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Design and Development of an IoT-Enabled Smart Streetlight Monitoring Enclosure for Intelligent Urban Infrastructure and Energy Management

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Abstract

The rapid expansion of smart cities and intelligent urban infrastructure has increased the demand for efficient, scalable, and data-driven public utility systems. Traditional streetlight infrastructure remains heavily dependent on manual inspection and reactive maintenance approaches, resulting in excessive energy consumption, delayed fault detection, high maintenance costs, and reduced operational efficiency. Existing lighting systems often lack real-time monitoring capability, predictive diagnostics, and remote infrastructure visibility, making them unsuitable for modern smart-city environments. Consequently, there is a growing need for integrated IoT-enabled monitoring systems capable of improving streetlight performance, infrastructure resilience, and energy management in urban environments.

This study presents the design and development of an IoT-enabled smart streetlight monitoring enclosure specifically engineered for intelligent urban infrastructure and energy management applications. The project focused on the engineering design, prototyping, and fabrication of a weather-resistant black-box enclosure capable of housing sensing electronics, embedded communication systems, power management units, and solar charging components for outdoor streetlight deployment. The system was developed using a structured engineering methodology involving computer-aided design (CAD), additive manufacturing principles, embedded system integration, and outdoor infrastructure optimization. The enclosure was designed using SolidWorks CAD software and optimized for additive manufacturing through Fused Filament Fabrication (FFF) and Stereolithography (SLA) 3D-printing techniques. Several engineering considerations were incorporated during development, including thermal management, UV resistance, aerodynamic performance, environmental protection, mounting flexibility, solar-panel inclination optimization, and accurate housing of embedded electronics such as sensors, printed circuit boards (PCBs), GPS modules, and communication units.

The final system integrates a modular IoT sensing architecture with solar-powered energy support, wireless communication capability, and real-time monitoring functionality suitable for smart infrastructure deployment. The developed enclosure demonstrated strong outdoor durability characteristics, modular scalability, ease of maintenance, and compatibility with smart-city monitoring applications. The project contributes to the advancement of intelligent public infrastructure by providing a low-cost, scalable, and energy-efficient monitoring solution for urban streetlight systems. The proposed system has significant applications in smart-city development, predictive maintenance, energy optimization, infrastructure monitoring, and sustainable urban management.

Keywords

IoT, Smart Infrastructure, Smart Streetlight, Embedded Systems, Smart Cities, Energy Monitoring, Renewable Energy, Predictive Maintenance.

1. Introduction

The rapid global expansion of urban populations has accelerated the development of smart cities and intelligent infrastructure systems aimed at improving sustainability, operational efficiency, and public service delivery. Smart-city technologies increasingly rely on interconnected sensing systems, Internet of Things (IoT) architectures, and data-driven infrastructure management platforms to optimize urban operations and improve the quality of life of citizens. According to recent studies, smart infrastructure systems are becoming central to urban modernization strategies because they enable real-time monitoring, predictive maintenance, automated decision-making, and improved resource management across transportation, energy, water, and public utility sectors (Khan et al., 2023; Gupta and Hall, 2022). Among these infrastructures, streetlight systems represent a major component of urban energy consumption and public safety operations.

Traditional streetlight systems are primarily designed for static operation and generally lack intelligent monitoring and adaptive control capabilities. In many urban environments, streetlight infrastructure still depends on manual inspection procedures to identify failures, energy losses, and operational inefficiencies. This reactive maintenance approach often leads to delayed fault detection, increased maintenance costs, prolonged service outages, and excessive energy consumption (Rahman et al., 2022). Furthermore, conventional systems offer limited visibility into infrastructure performance, making it difficult for municipalities and utility operators to collect operational data required for optimization and long-term planning. Studies have shown that inefficient public lighting systems contribute significantly to urban energy waste and maintenance expenditure, particularly in developing smart-city environments where infrastructure scalability is becoming increasingly important (Zhang et al., 2024).

The integration of IoT technologies into public lighting infrastructure has emerged as an effective solution for addressing these limitations. IoT-enabled smart streetlight systems utilize embedded sensors, wireless communication networks, microcontrollers, and cloud-based monitoring platforms to provide real-time operational intelligence and remote infrastructure management (Singh et al., 2021). These systems allow operators to monitor streetlight status remotely, detect failures automatically, optimize energy consumption, and implement predictive maintenance strategies. In addition, IoT-enabled infrastructures support the broader objectives of smart cities by improving operational efficiency, enhancing sustainability, and enabling data-driven urban management (Almutairi et al., 2023).

Recent advancements in embedded systems, additive manufacturing, and renewable energy technologies have further expanded the capabilities of smart infrastructure systems. Embedded microcontrollers and low-power wireless communication modules now enable the development of compact and energy-efficient monitoring devices suitable for outdoor deployment. Similarly, additive manufacturing technologies such as Fused Filament Fabrication (FFF) and Stereolithography (SLA) allow rapid prototyping and low-cost fabrication of customized infrastructure enclosures with improved geometric flexibility and reduced production complexity (Wang et al., 2022). The integration of solar energy systems into IoT infrastructure also improves deployment flexibility and supports sustainable energy utilization in public utility applications.

Despite these advancements, several challenges remain in the development of scalable smart streetlight monitoring systems. Many existing solutions focus primarily on software functionality while paying limited attention to the physical infrastructure housing required for reliable outdoor deployment. Environmental exposure, thermal effects, moisture ingress, solar sensitivity, mounting stability, and long-term outdoor durability significantly influence the operational performance of embedded monitoring systems (Kim and Lee, 2023). Inadequate enclosure design may result in sensor degradation, communication instability, overheating, and reduced system lifespan. Consequently, there remains a need for optimized enclosure systems specifically designed for outdoor IoT-enabled smart streetlight applications.

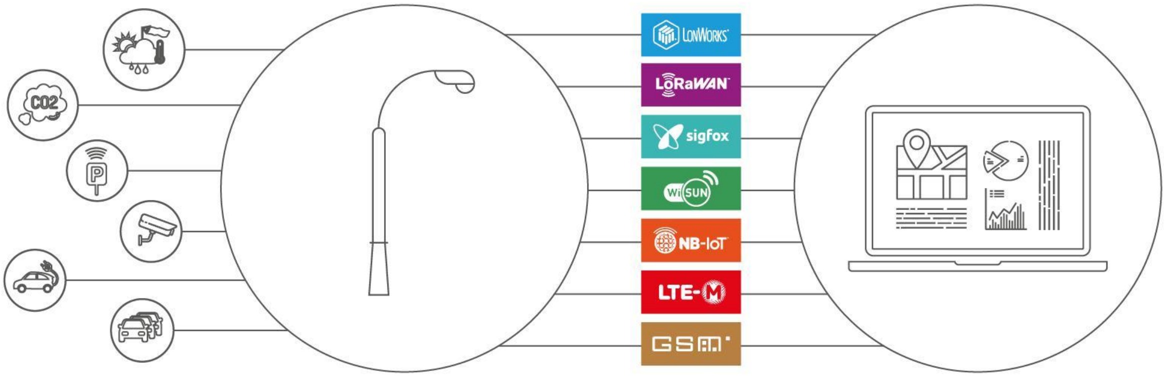
This study presents the design and development of an IoT-enabled smart streetlight monitoring enclosure intended for intelligent urban infrastructure and energy management applications. The project focused on the engineering design, additive manufacturing optimization, and integration of embedded sensing architecture within a durable outdoor enclosure capable of supporting real-time streetlight monitoring and feedback communication. The developed system incorporates solar-powered support, embedded sensing components, GPS integration, communication modules, and modular mounting mechanisms suitable for deployment on urban streetlight poles. The design process considered environmental protection, thermal management, aerodynamic performance, manufacturability, and system scalability to ensure long-term operational reliability in outdoor environments.

The novelty of this work lies in the development of a fully integrated smart monitoring enclosure that combines additive manufacturing optimization, renewable energy support, modular IoT sensing architecture, and outdoor infrastructure durability within a scalable low-cost design. Unlike many existing smart streetlight systems that prioritize software-level monitoring alone, this project emphasizes the complete engineering integration of embedded electronics, enclosure architecture, solar-power optimization, and infrastructure deployment considerations. The developed enclosure contributes to smart-city advancement by enabling efficient monitoring, predictive maintenance capability, energy optimization, and intelligent public infrastructure management.

2. Literature Review

2.1 Smart Streetlight Systems

The increasing adoption of smart-city technologies has accelerated the development of intelligent streetlight systems capable of improving energy efficiency, public safety, and infrastructure management. Traditional streetlight systems are generally based on fixed operational schedules and manual maintenance procedures, which often result in excessive energy consumption and delayed fault response. In contrast, modern smart streetlight systems integrate sensors, wireless communication technologies, and centralized monitoring platforms to provide automated and adaptive lighting control (Singh et al., 2021). These systems allow municipalities to monitor lighting conditions remotely, optimize power consumption, and improve maintenance efficiency through data-driven operations.



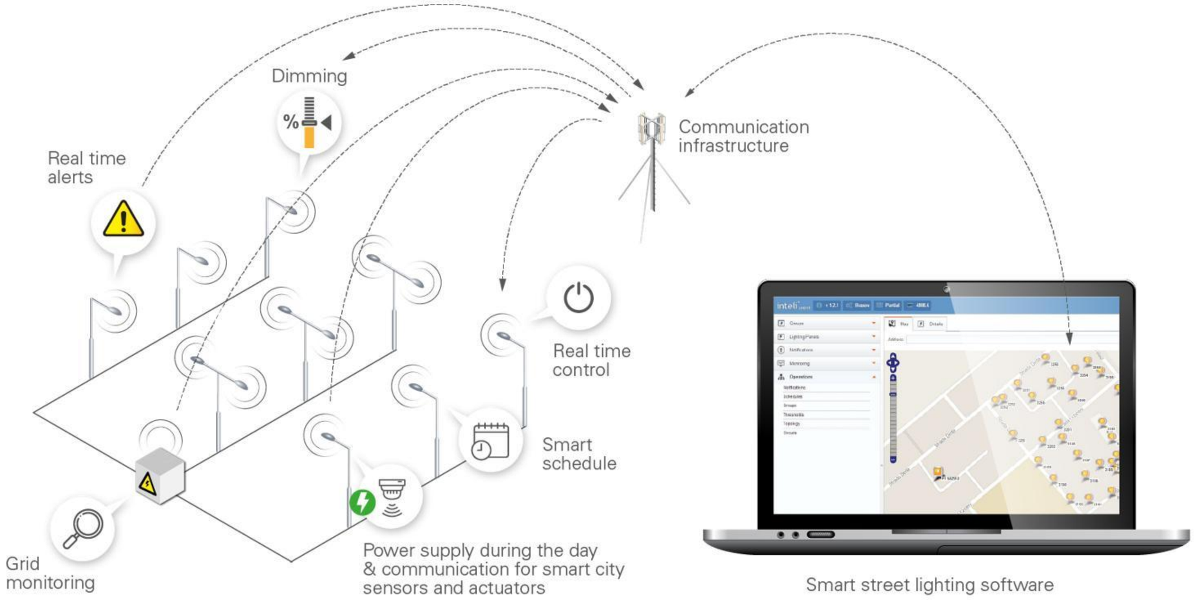
Existing intelligent lighting systems commonly utilize embedded controllers, light-dependent sensors, motion sensors, and wireless communication modules to automate streetlight operations. Several studies have demonstrated that adaptive lighting systems can significantly reduce urban energy consumption by dynamically adjusting illumination intensity based on traffic density, pedestrian movement, and environmental conditions (Rahman et al., 2022). Smart streetlights are increasingly integrated with centralized dashboards that provide operators with real-time infrastructure visibility, fault notifications, and operational analytics. These systems contribute to reduced operational expenditure and enhanced service reliability.

The integration of IoT technologies into urban infrastructure has transformed the functionality of streetlight systems from simple lighting devices into intelligent infrastructure assets. IoT-enabled streetlights can collect, process, and transmit operational data continuously through cloud-connected networks, enabling predictive analysis and automated system management (Almutairi et al., 2023). In many smart-city deployments, streetlight systems are now integrated with environmental monitoring sensors, surveillance systems, traffic management networks, and public safety infrastructure. This convergence of technologies has expanded the strategic importance of smart lighting systems within urban digital transformation initiatives.

Despite these advancements, many existing smart streetlight systems still face limitations relating to scalability, deployment cost, and long-term outdoor durability. Several systems rely heavily on expensive proprietary architectures and centralized infrastructure, making large-scale deployment difficult for municipalities with budget constraints (Khan et al., 2023). Furthermore, inadequate environmental protection of sensing hardware and communication systems often reduces operational reliability in harsh outdoor conditions. Consequently, research attention has increasingly shifted toward the development of modular, low-cost, and durable smart streetlight infrastructures capable of supporting scalable smart-city deployment.

2.2 Smart Sensors and Embedded Electronics

Embedded electronics and smart sensing technologies form the foundation of modern IoT-enabled infrastructure systems. Embedded systems combine microcontrollers, sensors, communication modules, and power-management components to provide intelligent monitoring and automated operational control. Recent advancements in embedded electronics have enabled the development of compact, energy-efficient, and highly scalable monitoring platforms suitable for smart-city infrastructure applications (Kim and Lee, 2023). These technologies are particularly important in smart streetlight systems, where continuous sensing, data acquisition, and remote communication are required under varying environmental conditions.



Microcontrollers play a critical role in the operation of smart monitoring systems by serving as the central processing unit responsible for sensor management, communication coordination, and data processing. Commonly used embedded controllers include ARM Cortex-based systems, ESP32 modules, and Arduino-compatible platforms due to their low-power operation and flexible interfacing capabilities (Wang et al., 2022). These controllers support real-time processing of sensor data and facilitate communication between sensing devices and cloud-based monitoring platforms. Their integration into smart streetlight infrastructure enables adaptive system behavior and automated operational decision-making.

Wireless communication systems are equally important in enabling IoT-based infrastructure management. Modern smart streetlight systems frequently utilize wireless communication technologies such as LoRaWAN, GSM, NB-IoT, Wi-Fi, Zigbee, and LTE-M to support long-range data transmission and remote device management (Singh et al., 2021). These communication technologies allow distributed infrastructure assets to transmit operational information to centralized monitoring platforms in real time. The selection of communication protocols often depends on energy consumption, transmission range, infrastructure density, and deployment environment.

Real-time monitoring capability has become a major requirement in intelligent urban infrastructure systems. Smart sensors integrated into streetlight systems can continuously monitor electrical parameters, environmental conditions, infrastructure status, and equipment performance. Real-time sensing allows infrastructure operators to identify abnormal operational conditions immediately and initiate corrective actions before major failures occur (Zhang et al., 2024). This improves operational reliability, reduces maintenance response time, and supports predictive maintenance strategies. However, the long-term performance of embedded systems in outdoor environments remains dependent on robust enclosure design, thermal management, and environmental protection.

2.3 Predictive Maintenance in Smart Cities

Predictive maintenance has emerged as a critical component of modern smart-city infrastructure management. Traditional maintenance approaches are largely reactive, relying on manual inspections or user complaints before faults are addressed. This maintenance model often results in infrastructure downtime, inefficient resource utilization, and increased operational expenditure. Predictive maintenance systems utilize sensors, real-time monitoring technologies, and data analytics to identify early signs of infrastructure degradation before failures occur (Gupta and Hall, 2022). This proactive maintenance strategy significantly improves infrastructure reliability and operational efficiency.

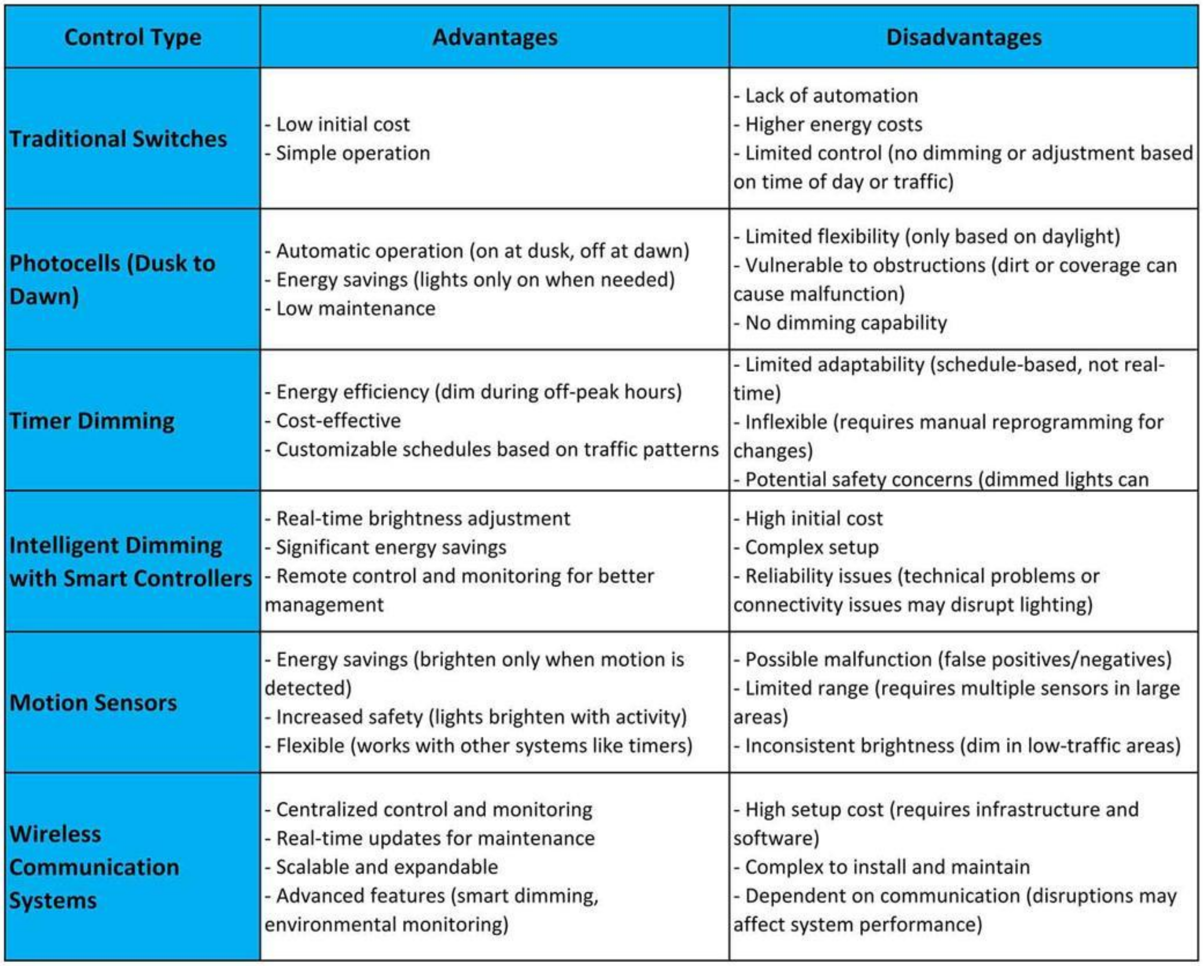
Infrastructure reliability is particularly important in public utility systems such as streetlight networks, where operational failures can affect public safety, transportation efficiency, and urban productivity. Smart infrastructure systems equipped with embedded sensors can continuously monitor equipment performance, electrical conditions, and environmental parameters to detect anomalies in real time (Rahman et al., 2022). The availability of continuous operational data enables engineers to assess infrastructure health and identify components approaching failure conditions. This improves maintenance scheduling and minimizes unplanned service interruptions.

Fault detection systems represent a major advancement in smart-city infrastructure management. Embedded fault-monitoring algorithms can automatically identify abnormal conditions such as power interruptions, communication failures, battery degradation, sensor malfunction, and unusual energy consumption patterns. These systems generate automated alerts and maintenance notifications that improve maintenance response time and operational accountability (Almutairi et al., 2023). Automated fault detection also reduces dependence on manual inspection procedures, lowering operational costs and improving infrastructure visibility.

The integration of analytics and automation technologies further enhances predictive maintenance capability within smart infrastructure systems. Advanced analytics platforms can process large volumes of operational telemetry data to identify hidden patterns and forecast potential failures using machine learning algorithms and statistical models (Khan et al., 2023). Automated maintenance systems can prioritize infrastructure assets based on risk level, operational criticality, and maintenance urgency. These technologies support long-term infrastructure sustainability and contribute to more efficient urban management. However, many existing predictive maintenance systems remain expensive and difficult to scale across large municipal infrastructure networks.

2.4 Research Gap

Despite the growing adoption of IoT-enabled streetlight systems and smart infrastructure technologies, several critical gaps remain within existing research and practical deployment frameworks. Many current smart streetlight solutions primarily focus on software-level monitoring and communication functionality while placing limited emphasis on physical infrastructure design and outdoor deployment durability. Existing studies frequently overlook the importance of enclosure optimization, environmental protection, thermal management, and long-term outdoor reliability, all of which significantly influence system performance and operational lifespan (Kim and Lee, 2023).



Control Type	Advantages	Disadvantages
Traditional Switches	- Low initial cost - Simple operation	- Lack of automation - Higher energy costs - Limited control (no dimming or adjustment based on time of day or traffic)
Photocells (Dusk to Dawn)	- Automatic operation (on at dusk, off at dawn) - Energy savings (lights only on when needed) - Low maintenance	- Limited flexibility (only based on daylight) - Vulnerable to obstructions (dirt or coverage can cause malfunction) - No dimming capability
Timer Dimming	- Energy efficiency (dim during off-peak hours) - Cost-effective - Customizable schedules based on traffic patterns	- Limited adaptability (schedule-based, not real-time) - Inflexible (requires manual reprogramming for changes) - Potential safety concerns (dimmed lights can
Intelligent Dimming with Smart Controllers	- Real-time brightness adjustment - Significant energy savings - Remote control and monitoring for better management	- High initial cost - Complex setup - Reliability issues (technical problems or connectivity issues may disrupt lighting)
Motion Sensors	- Energy savings (brighten only when motion is detected) - Increased safety (lights brighten with activity) - Flexible (works with other systems like timers)	- Possible malfunction (false positives/negatives) - Limited range (requires multiple sensors in large areas) - Inconsistent brightness (dim in low-traffic areas)
Wireless Communication Systems	- Centralized control and monitoring - Real-time updates for maintenance - Scalable and expandable - Advanced features (smart dimming, environmental monitoring)	- High setup cost (requires infrastructure and software) - Complex to install and maintain - Dependent on communication (disruptions may affect system performance)

Another major limitation in existing systems is the high implementation cost associated with many commercial smart streetlight platforms. Several current architectures depend on proprietary communication systems, centralized infrastructure, and expensive sensing technologies, making them financially challenging for large-scale municipal deployment (Gupta and Hall, 2022). In many cases, smart infrastructure projects fail to scale effectively because the cost of hardware deployment, infrastructure maintenance, and system integration exceeds available municipal budgets. Consequently, there is increasing demand for low-cost, modular, and scalable smart monitoring systems that can support widespread deployment without compromising operational reliability.

Limited real-time fault detection capability also remains a major challenge in many smart infrastructure systems. Although several IoT-based monitoring systems provide basic remote visibility, they often lack advanced sensing architectures capable of performing predictive diagnostics and adaptive operational control (Singh et al., 2021). Existing systems may experience communication latency, unreliable sensor integration, or insufficient operational intelligence for proactive maintenance. Inadequate real-time monitoring reduces the ability of infrastructure operators to respond quickly to system failures and operational inefficiencies.

Furthermore, many current research studies provide limited integration between additive manufacturing, renewable energy systems, embedded electronics, and outdoor infrastructure engineering. There remains insufficient research focused on the complete engineering integration of IoT hardware, environmental enclosure systems, solar-powered operation, modular mounting structures, and scalable smart-city deployment strategies. This study addresses these gaps by developing a low-cost, IoT-enabled smart streetlight monitoring enclosure optimized for additive manufacturing, outdoor durability, modular scalability, renewable energy integration, and real-time infrastructure monitoring. The proposed system contributes a practical and scalable engineering solution for intelligent urban infrastructure and sustainable energy management.

3. System Design and Methodology

3.1 Overview of the Proposed System

The proposed system was designed and developed as an IoT-enabled smart streetlight monitoring enclosure intended for intelligent urban infrastructure and energy management applications. The system integrates embedded electronics, environmental sensing technologies, wireless communication capability, renewable energy support, and modular enclosure architecture into a unified smart monitoring platform. The primary objective of the system was to create a durable and scalable outdoor infrastructure device capable of monitoring streetlight intensity, transmitting operational feedback signals, and supporting predictive maintenance activities within smart-city environments.

The developed enclosure functions as a protective black-box architecture capable of housing embedded electronic components including the sensing module, communication system, microcontroller unit, GPS module, battery management system, and solar charging interface. The system was specifically engineered for deployment on outdoor streetlight poles where environmental exposure, thermal stress, moisture accumulation, and ultraviolet radiation significantly affect the long-term performance of embedded electronics. Consequently, the design process emphasized environmental protection, manufacturability, scalability, and operational reliability.

