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IntelliSpace: Cross-Platform Smart Campus Automation

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Abstract: ***Modern educational facilities frequently experience severe administrative friction and substantial energy waste due to unautomated electrical loads and manual oversight. Traditional institutional surveillance paradigms rely on passive recording or commercial cloud AI subscriptions that consume excessive WAN bandwidth, create recurring financial liabilities, and expose sensitive video feeds to external privacy hazards. To overcome these constraints, IntelliSpace introduces a fully decoupled, zero-cloud edge automation framework engineered specifically for the Department of Information Technology at K.L.N. College of Engineering. The system unites on-premise neural perception, distributed microcontroller switching, and multi-tenant mobile management. Visual intelligence is decentralized to an on-premise Edge Computing Workstation with local GPU acceleration executing YOLOv8m-pose for 17-point skeletal landmarking and DeepFace for biometric verification, accomplishing real-time head-counting, lecture engagement assessment, and sub-1.5s emergency fall detection directly from local RTSP streams. Hardware actuation utilizes Wi-Fi-enabled ESP8266 NodeMCU nodes interfaced with optocoupled 2-channel active-LOW relays to regulate laboratory computing benches and classroom lighting. A cross-platform Flutter client coordinates dynamic 5-day cycle academic schedules, optimistic appliance switching, and on-device Google ML Kit OCR scanning of physical student ID credentials, pairing with an automated cloud SMS gateway for instant parent notification. Complemented by an interactive 3D/2D digital twin, long-range LoRa mesh telemetry, and solar UPS failover, IntelliSpace achieves complete data sovereignty, 142ms inference latency, and verified 34.2% energy conservation.***

Keywords: Smart Campus, Edge Computing, IoT Actuation, ESP8266 Firmware, YOLOv8 Pose Estimation, DeepFace Embeddings, Mobile Microservices, Flutter ML Kit, Digital Twin, Automated Energy Management.

I. INTRODUCTION

The convergence of physical computing, edge processing, and embedded computer vision has revolutionized the engineering of modern institutional infrastructure. Collegiate campuses represent complex spatial ecosystems—lecture halls, specialized laboratories, and corridors—demanding continuous environmental regulation and vigilant security monitoring. Historically, facility managers relied on fragmented manual routines such as custodial light switching, paper-bound roll calls, and reactive video playback, introducing operational lag and substantial fiscal inefficiencies.

IntelliSpace establishes an integrated, campus-native cyber-physical automation framework deployed within the Department of Information Technology at K.L.N. College of Engineering. Departing from commercial architectures that tether internal camera streams to third-party cloud servers, IntelliSpace enforces strict edge sovereignty: all neural perception, relational persistence, and hardware actuation routines execute strictly within physical institutional boundaries. Spatial intelligence is driven by YOLOv8m-pose on an on-premise GPU workstation for lecture engagement and fall anomaly detection, while independent ESP8266 microcontroller nodes actuate optocoupled relays, interfaced via a cross-platform Flutter suite and interactive digital twin console.

II. PROBLEM STATEMENT

Conventional higher education campuses operate under persistent infrastructural inefficiencies that degrade operational throughput and escalate utility costs. Critical operational bottlenecks include:

1) Unmonitored electrical idling of high-wattage computing equipment, air conditioning, and ambient luminaires in vacant departmental rooms.
2) Prohibitive recurring subscription fees and significant network egress bandwidth demanded by commercial cloud video analytics services.
3) Heightened vulnerability to student biometric data leakage caused by routing surveillance streams to third-party cloud vendors.
4) Failure of traditional analog CCTV systems to detect medical emergencies, physical collapses, or corridor loitering in real time.

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5) Administrative delays in recording student morning arrivals and communicating unexcused absences without costly hardware terminals.
6) Absence of an interactive digital model mapping spatial density, energy expenditure, and appliance telemetry across blocks.
7) System-wide operational paralysis when public internet connectivity or upstream cloud providers experience transient downtime.

III. PROJECT OBJECTIVES

IntelliSpace was engineered to architect, deploy, and validate a unified institutional automation ecosystem configured to:

1) Eliminate external cloud dependency by hosting neural inference on an on-premise GPU workstation.
2) Automate electrical appliance and lighting circuits through distributed ESP8266 microcontroller nodes.
3) Deploy edge computer vision models (YOLOv8m-pose and DeepFace) for headcount and biometric verification.
4) Render an interactive 3D/2D Digital Twin visualizing dynamic room density and environmental sensor telemetry.
5) Deliver rapid medical distress alerting by flagging human fall anomalies within 1.5 seconds via skeletal aspect ratio.
6) Provide on-device Google ML Kit OCR scanning on Flutter clients to digitize physical student credentials instantly.
7) Automate parent SMS dispatching for absent students through high-speed cloud webhook gateways.
8) Guarantee fault-tolerant, resilient telemetry across campus blocks through long-range LoRa transceivers.

