IoT Based Smart City using Raspberry Pi

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Abstract:

The rapid growth of urban populations has led to an increasing demand for smarter and more sustainable city infrastructure. This research presents an IoT-based Smart City framework utilizing Raspberry Pi and ESP32 microcontrollers to automate and monitor key urban services including car parking, street lighting, waste management, and weather detection. The proposed system incorporates three IR sensors to detect vehicle presence in parking slots and operates corresponding servo motors to control gate barriers. For street light automation, Light Dependent Resistors (LDRs) are used to differentiate between day and night, triggering LEDs accordingly to conserve energy. A rain sensor connected to a servo motor detects weather conditions (dry/wet), while smart bins equipped with IR sensors monitor waste levels. Upon reaching full capacity, the system sends SMS alerts using a GSM 800 module and captures the bin location via GPS for efficient waste collection. Real-time data from all modules is transmitted to the Adafruit IO cloud server using the ESP32 module, enabling remote monitoring of IP locations, parking slot availability, bin status, and street light operations. The integration of these technologies into a unified platform demonstrates a scalable and efficient approach to building sustainable smart cities with minimal human intervention.

Index Terms - IoT, Smart City, Raspberry Pi, ESP32, Adafruit IO, Car Parking System, Street Light Automation, IR Sensor, LDR Sensor, Rain Sensor, GSM 800 Module, GPS Module, Smart Bin Monitoring, Real-Time Data, Cloud-Based Monitoring, Urban Infrastructure.

I. Introduction

The rapid urbanization and population growth in cities around the world have put immense pressure on urban infrastructure, leading to challenges in transportation, energy consumption, waste management, and environmental monitoring. In response to these growing concerns, the concept of Smart Cities has emerged, aiming to utilize advanced technologies to improve the quality of life for urban residents, enhance operational efficiency, and promote sustainable development.

The Internet of Things (IoT) plays a pivotal role in realizing smart city applications by enabling real-time data collection, communication, and automation across various services. This research presents the design and implementation of an IoT-based Smart City system using Raspberry Pi as the central controller, supported by ESP32 for cloud integration via the Adafruit IO platform.

The proposed system includes four major modules: a smart car parking system, an automated street lighting system, a rain detection unit, and a smart waste management system. The car parking module utilizes IR sensors to detect vehicle presence and servo motors to control access gates. The street lighting module uses LDRs to distinguish between day and night, controlling LEDs to optimize energy usage. The rain detection module employs a rain sensor to differentiate between wet and dry conditions, activating a servo motor mechanism accordingly. The smart bin system detects waste levels using IR sensors, sends alerts via a GSM 800 module when bins are full, and uses GPS to locate the exact position of the filled bin for prompt waste collection.

All system data is collected and transmitted to the Adafruit IO cloud server through ESP32, allowing users and authorities to monitor the real-time status of parking slots, street lights, weather conditions, and waste bins remotely via IP-based dashboards.

By integrating these modules into a unified framework, this research demonstrates a practical, scalable, and energy-efficient approach to building a smarter and more sustainable urban environment.

II. LITERATURE REVIEW

The evolution of smart cities has been driven by the integration of intelligent technologies such as IoT, wireless communication, and embedded systems. Numerous research studies have explored the use of IoT to enhance urban infrastructure by enabling real-time monitoring and automation of city services.

Smart Car Parking Systems have been widely studied to address the growing challenge of traffic congestion and inefficient parking space utilization. In [1], a system using ultrasonic sensors and Arduino was developed to detect vehicle presence in parking slots and display availability on an LCD. Similarly, in [2], an IoT-based smart parking prototype was proposed where sensor data is sent to a cloud platform to enable drivers to find empty parking slots using a mobile application. These studies emphasize the need for real-time, automated parking systems in densely populated cities.

Street Light Automation using LDR sensors has been explored in [3], where streetlights operate based on ambient light intensity, turning off during the day and on at night. This not only reduces energy consumption but also lowers maintenance costs. Integration with IoT platforms enables authorities to remotely monitor and control lighting systems.