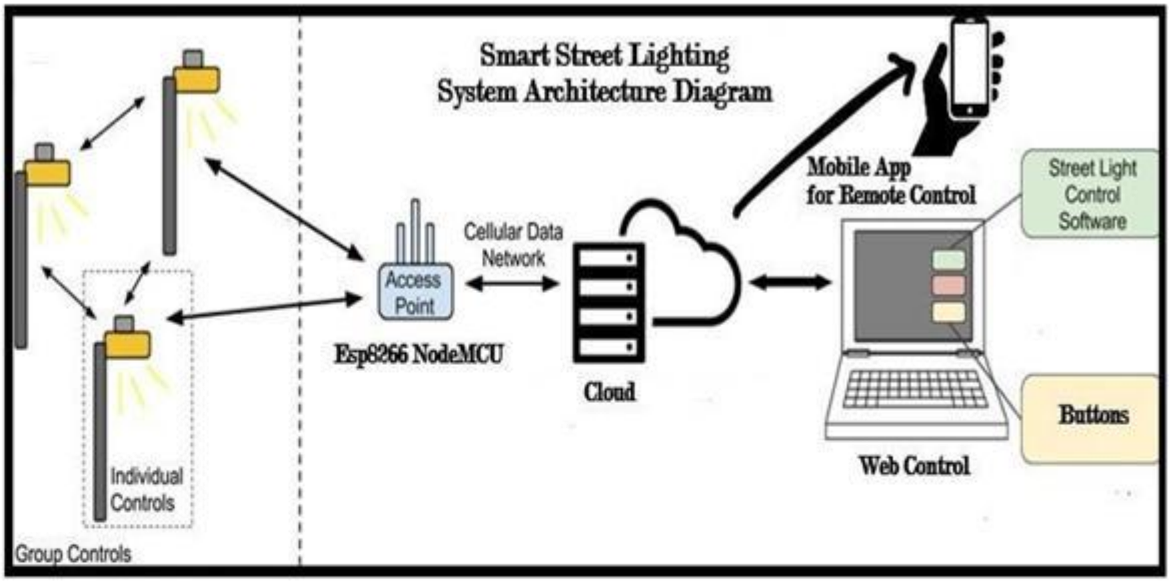
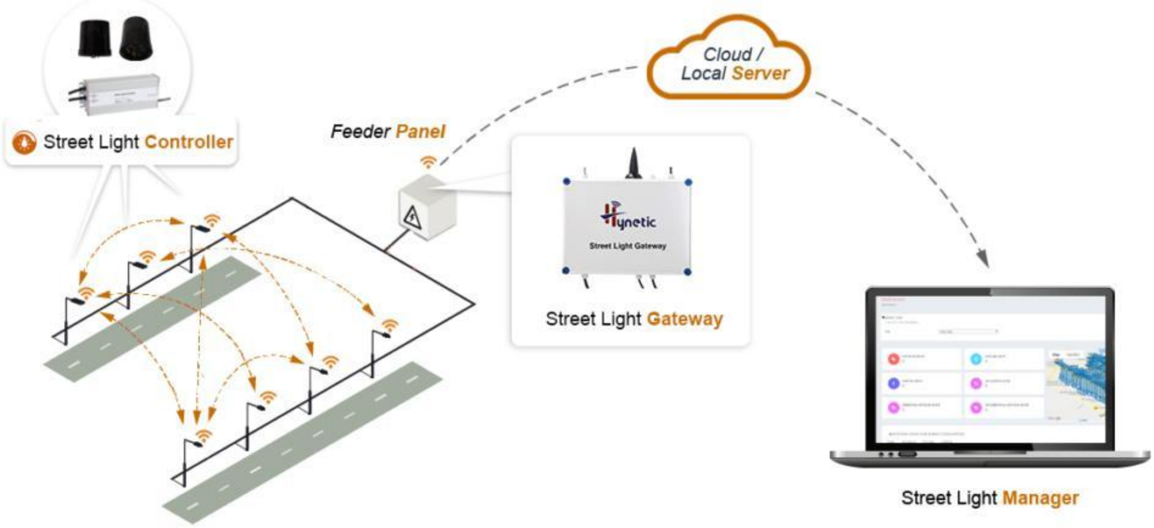
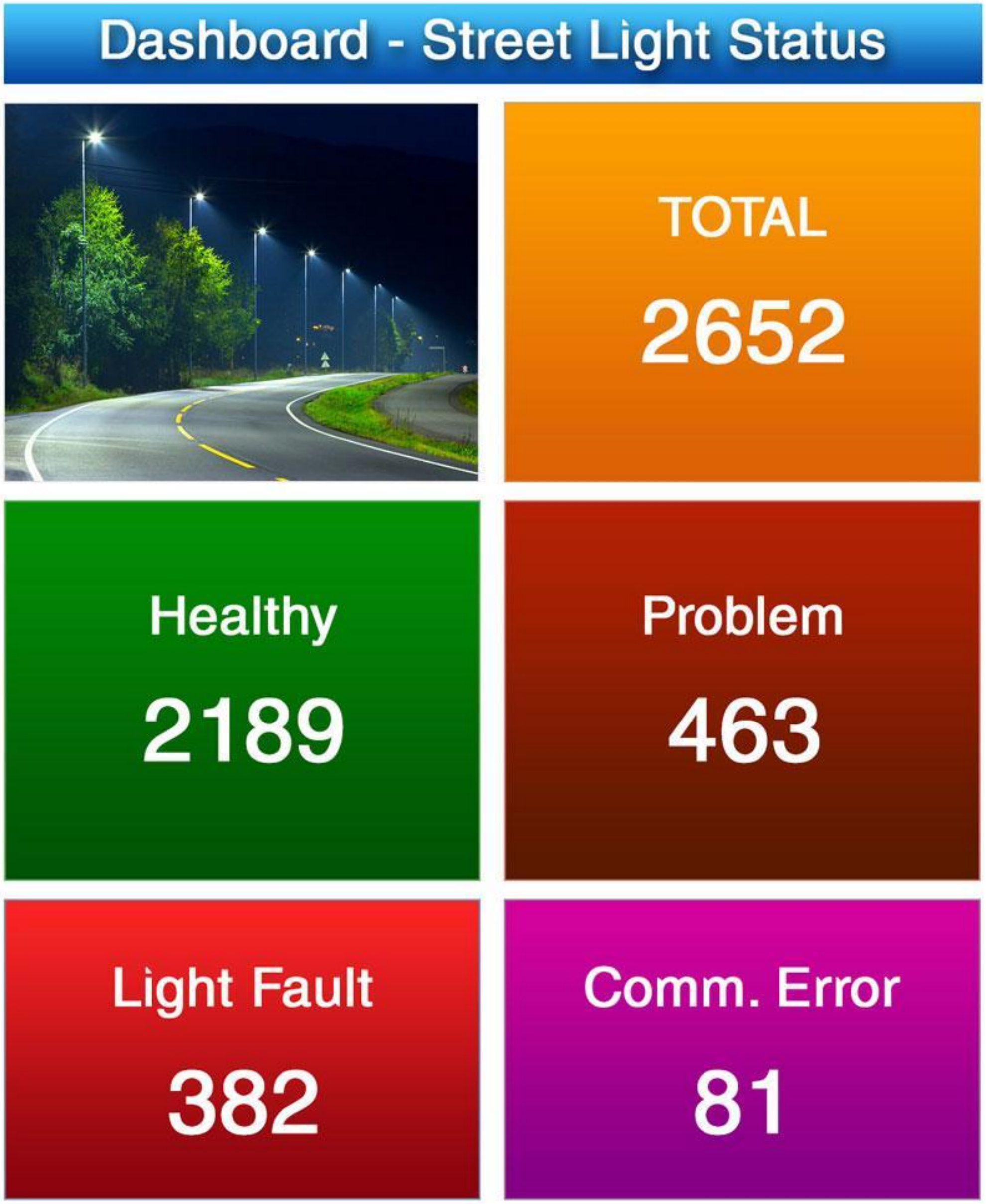


Fig. IoT for street lighting system


Street Light Controller
Feeder Panel
Cloud / Local Server
Hynetic
Street Light Gateway
Street Light Gateway
Street Light Manager



Dashboard - Street Light Status

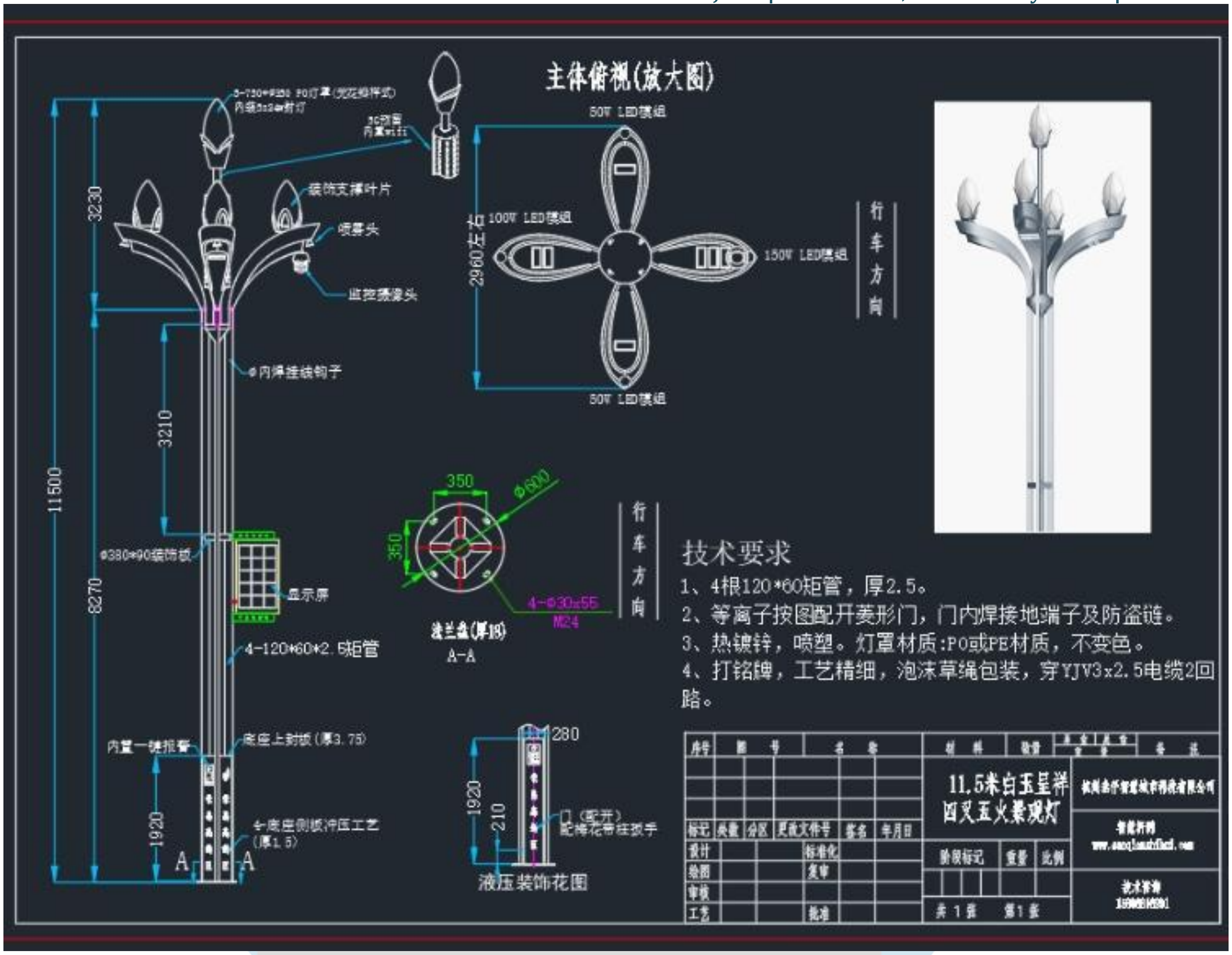
TOTAL 2652

Healthy 2189

Problem 463

Light Fault 382

Comm. Error 81



技术要求

1、4根120*60矩管，厚2.5。

2、等离子按图配开菱形门，门内焊接地端子及防盗链。

3、热镀锌，喷塑。灯罩材质:PO或PE材质，不变色。

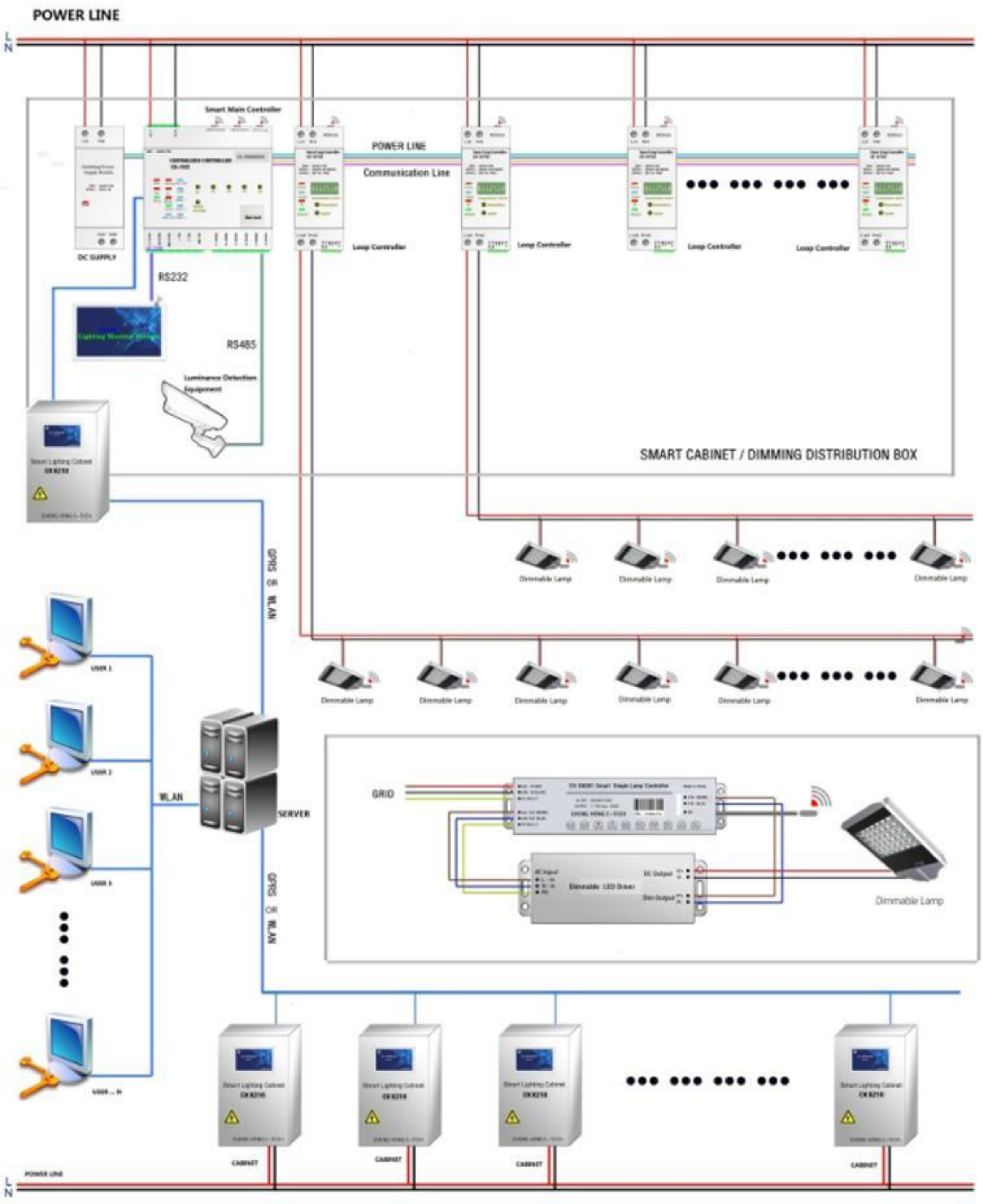
4、打铭牌，工艺精细，泡沫草绳包装，穿YJV3x2.5电缆2回路。

The system architecture combines sensing and communication subsystems to enable real-time operational monitoring of public lighting infrastructure. The sensing subsystem continuously monitors streetlight intensity and operational conditions using embedded sensors connected to the microcontroller unit. The communication subsystem transmits operational information through wireless communication modules into centralized monitoring environments where data can be analyzed and visualized. The integration of solar energy support improves deployment flexibility by enabling partial autonomous operation in outdoor environments.

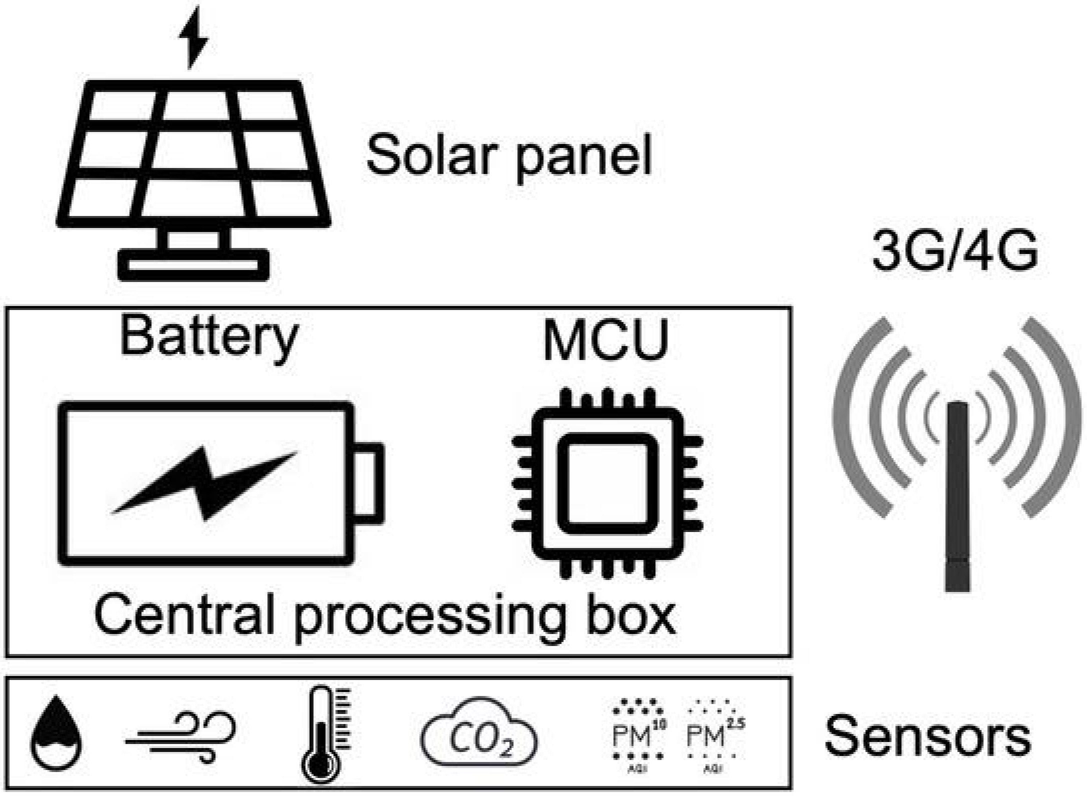
The proposed system was designed using a modular engineering approach to simplify manufacturing, maintenance, and future scalability. The enclosure geometry was optimized for additive manufacturing through 3D-printing technologies while maintaining adequate internal spacing for PCB housing, battery integration, communication modules, and airflow management. Modular assembly also allows future integration of additional smart-city sensing capabilities such as environmental monitoring, traffic analytics, and infrastructure health assessment systems.

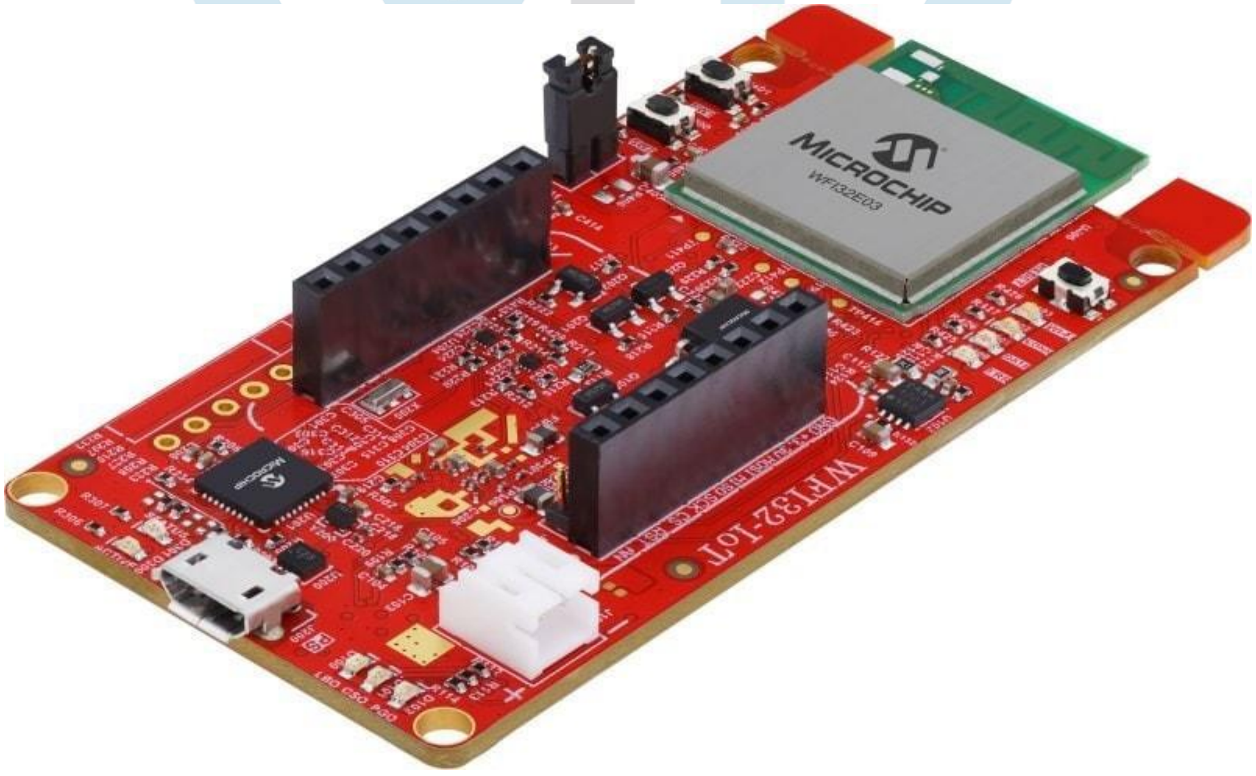
3.2 Hardware Architecture

The hardware architecture of the developed smart streetlight monitoring system consists of several integrated subsystems designed to support sensing, communication, energy management, and infrastructure monitoring operations. The architecture was developed to ensure compact integration of components while maintaining operational efficiency, environmental protection, and ease of maintenance. The primary hardware subsystems include the embedded microcontroller unit, sensing module, wireless communication system, GPS integration module, solar charging system, and rechargeable battery infrastructure.




Internet
Server
Computer
Cellphone APP
Gateway powered by solar system
RF:LORA/SUB1G
RF:LORA/SUB1G
RF:LORA/SUB1G
RF:LORA/SUB1G
Ethernet/2G/3G/4G+5G
Gateway
Internet
4G+5G


Solar panel
3G/4G
Battery
MCU
Central processing box
CO2
PM10
AQI
PM2.5
AQI
Sensors


MICROCHIP
WFI32E03
WFI32-IoT

The central processing unit of the system consists of an embedded microcontroller platform responsible for sensor interfacing, communication coordination, operational control, and data processing. The microcontroller continuously collects data from the sensing units, processes operational conditions, and coordinates information transmission through the communication subsystem. The embedded controller architecture was selected based on low-power operation, compact integration capability, and compatibility with multiple communication interfaces required for IoT infrastructure systems.

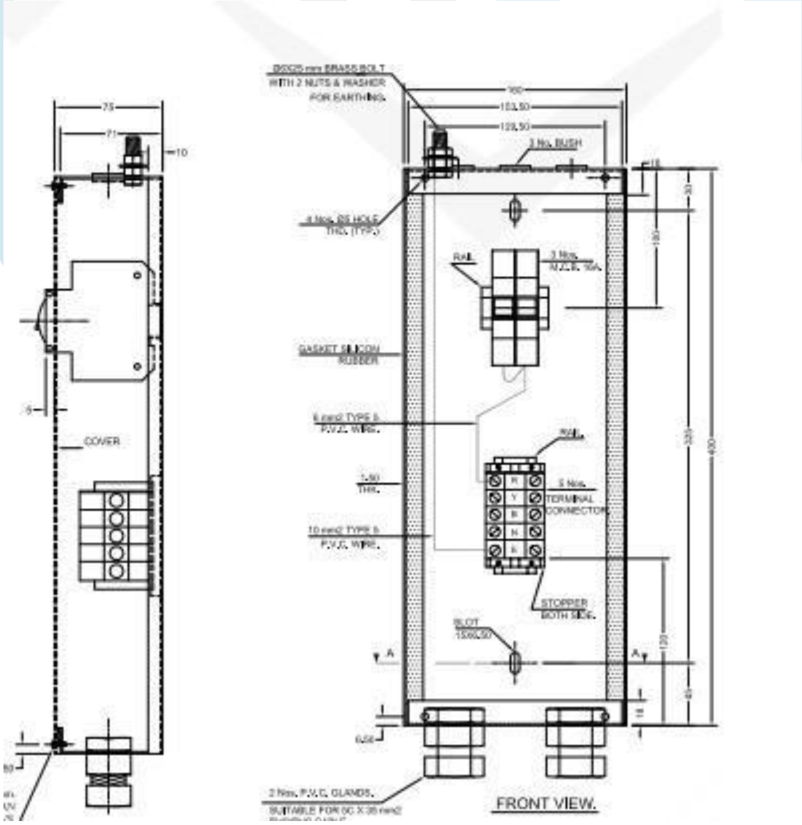
The sensing subsystem was developed to monitor streetlight operational intensity and environmental conditions. Sensor positioning and orientation were optimized during the CAD development process to improve sensing accuracy and operational consistency. The sensing module was mounted on a 30-degree inclined surface to improve directional sensitivity toward the streetlight illumination source. This design consideration improved the consistency of intensity measurement while minimizing interference from surrounding environmental light conditions.

