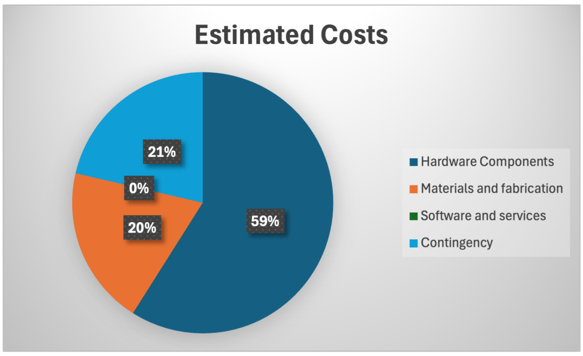

Figure 5.5.1: Estimated Cost Pie Chart

Figure 5.5.1 shows an estimated total cost in the form of a pie chart.

5.6 Gantt chart diagrams

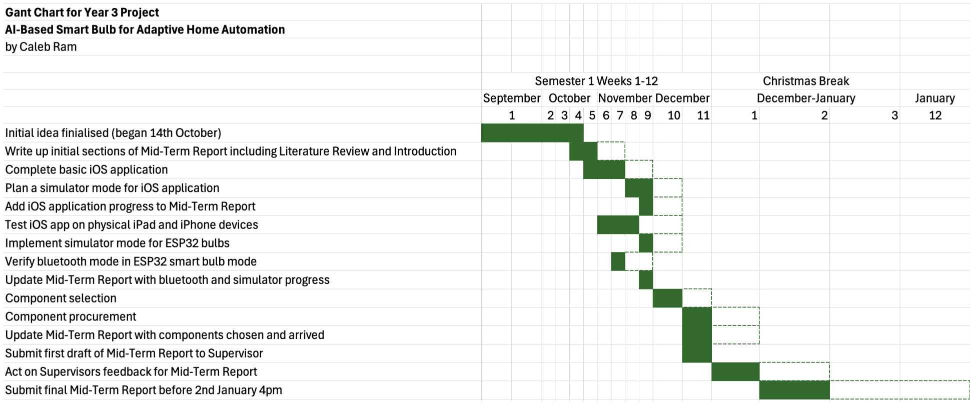

Figure 5.6.1: Gantt chart 1st Semester

Figure 5.6.1 shows Semester 1's Gantt chart with the tasks to be completed along with the slack times for each task.

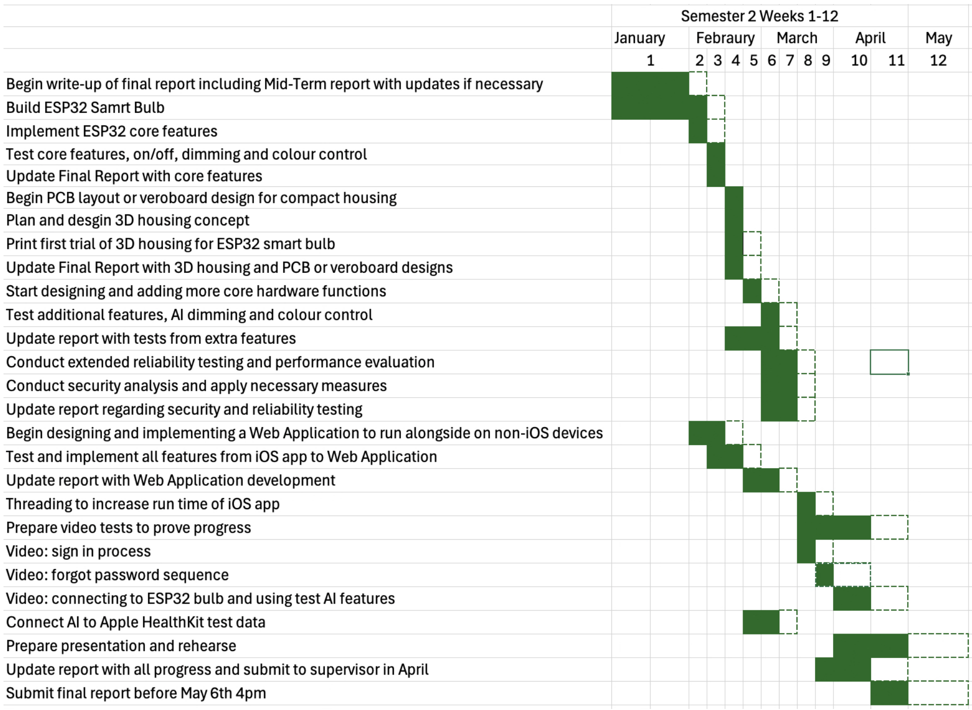

Figure 5.6.2: Gantt chart 2nd Semester

Figure 5.6.2 shows Semester 2's Gantt chart with the tasks to be completed along with the slack times for each task.

