# A Modular Teleoperated Mobile Robot for Environmental Exploration and Real-Time Data Acquisition with Visual Surveillance

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***Abstract*—Human operators need to use special equipment when they enter hazardous locations which also present challenging access difficulties. The paper presents a wheel-based robotic platform which operates remotely for visual checks and environmental data collection during live monitoring sessions. The system achieves architectural separation between motion control and monitoring subsystems through its use of various microcontrollers. The joystick-operated ESP32 system allows users to control motor movement through its high-current motor driver and wireless ESP-NOW protocol which enables fast response times. The system uses multiple sensors which connect to different ESP32 units to collect data about the environment and the movement of the device. A Raspberry Pi 3 receives processed telemetry data via UART. The system shows live sensor information together with USB camera video feed through a web-based monitoring interface. The system establishes compatibility between different sensor interfaces and microcontroller logic levels through signal conditioning and voltage level conversion processes. The experimental evaluation showed that the system allows users to navigate manually while it displays synchronized telemetry data and streams stable video footage which proves its usefulness for monitoring remote areas that have dangerous or limited access.**

***Index Terms*—Teleoperated Mobile Robot, Environmental Monitoring, Real-Time Telemetry, Visual Surveillance, ESP32-Based Control, Raspberry Pi Dashboard, Wireless Robotics, Sensor Fusion, Hazardous Environment Monitoring, Modular Robotic Systems**

## I. INTRODUCTION

Robotic systems have taken over extensive operational areas which include dangerous zones and remote locations and places that pose threats to human health such as polluted environments and underground tunnels and industrial inspection areas and disaster-stricken regions. People face major safety threats because they need to deal with dangerous gases while navigating through dangerous ground and having limited visibility. A practical answer exists through teleoperated mobile robots which enable operators to monitor and explore these spaces from a secure distance. Mission completion becomes possible through teleoperation because operators can control everything from a distance while receiving instant feedback which keeps human operators out of harm's path. Robotic platforms which operate through teleoperation need to provide their operators with ongoing operational awareness as their most essential requirement. The system tracks positions through data collection while it uses environmental sensors to produce live visual feedback and monitors system operational status. The cameras on board provide operators with visual monitoring which enables them to understand environmental conditions and detect obstacles and choose appropriate control actions. The environmental sensors provide numerical data about temperature and humidity and gas levels and atmospheric conditions which help scientists detect hazards and choose proper actions.

The robots designed for current environmental monitoring typically focus on limited sensing capabilities or autonomy of the robot. Despite the fact that the robots with the capability of autonomy can operate without any input from the user, in some cases, these robots may not be suitable because of their excessive unpredictability. Moreover, there exists many teleoperated robots, which do not have modular architecture and thus cannot easily include new components and sensors. Moreover, a strong interrelation between motion control unit and monitoring modules can affect scalability and even stability of the robot.

This paper proposes a modular teleoperated mobile robotic platform where both monitoring and motion control are split into different units. The monitoring and visualization processes are separately controlled while the motion control is performed using dedicated microcontrollers to achieve fast response of actuators and reduce latency. Besides avoiding mutual interference between monitoring and actuation processes, such architecture increases system reliability.

Since controllability and safety can be greatly impacted by delays or packet losses, wireless communication is essential in teleoperated systems. Because of their low latency, dependability, and compatibility with peer-to-peer communication protocols, ESP32 microcontrollers are used in the suggested system for wireless communication and control. This makes it possible to control the robot smoothly with a joystick without depending on third-party servers or cloud infrastructure.

Considering the impact of possible delay and packet losses in the context of controllability and safety, it is crucial to emphasize the significance of wireless communication when it comes to teleoperated robots. As it has been stated above that ESP32 controllers are going to be selected because of low latency, reliability and their ability to conduct peer-to-peer communication, it is currently possible to control the robot using a joystick without relying on external help. As far as monitoring and visualization of obtained information is concerned, a Raspberry Pi board will serve as the server and processing center that will receive telemetry data and visual information sent by sensors and a USB camera mounted on the robot. Thus, it will be possible to monitor two types of information at the same time.

The capability of expanding and adapting the proposed solution to the needs of different applications through the addition or substitution of some sensors and modules for communications becomes possible owing to the modular architecture of the system. This feature allows applying the designed solution to different areas of work, such as disaster response, environmental inspection, industrial monitoring, and hazardous locations exploration. Successful tests showed reliability of remote control, robustness of data transmission, and efficient visualization.