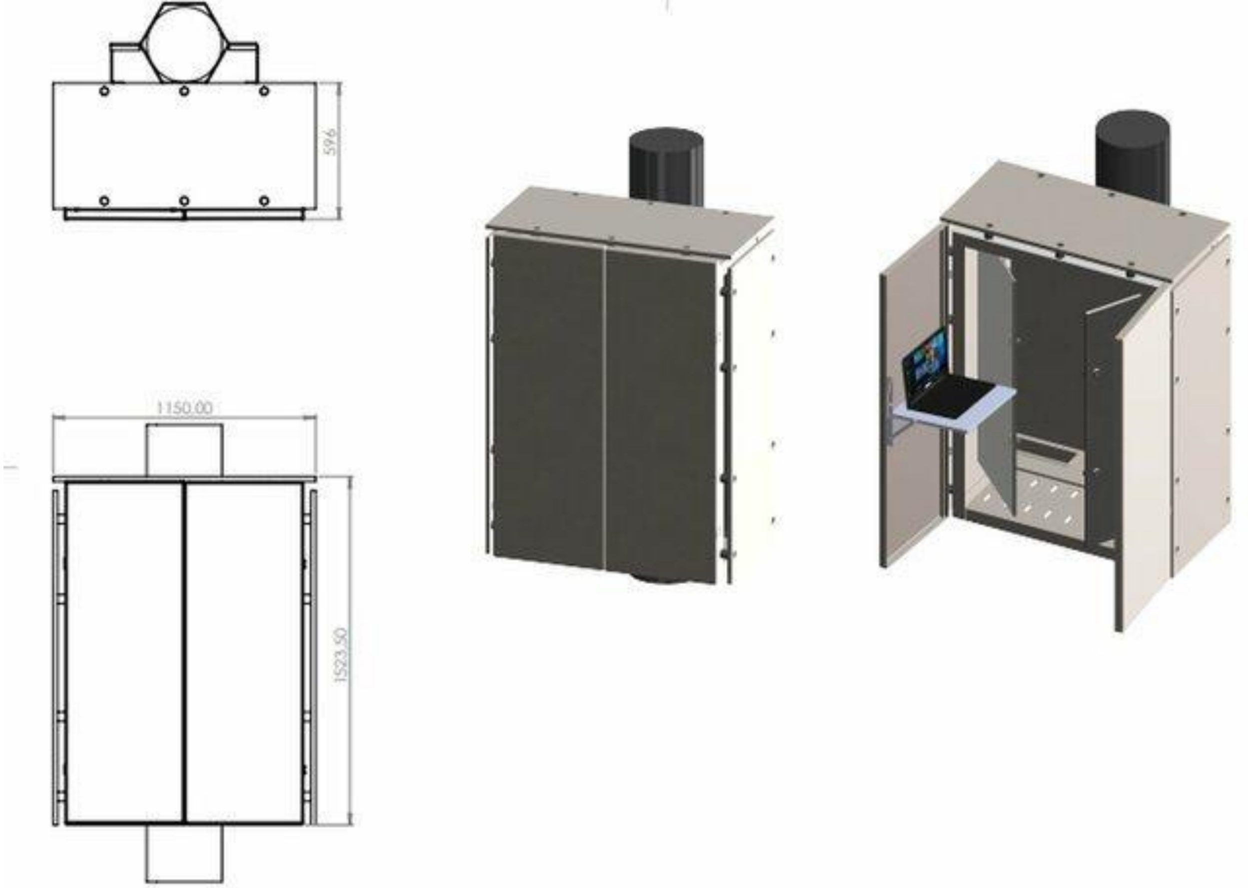
The wireless communication subsystem was integrated to enable real-time transmission of operational data from the deployed infrastructure node into centralized monitoring platforms. Communication capability was achieved through GSM-based wireless modules integrated within the enclosure architecture. The communication subsystem supports remote status reporting, operational feedback transmission, and infrastructure visibility. Additionally, the system incorporates a GPS module for geolocation capability, enabling accurate identification and tracking of deployed infrastructure assets across distributed municipal environments.

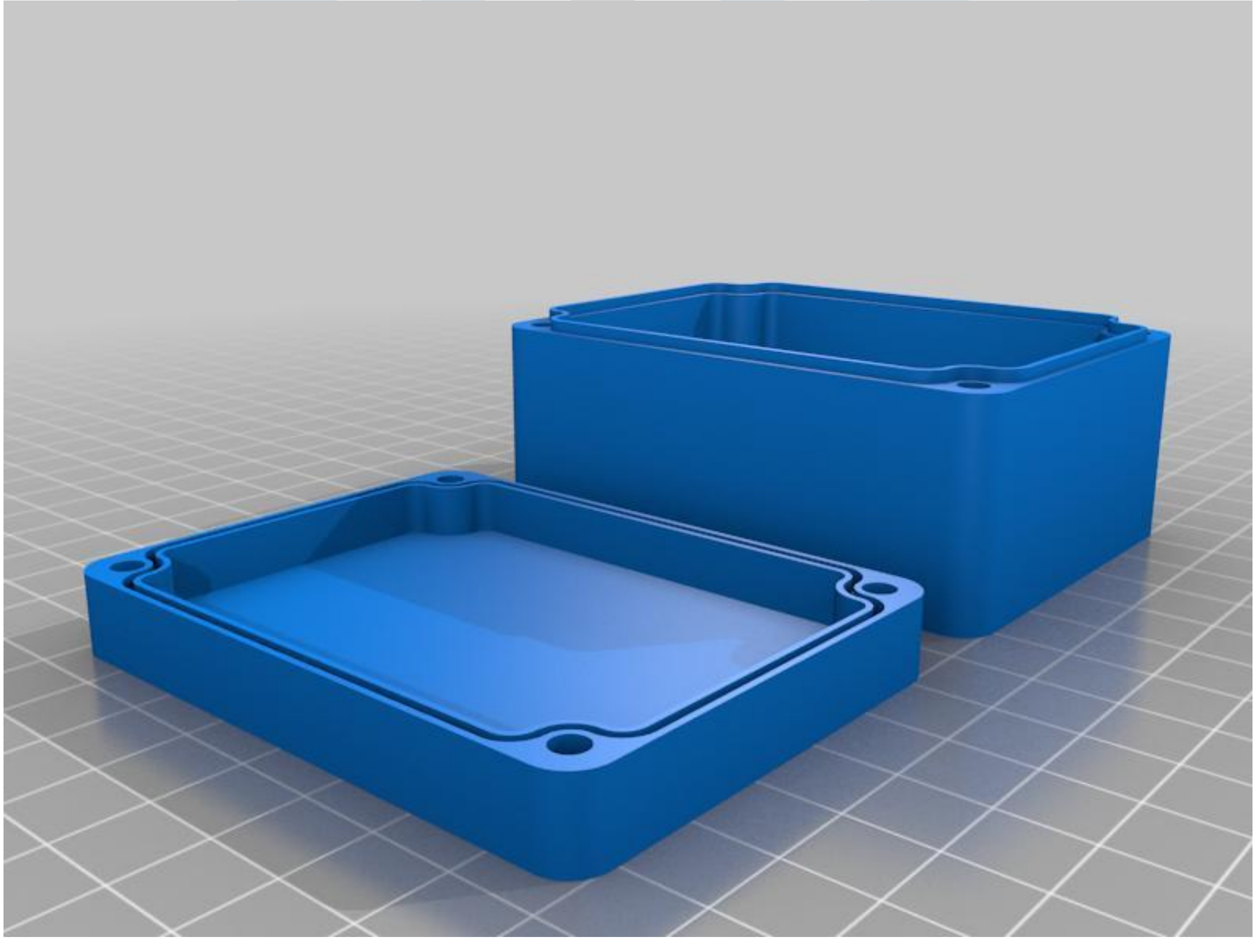
The energy subsystem integrates a solar charging architecture with rechargeable battery storage to support outdoor autonomous operation. The solar panel was mounted on a 12-degree inclined surface to improve solar exposure and charging efficiency during outdoor deployment. The rechargeable battery unit supplies operational power to the embedded electronics and communication systems during low-light conditions. The integration of renewable energy support improves energy efficiency and reduces dependency on continuous external power supply infrastructure.

3.3 CAD and Enclosure Design

The enclosure system was designed using Computer-Aided Design (CAD) methodologies to achieve accurate component integration, outdoor durability, manufacturability, and structural optimization. The entire enclosure architecture was modeled using SolidWorks CAD software, enabling detailed geometric development, dimensional optimization, assembly verification, and visualization of internal component positioning. The CAD development process focused on achieving compact integration of embedded electronics while maintaining structural rigidity and environmental protection suitable for outdoor deployment.




596
1150.00
1523.50




outdesign co.

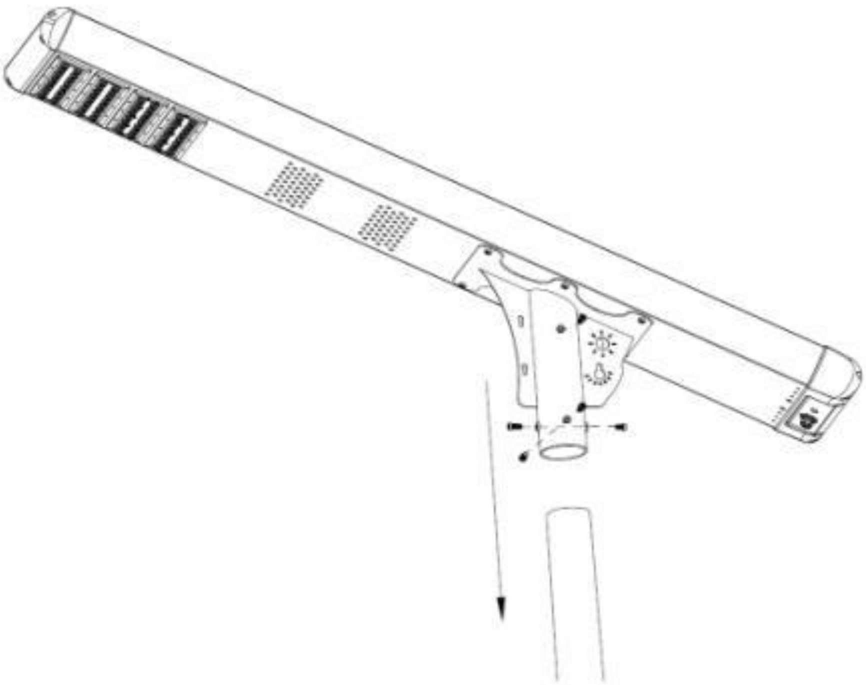
The enclosure geometry was specifically optimized for additive manufacturing processes including Fused Filament Fabrication (FFF) and Stereolithography (SLA) 3D-printing techniques. Design optimization for additive manufacturing included reduction of unsupported overhang structures, minimization of material usage, and simplification of assembly components. The modular enclosure design enabled easier fabrication, rapid prototyping, and straightforward replacement of internal components during maintenance activities.

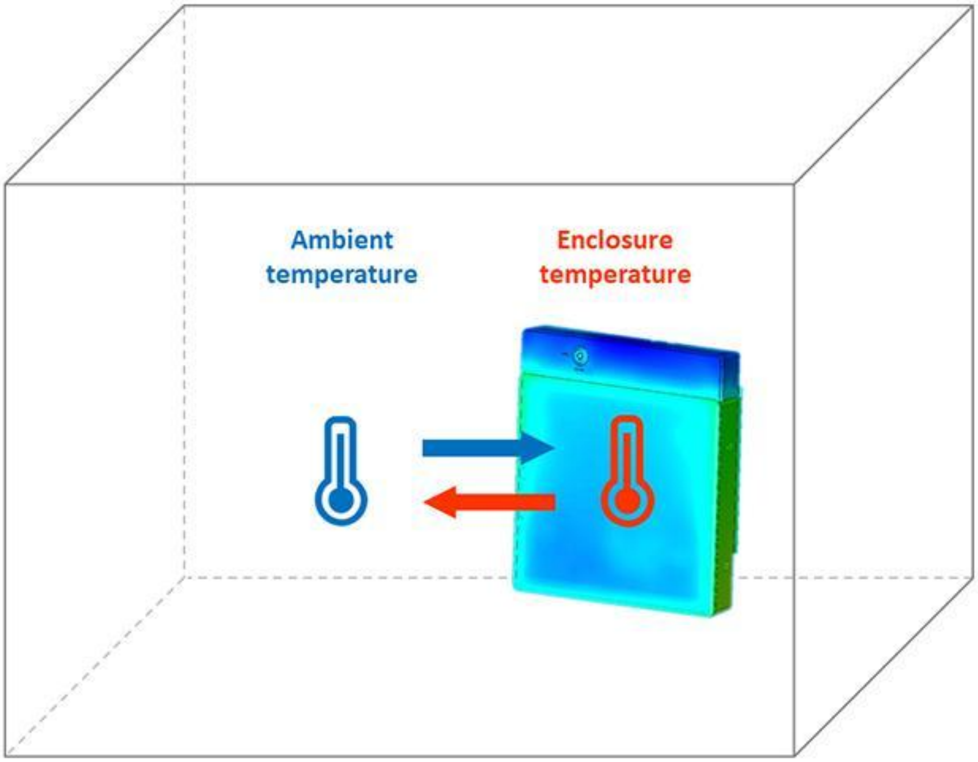
Several structural and environmental considerations influenced the final enclosure geometry. The enclosure was designed with an aerodynamic profile to reduce wind resistance and improve mechanical stability during outdoor installation. Ventilation openings were strategically positioned at the lower section of the enclosure to support thermal airflow and moisture drainage while minimizing direct environmental exposure to sensitive electronics. The enclosure assembly orientation was also designed to reduce internal moisture accumulation during rainfall conditions.

The CAD process also included accurate integration of mounting systems, sensor housing positions, PCB support structures, battery compartments, and solar panel mounting surfaces. Hose clamp mounting mechanisms were incorporated into the design to support compatibility with streetlight poles ranging between 40 mm and 100 mm in diameter. Detailed orthographic projections, isometric views, exploded assemblies, and internal architecture models were generated during the engineering development process to validate manufacturability and assembly feasibility.

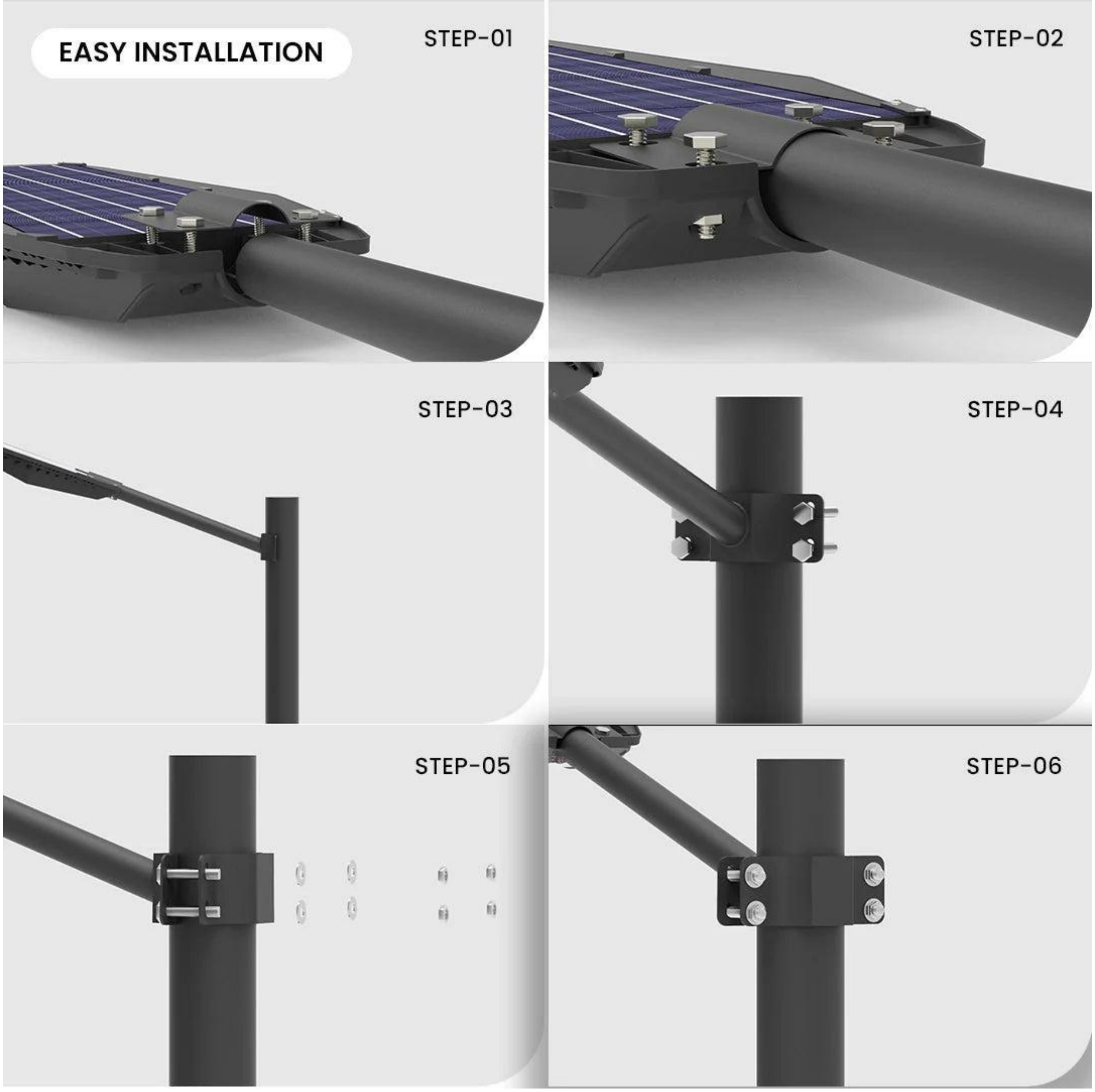
3.4 Design Considerations

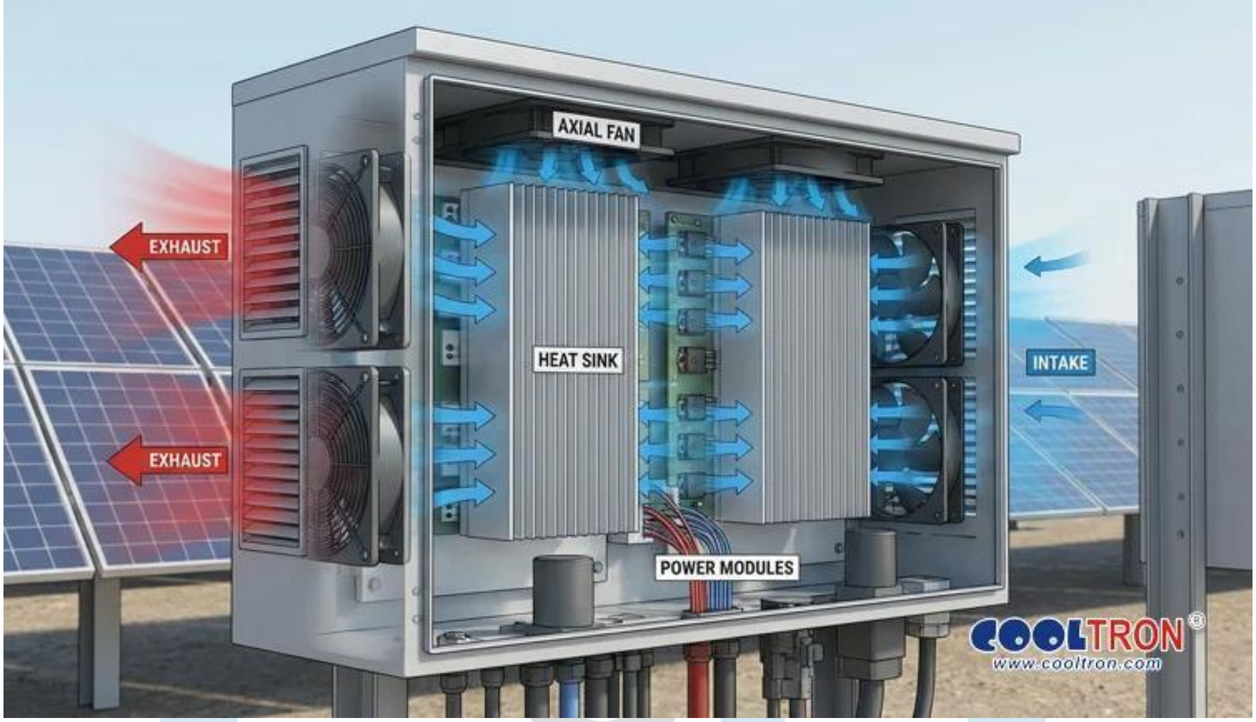
Several engineering considerations were incorporated during the design and development of the smart streetlight monitoring enclosure to ensure operational reliability, environmental durability, manufacturability, and long-term outdoor performance. These considerations influenced both the physical enclosure architecture and the integration of embedded electronics within the system.




Ambient temperature
Enclosure temperature


Smart IoT Box
IP66
Firm Structure
Modular Installation
Wi-Tek
AIOT
Industrial
Designed for the Outdoor Environment
Rainproof
Heat Dissipation
Lightning Protection
Dustproof
Firm Structure
Modular Installation
Anti-corrosion


EASY INSTALLATION
STEP-01
STEP-02
STEP-03
STEP-04
STEP-05
STEP-06



One of the major design considerations involved additive manufacturing compatibility. The enclosure geometry was optimized for 3D-printing technologies such as Fused Filament Fabrication and Stereolithography to enable low-cost fabrication and rapid prototyping. Material selection also formed an important aspect of the design process. Acrylonitrile Styrene Acrylate (ASA) material was recommended for final deployment because of its ultraviolet resistance, moisture resistance, and long-term outdoor durability. Polyethylene Terephthalate Glycol (PETG) was considered suitable for prototyping due to its affordability and ease of fabrication.

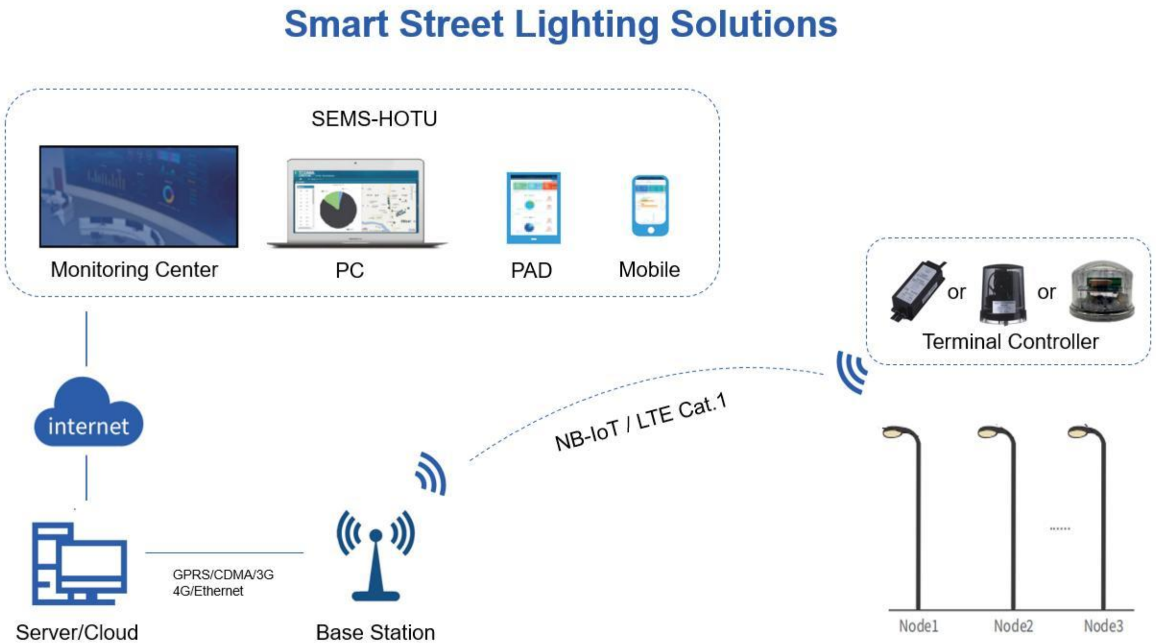
Thermal management was another critical design factor because embedded electronics operating in outdoor environments are vulnerable to overheating and moisture accumulation. Ventilation holes were integrated into the bottom section of the enclosure to improve airflow through natural and forced convection processes. The venting structure also supports moisture drainage, reducing the risk of water accumulation around sensitive electronics. Additionally, the enclosure assembly orientation was designed to minimize direct water penetration during outdoor exposure.

