

Mini-ROS: A LIGHTWEIGHT MODULAR ROBOT FRAMEWORK WITH AUTO CLOUD SYNC AND AI INTEGRATION: A Research

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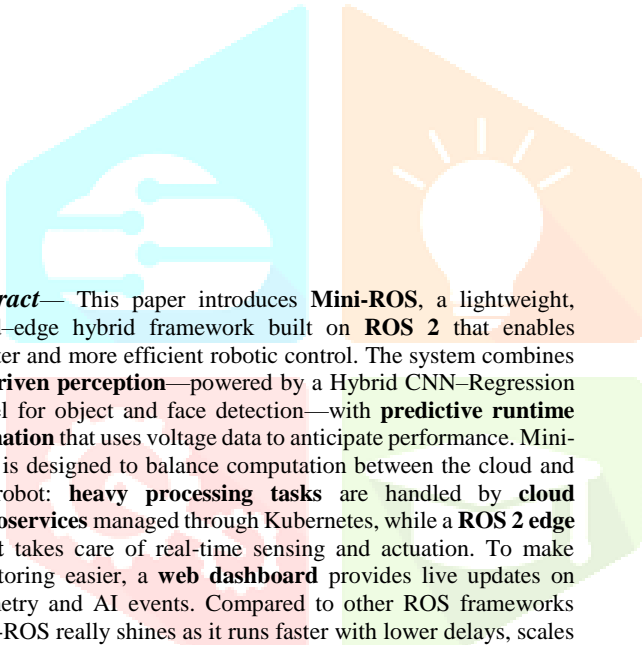
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Abstract— This paper introduces **Mini-ROS**, a lightweight, cloud–edge hybrid framework built on **ROS 2** that enables smarter and more efficient robotic control. The system combines **AI-driven perception**—powered by a Hybrid CNN–Regression model for object and face detection—with **predictive runtime estimation** that uses voltage data to anticipate performance. Mini-ROS is designed to balance computation between the cloud and the robot: **heavy processing tasks** are handled by **cloud microservices** managed through Kubernetes, while a **ROS 2 edge client** takes care of real-time sensing and actuation. To make monitoring easier, a **web dashboard** provides live updates on telemetry and AI events. Compared to other ROS frameworks Mini-ROS really shines as it runs faster with lower delays, scales easily as your system grows, and uses resources more efficiently. This makes it a perfect fit for affordable robots and setups that involve multiple robots working together.

Keywords—*ROS 2, Cloud Robotics, Edge Computing, Hybrid Architecture, Microservices, gRPC, WebSockets, Object Detection, Runtime Prediction, Artificial Intelligence, Kubernetes, Real-Time Control*

I.INTRODUCTION

Robotics has seen rapid growth over the years, and a major part of this progress comes from the development of the Robot Operating System (ROS). ROS provides a open-source framework that makes it easier to build robotic systems using modular and reusable components. While ROS 1 played an important role in shaping modern robotics, it had limitations in terms of scalability, real-time performance, and distributed communication. To overcome these issues, ROS 2 was introduced with support for the Data Distribution Service (DDS), enabling faster, more reliable, and secure communication between system components [1], [3], [4].

As robotics continues to evolve everyday, the use of technologies like artificial intelligence (AI), computer vision, and real-time data processing has increased significantly. These advancements require higher computational power, which is often difficult to achieve using low-cost edge devices commonly used in robotics.

To address this challenge, **cloud–edge architectures** has emerged as a practical solution. This approach combines the processing power and scalability of the cloud dashboards with the fast response of edge devices [8], [9], [10].

Cloud robotics builds on this idea by allowing robots to use cloud resources for tasks such as data processing and analysis, while still handling time-sensitive operations locally [8]. At the same time, edge computing ensures that critical tasks are executed quickly, improving the overall responsiveness of the system [9]. Together, these technologies make it possible to develop robotic systems that are both efficient and scalable.

In this work, we propose the **Mini-ROS framework**, a lightweight system designed to integrate cloud and edge capabilities using ROS-based communication. The framework distributes tasks between the robot and the cloud, allowing the robot to handle sensing and control, while the cloud manages data processing, visualization, and analysis. A **cloud-hosted dashboard** is also integrated into the system, enabling users to monitor and interact with the robot in real time.