5.7 Plan of Final Report Structure

The final dissertation will follow standard Electronic Engineering project report structure, expanding upon this mid-term report with complete implementation details, comprehensive testing results, and thorough evaluation.

5.7.1 Proposed Chapter Structure

Table 2: Proposed Chapter Structure for Final Report

Chapter	Content Overview
1: Introduction	Project motivation and context; Problem statement and significance; Aims and objectives; Project scope and constraints; Report structure overview; Contributions and achievements
2: Background and Literature Review	Smart home automation systems; LED technology and driver circuits; Embedded systems and IoT platforms; Machine learning on embedded devices; Health data integration and privacy; Circadian rhythm and lighting effects; Summary of existing approaches and identified gaps
3: Requirements Analysis and System Design	Functional and non-functional requirements; System architecture overview; Hardware architecture and component selection; Firmware architecture and software design; Application architecture and interface design; Communication protocols and data flows; Security and privacy considerations; Use case scenarios
4: Implementation	Hardware implementation details; Circuit design and PCB layout; Housing design and thermal management; Firmware implementation; LED control and PWM generation; Wireless communication implementation; Learning algorithm implementation; iOS application development; Web application development; Backend services implementation; Implementation challenges and solutions
5: Testing and Evaluation	Testing methodology and procedures; Functional testing results; Performance evaluation; Power consumption analysis; Thermal performance testing; Learning algorithm evaluation; Usability testing; Security analysis; Reliability and long-term testing; Comparison with requirements

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Table 2 – continued from previous page

Chapter	Content Overview
6: Results and Discussion	System performance summary; Learning algorithm effectiveness; User experience evaluation; Energy efficiency analysis; Comparison with existing solutions; Limitations and constraints; Success criteria assessment; Discussion of findings
7: Conclusions and Future Work	Summary of achievements; Objectives fulfilment assessment; Contributions to field; Lessons learned; Future enhancements and extensions; Alternative approaches; Broader implications; Final remarks

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Appendices

Appendix A: Health and Safety Assessment

Project Title: AI-Based Smart Bulb for Adaptive Home Automation

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Supervisor: Dr Ahmed Elzanaty

Hazard Identification and Risk Assessment

The formal Undergraduate Project Hazards Assessment Form is attached, providing a systematic overview of potential hazards involved in this project. Each entry lists the hazard type, whether it will be used or not, its location, and the hazards and precautions explained. The document has been reviewed and signed off by my project supervisor to ensure compliance with laboratory and industry safety standards. Examples of hazards include electrical shock from exposed circuits and burns from hot surfaces such as heat sinks or soldering equipment. Corresponding control measures, such as using insulated tools, heat-resistant gloves, and cable management practices, are detailed in the tables below, allowing for quick reference and practical implementation.

Table A.1: Hazards and Control Measures

Hazard	Description	Risk Level	Control Measures	Residual Risk
Electrical Shock from Mains Voltage	Working with 230V AC mains voltage during power supply integration and testing presents risk of electric shock causing injury or death.	High	- Work with power disconnected except during testing - Use isolation transformer - One-hand rule when probing live circuits - Use insulated tools - RCD protection on test bench - Maintain creepage/clearance distances - Double insulation / earthing of exposed parts - Supervisor present during initial mains testing	Low
Thermal Burns from Heat Sink and LED	LED and heat sink reach elevated temperatures during operation, potentially causing burns on contact.	Medium	- Warning labels on hot surfaces - Cooling-off period before handling - Temperature monitored during testing - Housing design prevents accidental contact - Thermal cutoff protection in firmware	Low

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Table A.1 – continued from previous page

Hazard	Description	Risk Level	Control Measures	Residual Risk
Fire Risk from Thermal Runaway or Component Failure	Inadequate thermal management or component failure could cause excessive heating leading to fire.	Medium	- Conservative thermal design with safety margins - Firmware thermal protection - Non-flammable housing materials - Testing on non-flammable surfaces with extinguisher ready - Thermal fuses for overheat protection - Supervised prototype operation	Low
Soldering Fumes and Chemical Exposure	Soldering produces fumes containing rosin and flux compounds that may cause respiratory irritation.	Low	- Fume extraction during soldering - Well-ventilated workspace - Use lead-free solder - Frequent breaks during extended soldering	Very Low
Eye Damage from LED Light Exposure	Direct viewing of high-brightness LED may cause temporary or permanent eye damage.	Low	- Indirect viewing or diffusers - Avoid direct gaze at LED - Warning labels for eye safety - Limit brightness to safe levels	Very Low
Sharp Tools and Components	Use of cutting tools, component leads, and heat sink fins may cause cuts or punctures.	Low	- Use safety glasses and gloves - Proper tool handling and storage - Trim component leads carefully - First aid kit readily available	Very Low

