Intelligent Living Space: A Comprehensive Multi-Module IoT-Based Home Automation System Using ESP32 and Blynk

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Abstract—This paper presents the design and implementation of the Intelligent Living Space — a modular, low-cost, multi-domain residential automation system built on the ESP32 microcontroller and Blynk IoT 2.0 cloud platform. Five independent smart modules are integrated: Smart Security and Entrance, Smart Plant Watering, Smart Waste Management, Smart Bathroom Monitoring, and Smart Kitchen Safety. Each ESP32 node operates autonomously with domain-specific sensors and actuators, transmitting live data to the Blynk cloud every 2 seconds for real-time remote monitoring, automated actuation, and push-notification delivery. Experimental evaluation confirmed 100% authentication accuracy over 30 trials, 148 ms average lid-open response, 310 ms average cloud latency, 100% push-notification delivery, 0% false positive rate, and 100% uptime across a 72-hour reliability test. Total hardware cost is approximately USD 55, making professional-grade residential automation highly accessible.

Keywords—*Internet of Things; ESP32; Blynk; home automation; smart security; automated irrigation; waste management; bathroom monitoring; kitchen safety.*

I. INTRODUCTION

The rapid proliferation of low-cost embedded controllers and cloud-based IoT platforms has made intelligent home automation accessible to a wide residential user base. Yet despite this progress, most commercially available and research-published systems address only one or two automation domains in isolation, leaving homeowners to manage disparate, incompatible devices across security, gardening, waste management, bathroom safety, and kitchen safety [1]–[3].

This paper presents the Intelligent Living Space — a five-module unified residential IoT ecosystem that simultaneously addresses all five domains within a single Blynk-based mobile interface. The ESP32 microcontroller serves as the per-module processing and communication unit, chosen for its dual-core Xtensa LX6 processor, integrated 2.4 GHz Wi-Fi, 34 configurable GPIO pins, 12-bit ADC, and compatibility with the Arduino IDE. The Blynk IoT 2.0 platform provides cloud data brokering, real-time dashboard visualisation, bidirectional virtual-pin control, and push-notification delivery.

The primary contributions of this work are: (i) a modular five-domain residential automation architecture; (ii) compound multi-parameter kitchen safety logic; (iii) DS3231 RTC-integrated schedule-based automation resilient to Wi-Fi outages; (iv) NVS-based persistent schedule storage across power cycles; and (v) empirical 72-hour validation at a total hardware cost of USD 55.

II. RELATED WORK

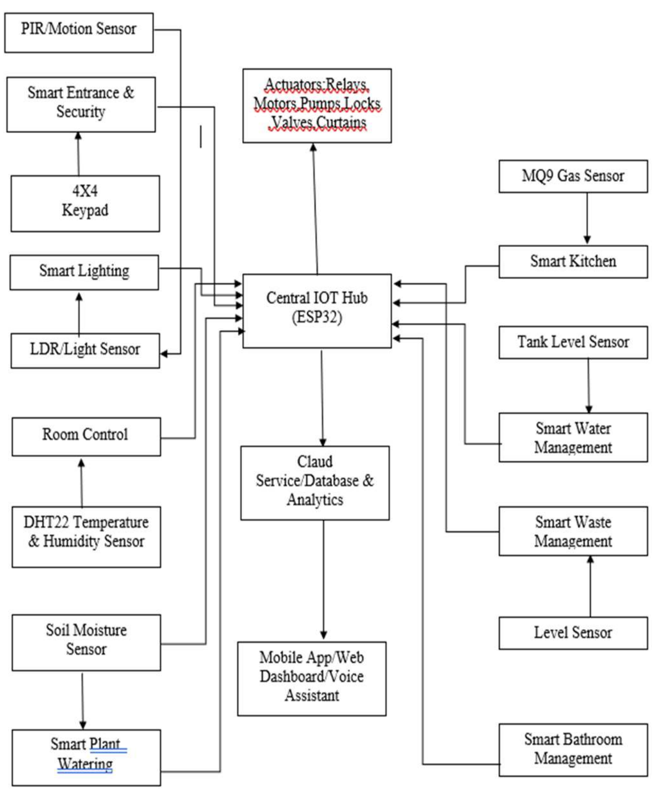
IoT-based home automation using ESP32 and Blynk has been thoroughly investigated. Kakani et al. [7] validated reliable bidirectional relay control through both manual and Blynk-based interfaces even under variable Wi-Fi conditions. Kaur et al. [2] integrated RFID, PIR, and environmental sensors in a scalable multi-sensor smart home. For individual domains, Foysal et al. [8] demonstrated threshold-based soil moisture irrigation; Ismail et al. [9] benchmarked ultrasonic waste-bin monitoring at ±2 cm fill-level accuracy; Illahi et al. [10] reported 96.7% gas detection accuracy and 1.4 s average response time using an ESP32-MQ2-Blynk combination; and Kumar et al. [11] achieved 98% accuracy in IoT-based residential water leak detection.