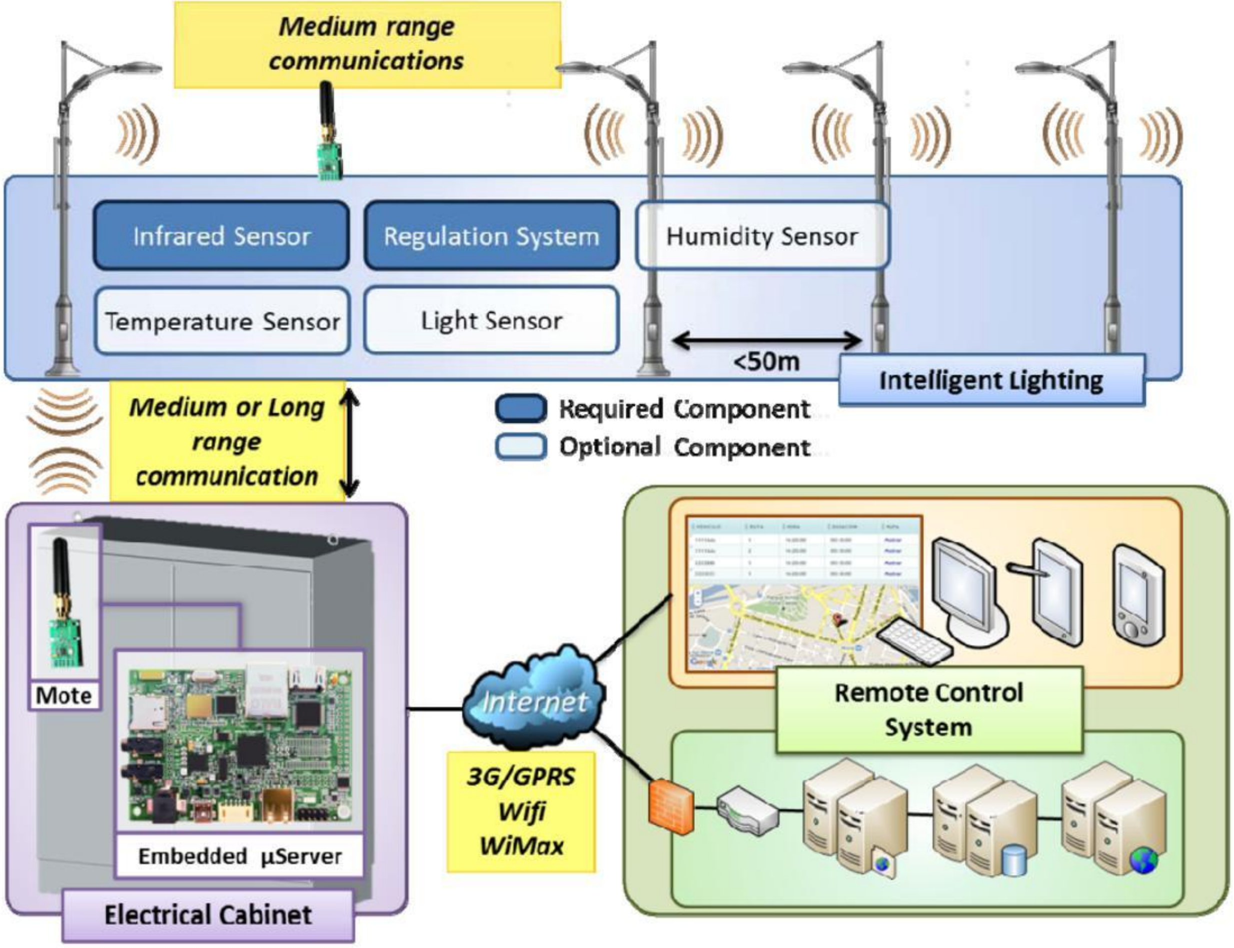
Sensor sensitivity and solar efficiency were also considered during the geometric optimization process. The streetlight sensing module was mounted at a 30-degree inclination to improve sensitivity toward illumination intensity, while the solar panel was mounted on a 12-degree inclined plane to maximize solar exposure and charging performance. The final enclosure architecture balances functionality, durability, manufacturability, and aesthetic integration suitable for intelligent urban infrastructure deployment.

3.5 Communication and Data Flow

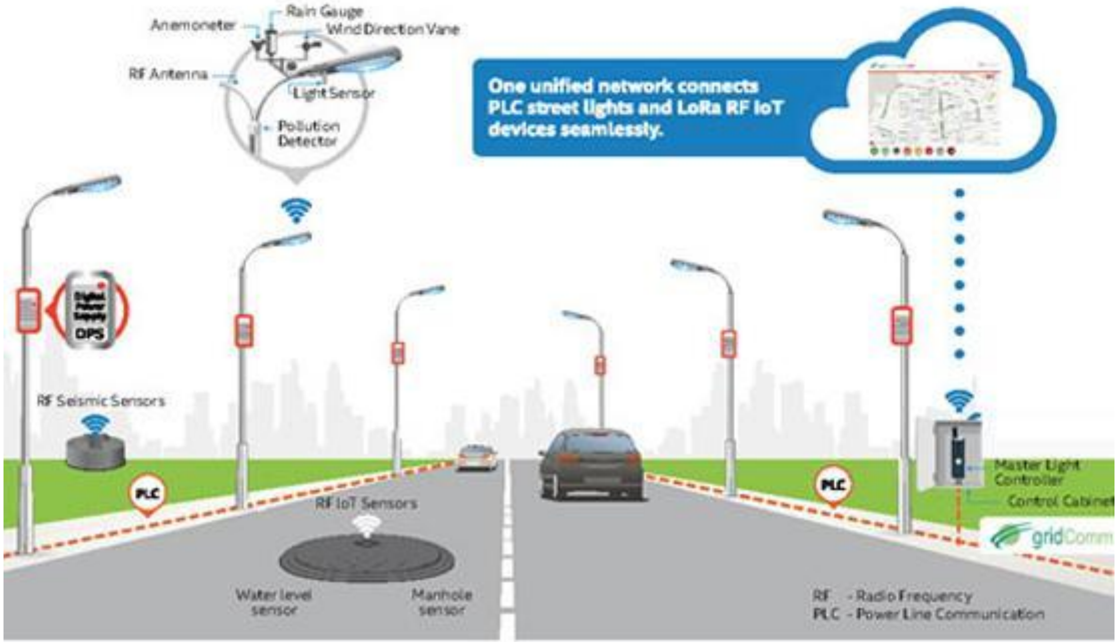
The communication and data flow architecture of the proposed smart streetlight monitoring system was designed to support real-time infrastructure visibility, remote operational monitoring, and intelligent data transmission within urban smart-city environments. The architecture integrates embedded sensing devices, wireless communication modules, cloud-based data handling processes, and centralized monitoring capability into a unified IoT infrastructure framework. The communication workflow enables the continuous acquisition, processing, transmission, and analysis of operational streetlight data for infrastructure management and predictive maintenance purposes.

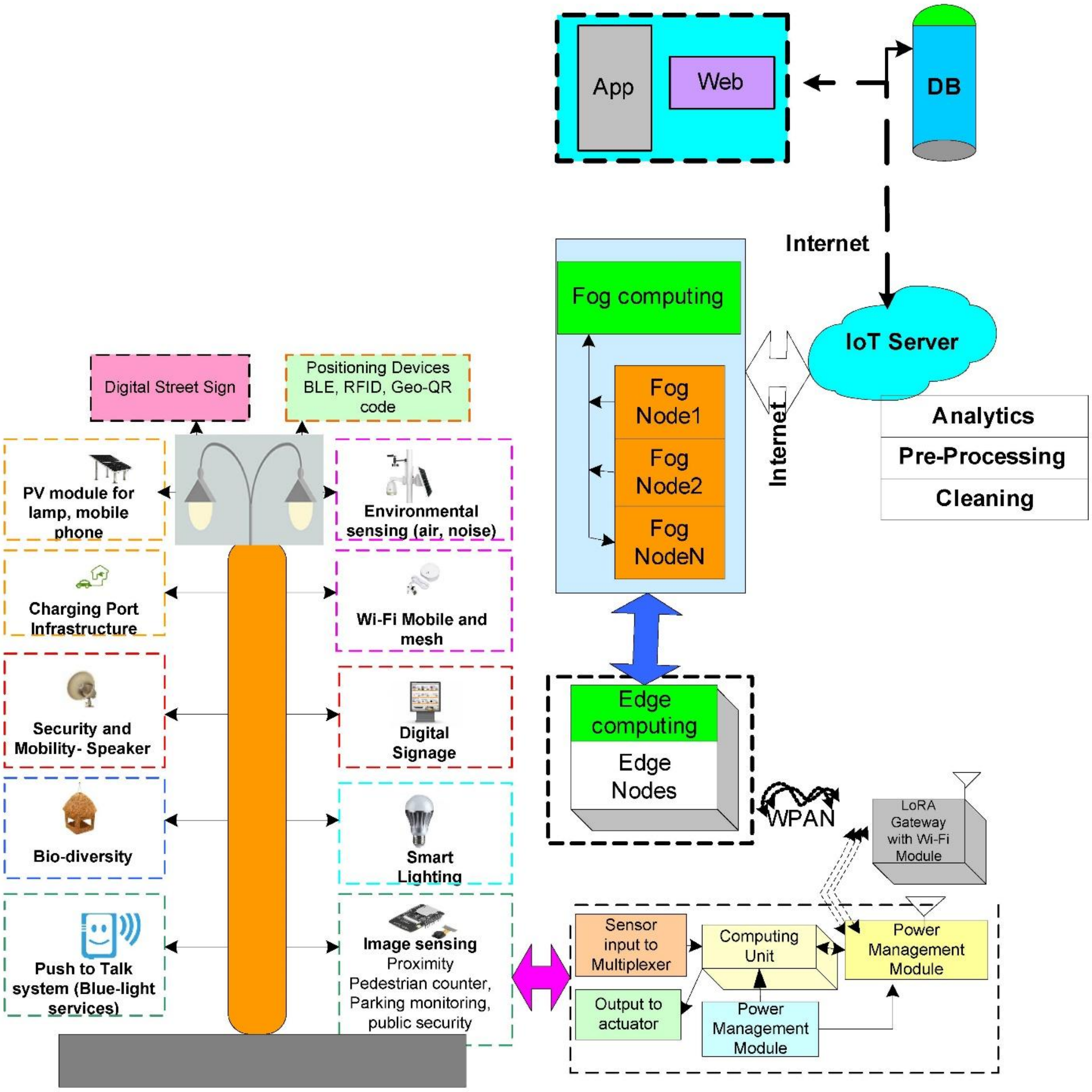
The operational process begins at the sensing layer, where embedded sensors continuously monitor streetlight intensity and environmental operating conditions. The sensing subsystem captures data associated with illumination levels, operational status, and device conditions at predefined intervals. These analog and digital sensor signals are transmitted directly to the embedded microcontroller unit, where preprocessing activities including signal conditioning, threshold verification, and basic operational analysis are performed. The microcontroller functions as the local processing node responsible for coordinating sensor interaction, temporary data storage, and communication management within the enclosure system.

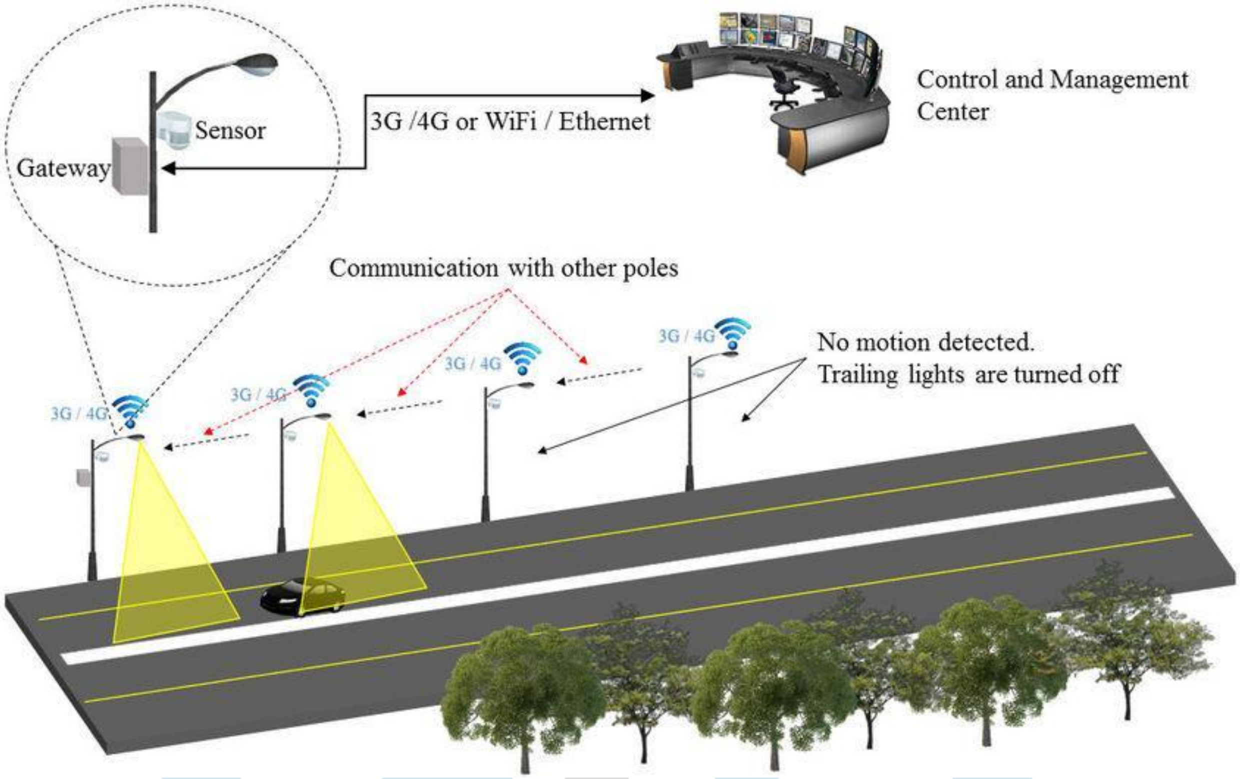


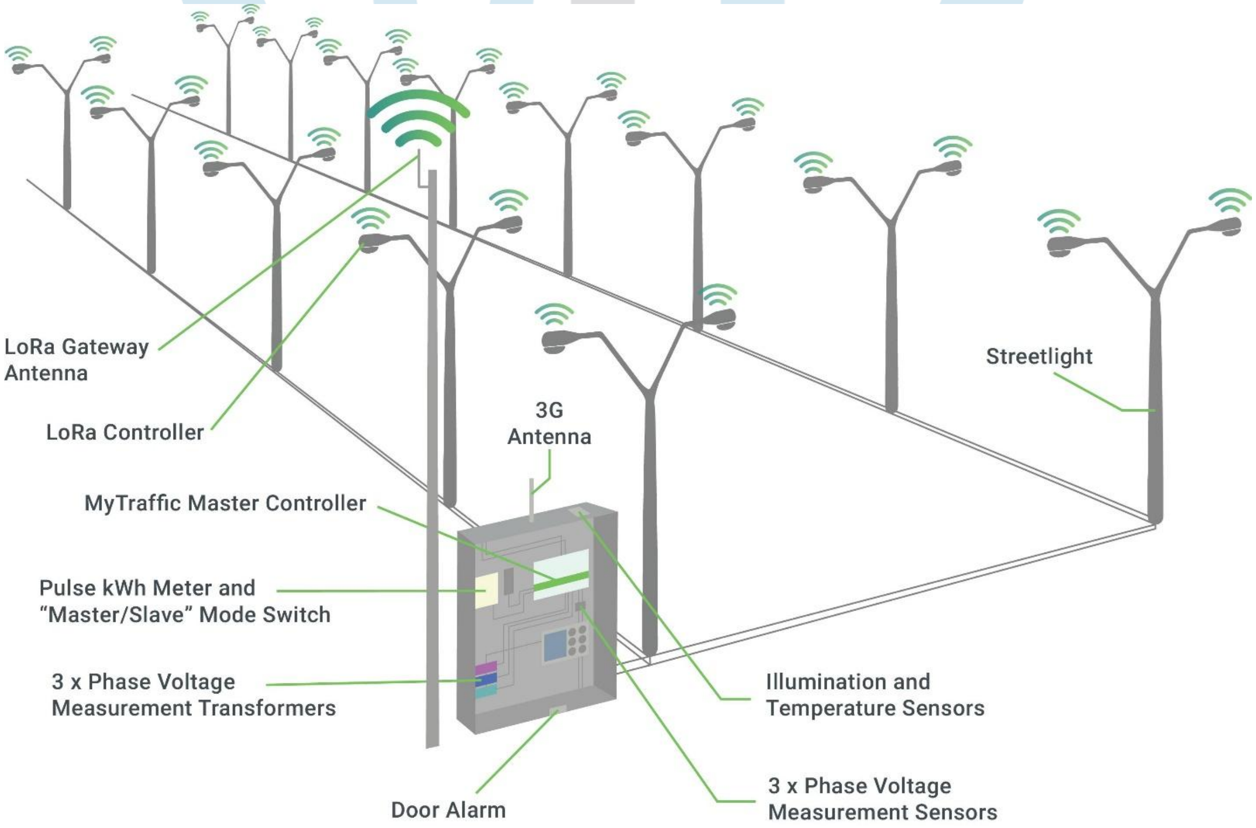

Medium range communications
Infrared Sensor
Regulation System
Humidity Sensor
Temperature Sensor
Light Sensor
<50m
Intelligent Lighting
Medium or Long range communication
Required Component
Optional Component
Mote
Embedded µServer
Electrical Cabinet
Internet
3G/GPRS
Wifi
WiMax
Remote Control System


Node 172 Offline
Rapid error detection via GNSS
Self-healing connection
Node 021
A potential risk detected


Rain Gauge
Anemoneter
Wind Direction Vane
RF Antenna
Light Sensor
Pollution Detector
One unified network connects PLC street lights and LoRa RF IoT devices seamlessly.
Digital Power Supply
DPS
RF Seismic Sensors
PLC
RF IoT Sensors
PLC
Master Light Controller
Control Cabinet
gridComm
Water level sensor
Manhole sensor
RF - Radio Frequency
PLC - Power Line Communication


App
Web
DB
Internet
Fog computing
Fog Node1
Fog Node2
Fog NodeN
IoT Server
Internet
Analytics
Pre-Processing
Cleaning
Digital Street Sign
Positioning Devices BLE, RFID, Geo-QR code
PV module for lamp, mobile phone
Environmental sensing (air, noise)
Charging Port Infrastructure
Wi-Fi Mobile and mesh
Security and Mobility- Speaker
Digital Signage
Bio-diversity
Smart Lighting
Push to Talk system (Blue-light services)
Image sensing
Proximity
Pedestrian counter,
Parking monitoring,
public security
Edge computing
Edge Nodes
WPAN
LoRA Gateway with Wi-Fi Module
Sensor input to Multiplexer
Computing Unit
Power Management Module
Output to actuator
Power Management Module





Following local processing, operational information is transmitted through the wireless communication subsystem integrated within the enclosure architecture. The developed system utilizes GSM-enabled communication capability to support remote data transmission across distributed urban environments. The GSM module allows the infrastructure node to establish communication with centralized monitoring platforms using wireless mobile communication networks. This communication framework enables remote monitoring of infrastructure assets without requiring extensive physical communication infrastructure or wired connectivity systems.

The transmitted operational data is received within centralized cloud-based or server-based monitoring environments where information is verified, recorded, and analyzed. The centralized system maintains infrastructure records associated with device identification, GPS location, operational status, and performance history. Real-time communication capability enables immediate identification of operational abnormalities, infrastructure failures, or maintenance requirements. Data received from the field devices can also be visualized through dashboard environments to support infrastructure management, fault tracking, and operational decision-making by municipal operators and maintenance personnel.

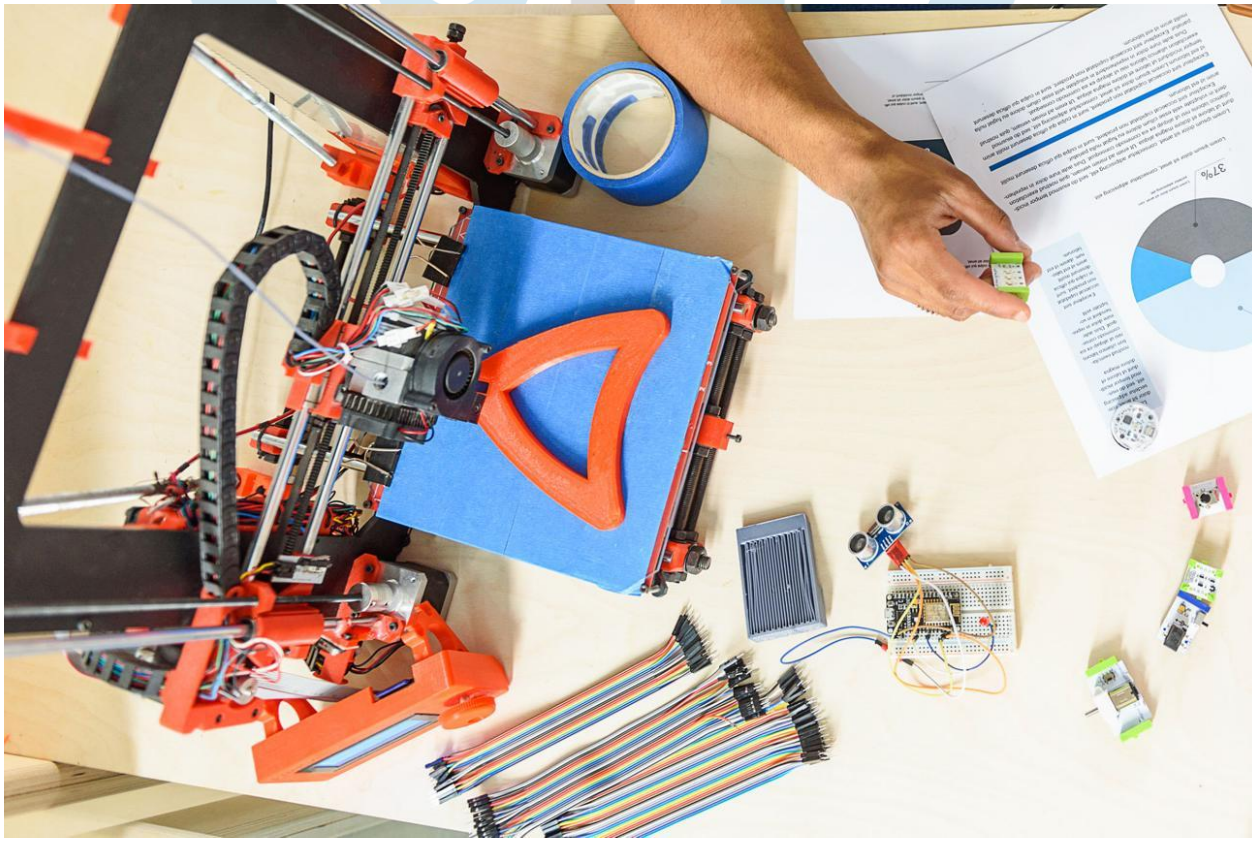
The developed communication architecture was designed with scalability and interoperability considerations to support future integration into larger smart-city ecosystems. The modular data transmission framework allows future compatibility with additional IoT communication technologies including NB-IoT, LoRaWAN, LTE-M, and cloud IoT platforms. This scalability improves the long-term applicability of the proposed infrastructure system for large-scale urban deployment. Furthermore, the integration of GPS-based location identification improves asset tracking and infrastructure management across distributed streetlight networks.

4. Prototype Development and Fabrication

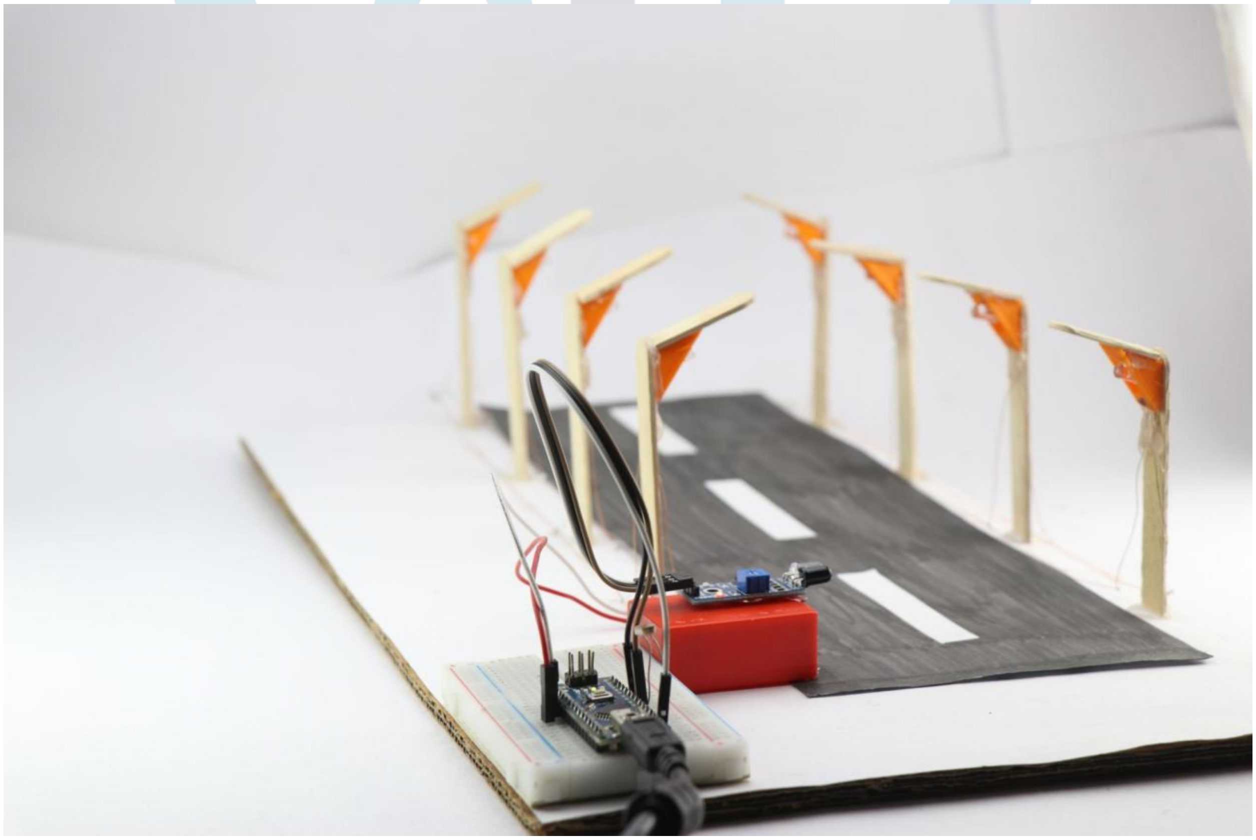
4.1 Prototype Development Process

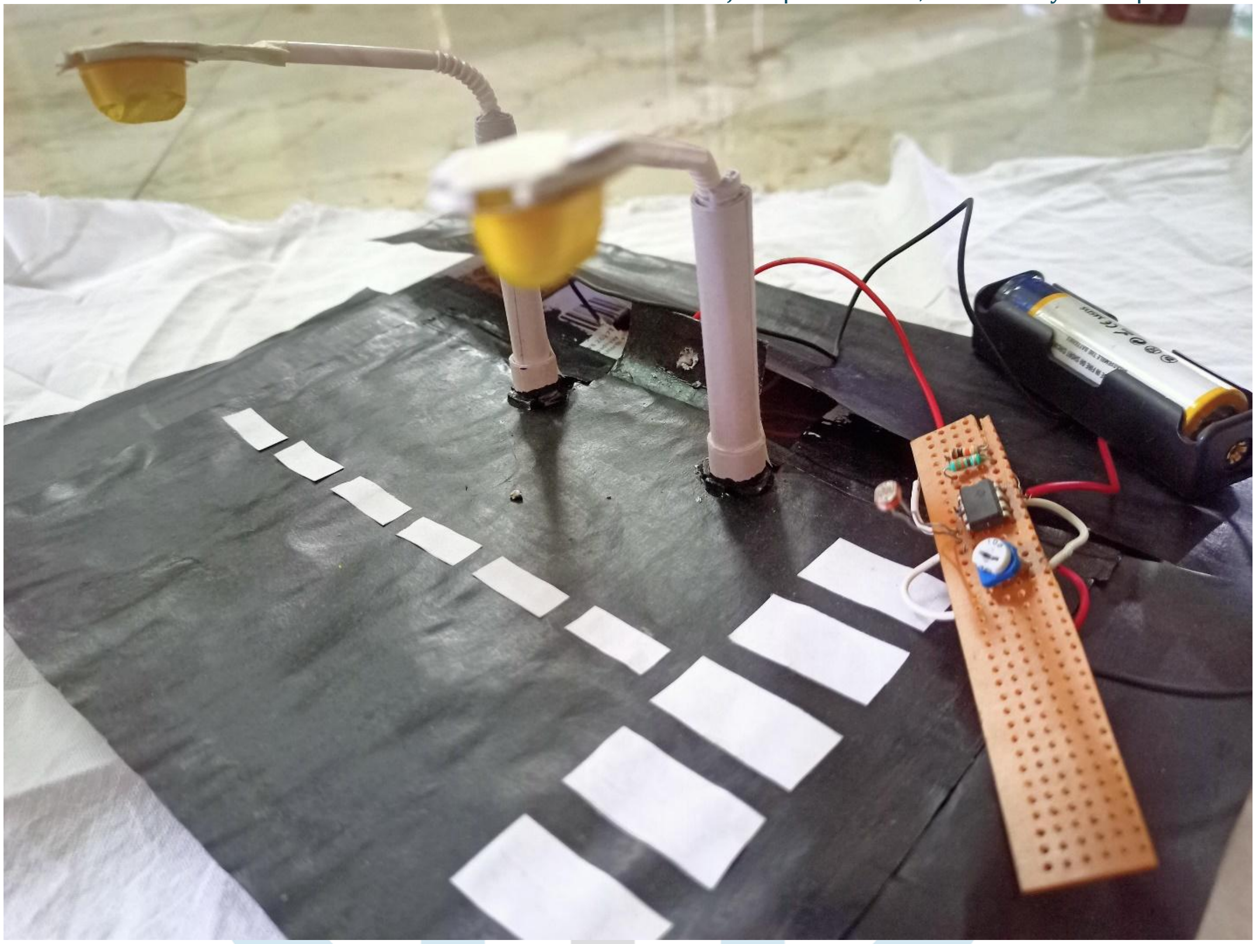
The prototype development process involved the transformation of the conceptual and CAD-based enclosure design into a functional physical smart monitoring system suitable for outdoor deployment. The development process integrated additive manufacturing, embedded electronics assembly, mechanical integration, and system-level testing to validate the operational feasibility of the proposed infrastructure solution. The prototype was developed iteratively to ensure accurate housing of components, structural integrity, and environmental compatibility.

