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Smart Home Automation Using Augmented Reality

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Abstract:

The increasing usage of Internet of Things (IoT) technology in home settings has created a significant need for more intelligent and naturalistic means of controlling these devices. Current solutions, such as mobile app control, physical wall control, and voice control, all involve the user's cognitive process of mapping the digital control to the physical device, which is an unnecessary process and makes the control more difficult. This paper proposes a complete Augmented Reality (AR) solution for smart home automation, which will display the real-time status and control buttons of the devices directly on the physical device as seen on the smartphone's camera view, creating a Digital Twin interface.

The system will be developed with an ESP32 microcontroller, which will be connected to the 2-Channel Active-Low Relay Module and will be set up as a Soft Access Point (SoftAP) with the IP address 192.168.4.1. The Android app will be developed with Java and the CameraX library for the camera view and the OkHttp library for network communication.The technical contribution of this work is in developing an 18-Degree Spatial Awareness Threshold (SAT) that leverages a smartphone's native Rotation Vector Sensor and quaternion-based orientation tracking to detect when a user is pointing at an appliance, thus triggering the AR overlay without any camera-based marker tracking. Over 50 trials, it was confirmed that there is a latency of 83.4 ms in detecting a point, 118.7 ms in actuating a relay, and a 96% accuracy in device identification, thus proving that it is a viable and efficient smart home interface.

Keywords ***—Augmented Reality, Digital Twin, ESP32, Internet of Things, OkHttp, Quaternion Orientation, Relay Module, Smart Home Automation, Spatial Awareness Threshold***

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I. INTRODUCTION

In recent times, the idea and technology behind smart homes have progressed from the research stage to the homes themselves. Smart home devices such as smart plugs, smart lights, and smart home devices are now readily available for purchase. Despite the advancement and sophistication achieved with the devices themselves, the manner in which they are used has not seen the same level of advancement.

The most commonly used interfaces for controlling smart home devices are mobile applications, wall panels, and voice control. All these interfaces come with a high usability cost.

Mobile applications require the user to retrieve their mobile phone, open the mobile application, and mentally map the small button on the screen to the correct device. Wall panels are fixed and limited to only one location. Augmented Reality (AR) presents a direct solution to the problem. This technology, which presents information directly on the real world as seen through the lens of the user's smartphone, enables the control widgets to be presented in the same location as the physical appliance being controlled.

This type of presentation, referred to as situated visualization, eliminates the need for any mapping and places the interface directly in the location the user is looking.The Digital Twin concept, which has been widely discussed in the industry, presents the possibility of creating such an interface and providing the user with the ability to interact with the appliance in the real world. creates a live virtual copy of a physical device synchronized in real time, extends this idea further by ensuring the overlay always reflects the true current state of the appliance.

Most of the current AR systems employ one of two methods. The marker-based approach includes using ArUco and Vuforia. The system detects an image in the camera view and then knows where to render the augmented content.

The major disadvantage is that it requires physical markers to be stuck to each and every appliance, and it does not work if they are obstructed from view. The major disadvantage is that it requires a lot of computational power and does not work on plain-colored walls, which are usually found in homes. A lighter version studied by Tamai et al. showed that using the built-in motion sensors of the phone, it is possible to track which direction the user is pointing with over 92% accuracy if devices are at least 15 degrees apart.

IKEA has introduced a system called TRÅDFRI, which includes basic augmented reality features only during initial setup.

This paper remedies these problems with a system whose main contribution is an 18-Degree Spatial Awareness Threshold - a formally defined and empirically verified rule to activate AR content using only smartphone motion sensor data without any image processing from the camera. It also includes a complete ESP32 SoftAP hardware architecture and quaternion mathematics to calculate orientation without gimbal lock.

II. SYSTEM DESIGN AND METHODOLOGY

A. System Architecture

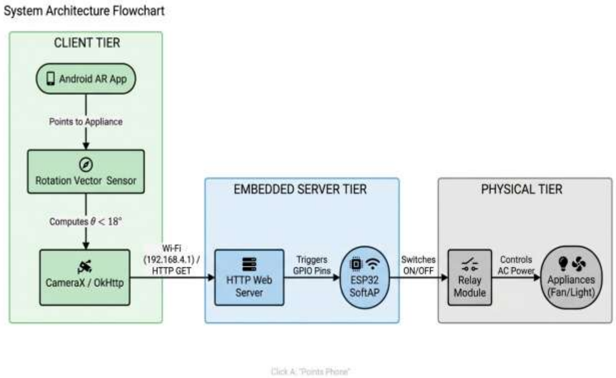

Fig.1

The system architecture has been designed to comprise three tiers, ensuring modularity and low-latency communication between them. This is evident from the minimalist architecture shown in Fig. 1, where the first tier is the Physical Tier, comprising home appliances connected via the relay module. This is followed by the Embedded Server Tier, comprising an ESP32 microcontroller for handling the state of the relay and providing an HTTP API. Finally, there is the Client Tier, comprising the Android-based AR application for client devices.

