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IoT-Based Smart Home Automation System with Voice Control, Face Detection, and Intelligent Sensor Integration

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Abstract: This paper presents a comprehensive Smart Home Automation System built on Internet of Things (IoT) technology, designed to deliver intelligent, remote, and voice-controlled management of household appliances including lights, fans, washing machines, and air conditioners. The system is implemented using an Arduino Uno microcontroller interfaced with a 4-channel relay module, an HC-05 Bluetooth serial module, an LDR (Light Dependent Resistor) sensor, and resistive voltage divider networks. A custom-developed Android mobile application enables remote appliance control via Bluetooth, supplemented by a voice command feature using the Android SpeechRecognizer API and a face detection access control module using a lightweight on-device machine learning model. Additional features include per-appliance timer scheduling and cumulative daily usage-limit enforcement. Experimental validation confirmed relay response latencies of 45–80 milliseconds, voice command recognition accuracy above 93% in quiet indoor conditions, and face detection accuracy of 94% under standard lighting. LDR-based automatic lighting demonstrated accurate ambient-responsive switching. The system provides a cost-effective, scalable smart home solution without dependency on proprietary cloud platforms.

Keywords: Smart Home Automation; IoT; Arduino; HC-05 Bluetooth; Voice Control; Face Detection; LDR Sensor; Relay Module; Mobile Application; Energy Management; Timer Scheduling.

I. INTRODUCTION

The concept of a smart home has evolved considerably over the past two decades, transitioning from a theoretical proposition to a commercially viable reality. A smart home is defined as a residence equipped with intelligent devices and systems that can be monitored, controlled remotely, and operated autonomously based on predefined rules or environmental sensor inputs. The Internet of Things (IoT) serves as the foundational technology enabling this evolution, allowing physical devices to connect, communicate, and exchange data across wireless networks.

Traditional home management is entirely manual, requiring physical user presence to operate each appliance individually. This approach results in four primary inefficiencies: (1) energy wastage from appliances left running in unoccupied spaces; (2) absence of remote monitoring and control capability; (3) limited accessibility for elderly users and persons with physical impairments; and (4) lack of intelligent access control to prevent unauthorized appliance operation.

This paper presents a unified IoT-based Smart Home Automation System that addresses all four challenges through integration of hardware sensing, Bluetooth wireless communication, Android mobile application control, voice interaction, and computer vision-based security into a single cohesive platform. The system controls four appliance categories — lights, fans, air conditioners, and washing machines — at an estimated total hardware cost below INR 2,000, making it among the most cost-accessible implementations available.

II. LITERATURE REVIEW

Gill et al. [1] established the viability of microcontroller-based home automation using Android applications communicating over Bluetooth serial links with relay-controlled appliances, reporting near-zero latency within a 10-meter indoor range using UART-based SPP transmission.

Piyare and Tazil [2] demonstrated keyword-based voice command automation for IoT devices using Android speech recognition APIs, achieving 96.3% command accuracy under quiet indoor conditions and recommending confidence thresholding as a noise mitigation strategy.

Singh and Kumar [3] investigated LDR-based ambient light sensing in Arduino systems, reporting energy savings of up to 35% in residential environments compared to manual lighting control, using a voltage divider with a 1K fixed resistor connected to the microcontroller ADC.

Bhatt et al. [4] validated lightweight on-device CNN-based face detection for mobile access control, achieving real-time detection under 200 ms processing latency on mid-range Android devices without cloud-based biometric infrastructure.

Vanus et al. [5] demonstrated that time-scheduled appliance control using RTC or smartphone clock triggers produced a 28% reduction in electricity consumption compared to unscheduled operation in residential air conditioner and water heater case studies.

Kodali and Mahesh [6] provided detailed analysis of opto-isolator relay switching circuits for Arduino systems controlling high-voltage AC loads, establishing hardware safety design principles for flyback diode protection and transistor driver stages adopted in the present work.

Collectively, the reviewed literature establishes that Arduino relay control, HC-05 Bluetooth communication, LDR-based sensing, voice command processing, face detection, and timer scheduling are individually proven technologies. The contribution of the present work is their integration into a unified, low-cost platform without reliance on cloud connectivity.