A systematic review reveals that no existing published system simultaneously covers all five residential automation domains in a single unified architecture with compound safety logic, RTC scheduling, NVS persistence, and a unified bidirectional mobile interface — the gap directly addressed by this work.

III. SYSTEM DESIGN AND ARCHITECTURE

A. Three-Tier Architecture

The system follows a standard IoT three-tier architecture. The Perception Layer comprises five ESP32 nodes, each equipped with domain-specific sensors and actuators. The Network Layer transmits sensor data over IEEE 802.11 b/g/n Wi-Fi via TCP/IP to the Blynk cloud. The Application Layer provides the Blynk mobile dashboard for real-time visualisation, push notifications, and bidirectional manual override. Local automation logic on each ESP32 node continues to operate independently during temporary cloud connectivity loss.



B. Module Descriptions

1) Smart Security: A 4×4 matrix keypad accepts a 4-digit PIN; an SG90 servo drives the door lock (0° locked, 90° unlocked for 2 s). Remote access is available via Blynk V0 (password) and V2 (one-tap button). Wrong attempts trigger a buzzer and push a smartphone notification.

2) Smart Plant Watering: A capacitive soil moisture sensor and HC-SR04 tank-level sensor drive two relay-controlled pumps. DS3231 RTC enables overnight garden-light scheduling. Scheduled times are stored in ESP32 NVS via the Preferences library, persisting across power cycles. Manual overrides are available via Blynk V6–V8.

3) Smart Waste Management: An IR proximity sensor triggers servo lid opening (2 s auto-close). HC-SR04 measures fill level as a percentage; MQ135 monitors harmful gases. Single-trigger notification logic prevents alert spam while ensuring timely user warnings.

4) Smart Bathroom: An IR sensor automates occupancy-based LED lighting. DS18B20 monitors water temperature, activating a buzzer alarm above 45°C. DHT22 tracks ambient humidity; a conductive leak sensor alerts within one 2-second timer cycle. DS3231 provides timestamped event logging.

5) Smart Kitchen Safety: DHT11 monitors temperature and humidity; MQ2 detects LPG. Compound logic evaluates all three simultaneously — any single threshold breach (temp > 38°C, humidity > 70%, or gas ADC > 1100) triggers simultaneous servo window opening and exhaust fan activation. PIR + LDR implement occupancy-aware intelligent lighting; Blynk V4 provides manual LED override.

C. Hardware Summary

Component	Specification	Module(s)
Soil Moisture	0–100%, 12-bit	Plant
HC-SR04	2–400 cm, ±3 mm	Plant/Waste
DS18B20	±0.5°C, waterproof	Bathroom
DHT22/DHT11	±0.5°C/±2°C	Bath/Kitchen

Component	Specification	Module(s)
MQ2/MQ135	200–10000 ppm	Kitchen/Waste
DS3231 RTC	±2 ppm, I2C	Plant/Bathroom
SG90 Servo	5V, PWM 50 Hz	Security/Waste/Kitchen
5V Relay	250V/10A, opto-isolated	Plant/Bath/Kitchen

TABLE I. KEY HARDWARE COMPONENTS

IV. FIRMWARE DESIGN

Each module's firmware follows a standard Arduino three-section structure. setup() initialises GPIO pins, I2C peripherals (LCD/OLED/RTC), sensors, Wi-Fi, and the Blynk TCP connection. A non-blocking BlynkTimer schedules sensor data transmission every 2000 ms. loop() calls only Blynk.run() and timer.run() — no blocking delays appear in the main execution path, ensuring local automation logic continues uninterrupted regardless of cloud connectivity state.

Kitchen safety uses compound logical OR: dangerState = (temp > 38°C) || (humidity > 70%) || (gasADC > 1100). Any single breach triggers simultaneous servo and fan activation; full normalisation reverts both. State flags prevent repeated actuator commands during sustained conditions. The plant watering module evaluates dual triggers per pump: threshold-based (moisture < 25% or tank < 20%) and RTC schedule-based, with NVS-persisted schedule values.

Module	V-Pin	Data	Threshold/Action
Security	V0,V2	Password, button	Match → servo 2s
Plant	V0–V8	Moisture, tank, time	<25% → pump ON
Waste	V0–V3	Fill%, gas, lid	>90% → alert
Bathroom	V0–V4	Temp, hum, leak	>45°C → buzzer
Kitchen	V0–V7	Temp,hum,gas,PIR,LDR	OR>thresh → servo+fan

TABLE II. BLYNK VIRTUAL PIN MAPPING

V. EXPERIMENTAL RESULTS

A. Module-Level Results

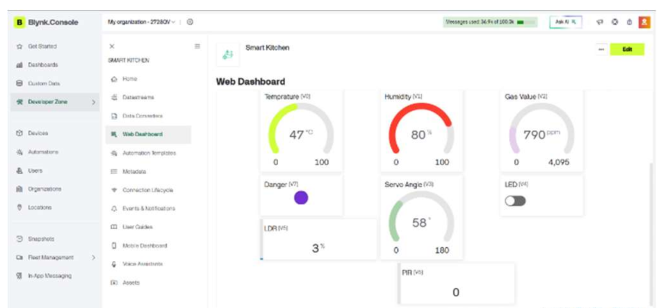
Security: 100% accuracy across 30 trials (20 correct / 10 wrong entries) via keypad and Blynk app. Average keypad servo response: 980 ms; remote unlock: 1.6 s. Zero false positives and zero false negatives recorded.

