

Fuzzy Logic Based Intelligent Energy Management System for Mobile Robot

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Abstract—This project presents an intelligent energy management system for mobile robots based on fuzzy logic to improve energy efficiency and operational reliability. The system keeps track of the important parameters like battery charge level, power requirement, and solar energy availability at all times to make real-time decisions regarding energy consumption. By using fuzzy logic, it manages uncertain and variable inputs effectively, allowing seamless switching between power sources such as solar and battery. The main building blocks consist of an ESP32 microcontroller, solar input through MPPT, DHT11 temperature sensor, and voltage and current sensors. Live data are shown on an LCD and at the same time uploaded to ThingSpeak for cloud monitoring and analysis. The smart controller gives priority to vital loads and saves energy under low power conditions. This approach stretches battery life, minimizes energy wastage, and is suitable for standalone systems in dynamic conditions. The fuzzy logic's flexibility and versatility allow the system to scale to use in renewable energy, robotics, and smart devices.

Index Terms—FUZZY LOGIC, ESP32, DHT11, LCD, MPPT, ENERGY MANAGEMENT

I. INTRODUCTION

With the growing deployment of autonomous and embedded systems in robotics, smart grids, and the Internet of Things (IoT), the need for effective and smart energy management is more than ever before. The energy sources, particularly in mobile robotic platforms, tend to be scarce and sensitive to fluctuating environmental conditions. Uncertain parameters like varying solar input, dynamic load requirements, and battery degradation render it difficult to control power with conventional control techniques. Under such conditions, traditional binary logic systems are inadequate since they are not capable of accommodating imprecise or uncertain inputs. To address these shortcomings, this project introduces a fuzzy logic-based intelligent energy management

system that facilitates real-time adaptive decision-making in resource-limited environments.

Fuzzy logic is a soft computing technique based on human reasoning that can handle fuzzy values instead of binary true/false states. In contrast to traditional control systems that are based on rigid thresholds, fuzzy logic can handle inputs with unclear or continuously changing states such as "low," "medium," and "high." This makes it well-suited for applications involving noisy, imprecise, or fast-changing sensor data. In the case of energy management, fuzzy logic allows for more adaptable and subtle control of power allocation, load prioritization, and source selection of energy.

II. LITERATURE SURVEY

Fuzzy logic-based energy management systems (EMS) for mobile robots represent a significant advancement in the field of robotics, particularly in optimizing energy consumption and enhancing operational efficiency. Mobile robots require effective energy management to ensure prolonged autonomy, especially in dynamic environments where power demands fluctuate. Fuzzy logic, known for its ability to handle uncertainty and approximate reasoning, is well-suited for these systems as it can adapt to varying conditions and make decisions based on imprecise inputs. The integration of fuzzy logic into EMS allows for more flexible and robust control strategies compared to traditional methods.

Several studies have demonstrated the effectiveness of fuzzy logic in managing energy in various robotic platforms, including autonomous vehicles, drones, and collaborative robots. These systems often combine fuzzy logic with optimization techniques like genetic algorithms or neural networks to improve performance. However, challenges remain, such as the

computational complexity of fuzzy logic systems and their scalability in large-scale applications. Future research is expected to focus on hybrid systems that integrate fuzzy logic with other AI techniques, as well as the real-time implementation of these systems to further enhance their reliability and efficiency. Overall, fuzzy logic-based EMS offers a promising approach to improving the energy efficiency and autonomy of mobile robots, with potential applications in a wide range of industries.

III. BLOCK DIAGRAM

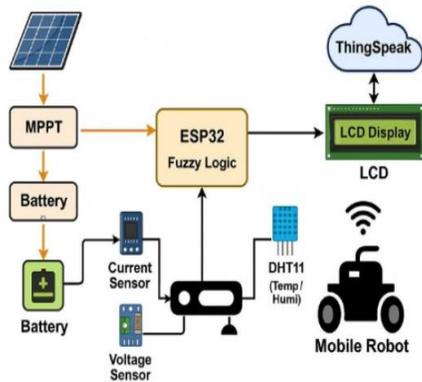


Fig 1. Proposed Block Diagram

The envisioned intelligent energy management system brings together various hardware devices and sensors, all regulated by a decision-making unit based on fuzzy logic realized on an ESP32 microcontroller. The block diagram captures the logical movement of energy and data within the system, whose primary aim is to regulate power in a mobile robot effectively through renewable energy resources and smart control schemes.