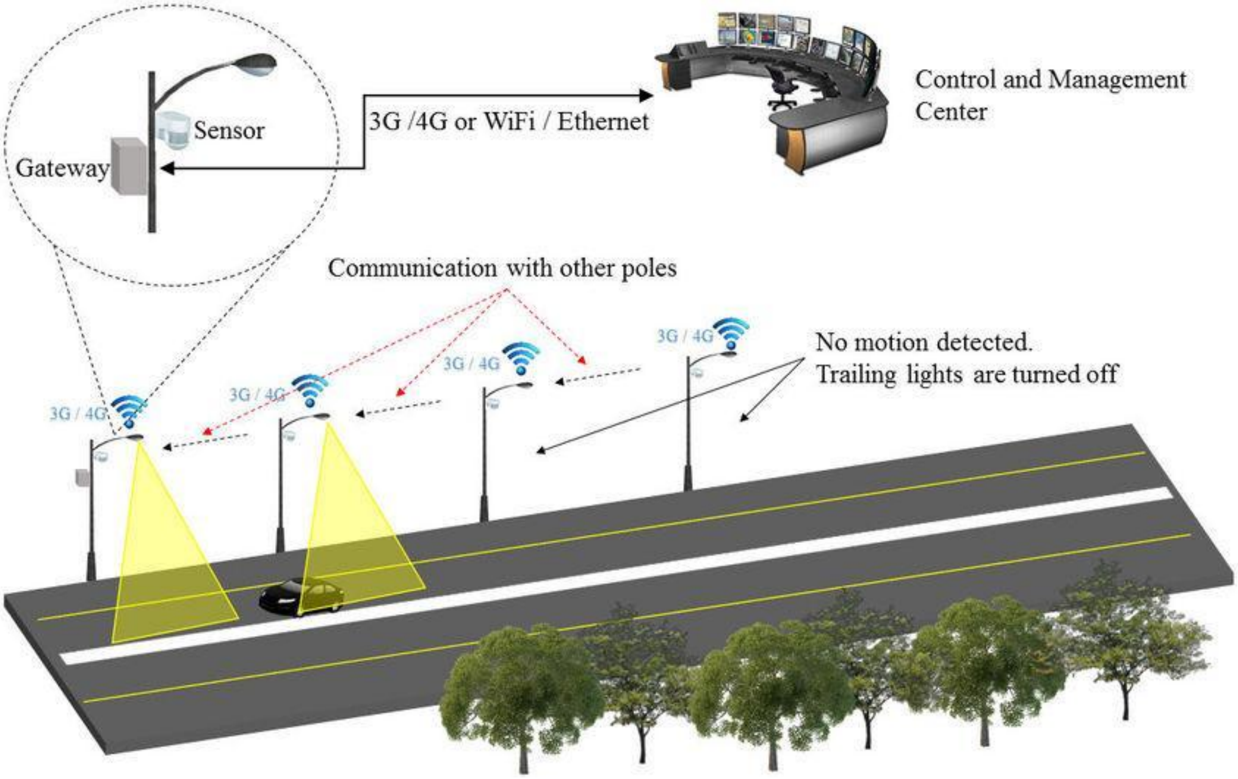
The development workflow began with CAD-based geometric optimization and assembly validation using SolidWorks software. The CAD process allowed accurate positioning of embedded components including the PCB module, battery system, communication unit, sensor architecture, and solar charging subsystem. Internal support structures and mounting geometries were incorporated into the enclosure design to improve assembly stability and component alignment during physical fabrication.




SIM7100E
CE







Following geometric optimization, the enclosure components were fabricated using additive manufacturing techniques. The enclosure architecture was specifically designed for compatibility with Fused Filament Fabrication (FFF) and Stereolithography (SLA) printing technologies. During prototype fabrication, PETG material was selected because of its affordability, ease of printing, and acceptable mechanical performance for initial testing and prototyping activities. The additive manufacturing approach enabled rapid iteration, reduced manufacturing cost, and improved flexibility during system refinement.

After fabrication of the enclosure components, embedded electronics and mechanical systems were assembled within the prototype architecture. The assembly process involved integration of the PCB module, embedded controller, sensing unit, rechargeable battery system, GPS module, GSM communication subsystem, and solar charging interface. Internal mounting points and screw-based fastening mechanisms were utilized to improve structural stability and reduce internal component movement during operation. The enclosure assembly also incorporated external hose-clamp mounting mechanisms to support attachment to streetlight poles during outdoor deployment.

4.2 Material Selection and Manufacturing Considerations

Material selection played an important role in ensuring the durability, thermal stability, and environmental resistance of the developed enclosure system. Outdoor infrastructure devices are continuously exposed to ultraviolet radiation, moisture, temperature variation, dust accumulation, and mechanical stress. Consequently, the enclosure material was required to possess strong environmental resistance characteristics while maintaining manufacturability and structural stability.


ASA


5G
T-CONNECT
IoT Gateway


LK
Shiny Enclosure

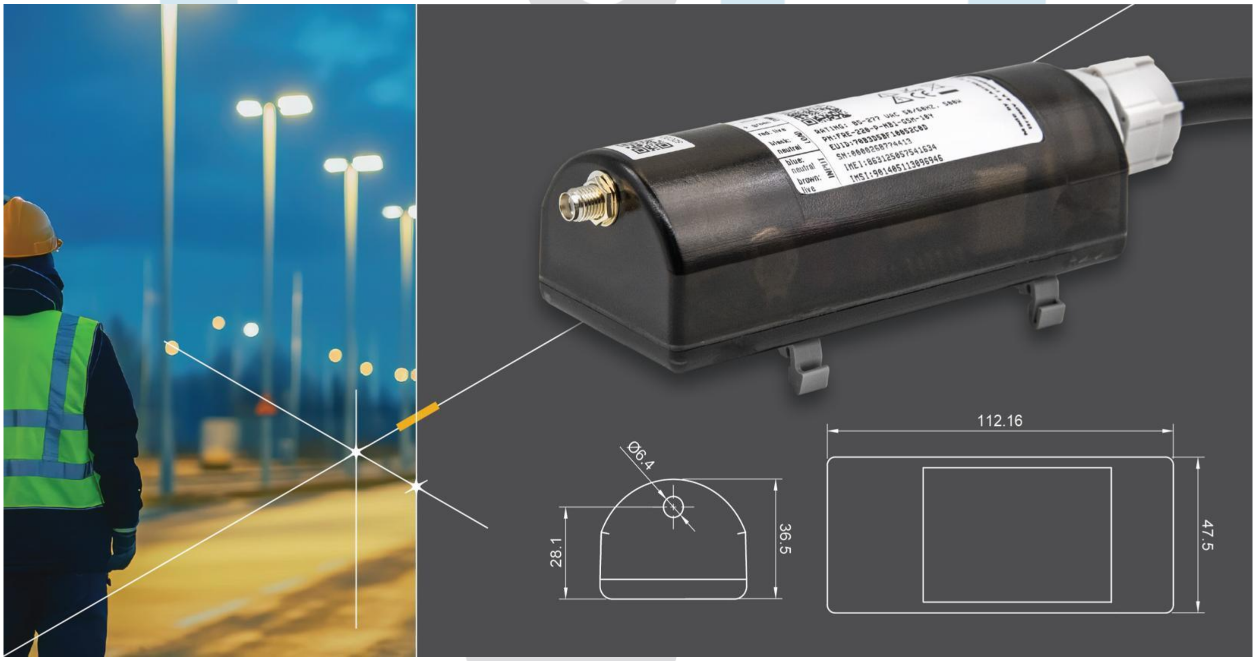
Two primary additive manufacturing materials were considered during the design process: Polyethylene Terephthalate Glycol (PETG) and Acrylonitrile Styrene Acrylate (ASA). PETG was selected for initial prototyping because of its ease of fabrication, affordability, and relatively stable dimensional behavior during printing operations. PETG also provides moderate moisture resistance and acceptable thermal stability suitable for early-stage development activities.

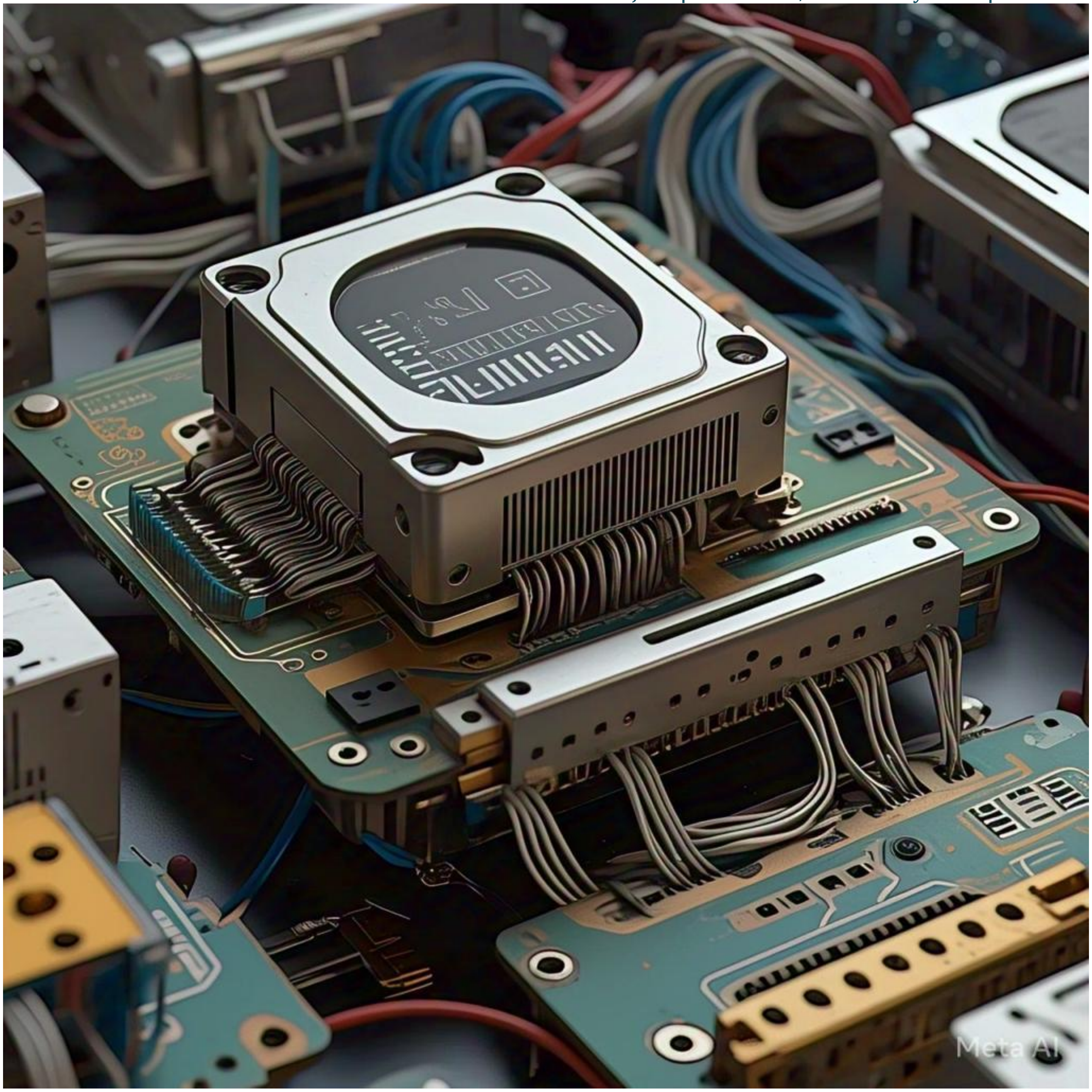
However, for long-term outdoor deployment, ASA material was identified as the preferred material because of its superior ultraviolet resistance, weather durability, thermal resistance, and outdoor lifespan characteristics. ASA materials exhibit reduced degradation under prolonged sunlight exposure compared with conventional additive manufacturing materials such as ABS and PLA. This makes ASA more suitable for smart-city infrastructure applications where long-term environmental exposure significantly influences system performance.

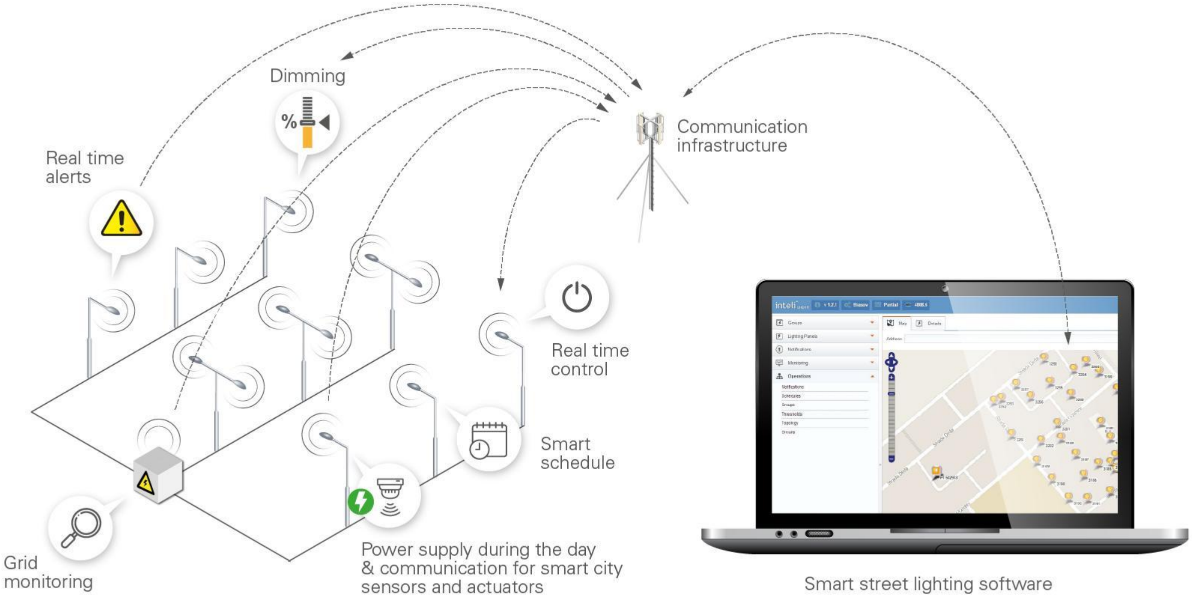
Manufacturing considerations also influenced enclosure geometry and assembly configuration. The design minimized unsupported overhangs and excessive material complexity to improve print quality and reduce fabrication time. Modular assembly structures were incorporated to simplify maintenance and component replacement during future system upgrades. Additionally, the enclosure geometry was optimized to support structural rigidity while minimizing material consumption and overall device weight.

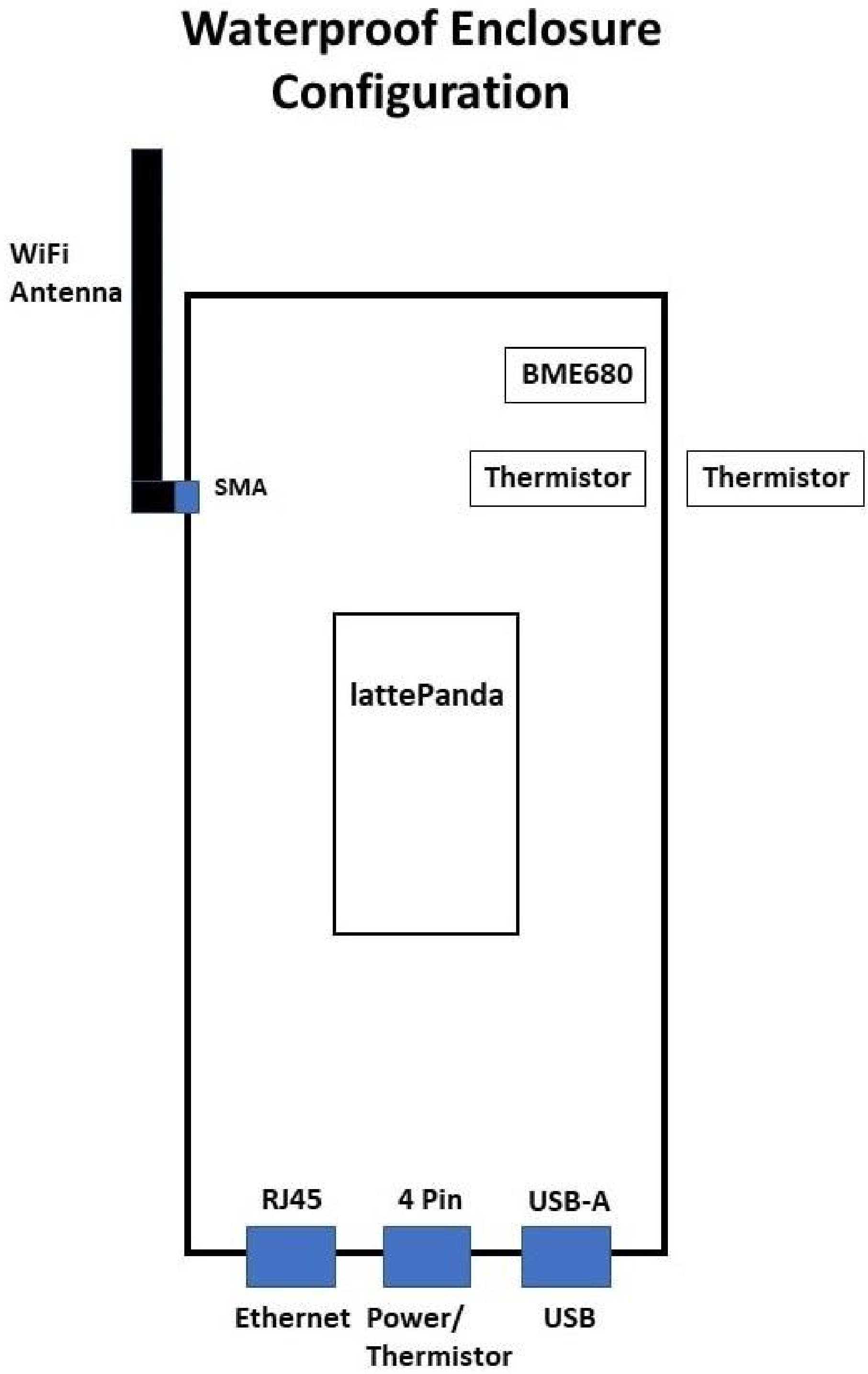
4.3 System Assembly and Integration

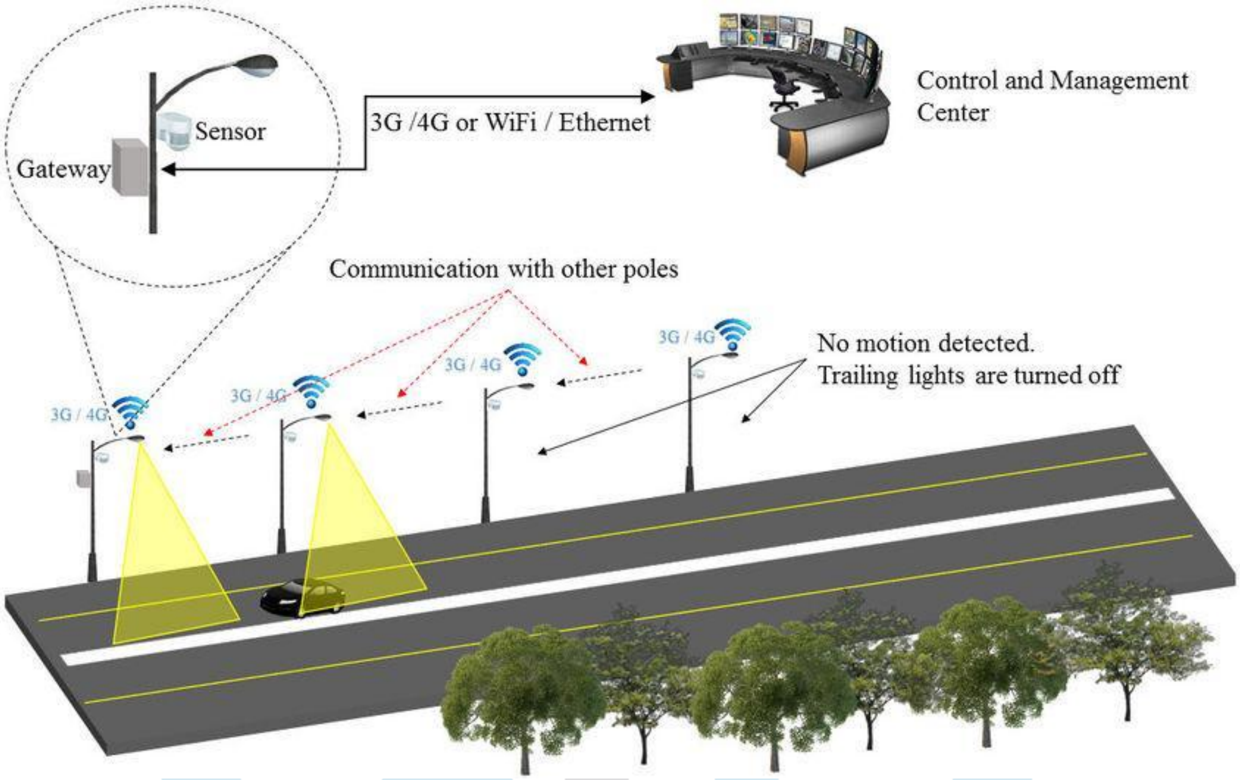
The final system assembly involved the integration of mechanical, electrical, and communication subsystems into a unified smart monitoring platform. The internal architecture was designed to maintain separation between sensitive electronics and external environmental exposure while preserving accessibility for maintenance and testing purposes. PCB mounting points, battery compartments, cable routing paths, and communication module supports were incorporated directly into the enclosure structure during CAD development.