## II. LITERATURE REVIEW

R. Murphy [1] introduced “Trial by Fire [Rescue Robots]”, where he describes a practical example of utilizing teleoperated robots in situations of disaster. Among the main obstacles for such remotely operated robots, the paper mentions problems associated with difficult terrain, lack of vision, and delays in information transfer. It shows that there is a need for efficient teleoperation systems in order to protect the operator's safety. The paper is a solid ground for motivating the usage of robotic systems as a tool for safe exploration.

In their paper “Human–Robot Interactions during the Robot-Assisted Urban Search and Rescue Response”, J. Casper and R. Murphy [2] analyze operator usability issues in teleoperated robots and provide an overview of how live telemetry helps to overcome obstacles during remote control. The main limitation revealed in this work concerns the situation awareness during teleoperation. In particular, this research can be used as a foundation for designing a human-in-the-loop system.M.

A GPS-GSM hybrid localization system was proposed by M. A. Al-Khedher [3]. In this paper, a practical real-world application is presented in order to provide accurate and robust tracking for vehicles. Real-world experiments prove that using GPS information together with wireless communications is reliable enough to achieve accurate positioning outdoors. Serial data transmission has been proven as an effective way of updating positions. GPS positioning can be justified by providing a very accurate and stable way of determining position in real time.

A GPS position tracking system was introduced by X. Zhang et al. [4]. In this work, the researchers concentrated on the problem of improving localization quality by employing real-time coordinate updating approaches. Outdoor robot position tracking experiments have proven the stability and reliability of the position estimations provided by the system. The GPS signal variation handling has been proven to be efficient. It is justified to employ GPS in outdoor robots due to its efficiency and stability.

Lee S. et al. [5] have created a smart environmental monitoring system based on an autonomous mobile robot. A combination of various sensors is employed

to collect environmental data. Processing is conducted in real time within the robot's onboard computer. Experimental findings confirm effective data acquisition under changing conditions. The robot proves able to adapt to changes in environment. Data visualization is implemented to allow monitoring. This scientific work confirms the potential of integrating various sensors in environmental monitoring systems.
Gomez A. et al. [6] have developed an open-source mobile robot environmental sensing system. A modular hardware approach and the ability to easily integrate different sensors are the core features of the studied technology. The authors emphasize scalability and affordability of their approach. Real-time data transmission and visualization are proven possible using open-source methods. Experimental findings support high flexibility and reliability of the designed system.
An IoT-based monitoring robot has been developed by Sharma et al. [7]. It includes an environment sensor, wireless connectivity, and cloud dashboards for data visualization. According to the experimental findings, it has been proven that it has a considerable potential for transmitting information. It can be concluded that IoT technologies may be used for robotics. Cloud computing facilitates more flexibility and accessibility. The research provides reliable information for the dashboard monitoring process.
The telemetry method has been suggested for developing a monitoring robot for efficient data transfer by Mehta et al. [8]. Telemetry enables efficient data transmission through communication protocols. At first, data is gathered using sensors, and afterwards, it is transmitted to the controller. It has been proved that telemetry works effectively.
Patil et al. [9] implemented a real-time video surveillance robot through Raspberry Pi. The proposed solution employs a USB camera and a local web server for the live streaming of video data. The study proves a low-cost approach to implementing the solution with good performance in terms of video streaming. Performance of wireless streaming is analyzed under various scenarios. Experiments show high efficiency of real-time video surveillance tasks. The proposed architecture allows remote control through conventional web browsers. This paper has direct relevance to real-time video systems implemented with Raspberry Pi.
Rao et al. [10] designed a wireless video surveillance robot based on IoT technologies. The proposed surveillance robot emphasizes reliable wireless data transmission and video streaming. Data encryption techniques are applied to ensure higher communication safety in the process of surveillance. Experiments proved minimum latency and efficient performance during video monitoring. Security issues were discussed in this work, indicating its contribution to video monitoring with robotics.
[11] L. Chen et al. propose an energy-efficient control mechanism for mobile robots. This paper studies the complexity of the environment to improve the motion planning and energy consumption of the robot. Runtime monitoring mechanisms facilitate dynamic control strategy adjustment. The results obtained from the experiments show that there are remarkable gains in energy efficiency. The developed framework can prolong the time of operations of the robot.
[12] A. Verma et al. introduced a real-time monitoring and surveillance robot for dangerous environments. It utilizes sensors in the environment, live video transmission, and Internet of Things connectivity. Remote monitoring capabilities provide enhanced safety measures for the operators in the dangerous sites. The experiments conducted proved its ability to perform real-time tasks. It has close relevance with hazardous environment monitoring.
Wireless control with lower latency using ESP32 microcontrollers was proposed by M. Singh et al. [13]. The experiment compares the efficiency of wireless protocols for remote robot control purposes. Experimental results confirm lower delay times and faster responses from the tested system. The system is capable of providing high-level stability of its performance regardless of the used network environment. ESP32 can be considered as a proper robot controller for teleoperated applications