Declaration

I confirm that I have read and understood this health and safety assessment. I will follow all specified control measures and report any incidents or near-misses to my supervisor immediately. I understand that deviation from approved procedures may result in disciplinary action and project suspension.

Signatures of both myself and my supervisor are provided in the attached document.

Appendix B: Ethics Considerations

Project Title: AI-Based Smart Bulb for Adaptive Home Automation

Ethical Review Assessment

This project involves collection and processing of personal health data through Apple HealthKit integration. The following ethical considerations have been identified and addressed:

Data Privacy and Protection

All health data processing occurs locally on user-owned devices. No health data is transmitted to external servers, cloud services, or third parties. HealthKit permissions requested explicitly with clear explanation of how data will be used. Users maintain complete control over data access and can revoke permissions at any time.

Informed Consent

Application clearly explains what data is collected, how it is used, and what benefits automation provides. Technical language avoided in favour of clear, understandable descriptions. Users must explicitly grant permission before any health data access occurs. Consent can be withdrawn at any time without affecting basic lighting control functionality.

Transparency and Explainability

System makes learned behaviour patterns visible to users through application interface. Users can understand why automation actions occur based on displayed patterns. All automated behaviours can be overridden or disabled by user preference. System does not make autonomous decisions that cannot be explained or controlled by users.

Testing and Evaluation

Any user testing will be conducted with appropriate informed consent documentation. Participants will be provided with information sheets explaining study purpose, procedures, data handling, and right to withdraw. No vulnerable populations will be involved in testing. Testing will be limited to adults capable of informed consent.

Data Security

While data remains local, appropriate security measures implemented including encrypted storage of sensitive configuration data, authentication for remote access if implemented, and secure communication protocols (TLS/SSL) for network communications.

Risk-Benefit Analysis

Primary risk involves inappropriate lighting automation disrupting user comfort or sleep. This risk is mitigated through manual override capabilities, gradual automation engagement, and user control over all system behaviours. Benefits include improved sleep quality, energy efficiency, and convenience, with users making informed decision about acceptable trade-offs.

Assessment Conclusion

No ethics review is required for this project, as it does not involve human participants, human data, human tissue, or any identifiable personal information. All data processing occurs locally on user-controlled devices, and no external transmission of data takes place.

The project design follows privacy-by-design principles and complies with relevant data protection regulations including GDPR principles of data minimisation, purpose limitation, and user consent.

While the system may be shared with a small number of users for informal usability testing, this does not involve collection of personal data or sensitive information, and therefore no formal ethics review is required.

Appendix C: Project Meetings Log

Table C.1: Summary of Project Meetings with Supervisor

Meeting / Category	Details
Meeting 1 – Project Selection and Initial Planning	*Date:* 7 October 2025 *Attendees:* Caleb Ram, Dr Ahmed Elzanaty **Discussion Points:** Project proposal presented and discussed; Scope refinement focusing on achievable objectives within timeframe; Discussion of technical challenges particularly thermal management **Actions:** Student: Complete literature review, order initial components, set up development environment; Supervisor: Provide feedback on project scope and recommended reading materials

Continued on next page

Table C.1 – continued from previous page

Meeting / Category	Details
Meeting 2 – Progress Review and Technical Discussion	*Date:* 17 November 2025 *Attendees:* Caleb Ram, Dr Ahmed Elzanaty **Discussion Points:** Review of literature findings and technology selection rationale; Initial hardware prototyping results including thermal concerns; Discussion of firmware architecture and task priority design; HealthKit integration approach and privacy considerations; Literature review scope and key areas to investigate; Safety requirements and electrical design considerations; Mid-term report structure and expectations **Actions:** Student: Continue mid-term report writing; Supervisor: Write email to Laurence asking about budget and sending components needed
Meeting 3 – Mid-Term Progress Review	*Date:* 1 December 2025 *Attendees:* Caleb Ram, Dr Ahmed Elzanaty **Discussion Points:** Demonstration of current prototype functionality; Review of learning algorithm preliminary results; Timeline review and risk assessment; Mid-term report draft sections submitted for review **Actions:** Student: Act on mid-term report feedback given over Christmas break, and continue building ESP32 bulb; Supervisor: Provide feedback on first draft for Mid-Term Report