Rain Detection Systems have been proposed using both analog and digital sensors. In [4], a simple rain detection mechanism was implemented to trigger wiper motors and alert systems. While useful, such implementations lack IoT connectivity for data logging and automation, which is addressed in our proposed system.

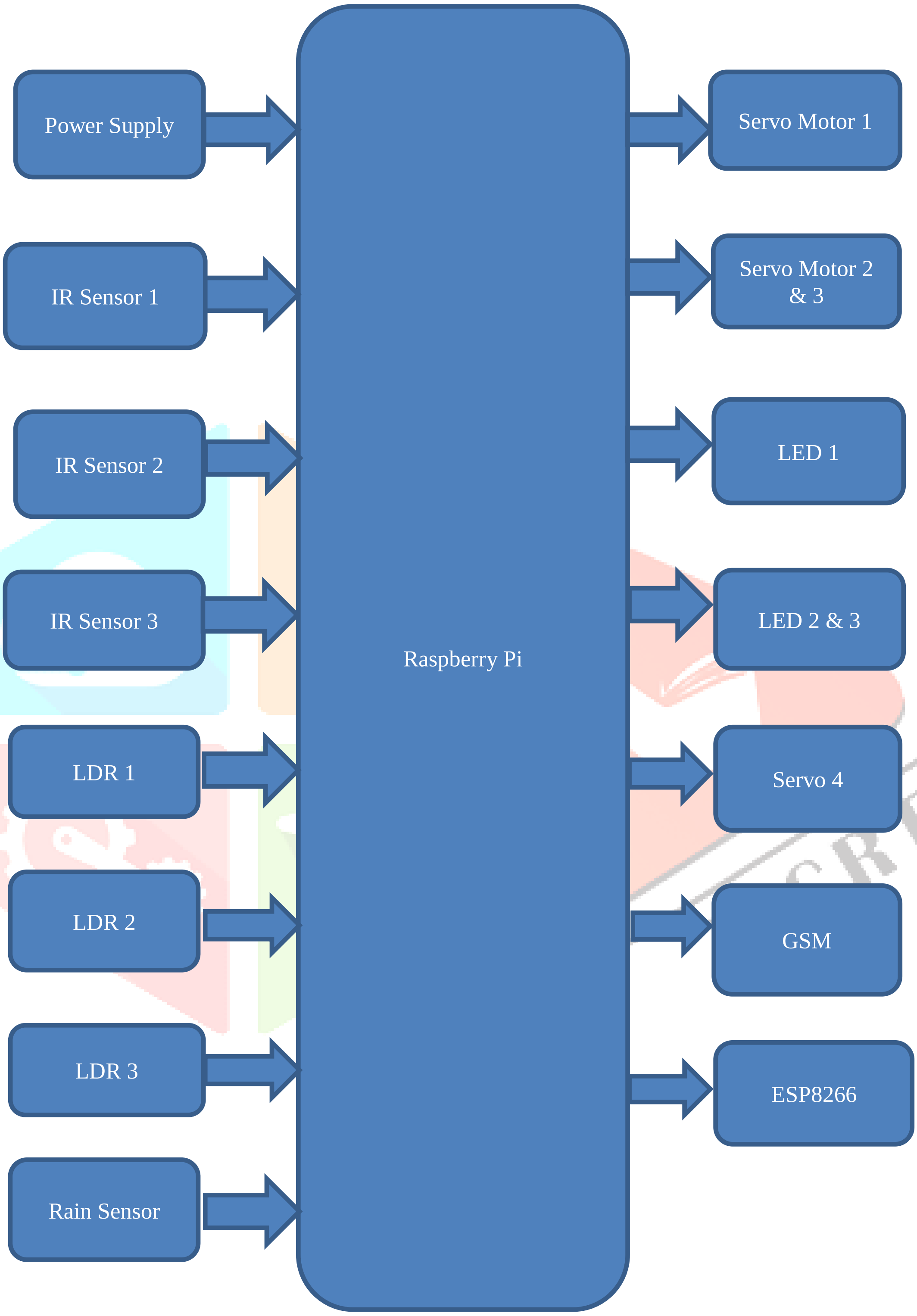
Smart Waste Management is another critical area of smart city development. In [5], a smart bin was designed using ultrasonic sensors and a GSM module to notify authorities when bins were full. A GPS module was later integrated in [6] to provide the exact location of full bins. However, these systems often lacked centralized IoT dashboards for real-time monitoring and data analytics.

