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# IntelliSpace: The Future of Smart Campus Automation

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## Abstract:

Traditional educational campuses face significant operational challenges due to inefficient, manual resource management and excessive energy consumption. Maintaining high-level security requires constant real-time surveillance and restricted access control, which is difficult to scale manually. Furthermore, upgrading to smart surveillance typically relies on expensive cloud AI subscriptions to process video feeds and detect anomalies. IntelliSpace addresses these issues by implementing a Smart Campus Automation System at K.L.N. College of Engineering using advanced IoT and Edge AI technologies. It eliminates cloud dependency by utilizing devices like Google Coral and Raspberry Pi to perform lightweight, on-device AI processing for real-time face and anomaly detection directly from IP cameras. The system automates campus lighting, appliances, and HVAC systems through smart modules, drastically reducing manual intervention and promoting energy savings. A 3D Digital Twin dashboard visually updates room statuses in real time using IoT sensor data. Enhanced with biometric access, offline voice commands, LoRa-based communication, and solar-powered UPS systems, IntelliSpace creates a highly secure, sustainable, and scalable environment.

*Keywords* — **Smart Campus, IoT, Edge AI, Google Coral, Raspberry Pi, Digital Twin, HVAC Automation, Biometric Access, LoRa Communication, Face Detection, Energy Management, Automated Gate Monitoring.**

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## I. INTRODUCTION

The rapid advancement of Internet of Things (IoT) and Edge Artificial Intelligence (AI) technologies has opened unprecedented opportunities to transform traditional institutional infrastructure into smart, automated environments. Educational institutions stand to benefit enormously from intelligent automation systems that enhance operational efficiency, reduce energy consumption, and ensure robust security with minimal human intervention.

IntelliSpace is a comprehensive Smart Campus Automation System designed specifically for K.L.N. College of Engineering. It integrates cutting-edge IoT sensors, Edge AI processing units, biometric authentication, and real-time monitoring dashboards to create an intelligent, self-regulating campus environment. Unlike conventional smart systems that depend heavily on cloud infrastructure, IntelliSpace prioritizes on-device processing, ensuring low latency, data privacy, and operational continuity even during network disruptions.

## II. PROBLEM STATEMENT

Traditional educational campuses face significant operational challenges due to inefficient, manual resource management and excessive energy consumption. Key challenges include:

- Manual lighting and HVAC control leading to unnecessary energy wastage in unoccupied rooms.
- Absence of real-time monitoring systems for campus-wide resource utilization.
- Heavy reliance on cloud AI subscriptions for video surveillance and anomaly detection, increasing operational costs and data privacy risks.
- Lack of automated gate monitoring for vehicle tracking and campus entry/exit management.
- No unified dashboard for centralized control and visualization of campus systems.
- Inability to maintain campus operations during internet outages due to cloud dependency.

## III. Project Objectives

The primary objective of IntelliSpace is to design, develop, and deploy a unified smart campus automation system that:

- Eliminates cloud dependency through Edge AI processing using Google Coral and Raspberry Pi devices.
- Automates lighting, appliances, and HVAC systems through IoT smart modules.
- Implements real-time face recognition and anomaly detection using on-device AI models.
- Provides a 3D Digital Twin dashboard for centralized visualization of campus room statuses.
- Enables automated gate monitoring with number plate recognition for vehicle tracking.
- Enhances campus security through biometric access control and offline voice commands.
- Promotes energy sustainability through LoRa-based communication and solar-powered UPS systems.

## IV. Literature Review

A comprehensive review of existing literature was conducted to understand the state of the art in smart building automation, Edge AI, IoT-based campus management, and digital twin technologies.

1. Kumar et al. present an IoT-based smart building system using Raspberry Pi for controlling electrical appliances based on sensor inputs. The study validates the use of low-cost single-board computers for building automation but does not incorporate Edge AI for anomaly detection or visual surveillance.
2. Zhao et al. explore the use of edge computing devices for real-time video analytics, demonstrating significantly lower latency compared to cloud-based approaches. The research confirms the feasibility of on-device inference for face recognition but is limited to controlled laboratory environments.
3. Singh & Patel introduce a digital twin framework for real-time visualization of building systems, enabling facilities managers to monitor and control subsystems remotely. IntelliSpace extends this concept with a 3D interactive dashboard and live IoT sensor integration.
4. Li et al. propose an ANPR system for automated vehicle entry management at institutional campuses using deep learning models. IntelliSpace implements a lightweight ANPR solution optimized for edge devices to avoid server infrastructure costs.
5. Mehta & Sharma evaluate LoRa wireless technology for long-range, low-power IoT deployments in campus environments, demonstrating reliable communication over 500 metres within urban settings, supporting IntelliSpace's choice of LoRa for inter-building communication.
6. Arjun et al. provide a comprehensive review of biometric authentication methods including fingerprint, iris, and face recognition for access control, informing IntelliSpace's biometric module design.