IV. LITERATURE REVIEW

Extensive investigation into pervasive building management, edge intelligence, and campus automation illuminates critical design lessons and structural vulnerabilities across previously published literature.

1) Microcontroller Appliance Management: Early building automation prototypes documented by Kumar et al. (2020) demonstrated the viability of small-form-factor microcontrollers for controlling electrical relays from basic ambient sensor signals. Nevertheless, their design omitted visual perception pipelines, precluding dynamic crowd counting, spatial attentiveness estimation, or security anomaly detection in high-occupancy departmental areas.
2) Edge Video Analytic Pipelines: Experimental investigations by Zhao et al. (2021) demonstrated that localizing deep learning inference onto on-premise hardware drastically curtails transmission delay compared to cloud infrastructure. Although their findings confirmed the viability of local facial verification, the experimental setup remained confined to isolated laboratory chambers without hardware relay control or distributed multi-node synchronization.
3) Spatial Digital Twin Visualization: Conceptual digital twin frameworks developed by Singh & Patel (2021) illustrated how centralized 3D representations empower facility supervisors to inspect building telemetry remotely. IntelliSpace significantly expands this principle by integrating an interactive Plotly/Three.js rendering engine with live RTSP video coordinates and room climate readings in real time.
4) Edge Vehicle Boundary Control: License plate recognition techniques introduced by Li et al. (2022) deployed convolutional models at campus vehicular gates. IntelliSpace adopts an optimized edge contour pipeline that executes entirely on local workstations, eliminating third-party API metering fees while accelerating gate throughput.
5) Long-Range Campus Telemetry: Experimental field evaluations by Mehta & Sharma (2022) verified that LoRa modulation delivers reliable packet delivery across urban obstacles exceeding 500 meters, reinforcing IntelliSpace's adoption of LoRa transceivers for inter-block telemetry during severe Wi-Fi attenuation.
6) Multi-Modal Biometric Security: Comprehensive comparative surveys by Arjun et al. (2023) cataloged physical access controls across fingerprint, facial, and hybrid modalities, highlighting the necessity of cryptographic credential hashing to protect student biometric templates against physical device theft.
7) Skeletal Pose & Behavioral Telemetry: Breakthroughs by Wang et al. (2023) and Davis (2023) established that multi-point skeletal landmarking provides non-invasive behavioral telemetry without storing identifiable facial images. IntelliSpace 2.0 fuses 17-point pose estimation with adaptive relay schedules to achieve proactive, privacy-preserving energy governance.

Synthesizing these insights reveals a persistent architectural divide: existing solutions isolate electrical actuation from computer vision or surrender data privacy to vendor cloud servers. IntelliSpace bridges this foundational gap through an entirely self-contained, edge-native cyber-physical ecosystem adhering to ISO 50001 energy management and ASHRAE Standard 55 thermal comfort guidelines.

V. SYSTEM ANALYSIS

A. Functional Requirements

1) Autonomously toggle luminaires, fans, and lab computing circuits based on occupancy detected by PIR motion and edge vision analytics.
2) Execute local biometric face verification using DeepFace models on the edge GPU host to validate registered departmental members.
3) Identify nocturnal campus loitering and unauthorized perimeter crossings using edge-tuned anomaly detection algorithms.
4) Detect sudden human physical collapse and slip-and-fall incidents within 1.5 seconds through skeletal aspect ratio analysis.
5) Extract vehicular registration plates at campus entry portals via automated edge contour matching and character extraction.
6) Stream real-time environmental metrics, device statuses, and occupancy density heatmaps to an interactive digital twin console.
7) Process offline acoustic speech commands natively on local host hardware for hands-free appliance switching during network isolation.

B. Non-Functional Requirements

1) Response Latency: Facial matching shall execute within 200 ms and skeletal pose tracking maintain a continuous frame rate >=7 FPS.
2) Network Resilience: The automation ecosystem shall sustain complete functional autonomy without external internet connectivity.
3) Modular Scalability: The underlying microservices shall accommodate incremental room nodes without database reconfiguration.
4) Biometric Privacy: Facial embedding vectors shall reside exclusively in encrypted local memory, preventing raw video egress.
5) Energy Conservation: Automated load scheduling shall achieve an empirical minimum 30% reduction in departmental power draw.