Functions of block:

1. Solar Panel: The system starts with a solar panel, which is a source of renewable energy. It is a device that collects sunlight and converts it to electrical energy. But the output energy of a solar panel changes with sunlight intensity, temperature, and load conditions.
2. MPPT (Maximum Power Point Tracking) Module: To guarantee that the solar panel is

always at its maximum power point, an MPPT unit is used. This module dynamically changes the voltage and current from the solar panel so as to get the highest available power. It enhances the overall efficiency of the solar energy harvesting process, particularly in changing conditions of sunlight.

3. Battery: The output energy from the MPPT module is utilized to charge a rechargeable battery, which serves as the primary energy storage device for the mobile robot. The battery stores surplus energy during the day and provides power to the system when solar power is inadequate or not available, e.g., during nighttime or during cloudy weather.
4. ESP32 Microcontroller (Central Control Unit): At the heart of the system is the ESP32 microcontroller, serving as the master control unit. It collects data from the sensors and makes decisions in real-time with a Fuzzy Logic Controller (FLC). The ESP32 has the following responsibilities:

Regulating the flow of energy in the system.

Making smart decisions on power source selection.

Regulating the charge and discharge cycles of the battery.

5. Voltage Sensor: The voltage sensor is attached to the battery and checks the present battery voltage level. This information is important in ascertaining the state of charge (SoC) of the battery, which is an essential input to the fuzzy logic system.
6. Current Sensor: The current sensor reads out direction and magnitude of current to or from the battery. It is used to determine if the battery is being charged (positive current) or drained (negative current), and the amount of power being drawn by the robot.
7. DHT11 Temperature and Humidity Sensor: The DHT11 sensor is used to measure environmental temperature and humidity. Temperature directly influences battery performance and solar panel efficiency. For example, temperature can decrease the life of the battery and reduce the output efficiency of the solar panel. This information is also utilized in fuzzy logic decisions for power optimization.
8. Fuzzy Logic Controller: The ESP32 is loaded with a Fuzzy Logic Controller (FLC) that accepts the sensor information (e.g., battery SoC, load

requirement, solar availability, temperature) and employs a rule-based decision framework to manage:

Switching power sources between solar and battery.
Load management: whether to run all systems, prioritize critical loads, or minimize use.
Battery charging/discharging strategies, depending on environmental and operational factors.
Fuzzy logic is employed since it enables the system to decide in uncertain or imprecise situations, like "low battery," "moderate load," or "high temperature."

9. LCD Display (16x2): A 16x2 LCD display is interfaced with the ESP32 to display real-time system parameters like:

Battery voltage
Current flow
Temperature
Power source in use:

This gives instant visual feedback to the user or operator.

10. ThingSpeak IoT Platform:

ESP32 also has in-built WiFi, which allows it to send data collected from sensors wirelessly to ThingSpeak, an open-source Internet of Things (IoT) platform. This provides remote monitoring of energy consumption patterns, environmental parameters, and system health. The data saved in the cloud can be utilized for performance analysis, predictive maintenance, or even future upgrade such as machine learning-based optimization.

- *Software Requirements:*

Arduino IDE: The Arduino Integrated Development Environment (IDE) is a software platform that facilitates coding and interacting with Arduino hardware. It features a text editor for writing code, a message box, a text console, and a toolbar with frequently used task buttons. The IDE establishes a connection between the program and Arduino hardware, enabling program uploading and communication.

Express PCB: Design of a PCB using layout software from ExpressPCB, which is freeware available at www.expresspcb.com. Before beginning you should make sure your computer has both ExpressPCB and ExpressSCH, if not then you should download the software. Before beginning the PCB process, you should come up with the initial design, build it and test it on a breadboard, fix any errors, and determine

specific components. It is also useful to have datasheets and dimensions for all of the "special" components such as transistors, ICs, sensors, actuators, etc., on hand. Entering the Schematic into ExpressSCH 1. Open ExpressSCH to create a fresh schematic. The first time you start ExpressSCH you will get a dialog box with a link to a quick start guide for ExpressSCH. This can be useful if you want to get a general overview for the tool.