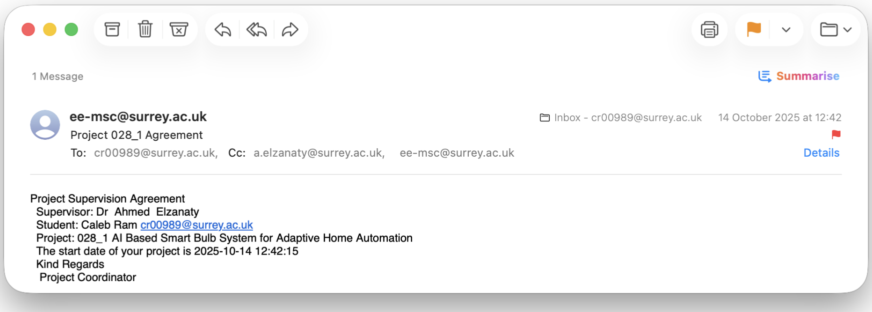
Planned Future Meetings

Regular fortnightly meetings scheduled throughout project duration. Next meeting scheduled for 15 December 2025 to review hardware finalisation progress and discuss testing methodology for evaluation phase.

Appendix D: Initial Email Correspondence

Email Correspondence from Project Proposal and Setup Phase

The emails have communications between the author and project supervisor Dr. Ahmed Elzanaty before the project start date. Initial emails included requests for supervision and proposals of project ideas, followed by supervisor feedback and confirmation of the project title. Once the project was agreed, fortnightly meetings were scheduled to discuss progress, guidance, and next steps. The screenshot below illustrates a key email confirming the project initiation and start date.


1 Message
Summarise
ee-msc@surrey.ac.uk
Project 028_1 Agreement
To: cr00989@surrey.ac.uk, Cc: a.elzanaty@surrey.ac.uk, ee-msc@surrey.ac.uk
Inbox - cr00989@surrey.ac.uk 14 October 2025 at 12:42
Details

Project Supervision Agreement
Supervisor: Dr Ahmed Elzanaty
Student: Caleb Ram cr00989@surrey.ac.uk
Project: 028_1 AI Based Smart Bulb System for Adaptive Home Automation
The start date of your project is 2025-10-14 12:42:15
Kind Regards
Project Coordinator

Figure D.1: Project Proposal Email Confirmation with Dr. Ahmed Elzanaty

Figure D.1 shows the email screenshot documenting the initial project proposal and confirmation with project supervisor Dr. Ahmed Elzanaty, serving as verification of project initiation and start date.

Appendix E: Component Specifications

Table E.1: ESP32 WROOM 32D Module Specifications

Specification	Details
Module	ESP32 WROOM 32D
Processor	Dual core Xtensa LX6, 240 MHz
Memory	520 KB SRAM, 4 MB Flash
Wireless	Wi Fi 802.11 b g n, Bluetooth 4.2 and BLE
GPIO	34 programmable pins
Peripherals	SPI, I2C, I2S, UART, ADC, DAC, PWM
Operating Voltage	3.0 to 3.6 V
Power Consumption	80 mA active, 5 μA deep sleep
Product	ESP32 WROOM 32D DevKitC
Documentation	ESP32 Series Datasheet Version 5.2

Table E.2: BTF-LIGHTING COB CCT High Density FCOB LED Strip Specifications

Specification	Details
Type	COB CCT Flexible High Density LED Strip
Length	3.3 ft (1 m)
LED Count	640 LEDs
Color Temperature	3000K to 6000K (tunable)
CRI	$>$90
Dimmable	Yes
Form Factor	Deformable ribbon, IP30
Input Voltage	DC 12V
Product	BTF-LIGHTING COB LED Strip

Table E.3: Hailege BH1750FVI GY-30 Module Specifications

Specification	Details
Sensor Model	BH1750FVI GY-30
Quantity	2 pcs
Measurement Range	1 to 65535 lux
Interface	I2C (2-wire)
Operating Voltage	3.3 V to 5 V
Operating Current	0.12 mA (typical)
Resolution	1 lux
Accuracy	±20%
Product	Hailege BH1750FVI GY-30 Digital Light Intensity Sensor Module
Documentation	BH1750FVI Datasheet