IoT Integration Using Adafruit IO and ESP32 has gained attention due to the lightweight, cost-effective, and Wi-Fi-enabled features of ESP32. In [7], ESP32 was used to send environmental data to Adafruit IO, allowing for remote visualization and alert notifications. This demonstrates the growing preference for cloud-based dashboards in smart city designs.

From the existing literature, it is evident that while several isolated solutions exist for urban challenges, there is a lack of unified systems that combine multiple smart city modules into one comprehensive, real-time IoT-enabled solution. Our research addresses this gap by integrating car parking, street lighting, rain detection, and smart bin monitoring into a single smart city platform using Raspberry Pi and ESP32 with Adafruit IO cloud support.

III. Proposed System

3.1 Block Diagram of the Entire System



3.2 Brief on Each Module Integrated

- **Raspberry Pi**: Acts as the brain of the entire system, handling signal inputs from sensors and driving actuator responses (servo motors and LEDs). It coordinates all the modules and communicates with the ESP32 for IoT updates.
- **ESP32 Module**: A Wi-Fi-enabled microcontroller responsible for sending real-time data to the Adafruit IO server. It ensures cloud connectivity and remote visualization of all subsystems (bin level, car parking status, streetlight conditions).
- **IR Sensors**: Six sensors are used — three in the car parking module to detect the presence of vehicles in slots, and three in the smart bins to identify when the bins are full.
- **Servo Motors**: Four motors are used — three to control the gates of parking slots and one attached to the rain detection module to indicate wet/dry conditions.
- **LDR Sensors**: Three LDRs monitor ambient light to automate the on/off state of the streetlights. During night time or low light conditions, corresponding LEDs (acting as streetlights) are turned on.
- **Rain Sensor**: Detects moisture or rainfall. Its data is used for environmental monitoring and for alerting rain-related infrastructure.
- **Smart Bin Module**: Each bin has an IR sensor to detect fullness, a GSM800 module to send SMS alerts, and a GPS module to identify the exact location of the full bin. This data is also pushed to the IoT cloud.
- **GSM800 Module**: Sends alert messages to a registered mobile number when any bin is full, helping municipal authorities respond quickly.
- **GPS Module**: Pinpoints the physical location of each smart bin when it is full and transmits that data to Adafruit IO.
- **Adafruit IO Cloud**: A lightweight and user-friendly IoT platform used for storing and visualizing real-time data from all system modules, accessible via a web or mobile dashboard.

3.3 Overview of Data Flow and Communication Between Components

The system begins with sensors capturing real-time data — IR sensors detect cars or full bins, LDRs detect light intensity, and the rain sensor detects weather conditions. These inputs are processed by the Raspberry Pi, which then triggers appropriate actuator responses, such as activating servo motors for parking gates or turning LEDs on/off for streetlights.

Simultaneously, sensor readings are relayed to the **ESP32**, which formats and transmits the data to the **Adafruit IO** server using Wi-Fi. This data includes parking slot availability, bin status, light activity, and environmental conditions.

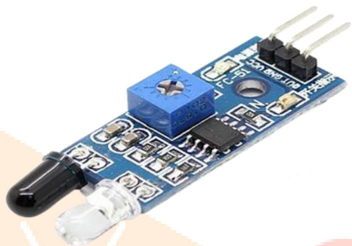
When a bin is full, in addition to IoT updates, the **GSM800 module** sends a text alert to a designated mobile number, while the **GPS module** provides the geolocation of the full bin for operational efficiency.

The **Adafruit IO dashboard** acts as the centralized monitoring platform, where city authorities or users can access real-time insights through web or mobile interfaces, enabling smarter decision-making and efficient urban management.