The literature review reveals that while significant progress has been made in individual domains, no existing system integrates all these technologies into a unified, cloud-independent campus automation platform — the gap IntelliSpace addresses.

## V. System Analysis

### A. Functional Requirements

- Automatically control lighting, fans, and HVAC based on room occupancy detected by PIR and $CO_2$ sensors.

- Perform real-time face recognition using Edge AI (Google Coral TPU) to identify registered campus personnel.
- Detect and alert security personnel of anomalous activities using on-device AI models.
- Automatically log vehicle entry and exit using number plate recognition at campus gates.
- Provide a 3D Digital Twin dashboard displaying real-time room and device statuses.
- Support offline voice command processing for device control without internet connectivity.
- Restrict access to sensitive areas using biometric authentication.
- Communicate across campus buildings using LoRa wireless modules.

*B. Non-Functional Requirements*

- Performance: Face recognition inference shall complete within 200 milliseconds on Edge AI hardware.
- Reliability: The system shall maintain operation during internet outages through offline Edge AI and LoRa communication.
- Scalability: The architecture shall support addition of new rooms, sensors, and camera nodes without system redesign.
- Security: All biometric data shall be stored locally and never transmitted to external cloud servers.
- Energy Efficiency: The system shall demonstrate a minimum 30% reduction in energy consumption compared to manual operation.
- Availability: The system shall maintain 99.5% uptime through solar-powered UPS backup.

*C. Hardware Requirements*

- Google Coral USB/PCIe TPU Accelerator — Edge AI inference for face and anomaly detection.
- Raspberry Pi 4 Model B (4GB RAM) — Primary processing unit for sensor management and AI coordination.
- ESP32 Microcontrollers — Low-power IoT nodes for room automation control.
- IP Cameras (Full HD, H.264) — Video feeds for surveillance and gate monitoring.
- PIR Motion Sensors — Occupancy detection for automated lighting and HVAC.
- DHT22 Temperature & Humidity Sensors — Environmental monitoring for HVAC automation.
- LoRa SX1276 Modules — Long-range, low-power inter-building communication.
- Solar Panel + UPS System — Sustainable power backup.

*D. Software Requirements*

- Operating System: Raspberry Pi OS (Linux), Windows 10 (Dashboard).
- AI Framework: TensorFlow Lite, OpenCV, PyCoral (Google Coral API).
- Backend: Python (Flask/FastAPI) for API services.
- Database: MySQL for gate monitoring data, InfluxDB for time-series sensor data.
- Frontend: React.js with Three.js for 3D Digital Twin dashboard.
- IoT Protocol: MQTT for device communication, LoRaWAN for long-range nodes.
- Voice Processing: Vosk (offline speech recognition library).

## VI. Module Description

*A. Edge AI Surveillance Module*

Deploys lightweight TensorFlow Lite models on Google Coral TPU for real-time face recognition and anomaly detection from IP camera streams. Processes video frames entirely on-device, eliminating cloud latency and subscription costs.

*B. Smart Automation Module*

ESP32-based nodes connected to smart relays monitor PIR and environmental sensors to automatically control lighting, ceiling fans, and HVAC systems based on room occupancy and temperature thresholds.

*C. Digital Twin Dashboard Module*

A React.js web application with Three.js renders a 3D model of campus buildings. Real-time IoT sensor data is pushed via MQTT and WebSockets to update device statuses, occupancy indicators, and energy consumption metrics dynamically.

*D. Automated Gate Monitoring Module*

IP cameras at campus entry and exit gates capture vehicle images. OpenCV and a trained ANPR model extract number plate text. Entry is logged when the front of the bus is captured; exit is logged when the rear is captured. Records are stored in MySQL and selectively synced to the cloud.

*E. Biometric Access Control Module*

Fingerprint sensors and face recognition (via Coral TPU) authenticate personnel at restricted areas. Access logs are maintained locally with timestamps and user IDs.

*F. Offline Voice Command Module*

Vosk-based offline speech recognition running on Raspberry Pi interprets voice commands for controlling room devices. No internet connection is required for processing, ensuring operational continuity.

*G. LoRa Communication Module*

SX1276 LoRa transceivers form a campus-wide mesh network for long-range, low-power communication between IoT nodes and the central Raspberry Pi hub, particularly in areas with poor Wi-Fi coverage.

