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A Unified IoT–RTC Enabled Smart Urban Utility Framework for Real-Time Fault Localization, Autonomous Control, and Energy-Efficient Infrastructure Management

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ABSTRACT

Municipal infrastructure management has traditionally relied on manual monitoring and fixed operational schedules, which often lead to inefficiencies, delayed responses, and resource wastage. Over time, the rapid growth of urban populations has increased the demand for reliable water distribution, effective drainage systems, and energy-efficient street lighting. Conventional systems for controlling water pumps and monitoring manholes lack real-time data acquisition and automation, making them prone to overflow incidents, equipment failures, and increased maintenance costs. With the advent of the Internet of Things (IoT), there has been a significant transformation in how urban utilities are managed, enabling real-time monitoring, remote control, and intelligent decision-making. Modern microcontrollers like ESP32, combined with sensors and communication technologies, provide a cost-effective and scalable solution for smart city applications. The proposed system focuses on integrating IoT technology into municipal operations by automating water pump control, monitoring manhole water levels, and managing street lighting efficiently. The system utilizes sensors for continuous data collection, an RTC module for precise scheduling, and IoT connectivity for remote supervision and alerts. This evolution from manual to intelligent systems not only improves operational efficiency but also enhances public safety, reduces human intervention, and supports sustainable urban development.

Keywords: Ultrasonic Sensor, Smart Municipal System, Smart Street Lighting, RTC-Based Scheduling, Urban Infrastructure Management

1. INTRODUCTION

Street lighting systems account for nearly 5% of total energy consumption, including illumination of roads, parking areas, pedestrian pathways, and parks. A significant portion of this energy is wasted due to inefficient manual operation and fixed timing schedules. This study presents an energy-efficient solution implemented in Mirpur Cantonment, Dhaka, Bangladesh, utilizing a GSM-GPRS-based control system. The proposed model supports three modes of operation: fully automated, semi-automated, and manual. In the fully automated mode, GPRS connectivity enables real-time synchronization with sunrise and sunset data via the internet, ensuring optimal operation. The semi-automated mode leverages GSM communication and an RTC module, allowing predefined scheduling or remote control through SMS. Additionally, manual control ensures reliability during system failures. The system, powered by an ATmega328P microcontroller, also incorporates fault detection mechanisms using potential and current

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transformers. Expanding the scope, IoT-based automation enhances resource efficiency in daily life by enabling remote control of appliances and context-aware operations, such as motion-based lighting. Furthermore, an IoT-enabled water level monitoring system using IC555 timers and oscillators prevents water and energy wastage by automatically turning off motors when tanks are full, thereby promoting sustainable resource management.

The proposed system operates using an IC555 timer integrated with a sensing oscillator to automate water level control in a storage tank. The oscillator, positioned at the top of the tank, detects changes in water level through vibrations or contact sensing. When the water reaches the maximum level, the oscillator generates a signal that is transmitted to the IC555 through the connected circuitry. The IC processes this signal and sends a control command to the relay, which is directly connected to the water pump motor. As a result, the relay breaks the electrical circuit, stopping the motor and preventing water overflow. Similarly, when the water level drops, the oscillator detects the absence of water and signals the IC555 to activate the relay, allowing current to flow and turning the motor back on.

The hardware design ensures stable and safe operation through a regulated power supply system. A battery source provides the required voltage, which is passed through a diode to ensure unidirectional current flow and prevent reverse damage. A voltage regulator is incorporated to maintain a constant output and protect the circuit from fluctuations that could otherwise lead to component failure. All components, including LEDs, switches, push buttons, IC sockets, and the crystal oscillator sensor, are mounted on a PCB and interconnected efficiently. The relay acts as a critical switching element, enabling automatic control of the pump based on real-time water level conditions, thereby reducing both water and electricity wastage.