IV. METHODOLOGY

The methodology adopted in this project is a formal method to designing, executing, and testing an energy management system based on fuzzy logic. The aim is to maximize the power consumption by controlling energy from the renewable resource (solar) and the storage facility (battery) based on real-time system and environmental inputs. Following are the steps adopted:

1. Problem Definition

The primary goal of the project is to develop an energy management system for a solar-powered mobile robot that can intelligently distribute power among a solar panel, battery, and loaded devices. The system should learn to adapt to varying environmental conditions and maintain operation by smartly switching between power sources and optimally utilizing energy.

2. System Design

The system consists of the following elements:

Solar Panel: Power generation.

MPPT Module: Optimize solar power output.

Battery: Is used to store energy for later use.

ESP32 Microcontroller: Serves as the brain and interprets sensor data.

Voltage and Current Sensors: Sensing the voltage of the battery and the amount of current passing through.

DHT11 Sensor: Senses environmental factors (temperature and humidity).

Fuzzy Logic Controller: Decides upon sensor readings.

LCD Display: Displays system status in real time.

ThingSpeak Platform: Used for remote viewing and cloud storage.

3. Fuzzy Logic Controller Development

A controller based on fuzzy logic is used to regulate energy flow optimally. FLC decides:

Power Source Choice: Solar, battery, or a combination thereof.

Load Regulation: Prioritization of important loads and control of power supply.

Battery Discharging and Charging: Control of battery health and extended life.

4. Integration with Sensors

Voltage and current sensors track battery usage and condition.

DHT11 logs temperature and humidity, influencing the performance of the battery as well as the efficiency of the solar panel.

5. Implementation of System

The elements are wired, and the ESP32 is loaded with fuzzy logic rules to manage the system using sensor information. The system is tested under different conditions, such as varying solar input, load demand, and environmental conditions.

6. Testing and Evaluation

The system is tested under different conditions (e.g., changing solar input, battery status) to assess:

Power optimization

Load management

Battery life extension

Fuzzy logic controller responsiveness

V. RESULTS

The fuzzy logic-based energy management system developed was subjected to different environmental and load conditions to determine its effectiveness in optimizing the use of power for a mobile robot. From the results, improvements in energy efficiency, decision-making accuracy, and system adaptability are evident.

6.1 Performance of the System Under Different Conditions To determine the system's adaptability, experiments were run under three different scenarios:
Scenario 1: High solar irradiance, low battery charge
Scenario 2: Low solar input, moderate battery charge
Scenario 3: No solar input, low battery charge, high load demand

In all scenarios, the fuzzy logic controller reacted as follows:

In Scenario 1, the system favored solar power and started charging the battery.

In Scenario 2, the system kept providing power from the battery and turning off non-essential loads.

In Scenario 3, the system cut down overall load consumption and activated a low-power operational mode.

6.2 Load Management and Energy Efficiency

The fuzzy logic controller could: Minimize unnecessary load usage by about 20–25% in low-power situations.

Ensure uninterrupted power supply to critical modules (navigation, sensors).

Extend battery discharge time by 15–30% based on the fuzzy logic choice.

6.3 Sensor Accuracy and Cloud Logging

The voltage and current sensors were accurate to ± 0.1 V and ± 0.05 A respectively, checked against a digital multimeter.

Data posted to ThingSpeak indicated steady trends and small transmission delay (mean delay < 2 seconds).

The LCD display allowed for real-time observation of battery voltage, current, and ambient temperature, facilitating debugging and system evaluation.

6.4 System Stability and Response Time

The fuzzy decision cycle, from sensor read to control action, was about 150–200 milliseconds, appropriate for real-time control in mobile robots.

The system was loaded switching stable without power disruptions or spurious trigger during testing.

Summary of Results

Parameter\tObservation

Power Saving\t20–25% when in low-energy mode

Battery Life Improvement\tUp to 30% prolongation in runtime

Sensor Accuracy\tVoltage: ± 0.1 V, Current: ± 0.05 A

Fuzzy Decision Response Time\t ~ 200 ms

Data Upload Lag (ThingSpeak)\t < 2 seconds.