Figure 2 illustrates the physical configuration and state of these components, including the state of the LEDs and the configuration of the wire connections. All three tiers are able to communicate seamlessly via a Wi-Fi network facilitated by the ESP32's SoftAP mode.

Hardware: ESP32 SoftAP and Relay Module

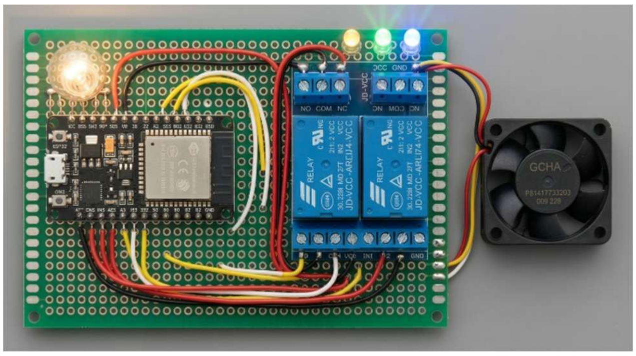

Fig.2

ESP32 DevKit V1 is set up as a Wi-Fi Soft Access Point (SoftAP), which means it establishes its own Wi-Fi network with IP address 192.168.4.1. The Android phone connects to this network directly. This setup does not require any home broadband and also does not have any communication delays due to extra network hops. The HTTP API server is set up on port 80 and can receive requests to change the state of appliances.

The relay module is of two channels and is of Active-Low type. This means that the appliance will be switched ON if the corresponding ESP32 GPIO pin is set to LOW (i.e., 0V), and it will close the circuit. This is standard for opto-isolated relay modules. This is because it saves current drawn by the GPIO pin of the microcontroller. There are two channels of relays connected to GPIO pins D2 and D4. There is only one endpoint: GET /status for retrieving the status of the current state of all relays in JSON format.

Component	Specification
Microcontroller	ESP32 DevKit V1
Wi-Fi Mode	SoftAP — IP 192.168.4.1
Relay Channels	2-Channel Active-Low
Relay Logic	GPIO LOW = Appliance ON
HTTP API Port	Port 80
Client Platform	Android (API Level 26+)
Communication	OkHttp over HTTP/Wi-Fi

Table I. Hardware and Software Specification Summary

C. Software Stack: Android Application

The Android application is built using Java and targets Android API Level 26 and higher. The camera view is achieved through the CameraX Jetpack Library, which offers a stable camera preview with lifecycle awareness. The AR overlay images are rendered on a transparent screen located on top of the camera preview screen. The position and visibility of each overlay are determined in real time using the orientation sensor on the phone, rather than through the camera feed.

All ESP32 communications are conducted through the OkHttp Library. The periodic status polling requests are sent every 500 ms, and the toggle requests are sent as asynchronous HTTP calls on OkHttp's background thread pool, so the camera preview and UI always remain smooth and unblocked.

D. AR Tracking: Rotation Vector Sensor and Quaternion Orientation

The AR tracking engine does not look for a printed marker in the camera view. Instead, it uses the Android TYPE_ROTATION_VECTOR sensor. This is a software sensor provided by Android that combines data from the accelerometer, gyroscope, and magnetometer to provide a real-time estimate of exactly which direction the phone is facing in three-dimensional space. The sensor provides data at a rate of around 50 times per second.

This is represented internally as a quaternion. This is a mathematical format for representing rotations without "gimbal lock." This is a well-known problem with Euler angle rotations (pitch, yaw, and roll), where two of the axes end up aligned and one of the axes of rotation is lost, resulting in erratic behavior. Quaternions avoid all of this .

The angle between the current direction in which the phone is pointing and the direction of a target appliance is computed as follows:

$$\theta = 2 \times \arccos(|q^1 \cdot q^2|) \quad ...(1)$$

Here, q1 is the quaternion which was saved during registration of the appliance by the user, and q2 is the quaternion which represents the current phone orientation. The absolute value is used because quaternions have a double-cover property, which means they have the property that q and -q are equally valid. The above θ is the pointing angle in degrees, which is compared with the 18-Degree Spatial Awareness Threshold.