Meta AI


Dimming
%
Real time alerts
Communication infrastructure
Real time control
Smart schedule
Grid monitoring
Power supply during the day & communication for smart city sensors and actuators
Smart street lighting software


Waterproof Enclosure Configuration
WiFi Antenna
SMA
BME680
Thermistor
Thermistor
lattePanda
RJ45
4 Pin
USB-A
Ethernet
Power/ Thermistor
USB



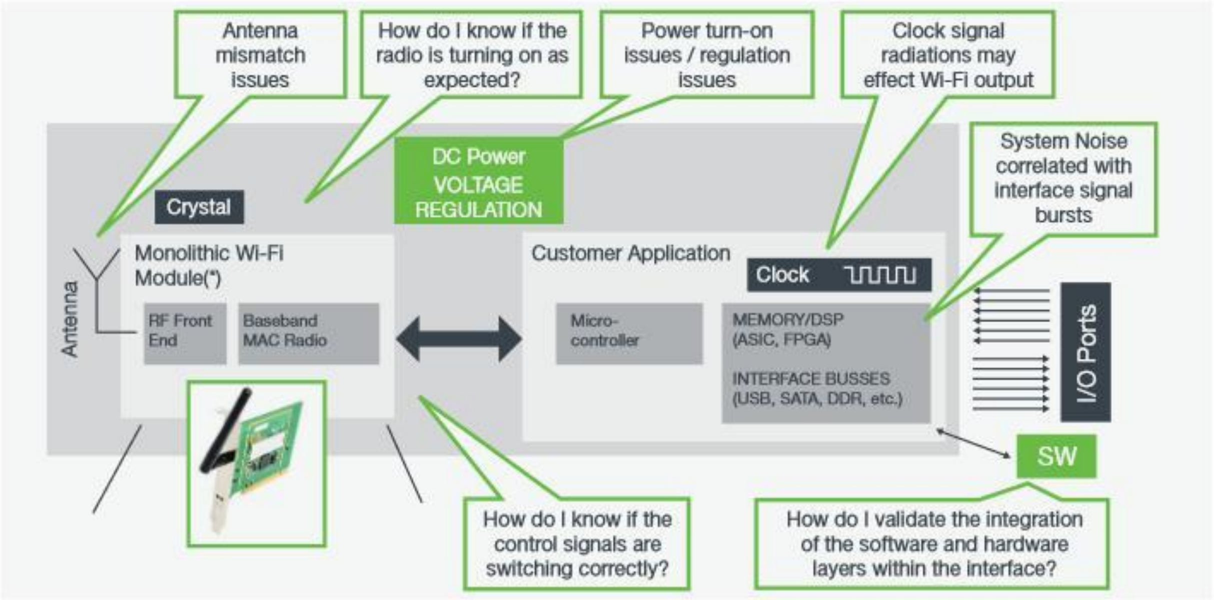
The embedded PCB module was positioned centrally within the enclosure to improve thermal distribution and structural stability. The rechargeable battery units were mounted securely within dedicated support structures to minimize movement during outdoor operation. The GSM communication antenna and GPS module were positioned to improve signal transmission and minimize communication interference. Sensor placement was also carefully optimized to improve sensitivity toward streetlight illumination while reducing external environmental interference.

The solar panel subsystem was integrated into the upper surface of the enclosure using inclined mounting geometry optimized at approximately 12 degrees to improve solar exposure and charging efficiency. The sensing unit was mounted on a separate inclined section at approximately 30 degrees to improve directional monitoring of streetlight intensity. These geometric optimizations improved the operational effectiveness of both the sensing and energy subsystems.

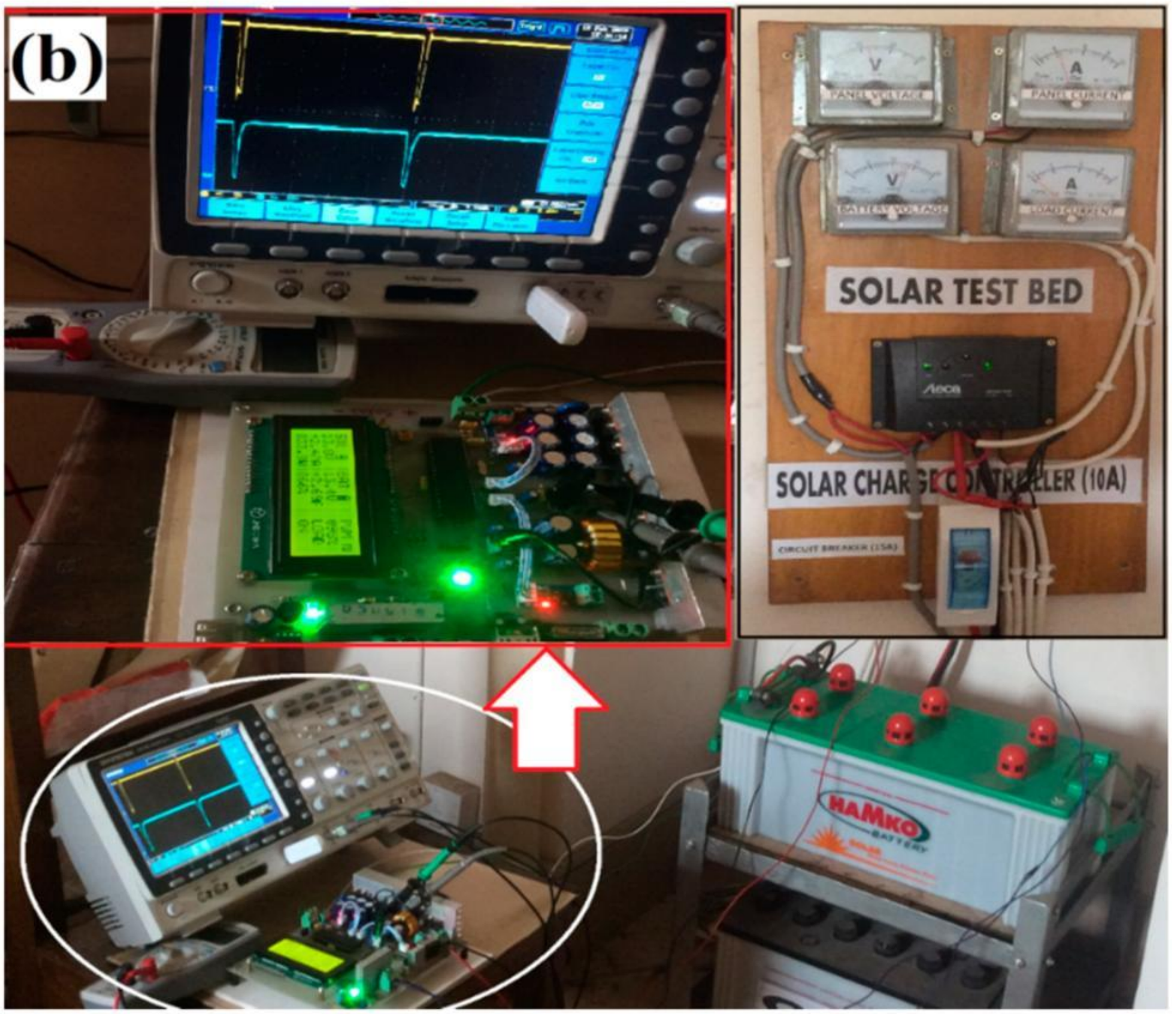
Final assembly validation involved inspection of component fitment, enclosure sealing, communication functionality, and structural stability. The modular architecture allows future system upgrades and simplifies maintenance operations by enabling replacement of individual components without complete system disassembly.

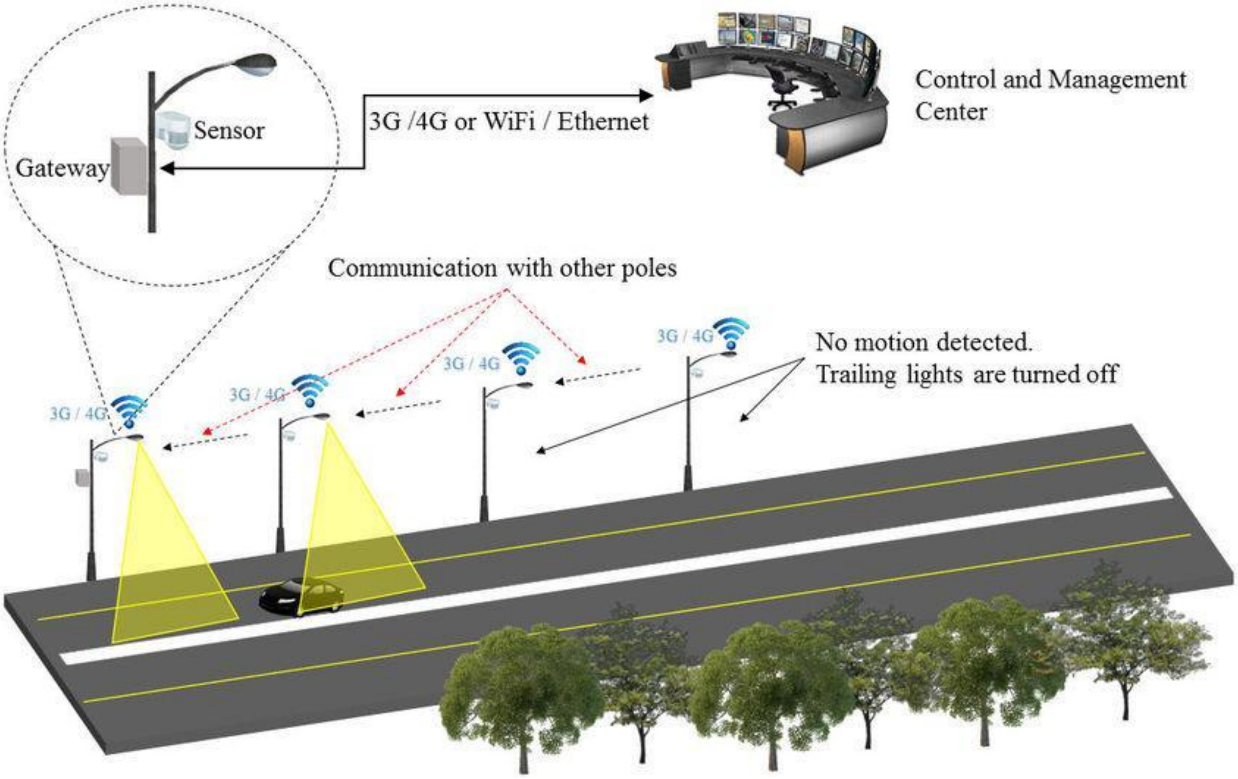
4.4 Preliminary System Testing

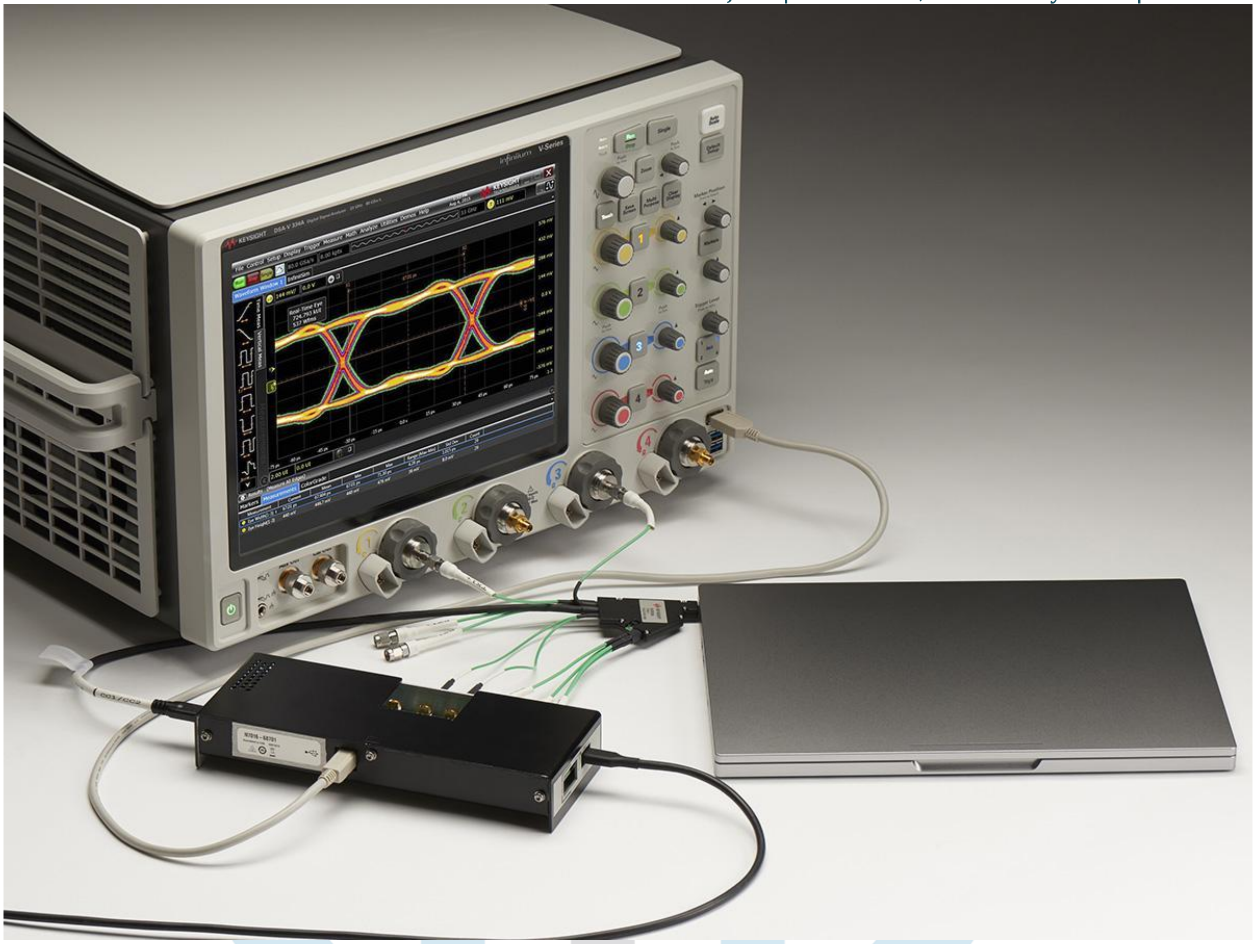
Preliminary system testing was conducted to evaluate the operational functionality, communication performance, structural integrity, and environmental suitability of the developed prototype. Initial testing activities focused on validating the interaction between sensing components, embedded processing systems, wireless communication modules, and power-management architecture.

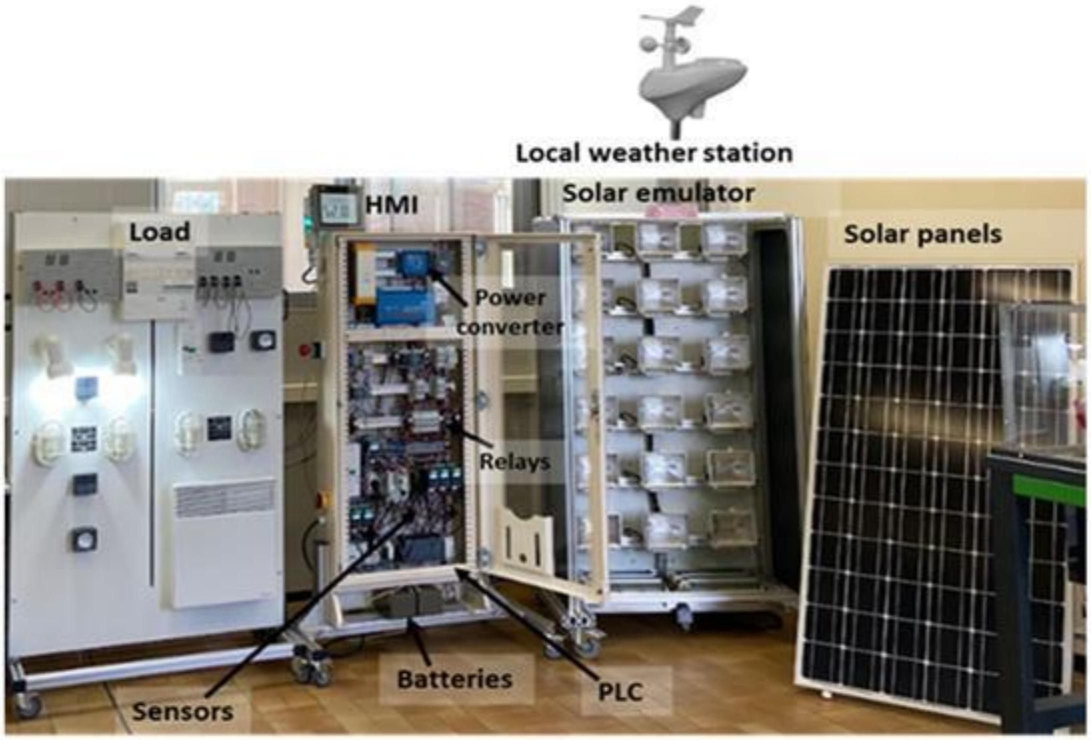

Antenna mismatch issues
How do I know if the radio is turning on as expected?
Power turn-on issues / regulation issues
Clock signal radiations may effect Wi-Fi output
System Noise correlated with interface signal bursts
DC Power VOLTAGE REGULATION
Crystal
Antenna
Monolithic Wi-Fi Module(*)
RF Front End
Baseband MAC Radio
Customer Application
Clock
Micro-controller
MEMORY/DSP (ASIC, FPGA)
INTERFACE BUSSES (USB, SATA, DDR, etc.)
I/O Ports
SW
How do I know if the control signals are switching correctly?
How do I validate the integration of the software and hardware layers within the interface?


(a)


(b)
PANEL VOLTAGE
PANEL CURRENT
BATTERY VOLTAGE
LOAD CURRENT
SOLAR TEST BED
SOLAR CHARGE CONTROLLER (10A)
CIRCUIT BREAKER (15A)
HAMKO BATTERY


Sensor
Gateway
3G /4G or WiFi / Ethernet
Control and Management Center
Communication with other poles
3G / 4G
3G / 4G
3G / 4G
3G / 4G
No motion detected.
Trailing lights are turned off





Functional testing confirmed successful operation of the sensing and communication subsystems. The sensor module was capable of detecting streetlight intensity variations and transmitting operational feedback through the embedded communication architecture. Communication testing demonstrated successful GSM-based wireless transmission between the prototype device and remote monitoring environments. GPS integration testing also confirmed successful location identification capability for infrastructure asset tracking.

Mechanical evaluation demonstrated adequate structural stability and component fitment within the enclosure architecture. The mounting system successfully supported attachment to cylindrical pole structures while maintaining enclosure stability. Ventilation openings improved airflow within the enclosure and reduced the likelihood of moisture accumulation around internal electronics.

The preliminary testing phase validated the overall feasibility of the proposed smart streetlight monitoring enclosure for outdoor infrastructure applications. The results demonstrated the practicality of integrating additive manufacturing, embedded sensing technologies, renewable energy support, and IoT communication systems into a scalable smart-city infrastructure platform.

5. Results and Performance Evaluation

5.1 Mechanical Performance Evaluation

The developed smart streetlight monitoring enclosure demonstrated satisfactory mechanical performance during prototype evaluation and assembly validation. The enclosure structure maintained adequate rigidity and dimensional stability throughout fabrication, assembly, and preliminary deployment testing. The integration of internal support structures, modular assembly points, and mounting interfaces contributed significantly to the overall structural integrity of the system. The enclosure geometry successfully accommodated the PCB architecture, communication modules, sensing units, battery compartment, and solar charging subsystem without significant internal interference or mechanical instability.


(주)이너스텍
P-6A


CHANZON
LED Driver (Constant Current)
Model:QH-40LC10-18X3
Input:AC100-240V 50/60Hz
Output: 600mA (Constant)
Output: DC30-57V
(CA0096)
White
Output
Red
Brown
Input
Blue

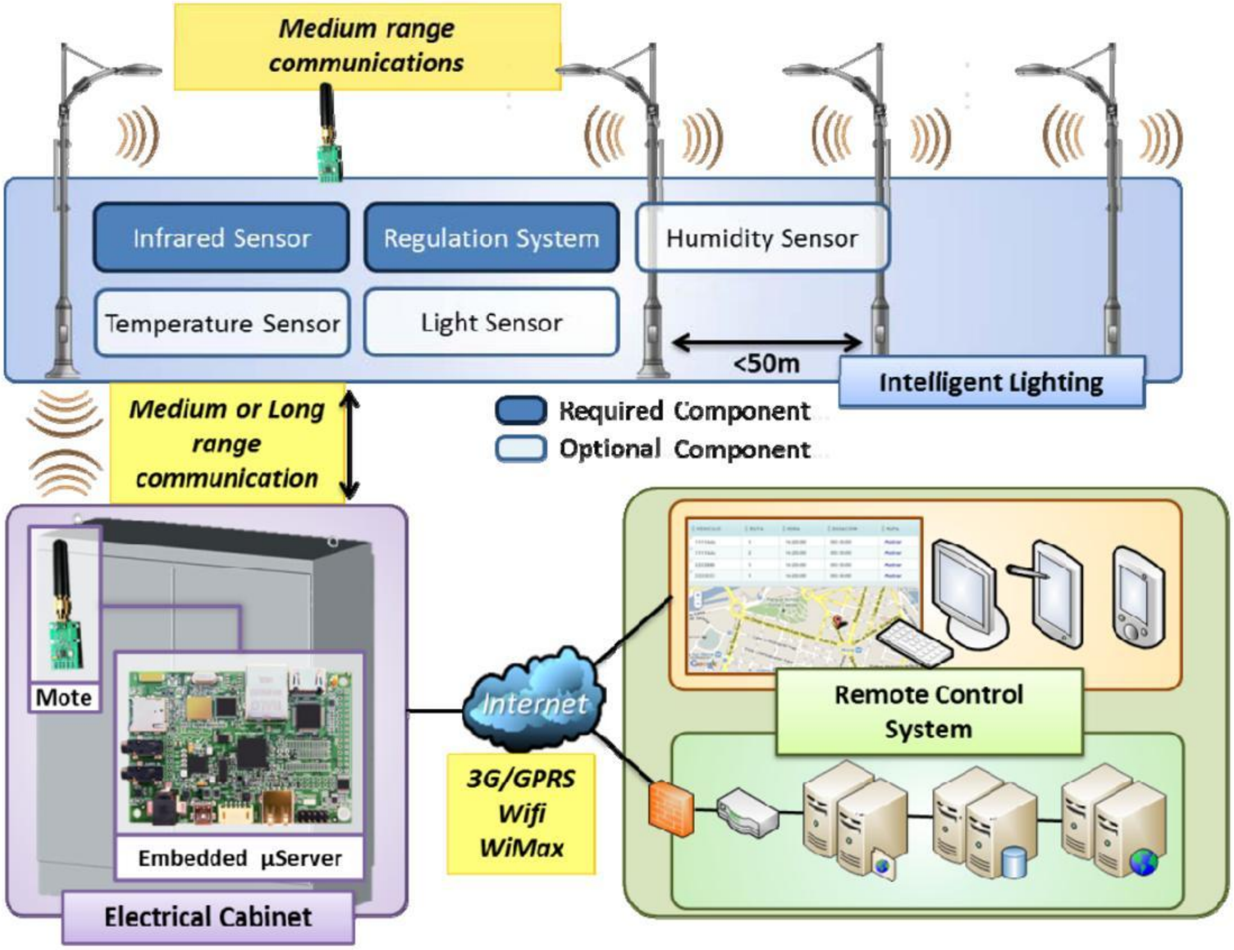
The aerodynamic enclosure profile also improved physical stability for outdoor infrastructure deployment. Rounded external surfaces reduced sharp-edge exposure and minimized potential environmental stress concentrations during outdoor operation. The hose-clamp mounting mechanism integrated into the rear enclosure section provided stable attachment capability for cylindrical streetlight poles ranging from approximately 40 mm to 100 mm in diameter. This mounting flexibility improves compatibility with various urban infrastructure configurations.

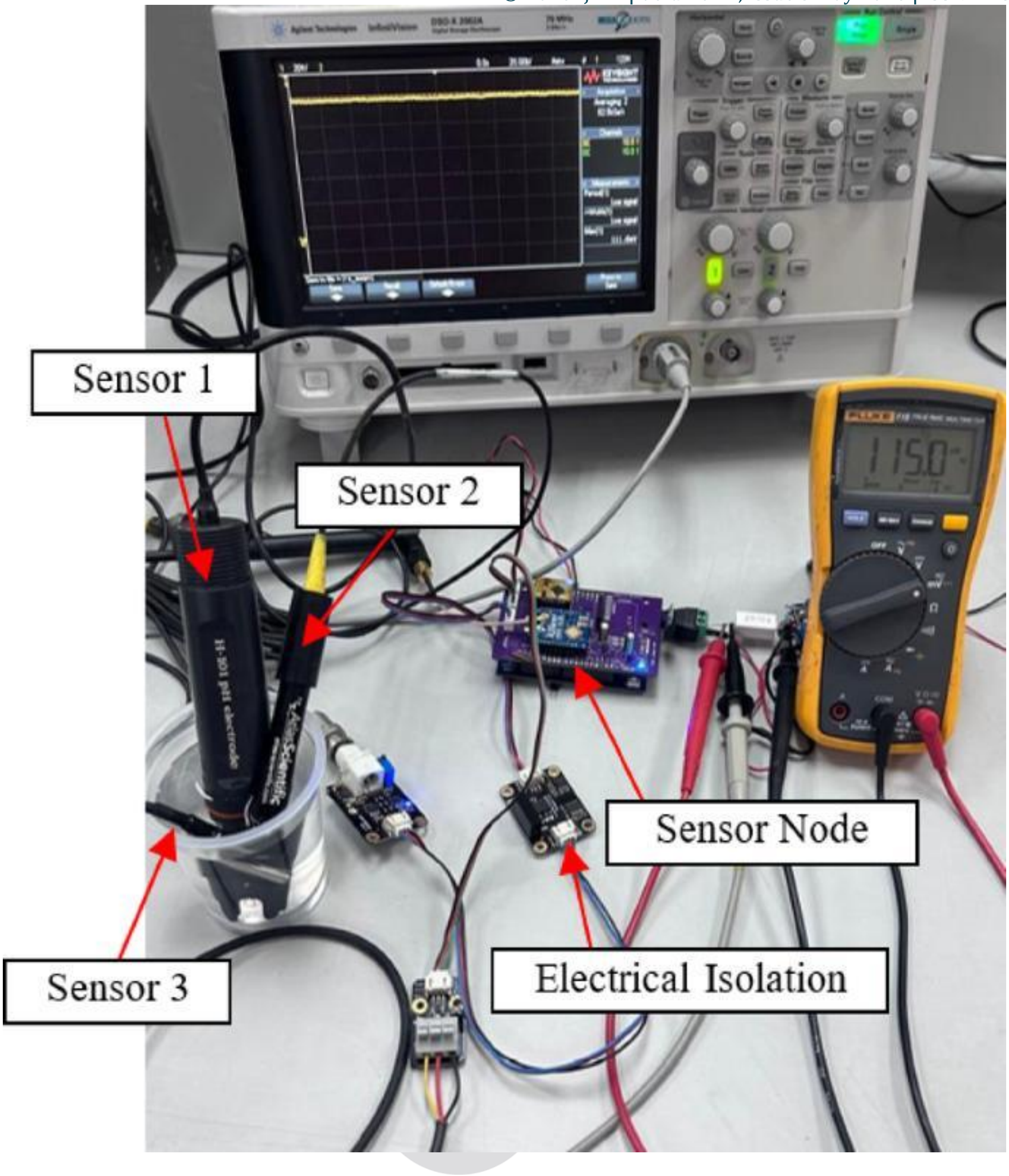
The additive manufacturing optimization process also contributed positively to the mechanical performance of the enclosure. The modular architecture reduced material complexity while maintaining structural rigidity across the enclosure assembly. Internal support ribs and reinforced connection points improved resistance to deformation during handling and installation. Furthermore, the separation of internal electronics compartments reduced the risk of component displacement during vibration or mechanical movement.