## III. HARDWARE DESIGN

The hardware architecture combines processing devices, sensing boards, actuation, and power control circuits to facilitate the teleoperated exploration as well as real-time monitoring. The server unit and the visualization are based on a Raspberry Pi 3, which also allows live video streaming through a USB camera and telemetry receipt by an independent ESP32 through the UART.

The two ESP32 development boards are used to control and acquire data in real-time. The ESP32 that is used in motion control by the joystick is one, and the other ESP32 is tasked with the functionality of environmental sensor, inertial measurement, and processing of positional data. The ESP-NOW protocol is used to provide wireless communication between the drive ESP32 and the controller ESP32 in order to have low-latency control.

The MG811 ($CO_2$) and MQ7 (CO), MQ131 ($O_3$) and BME680 sensors are applied to achieve environmental monitoring. The MPU6050 inertial measurement unit offers three-axis acceleration and gyroscopes so as to estimate the orientation. The GPS E108-GN03G-485 provides positional information. As the GPS module is RS-485, to convert the differential signals to logic levels appropriate to the ESP32, a MAX485 transceiver is used to achieve the conversion.

The DC gear motors make up the motion subsystem, and they are powered by a BTS7960 motor driver, which allows bidirectional motor control of high current. The control of power is done by a DC-to-DC buck converter LM2596S to maintain a constant voltage level. The networks of voltages dividers and resistors are used in order to provide logic-level compatibility of 5 V sensors with the 3.3 V ESP32 inputs.

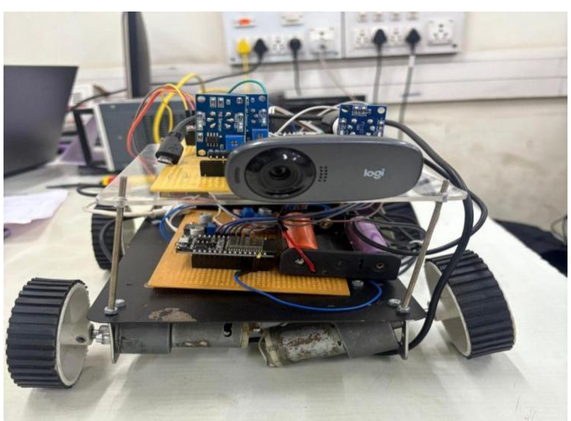


Fig. 1. Final prototype of the modular teleoperated mobile robot with integrated sensing, control, and visual surveillance modules

Fig. 1 shows the fully assembled prototype of the proposed modular teleoperated mobile robotic platform developed and tested in the laboratory environment. The platform integrates the motion control subsystem, environmental sensing unit, wireless communication modules, and onboard visual surveillance system on a compact wheel-based chassis. The modular hardware layout allows independent operation of control and monitoring subsystems while facilitating easy sensor expansion and maintenance.

## IV. SOFTWARE DESIGN

The software architecture follows a distributed design, where each processing unit is assigned specific responsibilities to ensure modularity and reliability. In the controller ESP32 firmware, the joystick inputs are read, converted and sent to the controller as control packets via the ESP-NOW protocol, which is wireless. The controller receives the control packets and sends pulse-width modulation (PWM) signals to the BTS7960 motor driver, which allows real-time actuation of the motor. This subsystem does not rely on the monitoring infrastructure making motion control independent.

The sensor ESP32 software provides sensor polling, signal conditioning, calibration mapping and telemetry packet structure. The environmental data, inertial measurements and GPS coordinates are coded in structured packets and sent to the Raspberry Pi 3 through UART communication.