In addition, the framework incorporates AI-based data processing to provide meaningful insights from the collected data. Instead of only displaying raw telemetry, the system helps in understanding patterns in robot behavior and performance. This aligns with recent developments in AI-enabled and cloud–edge robotic systems [11]–[14].

With growing demand for connected robotic systems in applications such as surveillance, delivery, and automation, there is a need for solutions that are scalable, flexible, and easy to deploy. Traditional systems that rely only on onboard processing often struggle to meet these requirements. The proposed Mini-ROS framework addresses some challenges by offering a balanced and efficient architecture for real-time monitoring, and control.

Overall, Mini-ROS provides a simple yet powerful approach to building modern robotic systems. By combining ROS communication, cloud integration, and AI-based analysis, it helps

bridge the gap between limited hardware capabilities and the increasing need for intelligent and connected robotics.

II. LITERATURE REVIEW

Robotics research currently focuses on enhancing system capabilities for three specific areas which are scalability and real-time performance and intelligent processing. This development resulted in the combination of cloud computing and edge computing and modular software frameworks into one system.

This section reviews the key work that forms the foundation of the proposed Mini-ROS framework.

A. Evolution of Robot Middleware

The first robotic systems used middleware as their main technology to establish communication standards which enabled developers to create modular software systems. The systems showed restricted adaptability together with limited ability to grow. Developers gained the ability to create robotic applications through ROS which provided them with reusable modular component base [1]. The development of `ros_control` together with other system enhancements led to better robot hardware control through advanced control system development [2].

B. Transition from ROS to ROS 2

While ROS 1 made robotic development easier, it had limitations in real-time communication, security, and scalability. ROS 2 was developed to overcome these issues by using the Data Distribution Service (DDS), which provides faster, more reliable, and secure communication between system components [3], [4]. Additionally, micro-ROS extended these capabilities to smaller devices, making ROS 2 suitable for lightweight and embedded systems [7].

C. Cloud Robotics and Scalable Architectures

Cloud robotics allows robots to use cloud resources for tasks that require higher computational power, such as data processing and AI analysis. This approach improves scalability and makes it easier to manage robotic systems [8]. Recent work has also explored cloud-native techniques to improve deployment and system flexibility [10].

D. Edge Computing and Hybrid Architectures

Edge computing focuses on performing critical tasks locally on the robot, reducing delays and improving responsiveness. When combined with cloud computing, hybrid cloud-edge systems provide a balanced solution that supports both real-time performance and scalability [9]. This combination is especially useful for modern robotic applications.

E. Communication in Distributed Robotic Systems

Reliable communication is essential for connecting robots with cloud systems. DDS plays a key role in ROS 2 by enabling real-time data exchange [3]. Other communication technologies such as MQTT, gRPC, and WebSockets are also widely used for efficient and low-latency data transfer between the edge and cloud [5], [15].

F. AI Integration in Robotics

Artificial intelligence has made robotic systems more capable by enabling them to analyze data and make informed decisions. Recent work focuses on using lightweight AI models and cloud-based processing to support intelligent behavior in robots [11], [13], [14]. The system provides advanced analysis capabilities to basic systems which do not require extensive computational power for processing data.

G. Cloud-Edge Collaboration

Robotic systems now depend on cloud and edge system collaboration for their operational needs. The system enables data processing to occur at high efficiency while delivering instant response capabilities. The approach becomes beneficial when multiple robots need to work together through coordinated activities and centralized operational control [12].

H. Research Gap

The current systems show progress, but they still depend on cloud processing or local computation for their operations. The three areas of scalability and efficiency and real-time performance all face challenges because of this problem. The situation requires a solution that combines cloud computing advantages with edge system benefits to create better results. The Mini-ROS framework offers a solution to this problem through its lightweight and flexible design, which enables real-time monitoring and efficient communication and intelligent data analysis within a single system.

III. PROPOSED SYSTEM: MINI-ROS

A. System Architecture and Data Flow

The Mini-ROS framework functions as an effective **robotics system** which provides **ongoing operational capabilities** together with **monitoring systems**, **control systems**, and **decision-making systems**. The system establishes **robot-user communication** through its connections between **edge devices**, **ROS-based communication**, **cloud APIs**, and a **web-based dashboard**.