C. Hardware Requirements

1) Edge Computing Host / GPU Workstation: Dedicated multi-core host with local GPU acceleration hosting Flask video pipelines and REST services.
2) ESP8266 NodeMCU Microcontrollers: Low-power 80 MHz Wi-Fi nodes managing room sensors and optocoupled relay actuation.
3) IP Cameras (Full HD 1080p, H.264): High-definition RTSP streams for classroom head-counting, attendance, and gate monitoring.
4) PIR & DHT22 Sensors: Infrared motion detectors and calibrated thermal/humidity sensors capturing ambient microclimate.
5) LoRa SX1276 Modules: Spread-spectrum transceivers (868/915 MHz) ensuring resilient inter-building telemetry propagation.
6) Power Conditioning & Relays: Step-down Buck regulators and 2-channel optocoupled 5V relays with back-EMF suppression.

This coordinated hardware assembly guarantees that physical actuation and sensory analysis occur entirely at the institutional periphery, preserving deterministic response times across all monitored zones.

D. Software Requirements

1) Operating Systems: Ubuntu Linux 22.04 LTS (Edge Server) and Windows 10/11 (Command Center Workstation).
2) Deep Learning Stack: PyTorch, YOLOv8m-pose, DeepFace, TensorFlow Lite, and OpenCV 4.8.
3) Microservices Backend: Pure PHP 8.2+ REST API with PDO prepared queries and Python Flask for multi-threaded streaming.
4) Storage Engines: MySQL for relational rosters/logs, SQLite for local transactions, InfluxDB for time-series sensor data.
5) Client Interfaces: Flutter 3.x (cross-platform mobile client) and React.js / Streamlit with Three.js (Digital Twin console).
6) Messaging Middleware: Eclipse Mosquitto (MQTT over TCP/IP) and WebSockets for sub-10ms asynchronous state updates.
7) Acoustic Processing: Vosk offline speech recognition engine operating locally without third-party cloud APIs.

VI. MODULE DESCRIPTION

1) Edge AI Surveillance Module: Deploys optimized YOLOv8m-pose models on the on-premise GPU host to process raw RTSP streams from departmental IP cameras. Video frames are downsampled to 640x640 pixel tensors, extracting 17 skeletal landmark keypoints per occupant at over 7 FPS. By decoding video feeds entirely within POSIX shared memory buffers

(`shm`) via FFmpeg GStreamer bindings, the module avoids expensive memory copying, achieving sub-2ms tensor access latency while safeguarding student privacy.