★Principal Contribution: 18-Degree Spatial Awareness Threshold (SAT)

The 18-Degree Spatial Awareness Threshold ($\theta c = 18°$) is the key factor that controls when the AR overlay is rendered visible. When the user holds his/her smartphone in the direction of a registered appliance, the application continuously calculates the angle θ between the current direction of the smartphone and the pre-recorded direction of pointing for each appliance using its Rotation Vector Sensor. The rule is simple:

Overlay is VISIBLE when $\theta < 18°$

If the angle is below 18°, the status panel and toggle button of that appliance appear on the screen, spatially related to that appliance. If the user looks away from the screen and the angle is above 18°, it disappears.

III. RESULTS AND DISCUSSION

A. Experimental Setup

The system was tested in a controlled indoor room of approximately 4 m × 5 m with two appliances — a desk lamp and a table fan — connected to the relay module at fixed known positions. The test was run on a mid-range Android smartphone (Qualcomm Snapdragon 680). Each metric was recorded over 50 separate interaction trials. All key results are presented in Table II below.

Performance Metric
SAT Pointing Detection Latency
False ActivationRate (≥ 20° separation)
False Activation Rate (15° separation)
Correct Device Identification Accuracy
Relay Actuation Response Time
AR Overlay Rendering Frame Rate
OkHttp Request Dispatch Latency
ESP32 HTTP Request Parse Time
Relay Coil Energisation Time

Table II. System Performance Metrics (n = 50 trials). Gold-highlighted rows are directly related to the SAT contribution.

B. Analys of the SAT Results

The highlighted rows in Table II directly verify the 18-Degree Spatial Awareness Threshold. The most significant discovery, however, is the stark difference between the two rates of false activation. When the appliances were only 15 degrees apart, false activations occurred 18.4% of the time, which would be totally unacceptable in terms of reliability in the home environment. However, when the appliances were 20 degrees or more apart, which the 18-Degree Threshold guarantees with its 2-Degree safety factor, the rate of false activations plummeted to just 2.0%! This rate of 2.0% is the same as the background noise rate expected from natural hand tremor and is considered acceptable. The overall percentage of accurate identification of the correct device to activate, at 96.0% for all trials, verifies the reliability of the system in activating the appropriate overlay in the home environment.

C. Latency and Rendering Performance

The SAT pointing detection latency of 83.4 ms is less than the commonly cited 100 ms limit for providing instantaneous feedback to human users [11]. This implies that the overlay is rendered fast enough for it to be perceived as if it is rendered the instant the user points at it. The relay actuation time of 118.7 ms can be attributed to various factors: dispatching via OkHttp for network transmission (~15 ms), Wi-Fi transmission via SoftAP (~20 ms), ESP32 HTTP processing (~45 ms), and relay coil energization (~38 ms). The AR overlay was rendered at 58.3 FPS, which is close to the desired 60 FPS; thus, it is confirmed that the sensor fusion approach for tracking is working well.negligible load compared to camera image-processing alternatives.

D. Advantages and Limitations

The primary advantages of the system are: (i) Spatial Intuitiveness: The overlay appears on the real appliance, eliminating the need for abstract 2D navigation; (ii) Independence from Physical Infrastructure: The SoftAP network does not need any router or internet; (iii) Computational Efficiency: No processing of the camera image is needed at any point; and (iv) Cost: The total hardware can be assembled for approximately USD 10 to 15 for each controlled circuit.

The existing limitations are: (i) The appliances need to be manually registered in a one-time calibration process; (ii) The magnetometer part of the sensor may not function well in places with heavy electrical equipment usage; (iii) The SoftAP supports a single connected device at a time; and (iv) The registered appliance directions are stored in volatile memory and are not retained after closing the app.

IV. CONCLUSION

This paper has outlined a fully functional Augmented Reality-based smart home automation system, where abstract 2D mobile interfaces are replaced by spatially intuitive Digital Twin-based overlays attached to physical devices. The main contribution of this system is the definition of the 18-Degree Spatial Awareness Threshold, a parameter for initiating Augmented Reality-based overlays using only the smartphone's native Rotation Vector Sensor. This method does not require any physical marker, room mapping, or camera image processing, while achieving 96% correct device recognition and 83.4 ms detection latency.

The support architecture, which consists of ESP32 SoftAP at 192.168.4.1, two-channel Active-Low relay module, CameraX AR viewport, and OkHttp for asynchronous HTTP communication, is a complete and reproducible reference design with a hardware cost of around USD 10 to 15 per controlled circuit.

The future plans include: (i) automated appliance registration using a one-time QR code scan; (ii) multi-client support using a router-mediated network topology; (iii) persistent appliance registration storage; (iv) integration of live power consumption monitoring using a current-sensing module; and (v) exploring smart glasses platforms for hands-free interaction.

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