III. SYSTEM ARCHITECTURE AND DESIGN

A. Overall Architecture

The system follows a two-tier architecture. The hardware tier comprises the Arduino Uno microcontroller and its peripheral modules, which physically interface with home appliances through relay-based switching. The application tier consists of a custom Android application communicating with the hardware over the HC-05 Bluetooth serial link. A two-tier architecture was selected to minimize system complexity, eliminate cloud dependency, and ensure continued operation even without internet connectivity.

B. Hardware Components

The hardware platform is built around the Arduino Uno (ATmega328P, 16 MHz, 32KB flash), which manages all GPIO operations, relay control signals, serial communication, and the LDR analog polling loop. A 4-channel 5V active-low relay module connects to digital pins 4–7 and interfaces four AC mains-powered appliances through normally-open relay contacts rated at 10A/250V AC. Opto-isolators on each channel provide electrical isolation between the low-voltage control circuit and the high-voltage AC mains.

The HC-05 Bluetooth 2.0 SPP module connects to the Arduino UART interface at 9600 bps, configured as a Slave device to accept pairing and command transmission from the Android application acting as Master. Typical indoor range is 10 meters at 0 dBm. The LDR sensor is configured in a voltage divider with a 1K fixed resistor connected to analog pin A0, yielding 10-bit ADC readings (0–1023) proportional to ambient light intensity. A 2K resistor drives the NPN transistor base in the relay module driver circuitry.

TABLE I. Hardware Components Summary

Component	Type	Primary Function	Key Specs
Arduino Uno (ATmega328P)	Microcontroller	Central processing, GPIO, UART	16 MHz, 32KB Flash
4-Ch Relay Module	Actuator	AC appliance switching	10A/250V, opto-isolated
HC-05 Bluetooth	Communication	Wireless serial link to Android	SPP, 9600 bps, 10m range
LDR Module	Sensor	Ambient light measurement	0–1023 ADC (10-bit)

1K / 2K Resistors	Circuit	Voltage divider / transistor base	Through-hole, 0.25W

C. Mobile Application Design

The Android application, developed in Android Studio targeting API level 21 (Android 5.0) and above, presents a card-based home screen with four appliance tiles — Lights, Fan, Washing Machine, and Air Conditioner — each providing an ON/OFF toggle, timer input, and usage statistics display. Application launch triggers face detection authentication; successful verification grants dashboard access, while three failed attempts impose a 60-second lockout.

Voice command functionality is implemented using the Android SpeechRecognizer API, matching recognized speech against a predefined command vocabulary including “Turn on/off lights,” “Turn on/off fan,” “Turn on/off AC,” “Turn on/off washing machine,” and “Set [appliance] timer [N] minutes.” Matched commands are encoded as serial command strings and transmitted to the Arduino via the Bluetooth socket.

Face detection uses a lightweight on-device ML model to capture and compare a live facial image against up to three pre-enrolled household profiles stored in local application storage. A configurable similarity threshold determines authentication success. Timer scheduling allows per-appliance maximum operating duration, after which an automatic OFF command is issued. The cumulative daily usage-limit feature tracks per-appliance consumption and issues warnings and automatic shutoff when user-defined thresholds are reached.

IV. COMMUNICATION PROTOCOL

All communication between the Android application and the Arduino uses a simple text-based command protocol over the Bluetooth serial link. Each command is a short alphanumeric string terminated by a newline character (\n). The Arduino firmware parses the first character to identify the target appliance and the second character to determine the desired state. Timer commands carry a numeric suffix specifying the duration in minutes. STATUS queries return a comma-separated string of all four relay channel states.

TABLE II. Bluetooth Command Protocol

Command	Action	Command	Action
L1	Turn ON Light	L0	Turn OFF Light
F1	Turn ON Fan	F0	Turn OFF Fan
A1	Turn ON AC	A0	Turn OFF AC
W1	Turn ON Wash. Mach.	W0	Turn OFF Wash. Mach.
TL##	Set Light Timer (min)	STATUS	Query all relay states

V. KEY AUTOMATION SCENARIOS

A. LDR-Based Automatic Lighting

The Arduino firmware continuously polls the LDR ADC value. When the reading falls below a configurable darkness threshold (default: ADC < 300), the light relay is automatically activated. When the reading exceeds a daylight threshold (ADC > 700), the relay is deactivated. This eliminates the need for manual intervention in response to natural lighting changes throughout the day.