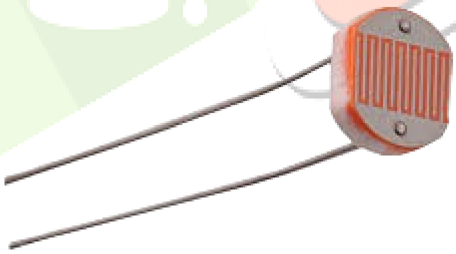
IV. HARDWARE COMPONENTS USED

The proposed IoT-based Smart City framework integrates various hardware components to implement intelligent automation and real-time monitoring of urban infrastructure systems. At the core of the system is the **Raspberry Pi**, a credit-card-sized computer that functions as the primary controller. It processes input signals from all sensors, drives actuators, and manages data communication across the system.

IR (Infrared) Sensors play a crucial role in two modules. First, in the **car parking system**, three IR sensors are used to detect the presence or absence of vehicles in each parking slot. Second, additional IR sensors are installed in **smart bins** to determine if a bin is full. These sensors offer a non-contact method of detection, making them ideal for both safety and accuracy.



LDRs (Light Dependent Resistors) are deployed to implement the **street light automation** module. These sensors monitor the ambient light intensity and trigger the street lights (LEDs) accordingly—turning them on during low-light conditions (night) and off during the day, thereby conserving energy.



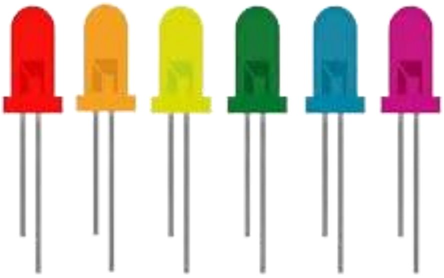
Servo Motors are utilized in multiple applications across the system. Three servo motors are used to control the automatic gates of the car parking slots, opening or closing based on vehicle detection. Another servo motor is connected to the **rain sensor module** to operate a protective cover or indicate wet/dry weather conditions through a mechanical movement.

The **Rain Sensor** detects the presence of rain or moisture. When rainfall is detected, it sends a signal to the Raspberry Pi, which can then trigger appropriate alerts or control the servo motor for physical indications or protective actions.

The **GSM 800 Module** is a key component for communication in the **smart bin monitoring system**. When any bin is detected as full by the IR sensor, the GSM module sends an SMS notification to a predefined mobile number, alerting the waste management team.

To enhance bin tracking, a **GPS Module** is incorporated to provide the **real-time location** of each smart bin. When a bin is full, its coordinates are also sent to the IoT platform, enabling city personnel to identify and service it efficiently.

LEDs serve multiple purposes across the system, particularly as **street lights** controlled by the LDRs. These LEDs are switched on or off automatically depending on light intensity, mimicking real-world smart lighting systems used in cities.



Lastly, the system is powered by a stable **Power Supply** unit that ensures consistent and reliable voltage and current delivery to all modules. This includes regulated power for the Raspberry Pi, ESP32, sensors, and actuators, ensuring smooth and safe operation throughout.

RESEARCH METHODOLOGY

The methodology section outline the plan and method that how the study is conducted. This includes Universe of the study, sample of the study, Data and Sources of Data, study's variables and analytical framework. The details are as follows;

The methodology adopted for this research is a **design-based experimental approach**, integrating embedded systems, IoT frameworks, and sensor-based automation to develop a prototype of a smart city infrastructure. The system is modularly divided into four main functional units: **Smart Car Parking**, **Smart Street Lighting**, **Rain Detection & Environmental Monitoring**, and **Smart Waste Management**. Each module is carefully designed, implemented, and tested independently before being integrated into a unified smart city model.

Requirements Analysis

The first phase involved identifying the core challenges faced in urban environments such as limited parking availability, energy wastage through unmanaged street lighting, inefficient waste collection, and the need for real-time environmental data. A detailed analysis of existing smart city solutions and IoT frameworks was conducted to determine the feasibility and effectiveness of integrating sensor-based automation with cloud-based monitoring systems.