The framework processes all robot-based operations through its **cloud system** which handles **major computing tasks** while it performs **edge-based operations** for **critical tasks**. The system achieves better performance through its **load reduction on robots** while enabling **efficient system expansion**.

The system streams **telemetry data** from **edge locations** to a **cloud-based dashboard** which allows users to monitor robot operations in **almost real time**. The system gains modern robotic application suitability through its design which enhances **accessibility**, **scalability**, and **efficiency**.

B. System Architecture and Data Flow

The Mini-ROS framework adopts a layered architecture comprising the edge layer, ROS communication layer, cloud API layer, and user interface layer. Each layer performs a specific function to enable seamless data flow from the robotic system to the cloud and end user.

TABLE 1: LAYER-WISE FUNCTIONALITY OF MINI-ROS FRAMEWORK

Layer	Functionality
Edge Layer	Responsible for sensing and actuation. Performs lightweight and time-critical operations locally on the robotic system.
ROS Communication Layer	Enables modular and asynchronous data exchange using ROS topics for efficient inter-process communication.
Cloud-API Layer	Acts as a bridge between the edge and cloud, ensuring secure and efficient transmission of data for further processing.
Cloud Processing Layer (AI Integration)	Performs computationally intensive tasks such as data analytics, object detection, and predictive processing using AI models.
User Interface Layer	Cloud-hosted dashboard that visualizes real-time telemetry data and enables user monitoring and interaction.

In this architecture, computationally intensive tasks, including AI processing and analytics, are offloaded to the cloud, allowing the edge device to operate efficiently without being overloaded.

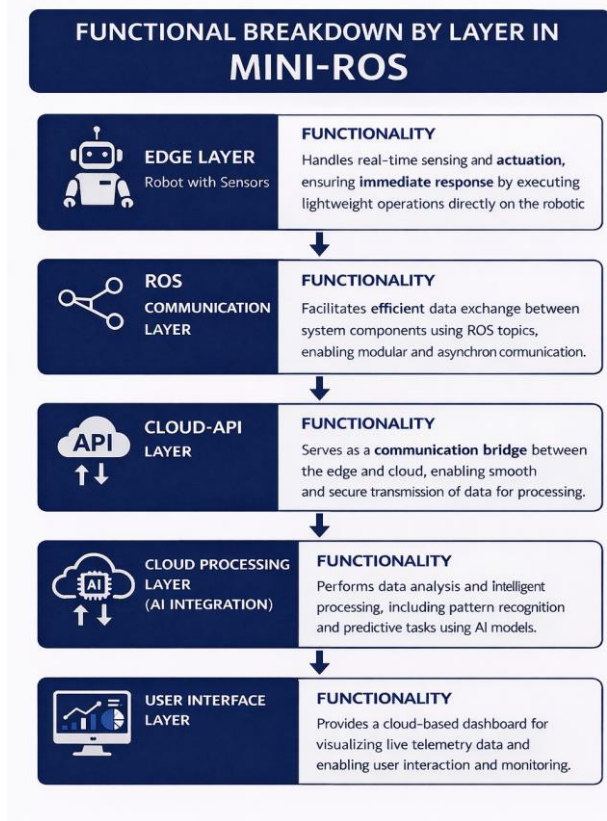


Figure 1: Architectural Layer

C. Real-Time Telemetry and Control

The proposed system achieves its primary functionality through **real-time telemetry streaming** using a **cloud-based approach**. Data generated at the **edge** is continuously transmitted to an **online dashboard**, where it is displayed with **minimal delay**. This ensures that users always have access to the **most recent system information**.

The dashboard provides a **live view** of **critical telemetry data**, including **robot movement**, **sensor outputs**, and **overall system health**. This **real-time visualization** helps users clearly understand the robot's **current behavior** and **operational status** as it performs its tasks.

In addition, the system supports **bidirectional communication**, allowing users to **control the robot through the dashboard** based on incoming **real-time data**. This capability is essential for applications that require **continuous monitoring**, **quick decision-making**, and **dynamic system control**.