Environmental design considerations also improved the outdoor suitability of the enclosure system. Ventilation structures positioned within the lower section of the enclosure supported moisture drainage and airflow circulation. The enclosure orientation and overhanging surfaces minimized direct water penetration into sensitive electronic compartments. These mechanical and environmental design optimizations collectively enhanced the suitability of the prototype for intelligent urban infrastructure deployment.

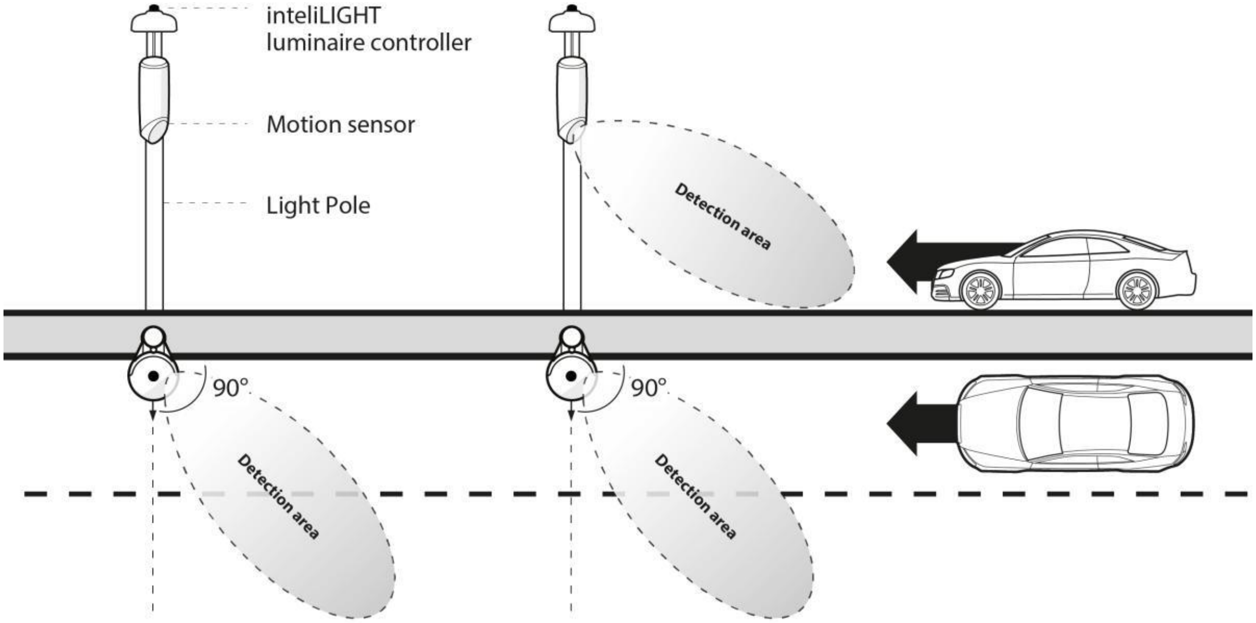
5.2 Sensor and Embedded System Performance

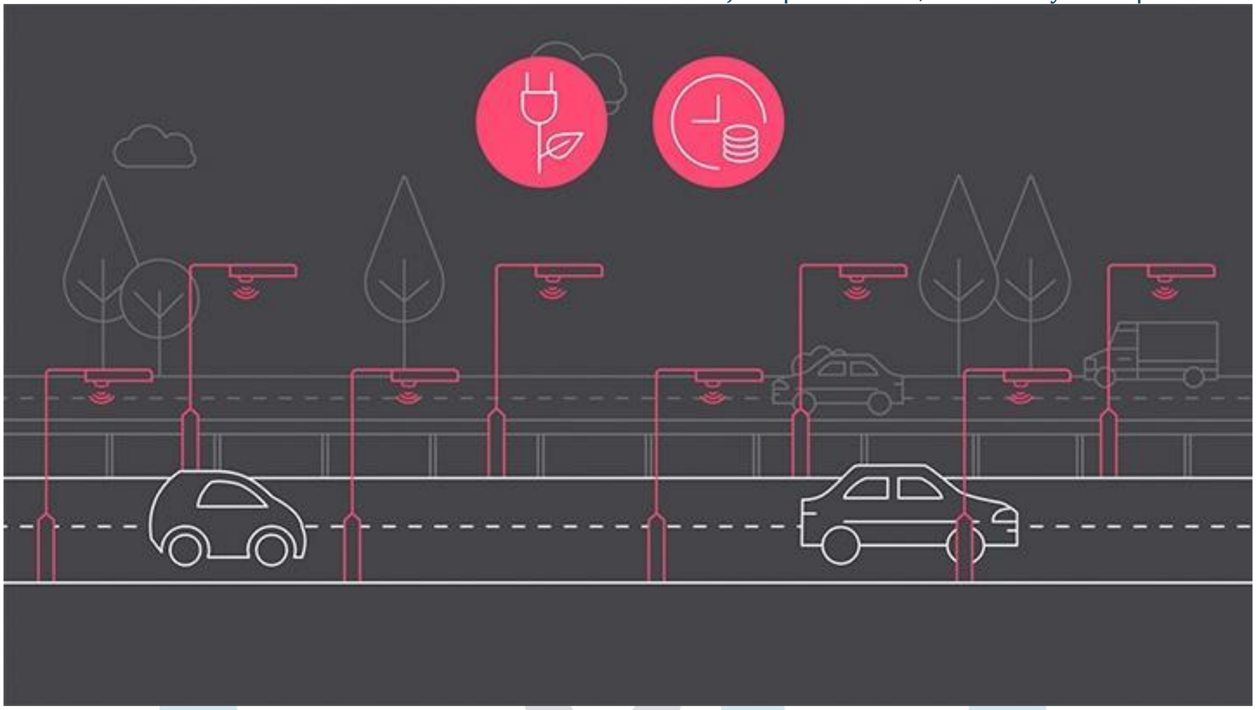
The sensing subsystem demonstrated stable operational performance during preliminary system evaluation. The embedded sensing architecture successfully detected changes in streetlight illumination conditions and transmitted corresponding operational data through the integrated communication framework. The optimized positioning of the sensor module on a 30-degree inclined surface improved directional sensitivity toward the monitored lighting source and reduced interference from surrounding environmental illumination.

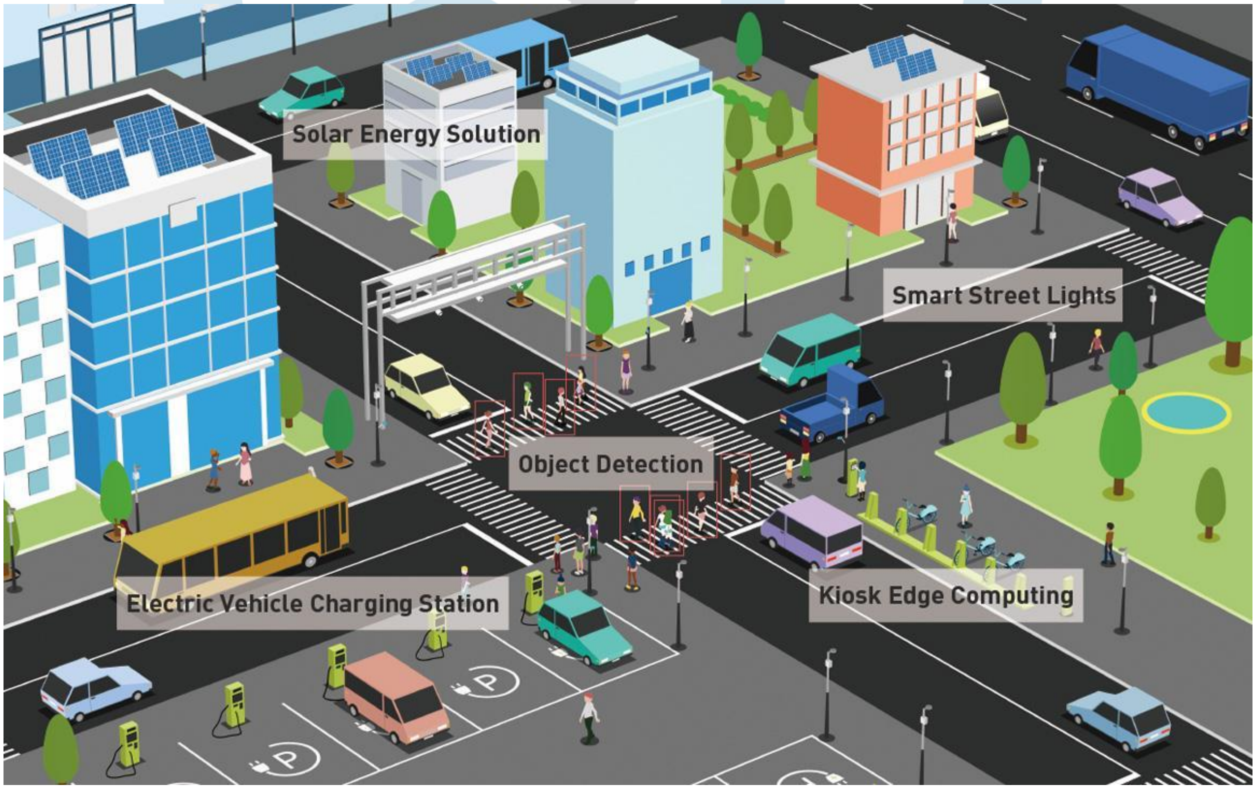

Medium range communications
Infrared Sensor
Regulation System
Humidity Sensor
Temperature Sensor
Light Sensor
<50m
Intelligent Lighting
Medium or Long range communication
Required Component
Optional Component
Mote
Embedded µServer
Electrical Cabinet
Internet
3G/GPRS
Wifi
WiMax
Remote Control System


Sensor 1
Sensor 2
Sensor 3
Sensor Node
Electrical Isolation
115.0


Motion
Audio
Video
Vibration
Ambient
Environment


inteliLIGHT luminaire controller
Motion sensor
Light Pole
Detection area
90°
Detection area
90°
Detection area





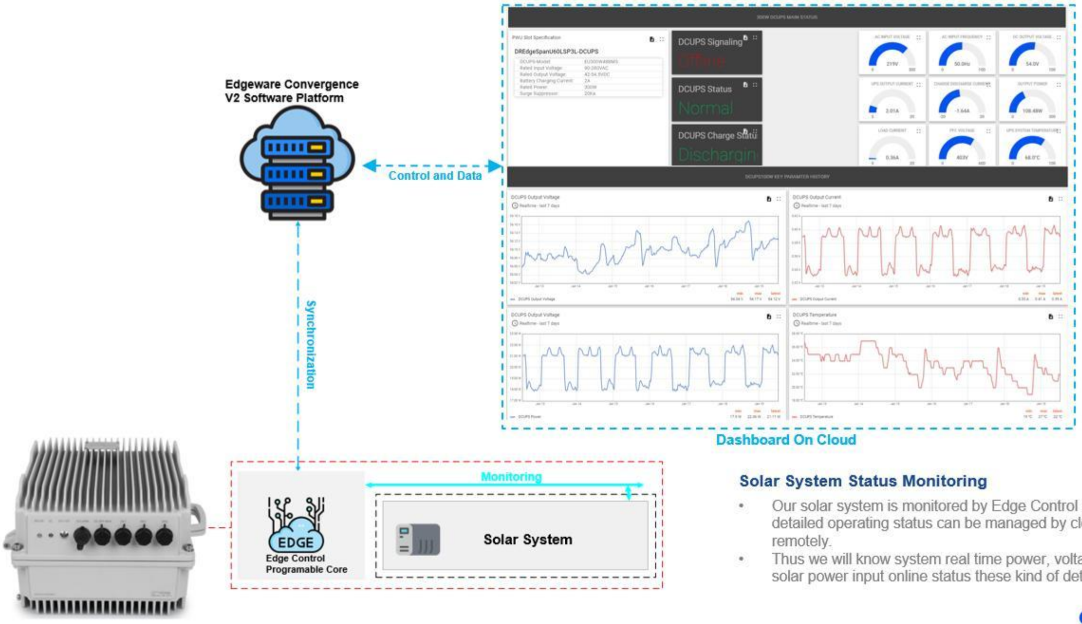
The embedded microcontroller system effectively coordinated sensor interaction, communication processing, and operational logic execution throughout testing activities. Real-time acquisition of sensor data was achieved successfully, demonstrating stable communication between sensing components and the processing subsystem. The microcontroller architecture also maintained consistent interaction with the GSM communication module and GPS subsystem without observable operational conflict during testing.

The wireless communication subsystem demonstrated reliable transmission capability for infrastructure monitoring applications. Operational status information generated by the sensing subsystem was successfully transmitted through GSM communication channels into remote monitoring environments. The integrated GPS subsystem also successfully provided geolocation identification capability, improving the ability to track distributed infrastructure assets within urban deployment environments.

The modular embedded system architecture also demonstrated flexibility for future scalability and system expansion. Additional sensing modules and communication interfaces can be integrated into the existing enclosure structure with minimal modification to the core infrastructure architecture. This modularity improves the long-term applicability of the proposed system within evolving smart-city ecosystems.

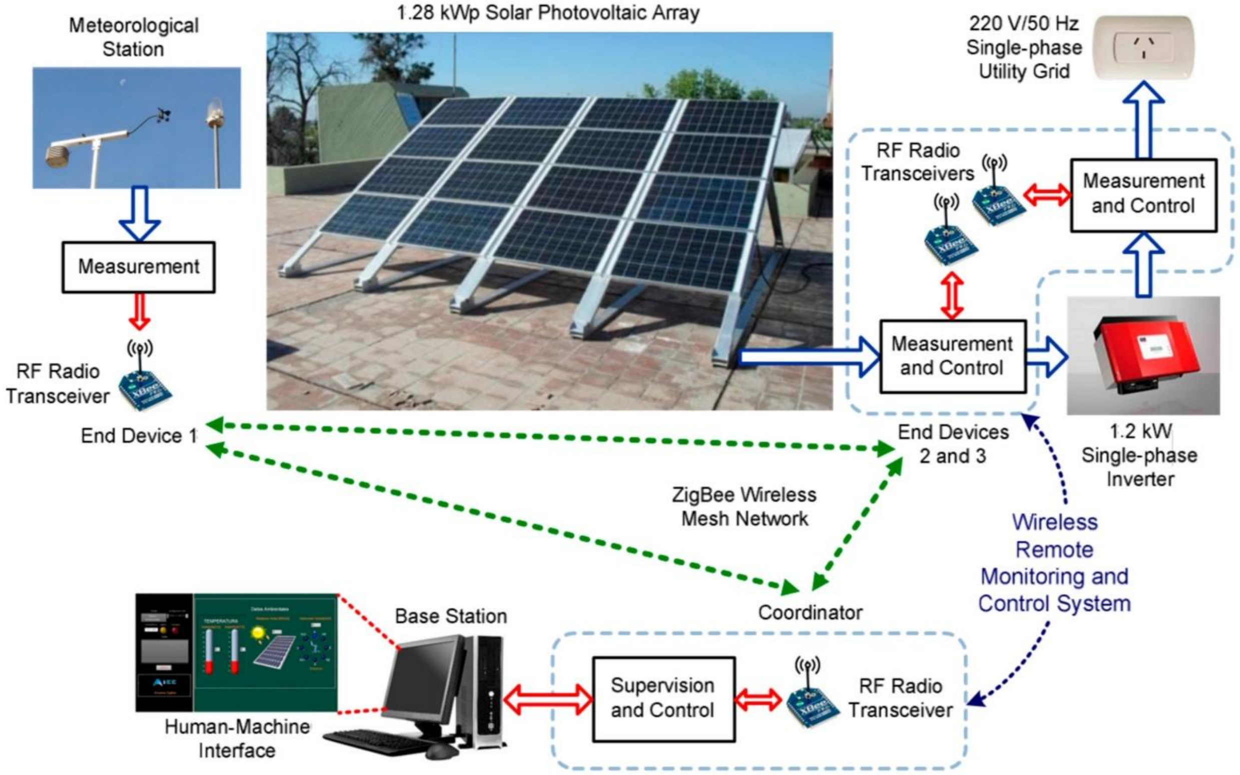
5.3 Power and Energy Performance

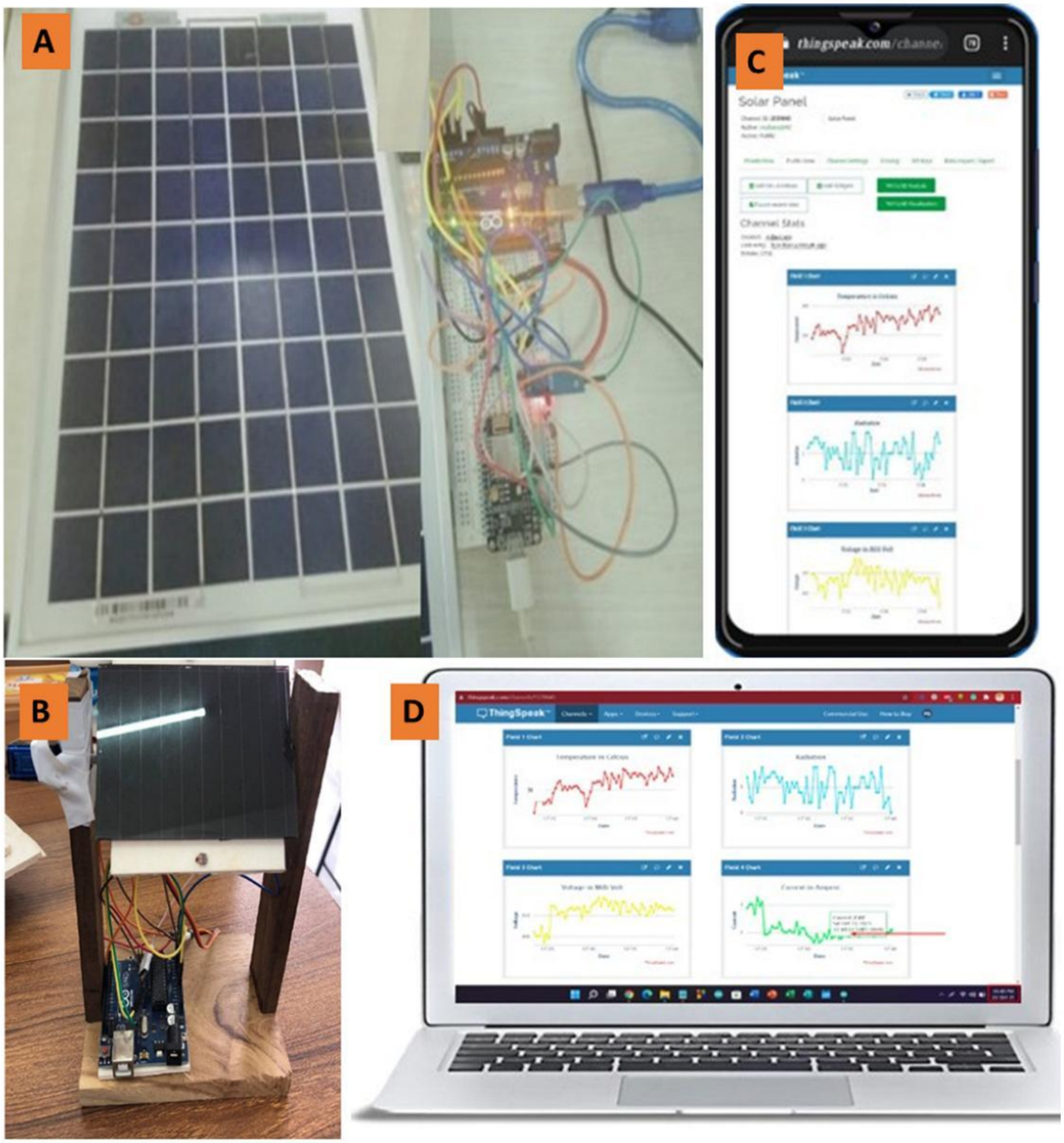
The renewable energy subsystem integrated within the enclosure architecture demonstrated effective operational support for the embedded monitoring system. The solar charging subsystem successfully supplied electrical energy to the rechargeable battery infrastructure during exposure to simulated and natural lighting conditions. The 12-degree inclination angle incorporated into the solar panel mounting geometry improved solar exposure efficiency and enhanced charging capability during outdoor testing.



Solar System Status Monitoring

- Our solar system is monitored by Edge Control unit. UPS detailed operating status can be managed by cloud platform remotely.
- Thus we will know system real time power, voltage, current , solar power input online status these kind of details.


Meteorological Station
1.28 kWp Solar Photovoltaic Array
220 V/50 Hz Single-phase Utility Grid
RF Radio Transceivers
Measurement and Control
Measurement
RF Radio Transceiver
End Device 1
Measurement and Control
End Devices 2 and 3
1.2 kW Single-phase Inverter
ZigBee Wireless Mesh Network
Wireless Remote Monitoring and Control System
Coordinator
Base Station
Supervision and Control
RF Radio Transceiver
Human-Machine Interface



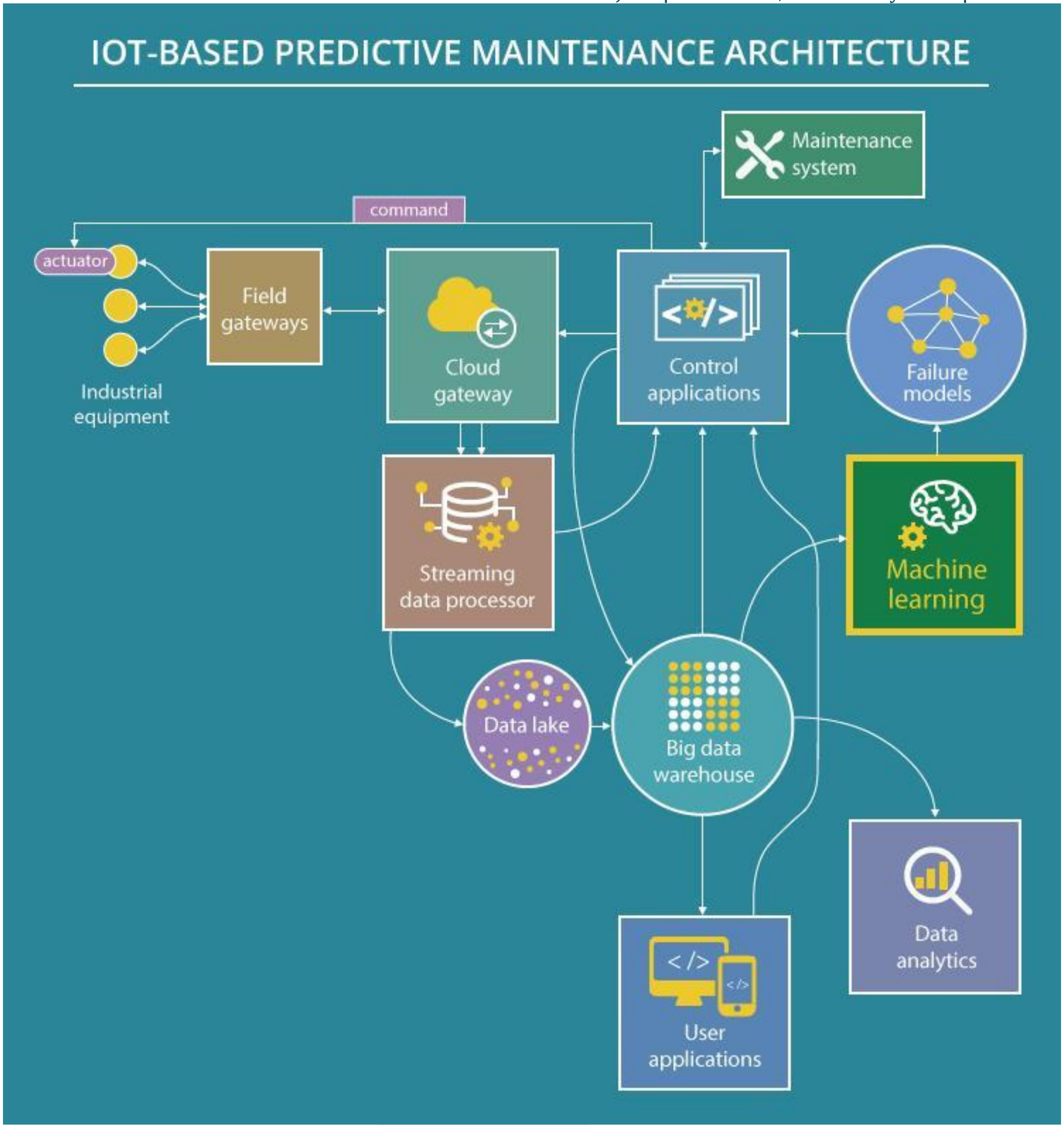
The rechargeable battery system provided stable power support for the sensing architecture, embedded processing unit, and communication subsystem during periods of reduced external energy availability. The low-power design of the embedded electronics contributed positively to operational efficiency and reduced overall power consumption requirements. This improves the practicality of the system for autonomous or semi-autonomous outdoor deployment within municipal infrastructure systems.