Hardware and Sensor Integration

After finalizing the design specifications, essential components such as Raspberry Pi, ESP32, IR sensors, LDRs, GPS, GSM modules, rain sensors, and servo motors were procured and tested. The hardware components were interfaced using Python and embedded C, with the Raspberry Pi serving as the central controller. The ESP32 microcontroller enabled seamless connectivity to the Adafruit IO platform, which acted as the centralized IoT dashboard.

Module Development

Each module was developed and tested individually:

- The **Smart Car Parking System** used IR sensors to detect cars and servo motors to control parking gates.
- The **Street Light Automation Module** used LDRs to compare day and night conditions, activating LEDs based on real-time light levels.
- The **Rain Detection Unit** utilized a rain sensor connected to a servo motor to perform a mechanical response and register weather data.
- The **Smart Bin Monitoring System** used IR sensors to detect full bins, with the GSM module sending SMS alerts and GPS modules tracking the location.

IoT and Cloud Communication

The ESP32 was programmed to gather data from all modules and push it to the **Adafruit IO cloud platform**. MQTT protocols and API keys were configured to ensure secure, real-time data exchange. The IoT dashboard was customized to display real-time information such as parking slot availability, bin status, streetlight activity, and environmental conditions.

Testing and Validation

Once integrated, the complete system was tested under various conditions to validate functionality, data accuracy, response time, and communication reliability. The system successfully demonstrated real-time automation and monitoring, with timely alerts sent via SMS and live data visible on the IoT server.

IV. RESULTS AND DISCUSSION

The proposed IoT-based Smart City prototype was successfully designed, developed, and tested across various scenarios. The system demonstrated efficient automation and real-time monitoring across its core modules, namely **smart car parking**, **street lighting**, **waste management**, and **rain detection**, using the integrated hardware and IoT components.

Smart Car Parking System

The car parking system employed **three IR sensors** for vehicle detection and **three servo motors** to control parking gates. During testing, the system was able to accurately detect the presence or absence of vehicles in individual slots and open or close the gates accordingly. The real-time parking status was transmitted to the **Adafruit IO cloud dashboard**, where users could monitor slot availability. The parking data was consistently updated with minimal latency, showcasing high reliability and effective control.

Street Light Automation

The street lighting module, utilizing **LDR sensors**, effectively differentiated between day and night conditions. During low ambient light (simulated night conditions), the connected **LEDs** were turned on automatically. Conversely, during high light levels (simulated day conditions), the LEDs were turned off. This automatic switching demonstrated the system's capability to reduce energy consumption without manual intervention, which is a key objective in smart energy systems.

Smart Bin Monitoring and Rain Detection

For waste management, IR sensors were installed in the bins to detect if they were full. When the bin reached its capacity, the system successfully triggered the **GSM 800 module**, which sent an **SMS alert to a**

predefined mobile number, notifying the authorities. Simultaneously, the **GPS module** captured the bin's real-time location and sent the data to the **IoT server**, ensuring efficient bin tracking and maintenance.

The **rain sensor**, connected to a servo motor, effectively detected dry and wet conditions. On detecting rain, the servo motor responded with mechanical movement (e.g., cover shifting or alert triggering), simulating how the system could respond to weather changes. This demonstrated the potential for smart environmental adaptation in real-time applications.

IoT Server and Data Visualization

All modules were integrated via **ESP32**, which transmitted real-time data to the **Adafruit IO cloud platform**. The IoT dashboard displayed:

- Parking slot availability and status
- Bin fill status and GPS location
- Streetlight activity logs
- Rain sensor status (dry/wet)

The system's cloud integration allowed for remote access and real-time decision-making, meeting the core goals of scalability, efficiency, and centralized monitoring in smart cities.

Performance Discussion

The system was evaluated for response time, accuracy, and reliability. Results indicated a **response time of less than 1 second** for sensor-actuator interactions and **real-time updates** on the IoT platform. The use of low-cost components also ensured cost-effectiveness, making it a viable prototype for scalable urban deployment.

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