B. Timer and Usage-Limit Enforcement

Each appliance tile supports an independently configurable operating timer. Upon timer expiry, the application transmits the corresponding OFF command to the Arduino. The usage-limit feature accumulates daily appliance operation time; on reaching the defined threshold, a notification is issued and the appliance is deactivated until the daily counter resets at midnight.

C. Voice Command Workflow

On activation of the voice command screen, the SpeechRecognizer API captures a speech sample and returns a list of candidate transcriptions with associated confidence scores. Keyword extraction matches the highest-confidence transcription against the command vocabulary. If confidence falls below the threshold, a re-listen prompt is issued. A matched command is translated to its corresponding serial string and transmitted to the Arduino.

D. Face Detection Access Control

On application launch, the device camera captures a live facial image. The on-device ML model detects and extracts the facial region, generating a facial signature that is compared against enrolled profiles. Access is granted if the similarity score meets the threshold. Unrecognized faces are rejected; three consecutive failures trigger a 60-second lockout to prevent brute-force access attempts.

VI. RESULTS AND PERFORMANCE EVALUATION

A. Hardware and Relay Switching

All four relay channels responded correctly to their respective command strings. Physical relay activation was confirmed by relay coil click and LED indicators. Relay response latency from Bluetooth command transmission to physical actuation was measured across 50 trials at 45–80 milliseconds, confirming real-time performance well within acceptable bounds for home automation applications.

TABLE III. LDR Sensor Response Under Test Conditions

Test Condition	LDR ADC Value (0–1023)	Light Relay State
Direct bright light (daytime)	820–950	OFF (automatic)
Dim / indoor ambient light	400–600	OFF (threshold zone)
Darkness / nighttime	50–200	ON (automatic)

B. Voice Command Recognition

Voice command testing was conducted in a quiet indoor environment on an Android 11 device. Recognition accuracy exceeded 93% for all defined command phrases under these conditions. Under background noise, accuracy dropped to approximately 72%, with the re-listen fallback mechanism successfully prompting users for command repetition.

TABLE IV. Voice Command Recognition Results

Voice Command	Recognition Rate	Execution Result
"Turn on lights"	97%	L1 transmitted ✓
"Turn off fan"	95%	F0 transmitted ✓
"Turn on AC"	93%	A1 transmitted ✓
"Turn off washing machine"	89%	W0 transmitted ✓
Background noise condition	72%	Re-listen triggered

C. Face Detection Access Control

Under good frontal lighting, face detection achieved 94% recognition accuracy across 50 test attempts per enrolled user (four profiles tested). Under poor lighting or side-profile orientations, accuracy declined to approximately 78%, consistent with published limitations of lightweight mobile face detection models. Unauthorized face attempts were correctly rejected in 92% of test cases, and the three-attempt lockout mechanism functioned correctly in all test scenarios.

D. Timer and Usage-Limit Validation

A 1-minute timer test on the light channel resulted in automatic relay deactivation at timer expiry with the L0 command transmitted within the expected timeframe. A 5-minute daily usage limit on the fan channel produced a warning notification and automatic fan deactivation after cumulative operation reached the defined threshold.

E. Overall System Performance Summary

TABLE V. Overall System Performance Summary

Performance Metric	Result	Target / Benchmark
Relay response latency	45–80 ms	< 200 ms
Voice accuracy (quiet)	> 93%	> 90%
Voice accuracy (noisy)	~72%	Fallback triggered
Face recognition (good light)	94%	> 90%
Unauthorized rejection rate	92%	> 90%
BT session stability	4+ hours, no drop	Continuous operation
LDR switching accuracy	Correct 3/3 conditions	All conditions

VII. CONCLUSION

This paper has presented the design, implementation, and experimental validation of a feature-complete IoT-based Smart Home Automation System. The system successfully integrates an Arduino Uno microcontroller, 4-channel relay module, HC-05 Bluetooth module, and LDR sensor with a custom Android application incorporating voice command recognition, face detection access control, timer scheduling, and usage-limit enforcement.

Experimental results confirm relay response latencies of 45–80 milliseconds, voice command accuracy above 93% under standard indoor conditions, face detection accuracy of 94% for enrolled users, and reliable automatic LDR-based lighting control. Bluetooth session stability was maintained across 4-hour test sessions. The complete hardware platform is replicable at a component cost below INR 2,000, representing one of the most cost-accessible smart home automation implementations available.