Key Advantages of Fuzzy Logic:

1. Handles Uncertainty and Imprecision

Fuzzy logic mimics human reasoning by allowing partial truths (e.g., “battery is somewhat low”), making it ideal for systems with uncertain or noisy inputs.

2. No Need for Precise Mathematical Models

Unlike conventional control systems, fuzzy logic doesn't require a complex mathematical model of the system. This reduces design time and complexity.

3. Robust Decision-Making

It performs reliably even when input data is incomplete, inconsistent, or approximate—useful for real-world systems like energy management under fluctuating conditions.

4. Flexibility and Scalability

Rules can be added or modified easily without redesigning the entire system, which allows future upgrades and scaling of the system.

5. Smooth Control Output

Fuzzy controllers avoid abrupt changes by providing gradual transitions, improving system stability and user experience.

6. Cost-Effective Implementation

It can be implemented on low-cost microcontrollers (like ESP32), making it suitable for embedded applications without high computational demands.

7. Adaptability to Real-World Applications

Fuzzy logic is ideal for nonlinear systems where traditional controllers struggle—such as energy management with solar fluctuations, battery degradation, or changing load conditions.

Potential Applications

1. Mobile and Autonomous Robots

Optimize onboard energy in delivery robots, farm bots, security drones, and planetary rovers where power is only available sporadically and dynamic conditions prevail.

2. Smart Home Energy Systems

Manage and optimize power consumption in solar-powered homes with battery backup, scheduling loads according to time of day, weather, and battery level.

3. Off-Grid Renewable Power Systems

Suitable for remote areas (such as villages, disaster camps) where electricity is solar- or wind-generated and requires intelligent distribution to the devices.

4. Electric Vehicle (EV) Energy Management

Optimize battery use and regenerative charging effectiveness by adjusting dynamically power flows on the basis of speed, road profile, and load using fuzzy logic.

5. IoT-Based Smart Devices

Increase efficiency of smart streetlights, weather monitoring systems, and wearable sensors by intelligent management of scarce energy resources.

6. Industrial Automation

Applicability in warehouses and factories using solar or battery-powered devices for energy-conscious scheduling and load distribution.

7. Military and Defense Uses

For field-deployed autonomous devices or mobile command centers where power is limited and must be apportioned intelligently in rough and indefinite conditions.

8. Biomedical and Healthcare Devices

For mobile diagnostic equipment or solar-powered rural clinics, fuzzy logic can ensure uptime by wisely partitioning power across essential systems.

9. Intelligent Grid Systems

Integrate into next-generation microgrids for local decision-making to enhance load balancing and energy saving.

VI. CONCLUSION

This project effectively illustrates the design and implementation of a fuzzy logic-based intelligent energy management system for a mobile robotic platform. Through the integration of renewable energy sources, real-time sensor inputs, and fuzzy control logic, the system can make intelligent decisions regarding power consumption, source selection, and load prioritization under different environmental and operational conditions. The application of fuzzy logic enables the system to deal with imprecise inputs and respond effectively to uncertain or dynamic situations—something conventional control systems can't.

ESP32 microcontroller acted as the unit of control, effectively managing sensors and implementing decisions of control while cloud integration with ThingSpeak supported real-time analysis and monitoring of data. Apart from enhancing efficiency in energy utilization and prolonging battery life, the system maximized operational dependability, something that is quintessential for automated systems.

In general, this work demonstrates the real-world advantages of merging fuzzy logic with embedded systems and IoT technologies. It provides the foundation for future developments like integration with machine learning, adaptive rule generation, or use in wider smart energy applications like microgrids, electric vehicles, and smart homes.

VII. ACKNOWLEDGMENT

We wish to offer our sincere appreciation to all individuals who inspired and assisted us through the successful completion of the project entitled "Fuzzy Logic-Based Intelligent Energy Management System."

Above all, we are immensely grateful to our project guide, [Guide's Name], for their consistent motivation, technical suggestions, and constructive criticism during each phase of the work. Their direction was instrumental in the direction and success of the project. We are also thankful to the department faculty and lab assistants for supporting the resources, facilities, and environment for experimentation and development. We thank [Your Institution/College Name] for providing us with the opportunity to do research and adopt innovative ideas. We appreciate the help of our friends and classmates as well, who provided us with their support, suggestions, and encouragement during difficult times.

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