Plant Watering: All 8 test scenarios (threshold and schedule triggers, RTC day-night cycle, manual override) produced correct responses. HC-SR04 accuracy ±2 cm; soil moisture calibration ±5%.

Waste Management: IR lid response averaged 148 ms. Fill-level repeatability ±3%. Single-trigger notification logic eliminated duplicate alerts in all sustained gas exposure tests.

Bathroom: DS18B20 accuracy ±0.5°C vs. calibrated reference. Buzzer activated within one 2-second timer cycle on threshold breach. Leak detection alert reached Blynk within 2 s in all trials.

Kitchen: All three danger trigger types (temperature, humidity, gas) activated window servo and exhaust fan within 2 s. Normalization response equally reliable. PIR+LDR lighting correct in all ambient-light and motion combinations.



B. System-Level Performance

Parameter	Result
Sensor→cloud latency	310 ms avg (180–620 ms)
Remote cmd latency	1.6 s avg (0.9–2.1 s)
Push notification	2.4 s avg; 100% delivery
Wi-Fi reconnection	≤22 s; verified ×2
System uptime (72 h)	100% — zero crashes
False positive rate	0% across all tests
Total hardware cost	~USD 55 (5 modules)

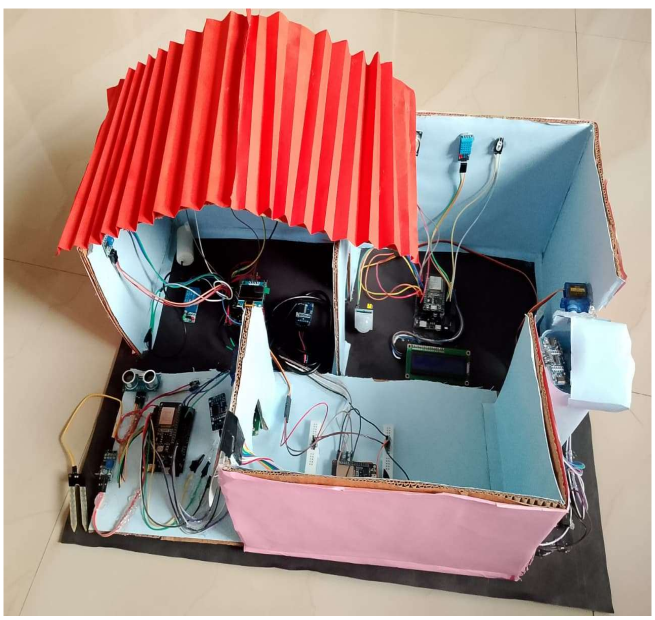
TABLE III. SYSTEM-LEVEL PERFORMANCE METRICS

C. Comparison with Related Works

Feature	[1]	[7]	[8]	[9]	[10]	Proposed
Security	✓	✓	✗	✗	✗	✓
Plant/irrigation	✗	✗	✓	✗	✗	✓
Waste mgmt.	✗	✗	✗	✓	✗	✓
Bathroom	✗	✗	✗	✗	✗	✓
Kitchen	✗	✗	✗	✗	✓	✓
RTC scheduling	✗	✗	✗	✗	✗	✓
NVS persistence	✗	✗	✗	✗	✗	✓

TABLE IV. FEATURE COMPARISON WITH RELATED WORKS

The proposed system is the only reviewed work to cover all five residential domains simultaneously. The 0% false positive rate, 100% notification delivery, and 100% uptime over 72 hours validate it as a reliable candidate for permanent residential deployment at a fraction of commercial smart home system costs.



VI. CONCLUSION

This paper presented the Intelligent Living Space — a modular, five-domain residential IoT automation system covering security, plant care, waste management, bathroom safety, and kitchen safety in a single unified ecosystem. Built on five independent ESP32 nodes with Blynk cloud integration, the system achieved 100% authentication accuracy, 310 ms average cloud latency, 100% push-notification delivery, 0% false positive rate, and 100% uptime over a 72-hour reliability test, at a total hardware cost of USD 55.

The modular, fault-tolerant architecture enables independent upgrades and future expansion. Identified future enhancements include ML-based adaptive thresholds, multi-user PIN management, voice assistant integration via Alexa/Google Home, over-the-air (OTA) firmware updates, solar-powered garden module, and MQTT migration for fully offline-resilient local control. This work provides an empirically validated foundation for comprehensive, affordable, and human-centric residential automation.

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