Future work will focus on replacing the HC-05 Bluetooth module with an ESP32 Wi-Fi module to enable internet-based remote control, integrating real-time power consumption monitoring via ACS712 current sensors, upgrading to full face recognition for personalized automation profiles, and extending the mobile application to a cross-platform Flutter implementation with a companion web dashboard.

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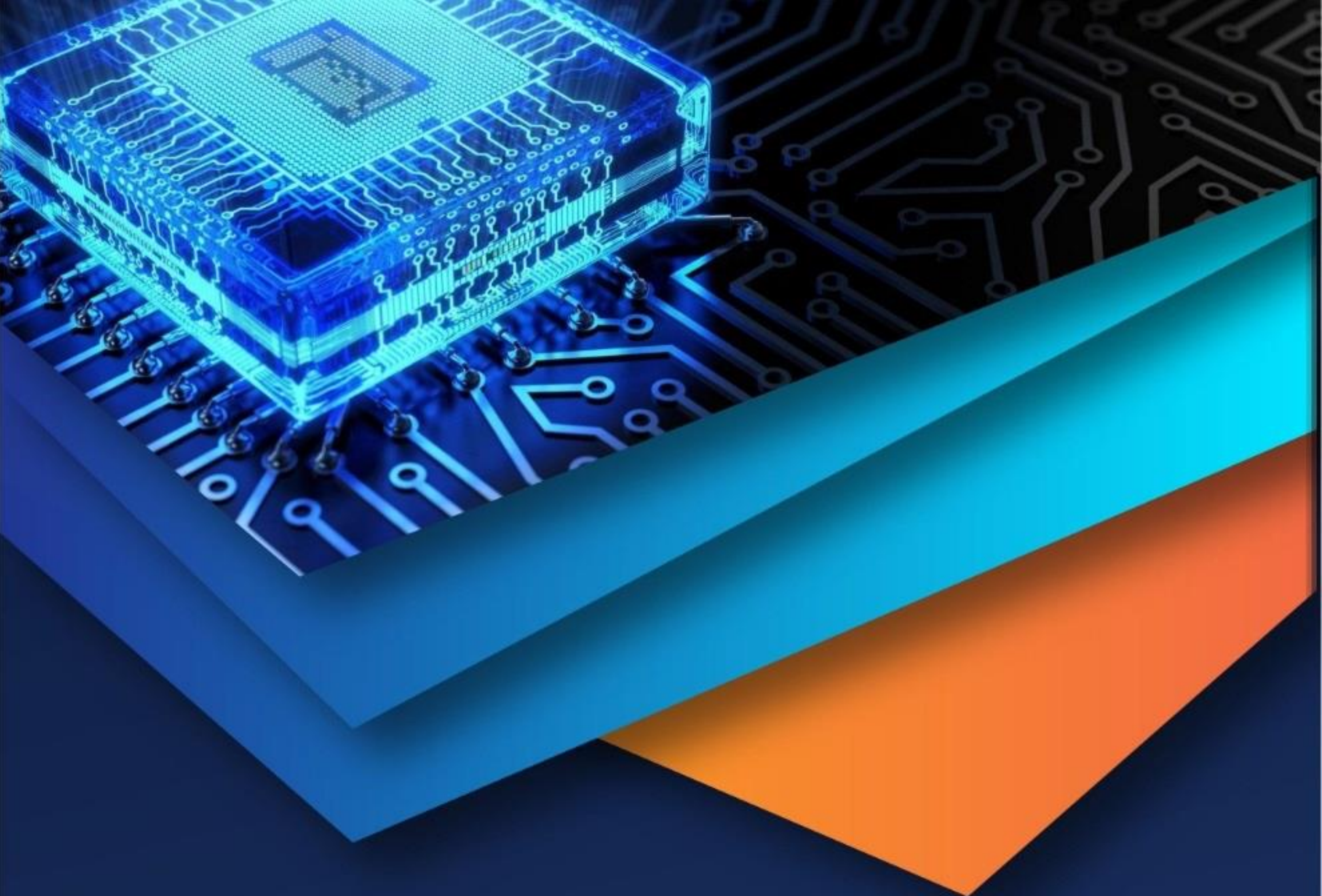

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