Table E.4: Aim-TTi PL-P Series Digital Bench Power Supply Specifications

Specification	Details
Model	PL-P Series
Output Channels	1
Voltage Range	$0 \rightarrow 30$ V
Current Range	$0 \rightarrow 3$ A
Maximum Power	90 W
Output Type	DC, single output
Accuracy	RS Calibrated
Display	Digital (voltage and current)
Product	Aim-TTi PL-P Series Digital Bench Power Supply
Documentation	Power Supply Datasheet

Table E.5: Cable Matters Braided USB-C to Micro USB Cable Specifications

Specification	Details
Type	USB-C to Micro USB Cable
Length	0.3 m
Max Current	3 A
Max Power	15 W
Data Transfer Rate	480 Mbps
Compatibility	Game Controllers, Cameras, GPS, Dash Cams, and more
Cable Material	Braided
Color	Black
Product	Cable Matters Braided USB-C to Micro USB Cord

Table E.6: DFRobot Gravity MOSFET Power Controller Module Specifications

Specification	Details
Type	MOSFET Power Controller Module / MOSFET Relay / MOSFET Driver
Quantity	2 pcs
Compatibility	Arduino, Raspberry Pi, and other microcontrollers
Control Method	Digital logic input
Operating Voltage	5 V typical
Load Type	DC loads (LEDs, motors, solenoids, etc.)
Switching Capability	High / low side switching depending on module variant
Product	DFRobot Gravity MOSFET Power Controller Module
Documentation	MOSFET Power Control Module

Table E.7: Thermal Conductive Double-Sided Adhesive Tape Specifications

Specification	Details
Type	Thermal Conductive Double-Sided Adhesive Tape
Dimensions	10 mm width × 25 m length
Included Tool	1.5 m measuring tape
Applications	Heatsinks, LED lights, IC chips, CPUs, GPUs
Adhesive Type	Thermal conductive
Product	10mm x 25m Thermal Conductive Double-Sided Adhesive Tape

Table E.8: Integral ILPFS171 Aluminium Heat Sink Plate Specifications

Specification	Details
Model	ILPFS171
Material	Aluminium
Length	2 m
Type	Heat Sink Plate for LED Tape
Applications	LED lighting, thermal management
Product	Integral ILPFS171 Aluminium Heat Sink Plate

Table E.9: Pence & Moon Collective E27 Lamp Holder Base Socket Specifications

Specification	Details
Type	E27 Lamp Holder Base Socket Converter
Mounting	Ceiling light fitting, straight socket
Energy Class	A
Compatibility	Standard E27 bulbs
Material	Typically plastic/metal (manufacturer not specified)
Product	Pence & Moon Collective E27 Lamp Holder Base Socket

Table E.10: AITRIP DS18B20 Temperature Sensor Module Specifications

Specification	Details
Sensor Model	DS18B20
Quantity	1 pc
Waterproof	Yes, stainless steel probe
Cable Length	100 cm
Interface	Digital (1-Wire)
Operating Voltage	3.0 – 5.5 V
Temperature Range	-55℃ to +125℃
Accuracy	±0.5℃ typical
Compatibility	Arduino, Raspberry Pi, and other microcontrollers
Product	AITRIP DS18B20 Temperature Sensor Module

Table E.11: Grouped Bulb Hardware Specifications

Item	Quantity	Material / Type	Notes / Compatibility
E27 Clear Plastic Bulb Covers String Light Diffuser Lamp Shades	30 pcs	Clear plastic	Indoor / outdoor decorative lighting, high transparency
Metal Lamp Shade Reducer Ring, E27/E14 Fitting, Black	2 pcs	Metal	Energy Class A, adapter / retainer rings for light fixture
E27 to E14 Lampshade Reducer Ring, 12 pcs	12 pcs	Metal	Adapter rings for E14 socket lampshades, screw collar
E27 Lamp Shade Reducer Ring Converter, Plastic, Heat-Resisting, Black	1 pc	Plastic	210℃ heat-resisting, lampshade fitting washer adapter
Edison Screw ES E27 Lamp Holder Light Bulb Pendant Socket, Black	2 pcs	Plastic / Metal	Screw lampholder adapter, 10mm threaded entry, safety lock, Energy Class A
E26/E27 Lampshade Collar Ring, 6 pcs, Black	6 pcs	Plastic	Lamp shade reducer rings, retaining rings for bedside / desk / floor lamps, inner diameter 38mm
E27 Edison Screw Lamp Holder Extra Shade Ring 48mm, Brass	1 pc	Brass	Does NOT fit Bayonet B22/BC lamp holders