The timing and control functionality of the IC555 is governed by an RC (resistor-capacitor) network, which determines the delay and pulse width of the output signal. Since certain resistor values like 45.5 kΩ are not standard, a commonly available 47 kΩ resistor can be used, resulting in a slight variation in timing (e.g., 517 ms instead of 500 ms). For precise timing requirements, multiple resistors can be combined or alternative capacitor values can be selected. For longer delays, instead of using large capacitors, higher resistance values (up to several megaohms) are preferred for efficiency and practicality. Additionally, by incorporating a multi-position rotary switch with different resistor values, the system can be configured to generate variable pulse widths, making the monostable 555 timer circuit adaptable to different operational needs.

2. LITERATURE REVIEW

2.1 Smart Street Lighting Systems

Smart street lighting has evolved significantly with the integration of automation and communication technologies. Kumar et al. [1] proposed a ZigBee-based street light control system using LabVIEW to enable efficient remote monitoring and control. Similarly, Abhishek et al. [2] developed a traffic flow-based street lighting system powered by solar energy, improving energy efficiency by adjusting lighting based on vehicle movement. Mohamed [3] introduced a VANET-based smart lighting system to optimize energy consumption through vehicle communication networks.

2.2 GSM and Wireless-Based Lighting Control

Wireless communication plays a crucial role in smart lighting systems. Amin et al. [4] designed a GSM-based autonomous street lighting system that reduces power consumption through automated control. Rajput et al. [5] further enhanced this concept by implementing an intelligent street lighting system using GSM technology for real-time control and monitoring

2.3 IoT-Based Smart Lighting Systems

The emergence of IoT has enabled advanced smart lighting solutions. Arthi et al. [6] developed an IoT-based LED street lighting system that allows remote monitoring and efficient energy usage. Salvi et al. [8] implemented a smart street lighting system using Arduino, demonstrating cost-effective automation and control.

2.4 Energy Efficiency and Economic Feasibility

Energy-saving and cost-effectiveness are key objectives in smart lighting systems. Velaga and Kumar [9] conducted a techno-economic evaluation of smart street lighting in rural India, highlighting its feasibility and long-term benefits in reducing operational costs and energy consumption.

2.5 Automation in Water Distribution Systems

Automation techniques are widely used in water management systems. Baranidharan et al. [10] proposed an automated water distribution system using PLC and SCADA for efficient control and monitoring. Similarly, Palkar et al. [11] developed an automated drinking water supply system with quality testing features to ensure safe distribution.

2.6 PLC-Based Water Control Systems

PLC-based automation provides reliable solutions for water management. Rote et al. [12] introduced an automatic water distribution system using PLC, focusing on efficient water allocation and system reliability. These systems demonstrate the importance of automation in resource management.

3. PROPOSED SYSTEM

The system architecture is designed around an ESP32 microcontroller that serves as the centralized intelligent controller, managing multiple interconnected subsystems responsible for sensing, processing, communication, and actuation within a smart utility environment. The lighting control module operates using an LDR sensor that continuously measures ambient light intensity, enabling adaptive streetlight automation by comparing real-time light values with predefined thresholds and RTC-based schedules; this ensures lights are turned ON during low-light conditions or configured time intervals and turned OFF otherwise to optimize energy usage. The RTC module provides precise timekeeping support, allowing the system to execute time-dependent operations such as scheduled lighting and pump control, while also enabling dynamic updates of date and time through remote configuration.