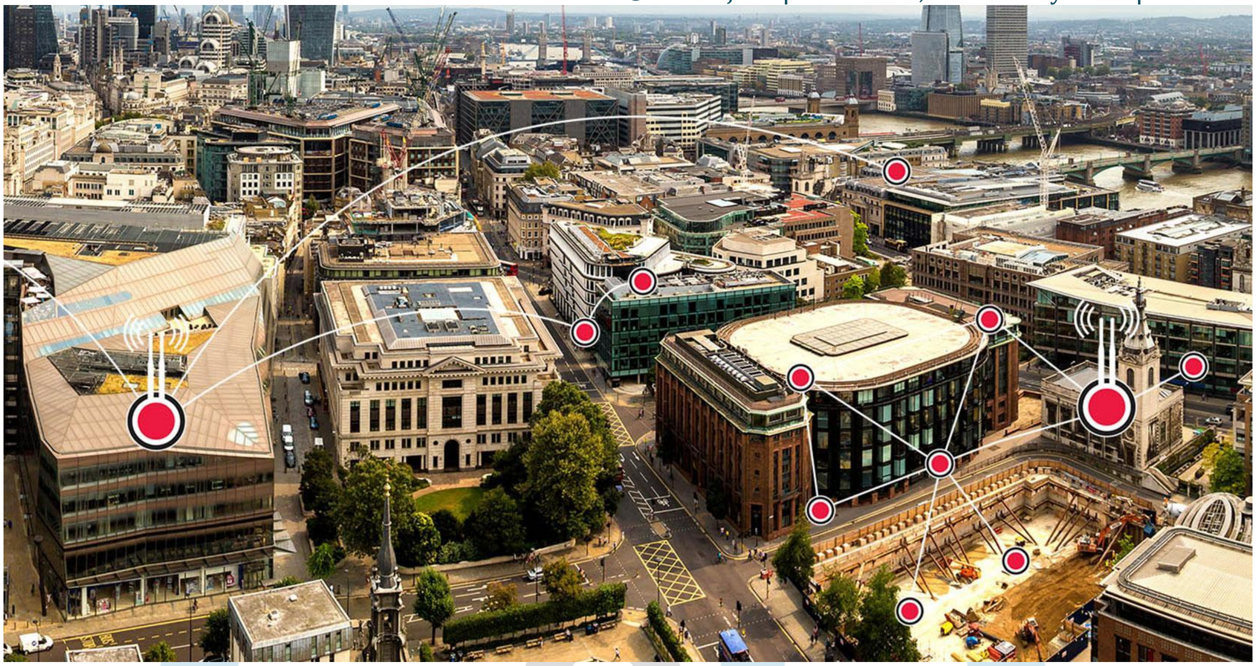
Energy efficiency represents a major operational advantage of the proposed smart monitoring architecture. Conventional streetlight systems often lack operational intelligence and continue functioning inefficiently regardless of environmental or infrastructure conditions. In contrast, the proposed IoT-enabled monitoring platform provides operational visibility that can support intelligent maintenance scheduling, optimized energy utilization, and reduced operational waste. The integration of renewable energy support further strengthens the sustainability potential of the system.

The incorporation of renewable energy technologies within the enclosure architecture also supports broader smart-city sustainability objectives. Solar-powered monitoring systems reduce dependency on centralized electrical infrastructure and improve deployment flexibility in remote or distributed urban environments. Consequently, the proposed design contributes to environmentally sustainable infrastructure management while improving operational reliability and infrastructure visibility.

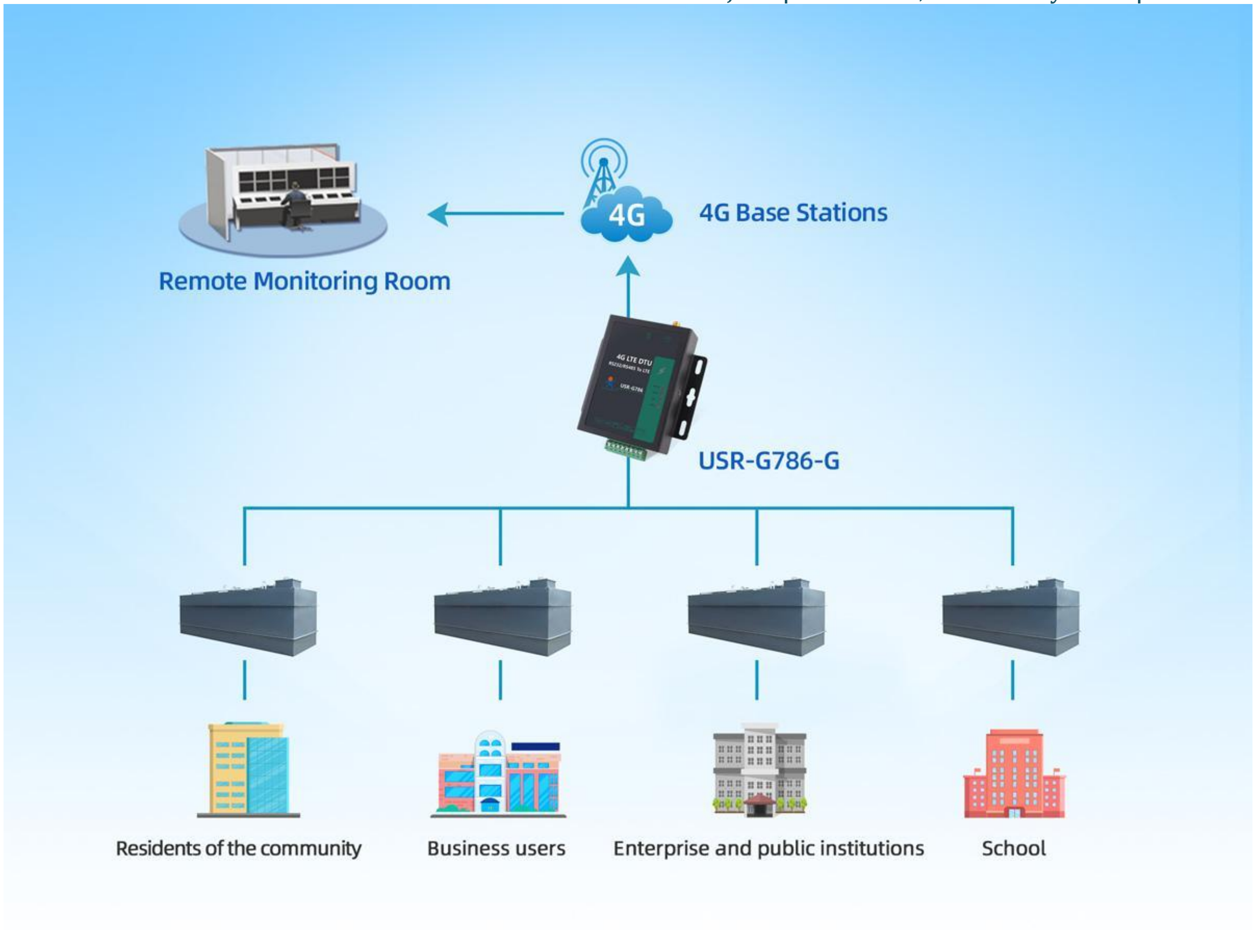
5.4 Smart Monitoring and Communication Performance

The smart monitoring architecture demonstrated effective real-time communication and operational feedback capability during preliminary evaluation activities. The integrated sensing, processing, and communication systems successfully operated as a unified infrastructure monitoring platform capable of supporting intelligent urban infrastructure applications. Real-time operational data transmission improved infrastructure visibility and demonstrated the feasibility of continuous monitoring for public utility systems.


IOT-BASED PREDICTIVE MAINTENANCE ARCHITECTURE
Maintenance system
command
actuator
Field gateways
Cloud gateway
Control applications
Failure models
Industrial equipment
Streaming data processor
Machine learning
Data lake
Big data warehouse
Data analytics
User applications




KWh
KWh
KWh
KWh



The communication subsystem successfully transmitted monitoring data from the field-deployed infrastructure node into remote monitoring environments using GSM communication protocols. The transmitted information included operational status signals, sensing outputs, and device identification information. This communication capability improves infrastructure responsiveness by enabling operators to identify failures or operational abnormalities without physical inspection procedures.

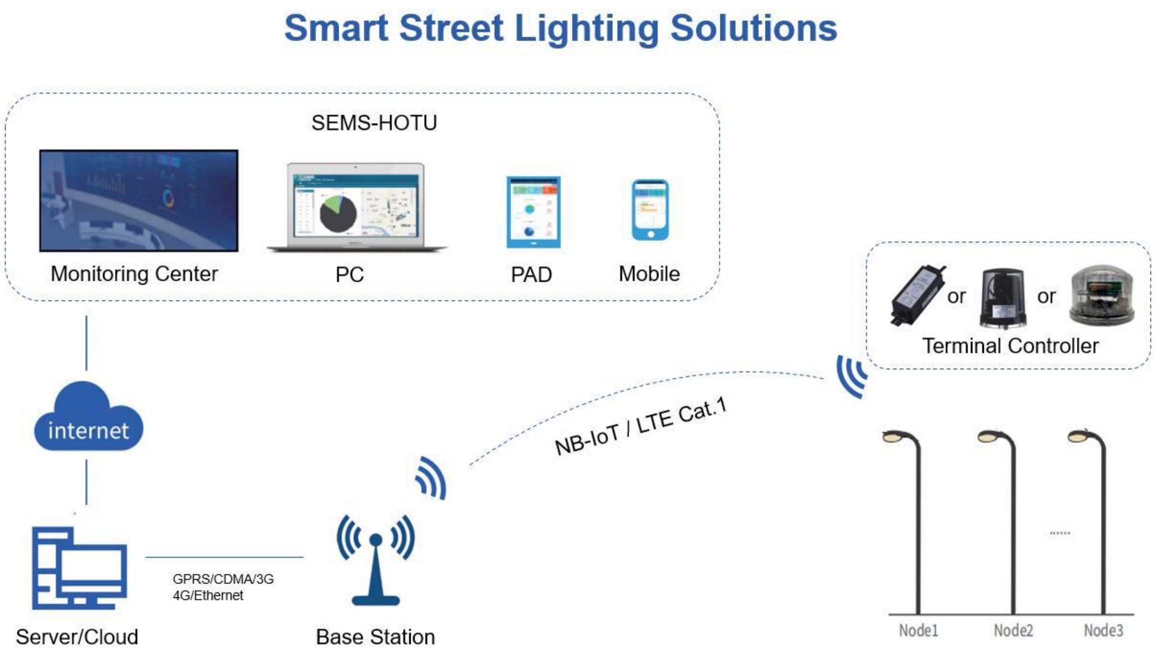
The developed monitoring framework also supports future predictive maintenance functionality. Continuous acquisition of operational data creates opportunities for future implementation of analytics-driven maintenance systems capable of identifying abnormal infrastructure behavior before complete system failure occurs. This predictive capability has significant implications for reducing maintenance costs, minimizing service downtime, and improving long-term infrastructure reliability within smart-city environments.

The preliminary results demonstrate that the proposed system successfully integrates additive manufacturing, renewable energy support, embedded sensing technologies, and IoT communication infrastructure into a scalable smart monitoring platform. The developed architecture provides a practical foundation for intelligent streetlight monitoring, infrastructure automation, and sustainable urban infrastructure management.

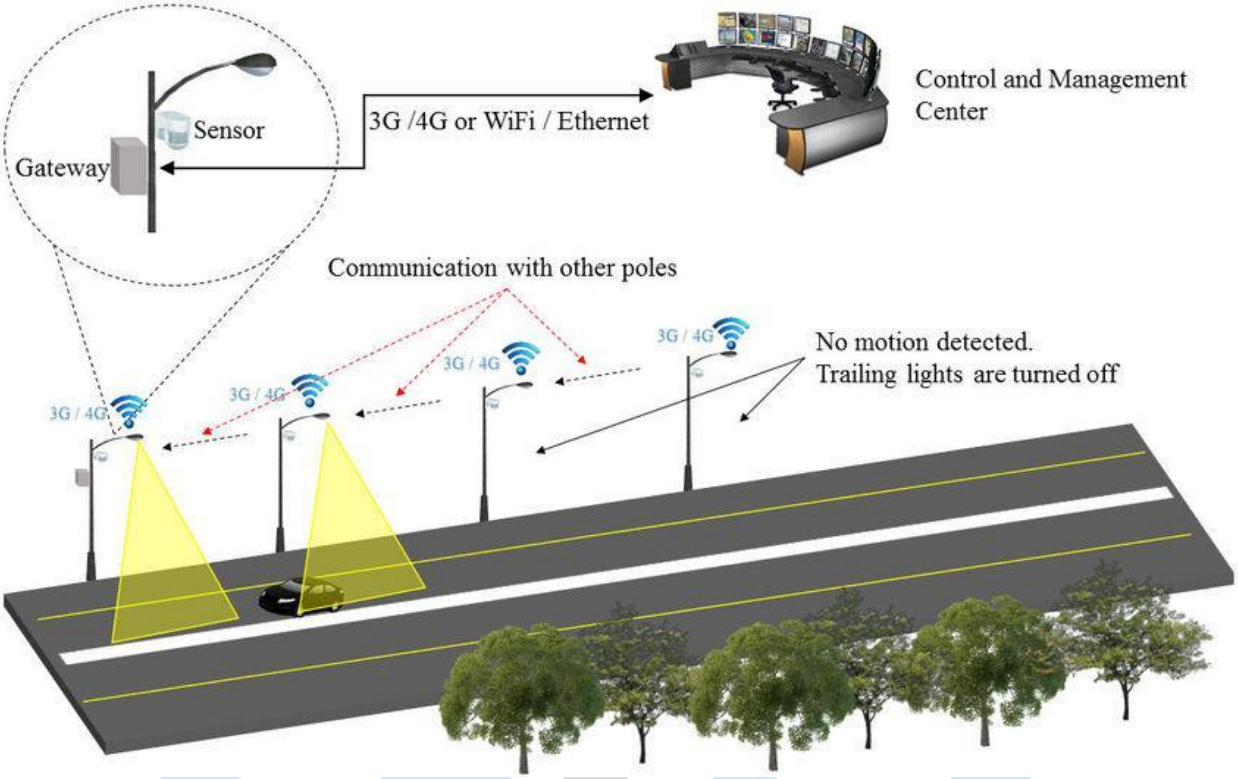
6. Discussion

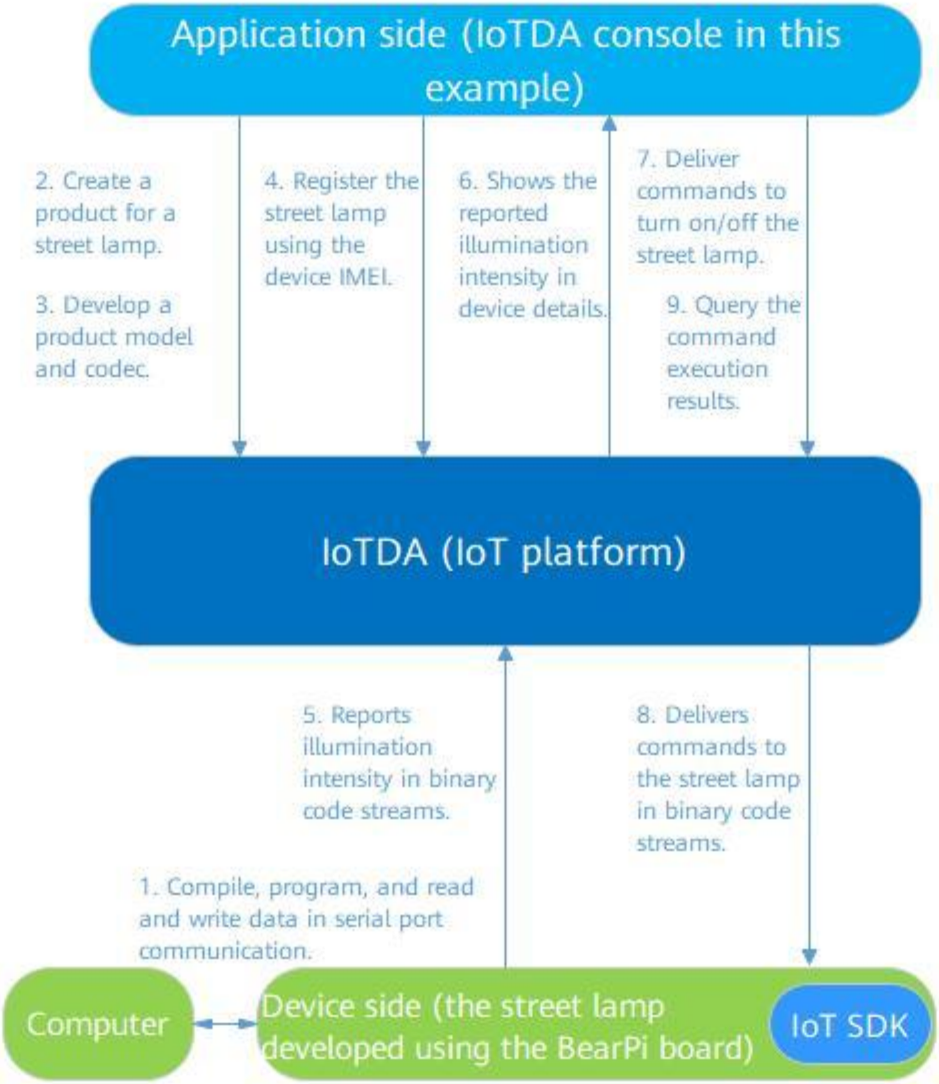
The findings of this study demonstrate the feasibility of integrating additive manufacturing, IoT-enabled sensing systems, embedded electronics, and renewable energy technologies into a unified smart infrastructure platform for urban streetlight monitoring applications. The developed enclosure system successfully addressed several limitations associated with traditional streetlight infrastructures, particularly in relation to infrastructure visibility, maintenance responsiveness, scalability, and environmental sustainability.

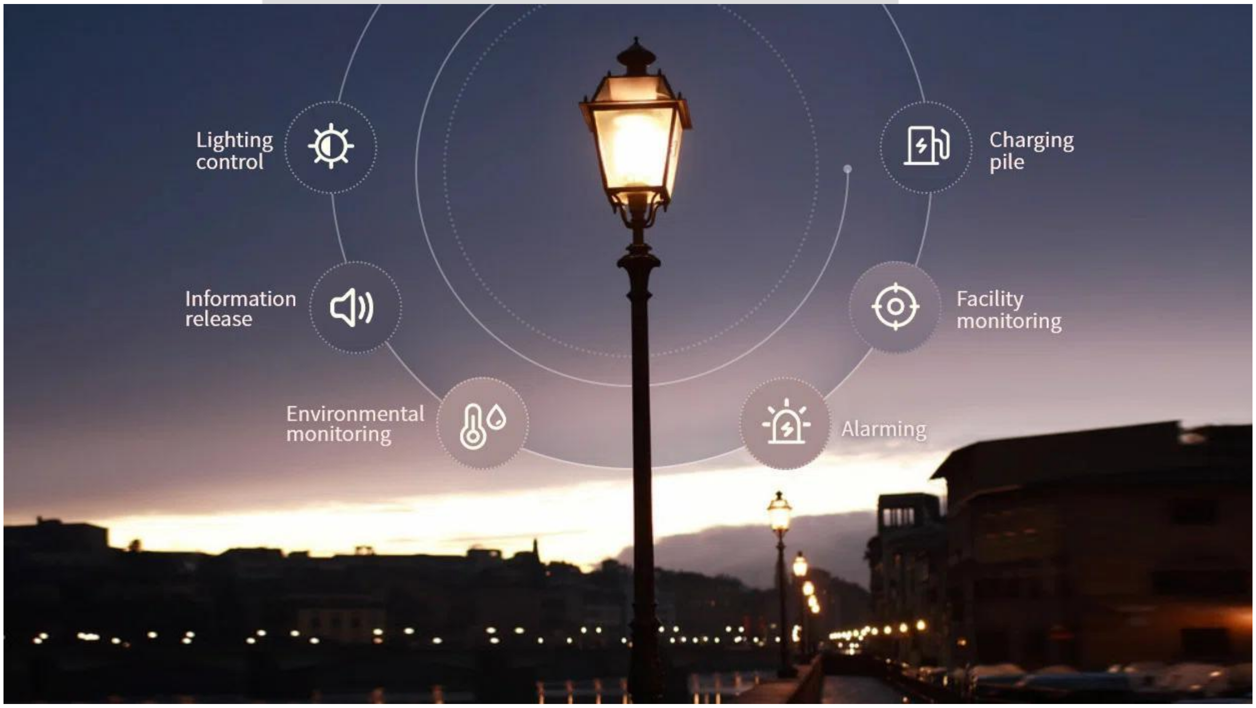

OWLET CLOUD
DIMMING STATUS
BURNING HOURS
POWER OFF
LUMINAIRE ID
DIMMING PROFILE
Liberty Seguros
BPI
BURGER KING

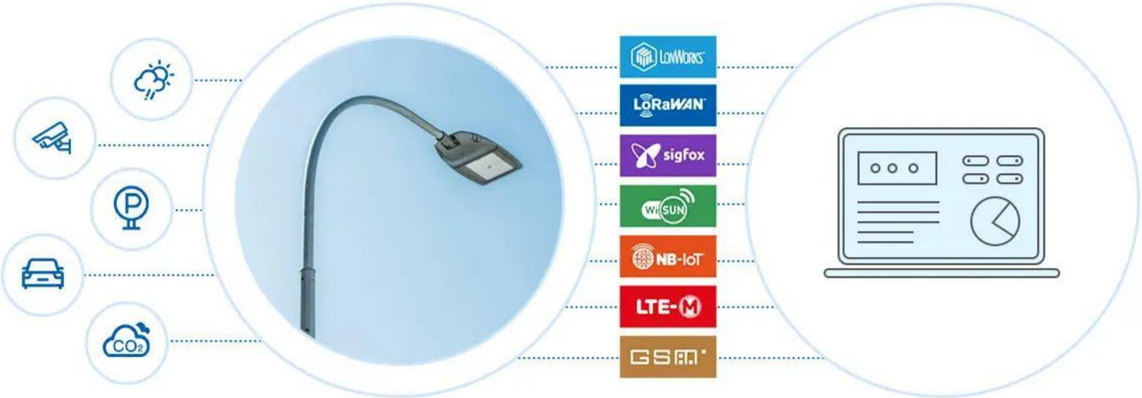

Smart Street Lighting Solutions
SEMS-HOTU
Monitoring Center
PC
PAD
Mobile
internet
Server/Cloud
GPRS/CDMA/3G
4G/Ethernet
Base Station
NB-IoT / LTE Cat.1
or
or
Terminal Controller
......
Node1
Node2
Node3


POLICE


Control and Management Center
3G /4G or WiFi / Ethernet
Sensor
Gateway
Communication with other poles
3G / 4G
3G / 4G
3G / 4G
3G / 4G
No motion detected.
Trailing lights are turned off


Application side (IoTDA console in this example)
2. Create a product for a street lamp.
3. Develop a product model and codec.
4. Register the street lamp using the device IMEI.
6. Shows the reported illumination intensity in device details.
7. Deliver commands to turn on/off the street lamp.
9. Query the command execution results.
IoTDA (IoT platform)
5. Reports illumination intensity in binary code streams.
8. Delivers commands to the street lamp in binary code streams.
1. Compile, program, and read and write data in serial port communication.
Computer
Device side (the street lamp developed using the BearPi board)
IoT SDK


Lighting control
Information release
Environmental monitoring
Charging pile
Facility monitoring
Alarming



One of the major contributions of the developed system lies in its emphasis on physical infrastructure engineering rather than software functionality alone. Existing smart streetlight research frequently focuses on communication platforms and monitoring dashboards while providing limited attention to enclosure optimization, environmental durability, manufacturability, and outdoor deployment feasibility. This study addressed these gaps by developing a fully integrated enclosure architecture specifically optimized for outdoor operation, additive manufacturing compatibility, embedded system integration, and renewable energy support.

The use of additive manufacturing technologies significantly improved development flexibility and reduced prototyping complexity. The ability to rapidly iterate enclosure geometries and integrate internal support structures demonstrates the suitability of additive manufacturing for smart infrastructure prototyping and customized urban infrastructure solutions. Furthermore, the modular architecture improves long-term maintainability and future scalability by allowing integration of additional sensing technologies and communication interfaces with minimal redesign requirements.

The integration of renewable energy support and real-time monitoring capability also strengthens the sustainability impact of the proposed system. Intelligent monitoring architectures improve infrastructure visibility, reduce operational inefficiencies, and support predictive maintenance strategies that minimize maintenance waste and service downtime. These advantages contribute directly to broader smart-city objectives relating to energy efficiency, infrastructure resilience, and environmentally sustainable urban development.

Although the system demonstrated strong preliminary performance, several limitations remain. Long-term outdoor field deployment and environmental endurance testing were not fully completed during the current study. Future work should include extended operational testing under varying climatic conditions, implementation of advanced predictive analytics algorithms, and integration of additional smart-city functionalities such as environmental sensing, edge computing, and machine learning-based infrastructure diagnostics. Despite these limitations, the developed system provides a strong engineering foundation for scalable intelligent infrastructure deployment within modern urban environments.

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