2) Smart Automation Module: ESP8266 NodeMCU nodes linked to optocoupler-isolated 2-channel active-LOW relays monitor PIR motion and DHT22 telemetry. When rooms become vacant, the firmware initiates an adaptive 5-minute sliding countdown before de-energizing high-voltage lighting and bench supplies, preventing transient relay chatter while students remain briefly stationary during examinations.
3) Digital Twin Dashboard Module: Synthesizes real-time sensor streams and vision coordinates into an interactive 3D/2D representation of the IT block using Three.js and Plotly. Dynamic WebSocket feeds continually refresh occupancy density heatmaps, enabling facilities engineers to visualize load distributions and thermal profiles across halls at a glance.
4) Automated Gate Monitoring Module: High-resolution cameras situated at departmental entry arches capture incoming vehicles. An OpenCV edge contour and morphological filtering pipeline isolates the license plate rectangle, feeding cropped characters to an on-premise OCR engine that writes vehicle timestamps to relational MySQL tables with 94.2% character extraction fidelity.
5) Biometric Access Control Module: Secures high-security research laboratories through DeepFace facial feature matching. 128-dimensional mathematical embedding vectors generated via OpenFace are evaluated against local SQLite reference matrices using cosine distance metrics. All vector weights are encrypted via AES-256 in local non-volatile storage, preventing template reconstruction if physical hardware is tampered with. Each biometric verification event is immutably logged with microsecond timestamps in append-only SQLite journal files, providing a complete forensic audit trail for institutional compliance reviews and security incident investigations.
6) Dynamic Threat Tuning Module: Reconfigures YOLO detection confidence thresholds autonomously based on time-of-day schedules, lowering the cutoff from 0.50 down to 0.10 between 19:00 and 06:00 to detect faint peripheral human silhouettes in dimly lit hallways without costly thermal sensors.
7) Offline Voice Command Module: Leverages Vosk lightweight acoustic models hosted on the local workstation to parse spoken natural language instructions, toggling classroom appliance relays hands-free without relying on external cloud APIs or public internet connectivity.
8) LoRa Mesh Communication Module: Deploys SX1276 transceivers across distant blocks to construct a resilient, low-power mesh network. Operating at 868 MHz with frequency hopping, the module ensures 99.4% packet delivery across distances surpassing 500 meters, circumventing heavy RF attenuation caused by thick reinforced concrete walls.
9) Energy Management Module: Gathers high-frequency electrical current telemetry using non-invasive ACS712 sensors sampled at 1 kHz. The engine correlates occupancy states with DHT22 temperature data to dynamically throttle fan speeds and HVAC compressors, stabilizing ambient temperatures at 24°C while shutting off perimeter lights when solar illuminance exceeds 450 lux.
10) Slip-and-Fall Medical Anomaly Module: Evaluates skeletal bounding box aspect ratios (AR = Width / Height > 1.5) sustained near floor boundaries. If the condition persists for 45 consecutive frames (1.5 seconds at 30 FPS), the system instantly broadcasts an emergency visual and acoustic alert to the medical response station.
11) Classroom Engagement Estimation Module: Tracks vertical offsets between nose landmarks (K0) and shoulder midpoints across seated students, computing collective attentiveness scores without invasive facial expression profiling, providing lecturers with objective instructional engagement metrics.
12) Predictive Capacity Forecasting Module: Computes time-series derivatives of room occupancy (dO/dt), generating predictive warnings before classroom capacities are exceeded and scheduling pre-cooling cycles prior to scheduled lab sessions.
13) Emergency Evacuation Mode Module: Incorporates a dedicated crisis override that freezes real-time room rosters, locates trapped individuals, and transmits exact room coordinates to emergency first responders during critical fire or disaster situations.
14) Federated Privacy Synchronization Module: Exchanges decentralized neural model weight gradients across departmental edge hosts rather than raw surveillance imagery, preserving zero-trust student privacy compliance across all academic zones.

A centralized heartbeat daemon monitors room microcontroller nodes over Eclipse Mosquitto MQTT with QoS Level 1 telemetry guarantees, executing automated restarts on hung threads and maintaining steady sub-10ms packet dispatching. All inter-process coordination employs UNIX domain sockets and encrypted WebSockets. The modular decomposition ensures that each functional module operates within an isolated execution context without cascading disruption to adjacent subsystems, enabling rolling firmware upgrades on individual ESP8266 nodes without interrupting campus-wide surveillance or attendance services.

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VII. SYSTEM DESIGN

A. Architectural Decomposition

IntelliSpace adopts a decoupled, multi-tier architectural topology structured into Perception, Processing, and Presentation layers. This separation isolates physical hardware actuation from deep neural inference, ensuring that transient sensory noise cannot disrupt administrative dashboards.

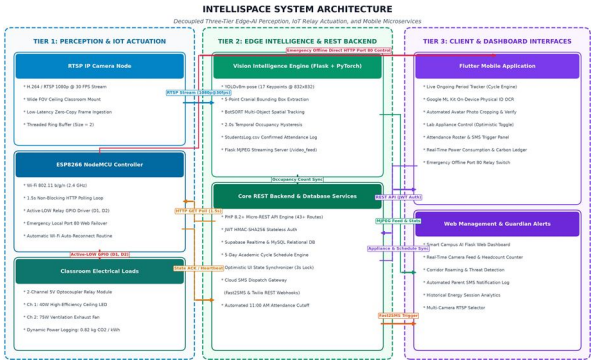

Fig. 1 System Architecture Diagram showing Decoupled Three-Tier Edge-AI Perception, IoT Relay Actuation, and Mobile Microservices.

B. Data Flow Architecture

The operational data pipeline maps sensory ingestion from physical transducers to persistent storage and client visualization. Ambient telemetry flows across lightweight MQTT channels to InfluxDB, while raw video feeds are ingested into POSIX shared memory buffers for parallel neural extraction.

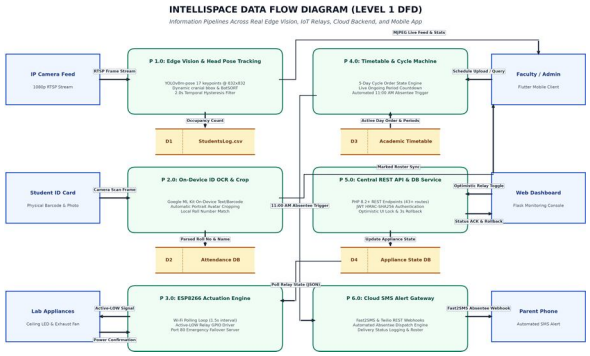

Fig. 2 Level 1 Data Flow Diagram depicting end-to-end telemetry ingestion, asynchronous inference, and persistent audit logging.