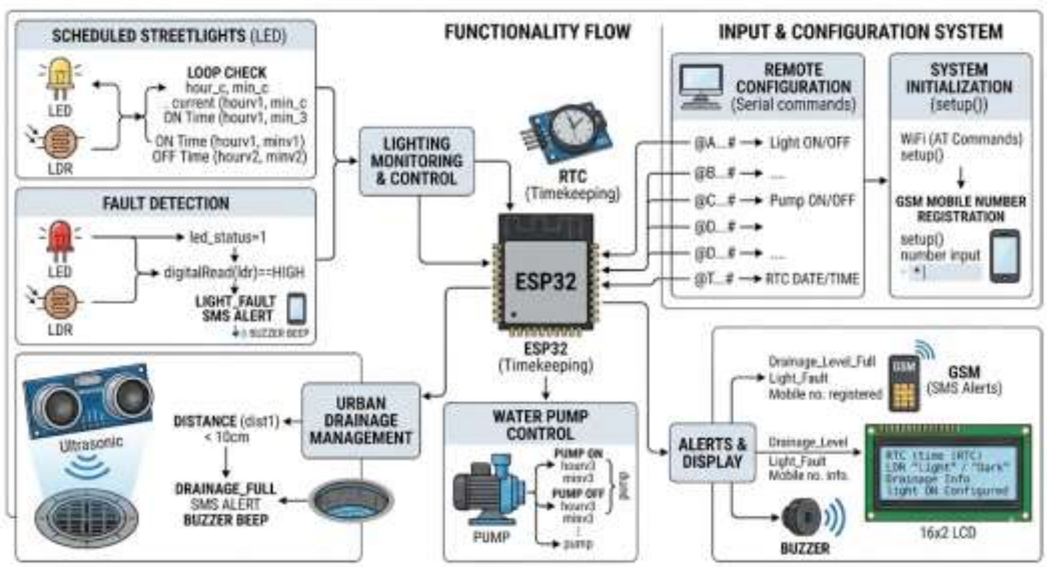

Fig. 1: Proposed system Architecture

A robust fault detection mechanism is embedded within the lighting subsystem, where digital feedback signals are analyzed to verify the actual operational state of the LED; if discrepancies such as light failure or abnormal behavior are detected, the system immediately triggers multi-level alerts including buzzer activation and GSM-based SMS notifications to registered users, ensuring timely intervention. The communication layer integrates both WiFi and GSM technologies, where WiFi (via AT commands) supports remote configuration commands such as light ON/OFF, pump control, and RTC updates, while GSM enables reliable long-range alert transmission even in the absence of internet connectivity. The urban drainage monitoring subsystem utilizes an ultrasonic sensor to measure the distance to the water surface, thereby estimating drainage levels in real time; when the measured distance falls below a critical threshold indicating potential overflow, the system generates alerts and can autonomously activate the pump to mitigate flooding risks. The water pump control unit is governed by a hybrid logic combining RTC-based scheduling and sensor-driven triggers, allowing flexible and efficient water management under varying environmental conditions. Additionally, an LCD interface provides continuous real-time visualization of system parameters including lighting status, RTC time, sensor readings, and alert

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messages, enhancing user awareness and system transparency, while a buzzer module delivers immediate audible alerts for critical events. The entire architecture follows a modular and scalable design approach where each subsystem communicates seamlessly with the ESP32 through well-defined interfaces, ensuring synchronized operation, low latency decision-making, and high reliability, as depicted in Fig. 1, ultimately delivering an intelligent, automated, and resilient solution for integrated lighting and drainage management in smart city infrastructure.

4. RESULTS AND DISCUSSION

Fig. 2 illustrates the embedded sensor interface and alert circuit prototype integrated with hardware components such as the ESP32 microcontroller, ultrasonic sensor, buzzer module, relay driver circuit, and 16×2 LCD display. The system performs real-time acquisition and processing of sensor data for automated monitoring and alert generation. The ultrasonic sensor provides distance measurements used for condition detection, while the buzzer is activated during abnormal states. The LCD displays key output values such as distance readings (in cm), alert status (ON/OFF), and system mode. This enables continuous visualization of sensor outputs and system responses.