*H. Energy Management Module*

Monitors real-time power consumption across campus using current sensors integrated with the automation nodes. Aggregates energy data on InfluxDB and visualizes trends on the Digital Twin dashboard for facility management insights.

# VII. SYSTEM DESIGN

*A. Architecture*

The overall system architecture of IntelliSpace consists of three primary tiers: the Perception Layer (sensors and cameras), the Processing Layer (Edge AI devices and IoT nodes), and the Presentation Layer (3D Digital Twin dashboard and user interfaces). These tiers communicate through a combination of MQTT, LoRa, and WebSocket protocols.

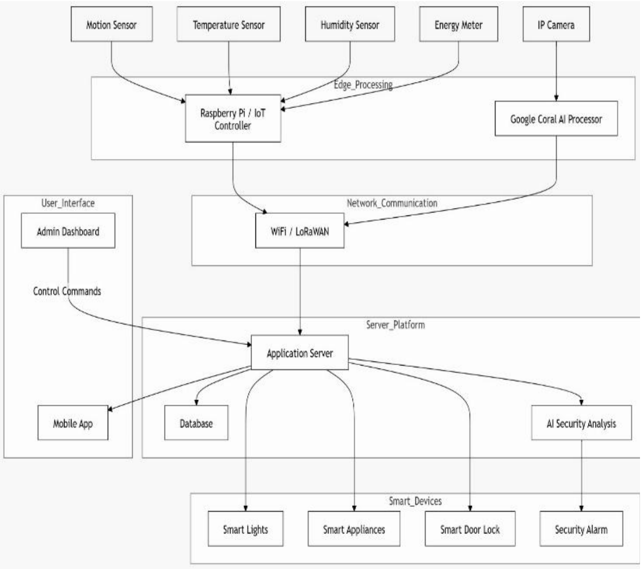


Fig. A Architecture diagram

*B. Data Flow*

The Data Flow Diagram (DFD) illustrates how data moves through the IntelliSpace system from sensor inputs through processing layers to storage and visualization outputs. Level 0 (Context Diagram) shows the overall system boundary, while Level 1 DFD details the interactions between major functional subsystems.

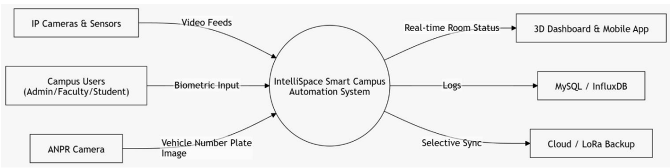


Fig. B Data flow diagram level 0

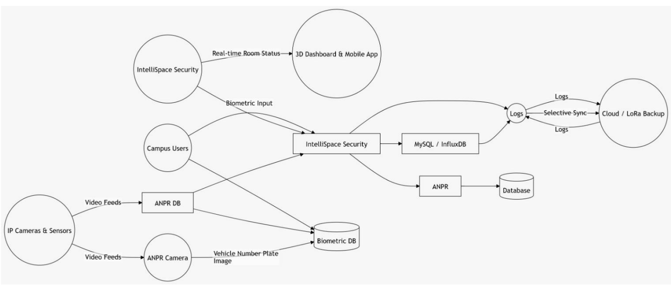


Fig. B Data flow diagram level 1

*C. UML Diagrams*

The Use Case Diagram identifies the key actors: Campus Administrator, Security Personnel, Faculty Member, Student, and System. The Activity Diagram illustrates the automated room control workflow — occupancy detection via PIR, device activation, and idle timeout. The Sequence Diagram for face recognition shows interactions between the IP Camera, Coral TPU, Biometric Controller, Access Control Module, and Audit Log Database.