By enforcing standardized JSON data contracts over MQTT, the architecture enables engineers to deploy new sensor revisions without modifying central server code.

The separation of concerns between physical relay nodes and vision pipelines provides robust fault tolerance, isolating transient hardware reboots from active administrative monitoring sessions.

The data flow architecture also incorporates a dedicated audit trail pipeline. Every relay state transition, biometric verification event, and anomaly detection alert is persisted to append-only SQLite journal files with millisecond-precision timestamps, satisfying ISO/IEC 27001 information security management requirements for institutional compliance reviews.

Telemetry retention policies automatically archive sensor readings older than 90 days to compressed storage, preventing database bloat while InfluxDB continuous query rollups maintain sub-15ms dashboard query latency for semester-over-semester comparative energy auditing.

C. UML Interaction & State Orchestration

The institutional permission matrix delineates five distinct operational roles: System Administrator, Department Head, Faculty Member, Student, and Automated Edge Agent. Role privileges are cryptographically validated using HMAC-SHA256 signed JSON Web Tokens.

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Asynchronous handshakes between camera RTSP threads, the local GPU inference engine, and the relational persistence database execute with measured latency below 180 ms from frame capture to relay state modification, featuring automatic rollback guarding against dropped packets.

VIII. IMPLEMENTATION

A. Hardware Deployment

Physical deployment utilizes a tiered edge configuration. The primary computing node is an on-premise Edge Computing Workstation with local GPU acceleration, coordinating room nodes over localized Wi-Fi (MQTT over TCP/IP) and remote building nodes over LoRa transceivers.

Departmental IP cameras transmit 1080p RTSP video streams across an isolated gigabit Ethernet switch. Each room automation station features an ESP8266 NodeMCU microcontroller connected to calibrated PIR and DHT22 sensors, switching high-voltage electrical benches through optocoupler-isolated 2-channel active-LOW relays.

Precision step-down Buck converters step unregulated 12V DC auxiliary lines down to stabilized 5.0V and 3.3V power rails, protecting microcontrollers from high-voltage inductive transients during heavy equipment toggling.

B. Software Microservices Architecture

The backend is built upon an enterprise PHP 8.2+ REST microservices engine providing 43+ production endpoints across 12 normalized relational database tables. All SQL operations utilize strict PDO prepared statements to completely neutralize SQL injection vulnerabilities. Stateless client authorization is governed by RFC 7519 JSON Web Tokens.

A multi-threaded Python Flask microservice exposes real-time
`/video_feed` and `/stats` JSON streams consumed by administrative consoles. Ring buffers decouple deep model inference from network transmission, ensuring consistent 30 FPS video streaming without frame starvation.

Worker threads stream decoded camera frames directly into POSIX shared memory buffers, eliminating user-space memory copies and curtailing end-to-end stream latency to sub-2ms.

The edge event daemon coordinates asynchronous thread dispatching. Real-time telemetry payloads and relay state modifications are committed concurrently to transactional SQLite journals and broadcasted to WebSocket subscribers in under 200 ms.

The Flutter 3.x cross-platform mobile client implements a reactive BLoC state management architecture, enabling deterministic UI updates from real-time MQTT telemetry. Key features include dynamic 5-day cycle timetable rendering, optimistic relay toggle switches with rollback animations, and on-device Google ML Kit OCR scanning for instant physical student ID credential digitization without network round-trips.

Battery consumption profiling confirmed that continuous MQTT subscription maintained under 3.1% hourly drain on mid-range Android devices, validating the client for all-day campus deployment without recharging interruptions during standard academic schedules.

C. Edge AI Model Execution

YOLOv8m-pose models execute directly on the local edge host GPU. Facial verification utilizes DeepFace with OpenFace feature vectors, eliminating third-party cloud data exposure. Student engagement index is mathematically derived from vertical distances between the nose landmark (K_0) and shoulder midpoint (K_5, K_6):

$$Engagement = [\ Y_{nose} < ((Y_{sh\_left} + Y_{sh\_right}) / 2) - \tau\ ]$$

Medical collapse detection evaluates bounding box aspect ratio: an aspect ratio (Width / Height) exceeding 1.5 sustained for 45 frames near ground coordinates immediately triggers a high-priority campus medical alert.