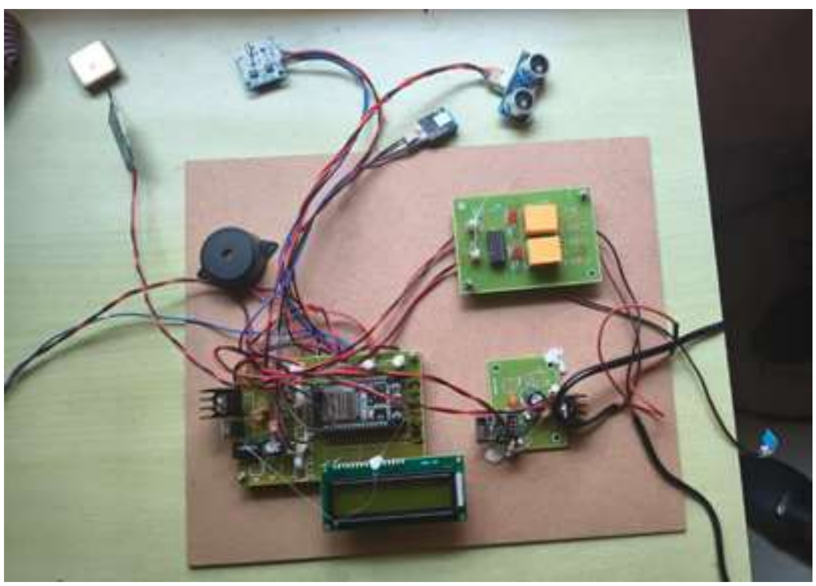

Fig. 2: Embedded Sensor Interface and Alert Circuit Prototype with LCD Display

Fig. 3 depicts the smart utility automation system operating in an active state with interconnected hardware components including the ESP32, ultrasonic sensor, relay modules, power supply unit, and LCD display. The system continuously processes sensor inputs and makes control decisions accordingly. Based on detected conditions, relay modules switch connected loads automatically. The LCD presents output values such as sensor readings, device status (e.g., light ON/OFF), and system activity messages like “Smart Utility Automation.” This reflects real-time system behavior and operational state.

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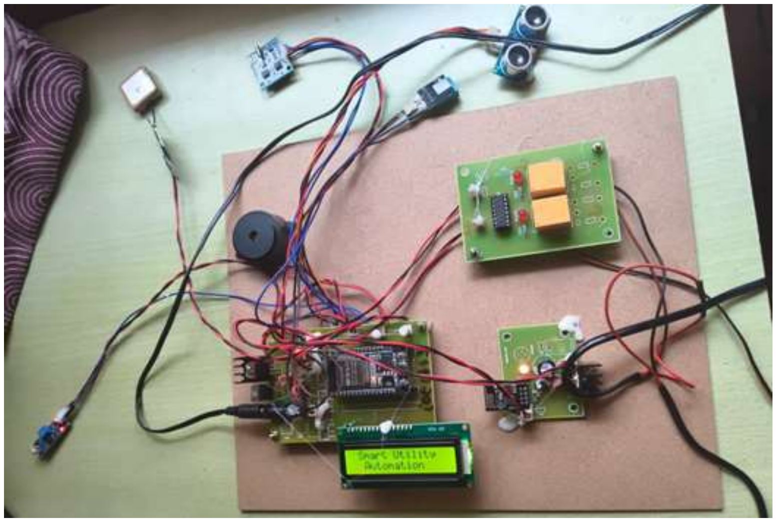

Fig. 3: Smart Utility Automation System in Active State with Sensor Inputs and LCD Output

Fig. 4 illustrates the mobile interface used for TCP Telnet communication with the ESP32-based system, enabling wireless monitoring and control of hardware components such as relay modules and sensors. The interface allows users to connect using IP and port details and send commands to the system. The ESP32 processes these commands and updates system operation accordingly. The outputs include device control responses and updated system states, which are reflected both on the mobile interface and the LCD. This ensures synchronized remote monitoring and control.

Fig. 4: Mobile Interface for TCP Telnet Connection Control

Fig. 5 depicts the smart utility automation system controlling an electrical load using hardware components such as the ESP32 microcontroller, relay module, ultrasonic sensor, and 16×2 LCD display. The system processes real-time sensor inputs and performs actuation through the relay to switch the connected load. The LCD interface simultaneously displays both control status and sensor output values, ensuring clear system feedback. The output values shown include parameters such as distance measurement (in cm) obtained from the ultrasonic sensor along with the load condition (e.g., Light ON).

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This combined display establishes a direct relationship between sensed conditions and executed actions. The figure highlights the system's ability to perform automated control while continuously presenting real-time operational data to the user.