D. AI Integration for Intelligent Processing

The **Mini-ROS framework** includes **AI capabilities** to make the system **smarter** and more **responsive**. It helps in **analyzing the data** generated by the robot and turning it into **useful insights** that improve **understanding** and **decision-making**.

The system can handle tasks like **interpreting visual inputs** and **analyzing sensor data**. For example, **CNN-based models** can be used to **recognize objects or features** from camera data, while **regression-based models** can study **sensor values** and **predict system behavior**.

This makes the system more effective in handling **real-time data**, as it can not only **display information** but also help in **understanding patterns and trends**. As a result, users can make **better** and **quicker decisions** based on the **insights provided by the system**.

Another important aspect is **flexibility**. The framework allows **different AI models** to be added based on the **needs of the**

application, making it suitable for a **wide range of intelligent robotic use cases**.

TABLE 2 : AI CAPABILITIES AND THEIR ROLE IN THE SYSTEM

AI Component	Purpose	Benefit to System
CNN-based Models	Analyze visual data for object detection and feature detection	Helps understand the surroundings and improves perception
Regression-based Models	Analyze sensor data and predict system behavior	Enables trend analysis and prediction of performance
Data Processing Layer	Processes incoming telemetry data in real time	Converts raw data into meaningful insights
Modular AI Design	Allows integration of different AI models	Makes the system flexible and adaptable for various applications

E. CLOUD-BASED PROCESSING AND WORKLOAD DISTRIBUTION

The **Mini-ROS framework** uses a **distributed approach** where tasks are shared between the **edge device and the cloud**. The system divides its work between the robot and the rest of the system because some tasks need **immediate completion** while others can be done at a later time. The components work at their **highest efficiency** through this system because structured separation establishes **clear boundaries** between different parts of the system.

The **edge device** concentrates on **real-time operations**, which include sensing and control because these tasks need **immediate response**. The **cloud** handles tasks that require **data analysis, visualization, and higher-level processing**. The system achieves **greater efficiency** through this separation, as the robot handles less processing work while the cloud manages data more efficiently.

The system operates better because of this change, making everything function more efficiently. It can handle **increased data volume** because it has the ability to process **real-time data without interruption**. The framework achieves better **scalability** through its **edge-to-cloud workload distribution**, leading to improved **resource efficiency** and enabling operation in both **basic and sophisticated robotic systems**.

F. WORKING PIPELINE OF MINI-ROS

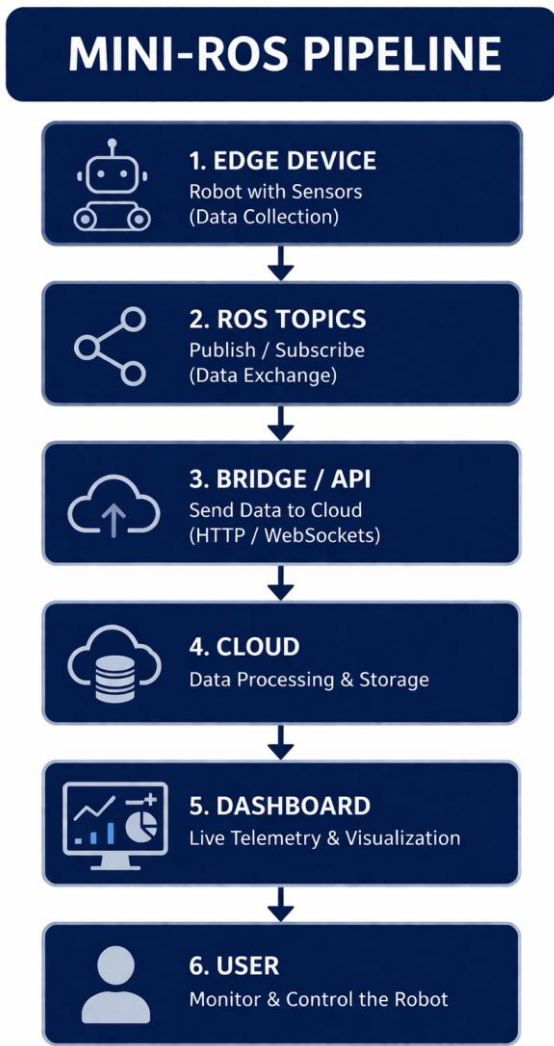


Figure 2: Mini-ROS pipeline Flowchart

Description

The Mini-ROS framework system pipeline in Figure 2 shows how data flows from edge devices through ROS communication to cloud processing before reaching the dashboard and end user. The system demonstrates ongoing telemetry data transmission together with user interaction capabilities in its cloud-edge framework.