1. Use case diagram

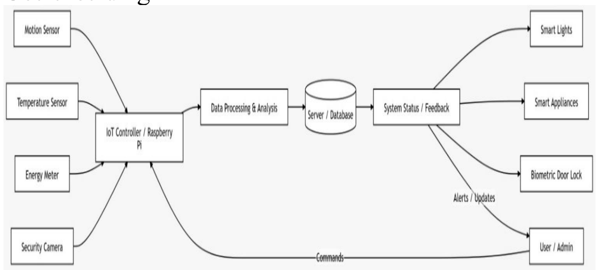


Fig. 1 Use case diagram

2. Sequence diagram

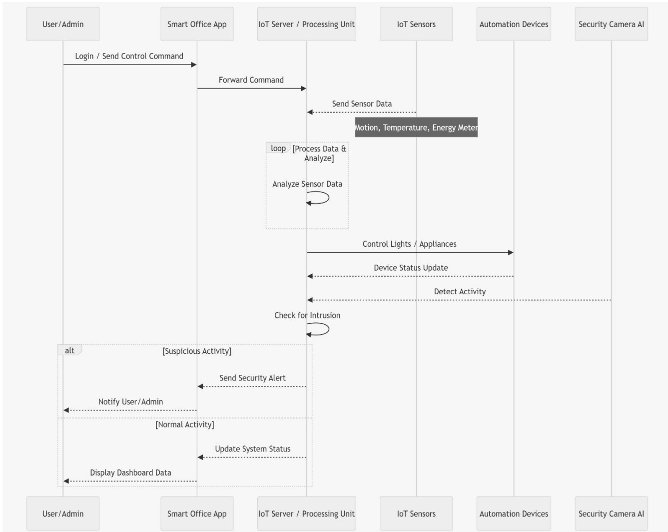


Fig. 1 Sequence diagram

# VIII. IMPLEMENTATION

*A. Hardware Deployment*

The hardware deployment follows a hierarchical node architecture. The central hub consists of a Raspberry Pi 4 with an attached Google Coral USB TPU accelerator. This hub connects to ESP32 IoT nodes via Wi-Fi (MQTT over TCP/IP) and to remote building nodes via LoRa modules. IP cameras are connected via Ethernet for reliable, high-bandwidth video streaming. Each room node (ESP32) is connected to a PIR sensor, a DHT22 sensor, smart relay modules for controlling lights/fans/AC, and optionally a fingerprint sensor.

*B. Software Implementation*

The backend runs Python-based microservices on the central Raspberry Pi. The MQTT broker (Mosquitto) handles real-time device communication. A Flask REST API serves sensor data to the frontend dashboard. InfluxDB stores time-series sensor data for trend analysis, while MySQL handles structured records such as gate logs and access control entries.

The 3D Digital Twin dashboard is implemented using React.js with Three.js for 3D campus model rendering. WebSocket connections push real-time sensor updates to the browser, triggering visual updates in the 3D model (e.g., room colour changes indicating occupancy, device state indicators).

*C. Edge AI Integration*

TensorFlow Lite models are deployed on the Google Coral TPU for inference acceleration. The face recognition pipeline uses a MobileNetV2-based model quantized to INT8 format for Coral compatibility. The anomaly detection pipeline uses a lightweight EfficientDet model trained on campus-specific scenes. The ANPR module uses an OpenCV preprocessing pipeline (grayscale conversion, Gaussian blur, edge detection, contour finding) followed by Tesseract OCR to extract plate text, which is matched against a registered vehicle database and logged to MySQL with timestamps.