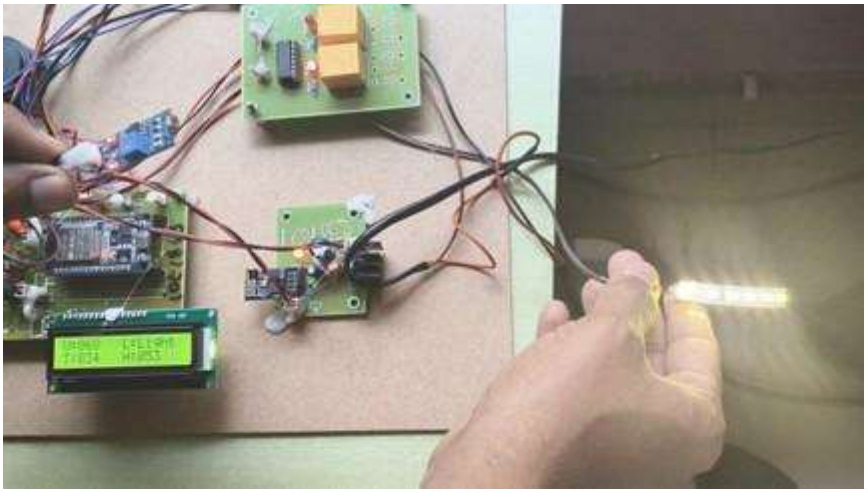

Fig. 5: Smart Utility Automation System Controlling Load (Light ON)

Fig. 6 illustrates the smart utility system providing real-time status updates through the 16×2 LCD display integrated with the ESP32 controller, sensor modules, and relay circuitry. The system continuously synchronizes sensing, processing, and display operations. The LCD shows output values such as date and time, sensor readings, and current system status. These values provide insights into system performance and environmental conditions. This enhances usability by allowing users to monitor real-time outputs and system functionality effectively.

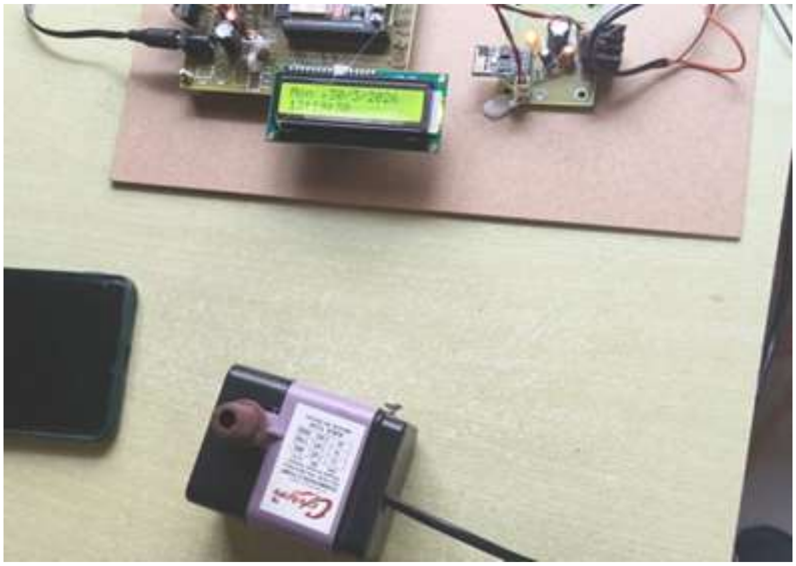

Fig. 6: Smart Utility System with Real-Time LCD Status Display

5. CONCLUSION

The developed system presents an integrated IoT-driven solution for automating key municipal services through the ESP32 platform. It combines sensing, control, and communication modules to enable intelligent management of water pumps, drainage monitoring, and street lighting operations. The incorporation of ultrasonic sensing facilitates accurate level detection for both water storage and manhole conditions. The RTC module ensures time-based automation, particularly for efficient streetlight scheduling. Additionally, the GSM-based alert mechanism provides instant notifications during abnormal or critical situations. The system operates in real time, minimizing the need for manual supervision and intervention. Overall, the implementation enhances operational efficiency, supports effective resource utilization, and contributes toward safer and more sustainable urban infrastructure.

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