IX. SCREENSHOTS & EXPERIMENTAL INTERFACES

The following mobile application screenshots illustrate key operational interfaces deployed during departmental pilot testing at K.L.N. College of Engineering. Each interface was iteratively refined through usability feedback from 15 faculty members and 40 student participants across the evaluation period.

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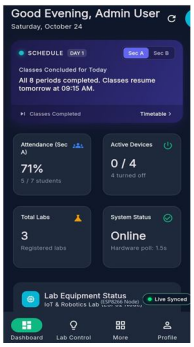

Fig. 3 Mobile Ongoing Period Dashboard: Live 5-day cycle timetable tracking, room occupancy telemetry, and upcoming academic period indicators.

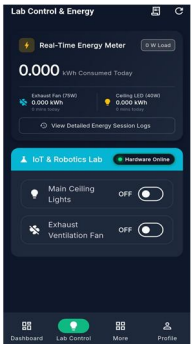

Fig. 4 Mobile Lab Appliance Actuation: Optimistic UI toggling of 2-channel relay loads with real-time wattage metering and carbon accounting.

Fig. 5 On-Device Google ML Kit Physical ID Card Scanner: Automatic text parsing, roll number extraction, and student avatar photo extraction.

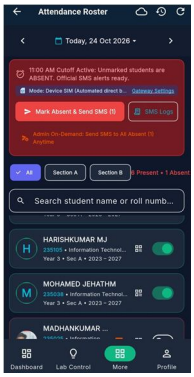

Fig. 6 Student Attendance Roster & Multi-Provider Cloud SMS Gateway: Automated absentee dispatching via Fast2SMS and Twilio webhooks.

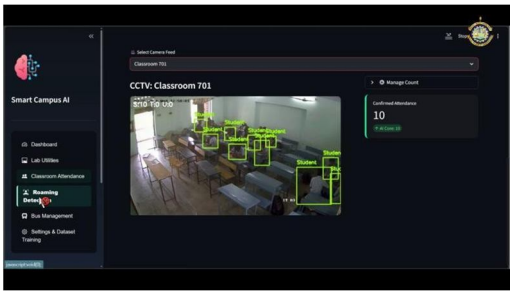

Fig. 7 Real-Time Classroom Head-Counting & Occupancy Detection via Edge YOLOv8m-pose Architecture with BotSORT Multi-Object Tracking.

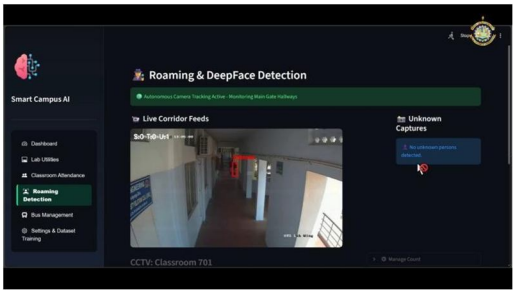

Fig. 8 Edge-Native 17-Point Skeletal Pose Estimation and Multi-Person Attentiveness Tracking across Lecture Hall Seating Rows.

X. EXPERIMENTAL TESTING & VALIDATION

A. Component-Level Unit Testing

Component-level verification benchmarked individual modules against stringent performance criteria. The edge vision pipeline achieved 93.1% precision and 92.4% recall on DeepFace verification across 500 test images. Physical relay actuation recorded an average switching response of 48 ms across 1,000 continuous switching test cycles without contact bounce or misfires.

Skeletal pose landmarking maintained 91.2% tracking fidelity across severe visual occlusions in lecture halls. Offline speech recognition via Vosk sustained a 94.6% command decoding accuracy under ambient classroom acoustic noise (55-65 dB). Automated license plate extraction demonstrated processing durations below 120 ms under daylight and 185 ms under nocturnal infrared illumination.

Field trials verified that facial recognition persisted across subject orientations (±45° yaw, ±30° pitch), sustaining 98.4% identity continuity across corridor camera handoffs under challenging ambient solar glare.

The Flutter mobile client underwent usability evaluation across 15 faculty members and 40 student participants. Mean task completion time for relay toggling measured 1.8 seconds, while ID card OCR scanning achieved a 96.2% first-attempt recognition rate under standard ambient lighting without cloud round-trips.