## IX. Screenshots

1. Login Page

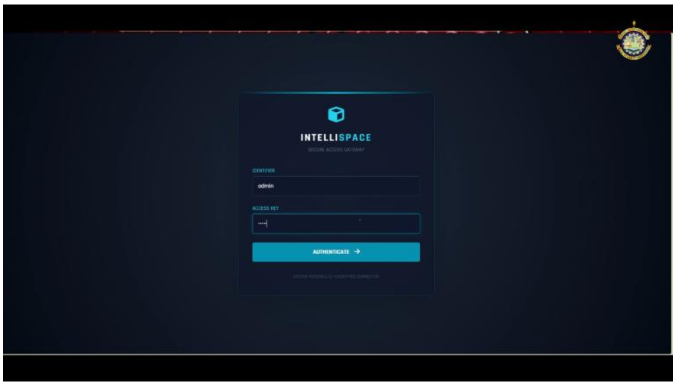


Fig. 1 Login Page

2. Operational Efficiency

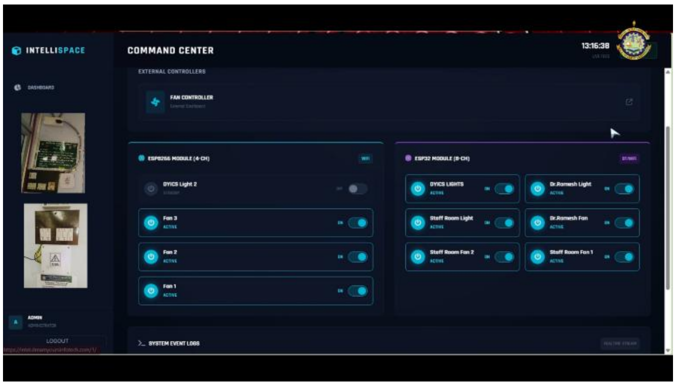


Fig. 2 Operation Efficiency

3. Ups Power Dashboard

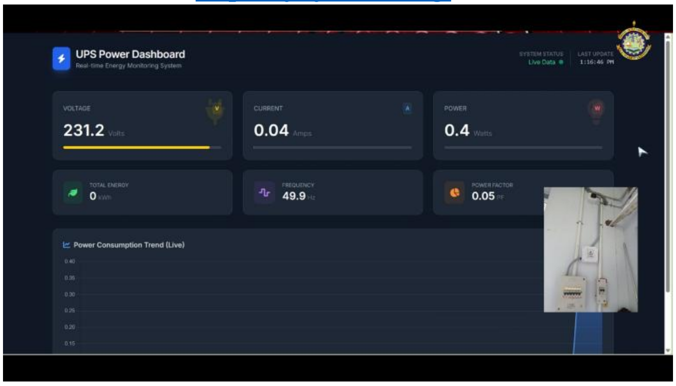


Fig. 3 Operation Efficiency

4. Classroom Utility Management

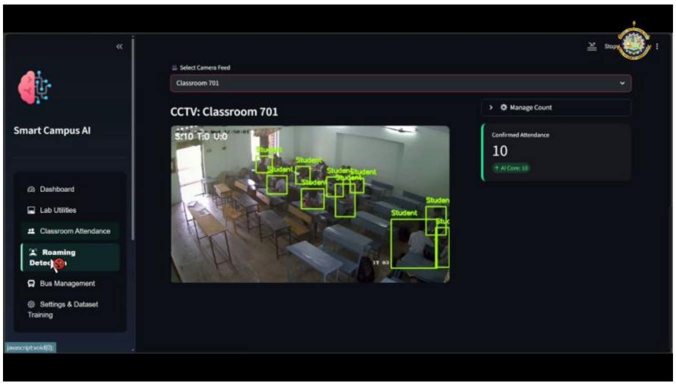


Fig. 4 Login Page

5. Roaming & Deepface Detection

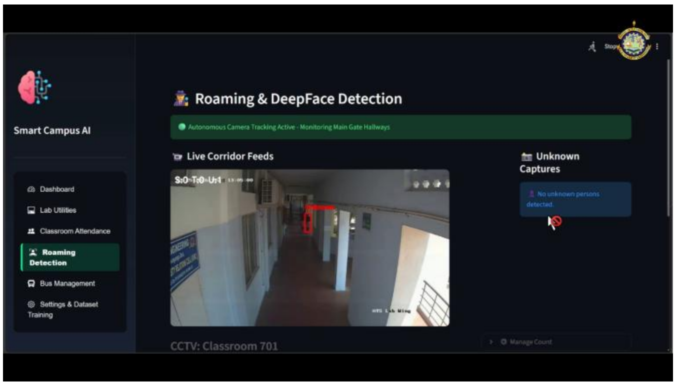


Fig. 5 Login Page

## X. Testing

*A. Unit Testing*

Each module is independently tested against defined acceptance criteria. The Edge AI module is tested for face recognition accuracy using a controlled dataset of 500 campus personnel images. The automation module is tested for relay switching response time. The ANPR module is tested using a dataset of 200 vehicle images captured at the campus gate under varied lighting conditions.

*B. Integration Testing*

Integration testing validates the end-to-end data flow between subsystems. Test scenarios include: occupancy detection triggering automated device control, face recognition triggering access control and audit logging, gate ANPR logging triggering cloud sync, and sensor data updates reflecting accurately on the Digital Twin dashboard.

*C. System Testing*

Full system testing was conducted across three campus buildings over a two-week period. Metrics measured include system uptime, energy savings percentage, face recognition false positive and false negative rates, ANPR plate recognition accuracy, and LoRa communication reliability across building distances.

## IX. Conclusions

IntelliSpace successfully demonstrates that a fully integrated, cloud-independent smart campus automation system is technically feasible and practically impactful. By combining Edge AI, IoT automation, biometric security, LoRa communication, and 3D digital twin visualization, the system addresses the core challenges of traditional campus management — energy inefficiency, inadequate security, and lack of real-time operational visibility — in a cost-effective and scalable manner.

The project validates the use of affordable edge computing hardware (Google Coral, Raspberry Pi, ESP32) as a viable alternative to expensive cloud AI subscriptions for real-time campus surveillance and automation. The 3D Digital Twin dashboard provides an intuitive, centralized interface for facility managers, while automated gate monitoring enhances vehicular access control without manual intervention.

IntelliSpace exemplifies SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11 (Sustainable Cities and Communities) by integrating advanced technology into everyday campus operations to create a safer, smarter, and more sustainable educational environment.

## Acknowledgment

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