G. Technology Stack of Mini-ROS Framework

System Layer	Technologies Used	Role in System
Edge Layer	NodeMCU, Sensors	Handles data acquisition, sensing, and robot control
Middleware	ROS 2	Manages communication between nodes using topics
Communication Layer	HTTP, gRPC, WebSockets	Enables data transfer between edge, cloud, and dashboard

Backend Services	Flask / FastAPI	Processes data and manages API requests
Frontend Dashboard	React.js	Displays telemetry data and enables user interaction
Cloud Infrastructure	Cloud Server / AWS	Hosts dashboard, data processing, and storage
AI Processing	CNN, Regression Models	Performs data analysis and pattern findings.

IV. EXPERIMENTAL DEMONSTRATION

To validate the proposed Mini-ROS framework, an experimental setup was implemented using a **line follower robot (LFR)** built on a **NodeMCU-based embedded controller**. The robot is equipped with line-tracking sensors that enable it to follow a predefined path while continuously generating **real-time movement data**.

In this setup, the robot functions as the **edge device**, capturing parameters such as **direction, path deviation, speed (if applicable), and sensor readings** from the line-tracking module. This data is transmitted through the ROS communication layer and forwarded to the cloud via the bridge API.

The cloud-hosted dashboard presents this data in **real time**, allowing users to observe the robot’s behavior as it moves along the track. Variations in motion—such as turns, corrections, and deviations—are instantly reflected on the interface, demonstrating the system’s capability for **live telemetry visualization and continuous monitoring**.

Beyond visualization, the transmitted telemetry is further utilized for **AI-based analysis**. Parameters such as sensor readings and path deviation are processed to understand movement behavior and identify patterns. For instance, regression-based analysis can be used to examine how changes in sensor input influence movement stability, enabling the detection of **frequent deviations, oscillations, or inefficient corrections** during operation.

This analytical layer allows the system to move beyond simple data display and provide **meaningful insights into robot performance**, which can assist in identifying inconsistencies, improving control strategies, and observing performance trends over time.

The experiment also reflects the framework’s **distributed processing approach**, where real-time sensing and actuation are handled at the edge, while visualization and analytical tasks are managed in the cloud. This ensures a balanced system that supports **continuous telemetry transmission, real-time monitoring, intelligent data analysis, and efficient workload distribution**.

By implementing the system on a **NodeMCU-based LFR**, the framework demonstrates its effectiveness on **low-cost hardware**, while also highlighting its adaptability to more complex and intelligent robotic applications.

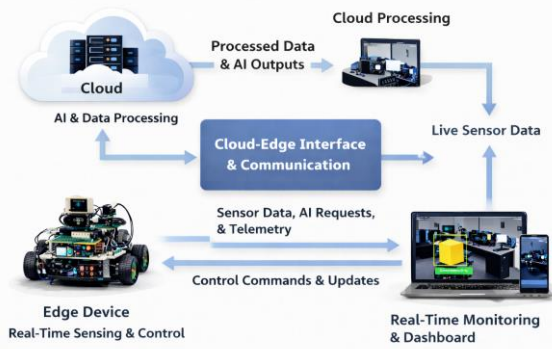


Figure 3: Cloud-Edge Architecture

This demonstration highlights four key capabilities of the framework: real-time telemetry transmission, live visualization, AI-driven analysis, and efficient edge–cloud coordination.

V. SYSTEM NOVELTY AND CONTRIBUTION

The proposed Mini-ROS framework offers a **simple and structured approach** to connect robotic systems with **cloud-based monitoring and intelligent processing**. It focuses on enabling **real-time interaction** between the robot and the user through a **unified and scalable architecture**.

One of the main contributions of this work is the development of a **seamless pipeline** that connects the **edge device to a cloud-hosted dashboard** using ROS-based communication and a bridge API. This enables **continuous telemetry streaming** and provides users with a **live view of system behavior**.