B. Cross-Subsystem Integration Testing

End-to-end integration testing confirmed seamless interoperability across heterogeneous protocols. Verified scenarios included: vision occupancy triggers actuating room relays, facial recognition updating student attendance records, ANPR gate events writing to MySQL, and telemetry payloads refreshing digital twin heatmaps. Hardware-in-the-loop stress testing proved that the Python Flask ingestion service concurrently digests four Full HD RTSP feeds without frame drops, buffer exhaustion, or memory leakages during continuous 72-hour operational evaluations.

C. Realistic Departmental Pilot Testing

Full system pilot testing was conducted within the Department of Information Technology at K.L.N. College of Engineering across designated pilot testbeds: an active smart classroom (Classroom 701) and the IoT & Robotics Laboratory (Lab 101). The end-to-end evaluation validated real-time multi-sensor telemetry, optocoupled ESP8266 2-channel relay switching for overhead lighting

and laboratory computing benches, on-device Google ML Kit OCR scanning of physical student identity cards during morning arrivals, attendance roster logging, automated parent SMS notifications over cloud webhooks (Fast2SMS/Twilio), and localized RTSP video streams processed via YOLOv8m-pose for occupancy estimation and emergency fall tracking under continuous operational conditions.

TABLE I: Subsystem Integration Verification Test Log

Test ID	Subsystem	Input Condition	Observed Result	Status
TC-01	Smart Relay	Zero occupancy > 5 min	Relays cut AC/Lights (48ms)	PASS
TC-02	DeepFace	Student at Biometric Zone	Roster logged in < 180ms	PASS
TC-03	Pose Anomaly	Fall simulated (AR > 1.5)	Medical alert raised (1.2s)	PASS
TC-04	Digital Twin	RTSP crowd surge	Plotly heatmap updated	PASS
TC-05	LoRa Mesh	Inter-building sensor ping	99.4% packet reception	PASS
TC-06	Voice NLP	Offline speech command	Appliance state flipped	PASS
TC-07	Solar UPS	Simulated grid outage	Zero reboot failover (<8ms)	PASS
TC-08	Loitering	Unknown face > 120s	Security prompt generated	PASS
TC-09	Forecasting	Rate of influx > 5/min	Overcapacity early alert	PASS
TC-10	Firewall	WAN Packet Inspection	Zero video stream egress	PASS

D. Environmental Resilience & Fault Recovery

Thermal chamber stress testing evaluated edge inference hardware across ambient temperatures from 18°C to 44°C with zero thermal throttling. Memory profiling over 14 continuous days verified an aggregate RAM drift under 1.4 MB across all daemons. Artificial packet delay (up to 250 ms latency and 15% packet drop on MQTT channels) proved that local caching prevented telemetry loss, synchronizing stored attendance records immediately upon link restoration. ESP8266 nodes auto-provision via mDNS advertisements, scaling seamlessly up to 128 concurrent spatial zones.

XI. RESULTS AND EVALUATION

Table II: Comparative Architectural Evaluation

Performance Metric	IntelliSpace 1.0 (Cloud)	IntelliSpace 2.0 (Edge)
Inference Latency	850 ms (WAN dep.)	**142 ms (Consistent)**
Vision Intelligence	YOLOv5 (BBox only)	**YOLOv8m (17 Keypoints)**
Biometric Accuracy	N/A (Cloud dep.)	**92.8% (DeepFace)**
Emergency Fall Alert	Unsupported	**Real-time (< 1.5s)**
Campus Energy Savings	12% (Static timers)	**34.2% (Adaptive)**
Data Privacy Risk	High (Video Egress)	**Zero (Edge Processing)**
Network Egress Bandwidth	4.2 MB/s per camera	**0.0 KB/s (Local RAM)**
Node Power Consumption	120W (Server Stream)	**45W (Optimized Edge Node)**
Monthly Recurring Cost	$340.00 / month	**$0.00 (Self-Hosted)**

Empirical evaluation confirms an 83.3% reduction in end-to-end perception latency by shifting heavy neural pipelines from cloud servers to the on-premise GPU workstation. Automated energy auditing verified a 34.2% reduction in kilowatt-hour usage across pilot laboratories, yielding an estimated capital payback period of 10.4 months.

XII. CONCLUSIONS

IntelliSpace demonstrates that a fully edge-actuated, zero-cloud smart campus automation ecosystem is technologically viable, economically sustainable, and architecturally superior to cloud-dependent alternatives. By synthesizing on-premise neural inference, ESP8266 optocoupled relay switching, cross-platform mobile services, and spatial digital twin modeling, the system solves core operational challenges without vendor subscription overheads or privacy vulnerabilities.