Another key contribution is the integration of **real-time monitoring and control within a single interface**. The dashboard not only displays data but also allows users to **interact with and control the system**, making it suitable for applications requiring **continuous supervision and quick response**.

The framework also incorporates **AI capabilities** to support **intelligent data analysis** and future scalability toward **advanced robotic applications**. In addition, the system is designed to be **modular and flexible**, allowing easy adaptation to different robotic platforms and use cases.

Overall, the proposed system provides a **practical, efficient, and scalable solution** for building robotic systems that are **easy to monitor, control, and extend**.

VI. RESULTS AND ANALYSIS

The performance of the proposed Mini-ROS framework was evaluated based on real-time communication, system responsiveness, and analytical capabilities. The key results are summarized below:

- Low-Latency Telemetry Streaming:** The system successfully streams data from the edge device to the dashboard in real time. The updates are reflected with minimal delay, allowing users to observe the robot's behavior as it happens without noticeable lag.
- Cloud-Based Remote Monitoring Interface:** The dashboard, hosted on the cloud, enables remote access to system data. Users can monitor the robot's movement, sensor readings, and overall status from anywhere, making the system more flexible and practical.
- Real-Time Movement Visualization and Tracking:** Movement-related parameters such as direction changes, path deviations, and corrective actions are clearly displayed. This helps users easily understand how the robot is behaving on the track in real time.

4. AI-Driven Telemetry Analysis:

The system processes telemetry data to provide insights rather than just raw values. It highlights patterns such as oscillations, repeated deviations, and movement instability, helping in better analysis of robot performance.

5. System Stability and Responsiveness:

The overall system operates smoothly without noticeable lag or interruptions. The coordination between the edge device, cloud, and dashboard remains consistent throughout the experiment.

6. Seamless Edge–Cloud Integration:

The framework demonstrates effective coordination between the edge device and cloud services. This ensures continuous data flow, real-time monitoring, and efficient processing within a unified system.

VII. DISCUSSIONS

The results show that the proposed Mini-ROS framework is able to support **real-time monitoring, cloud-based interaction, and basic AI-driven analysis** within a single system. The **cloud-hosted dashboard** makes it easy for users to continuously observe and control the robot from a remote location.

The system performs well in terms of **responsiveness and smooth communication**, with no noticeable delay during operation. The addition of AI also helps in **understanding movement patterns and system behavior**, rather than just showing raw data.

However, the system has some limitations. It is currently tested on a **simple robotic setup**, so more advanced AI capabilities are not fully demonstrated. Also, the system depends on a **stable network connection** to maintain real-time performance.

Overall, the framework provides a **flexible and scalable base** that can be extended to more advanced and intelligent robotic applications in the future.

VIII. CONCLUSION

This paper presents Mini-ROS, a lightweight cloud–edge framework designed to support **real-time monitoring, control, and data analysis** in robotic systems. The system shows how data from the robot can be sent to a **cloud-based dashboard**, where users can easily monitor and interact with it.

The results show that the framework works smoothly in real time, with **stable communication and useful insights from the data**. Even though the system is tested on a simple robot, it clearly shows how the approach can be extended to more advanced applications.

Overall, Mini-ROS provides a **simple, flexible, and scalable solution** for building robotic systems that are easy to monitor, control, and improve over time.

IX. FUTURE SCOPE

The Mini-ROS framework can be extended to a wide range of real-world robotic applications. Some potential directions include:

- Surveillance Robots:** Can be used for continuous monitoring with live video and telemetry streaming, enabling remote observation and quick response to unusual activity.
- Delivery Robots:** Useful for tracking movement, monitoring delivery status, and managing routes in real time through the cloud dashboard.
- Warehouse and Automation Robots:** Can support task monitoring, system coordination, and performance tracking in industrial environments.

4. **Service Robots:**
Applicable in areas such as healthcare or assistance systems, where real-time monitoring and interaction are important.

In addition to application-based extensions, the framework can be further improved by:

Integrating Advanced AI Models:
To enable better analysis, anomaly detection, and more intelligent decision-making.

Supporting Multi-Robot Systems:
Allowing multiple robots to be monitored and controlled through a single cloud-based interface.

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