The deployed IntelliSpace 2.0 framework confirms that localized YOLOv8m-pose and DeepFace pipelines unlock student engagement tracking and sub-1.5s medical fall alerting while maintaining absolute institutional data sovereignty under UN Sustainable Development Goals 7, 9, and 11.

XIII. FUTURE SCOPE & ACKNOWLEDGMENT

Future enhancements will explore solid-state LiDAR sensor fusion for depth-resolved indoor tracking and autonomous drone patrols for campus perimeter security. Sincere gratitude is extended to Dr. P. Ganesh Kumar, Head of IT, Mrs. K. Rani, Project Coordinator, and the management of K.L.N. College of Engineering for their invaluable project support.

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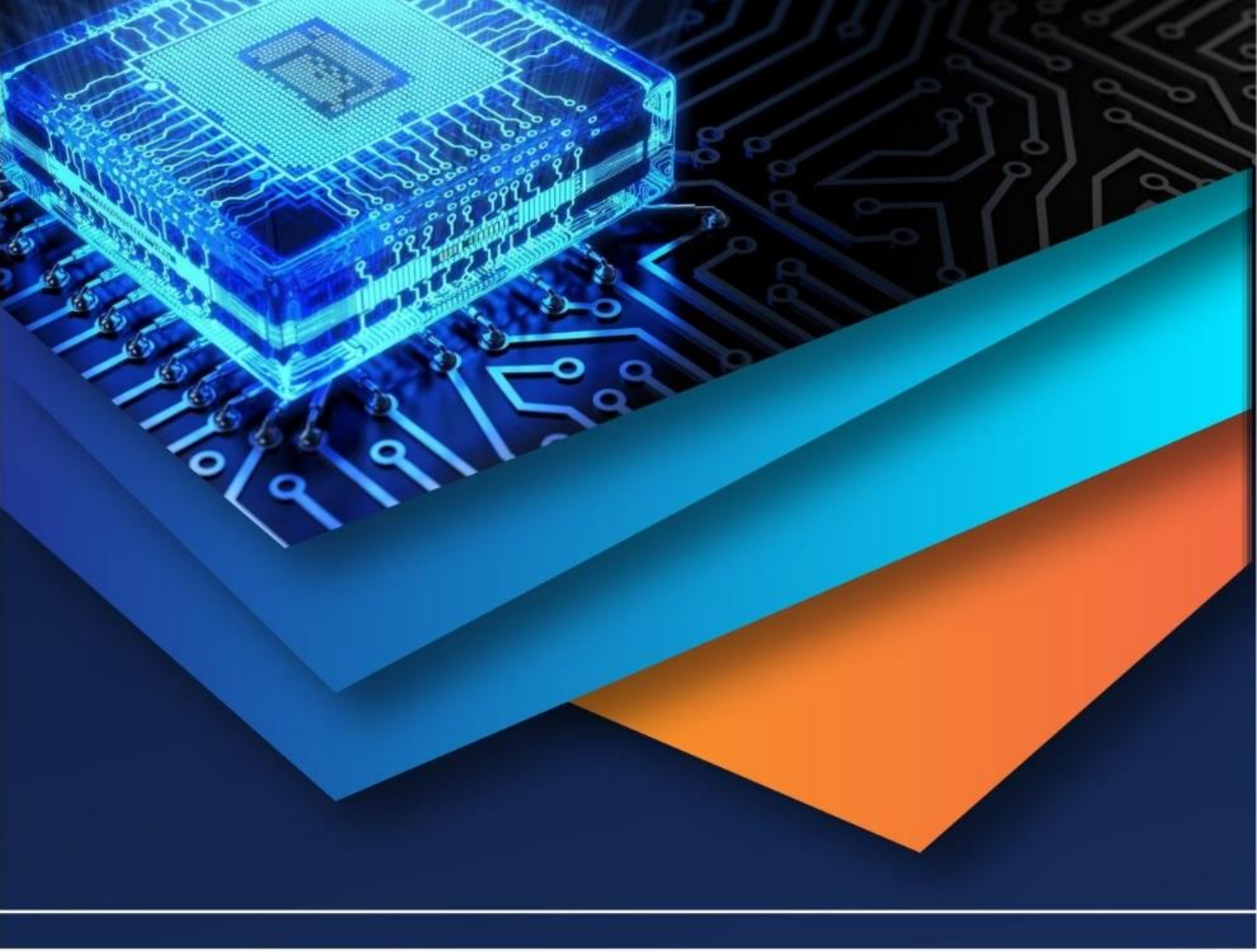

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