A lightweight server-side application is used on the Raspberry Pi 3 to control the reception of serial data, the processing of telemetry, and its visualization in real-time. The USB camera video streaming is managed simultaneously in the environment of the same server. The web-based dashboard continuously updates sensor values and shows the live video feed on one web page thus offering synchronized monitoring without affecting the motor control processes.

## V. METHODOLOGY AND EXPERIMENTAL SETUP

The operational methodology of the proposed system is divided into two independent subsystems: the motion control subsystem and the monitoring and telemetry subsystem. The final workflow of the proposed system is illustrated in Fig. 2

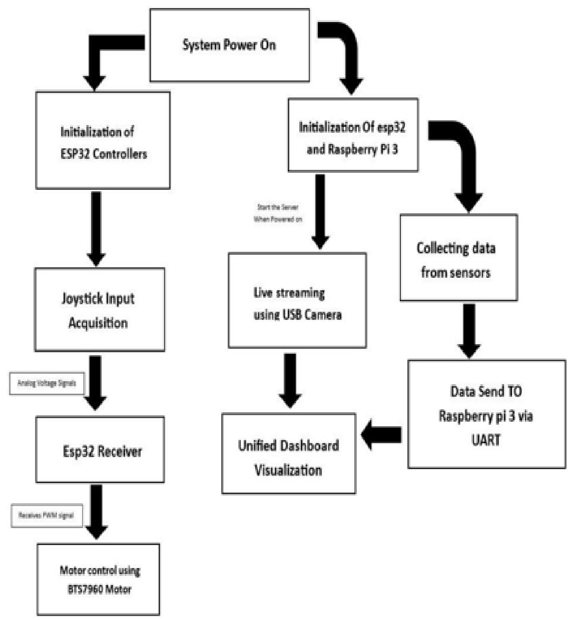


Fig. 2. Overall system workflow of the proposed teleoperated mobile robotic platform.

A. Motion Control Subsystem Flow

The motion control subsystem is responsible solely for robot actuation. Joystick inputs are continuously read by the controller ESP32 and mapped into speed and directional commands. These commands are transmitted to the drive ESP32 using the ESP-NOW protocol. Upon reception, the drive ESP32 decodes the control data and generates PWM signals to drive the BTS7960 motor driver, which regulates current delivery to the DC gear motors. This process executes continuously in a closed loop to ensure responsive and low-latency motion control.

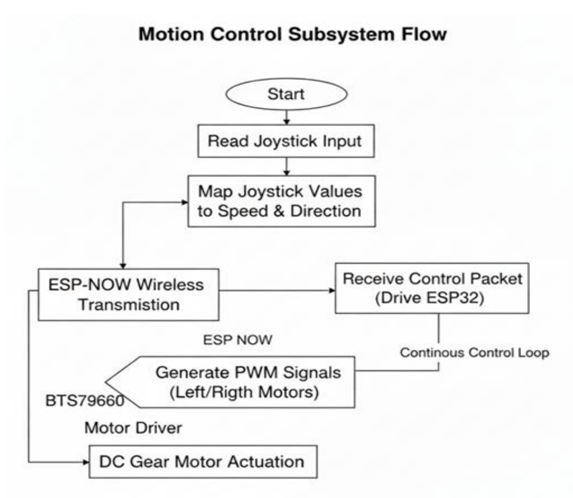


Fig. 3. Flowchart of the motion control subsystem.

B. Monitoring and Telemetry Subsystem Flow

The monitoring and telemetry subsystem is responsible for environmental sensing, inertial state estimation, positional tracking, and live video streaming. A dedicated ESP32 acquires sensor data, performs preprocessing, and transmits structured telemetry packets to the Raspberry Pi 3 via UART communication.

Environmental parameters are measured using gas sensors and the BME680 module, while orientation parameters are derived from MPU6050 accelerometer and gyroscope data using sensor fusion techniques to reduce noise and drift. Positional data is obtained from the GPS module through RS-485 to UART conversion using the MAX485 transceiver. The Raspberry Pi parses incoming telemetry data and updates the dashboard in real time. Simultaneously, the USB camera captures and streams live video through the locally hosted web server.

The detailed monitoring and telemetry workflow is shown in Fig. 4.

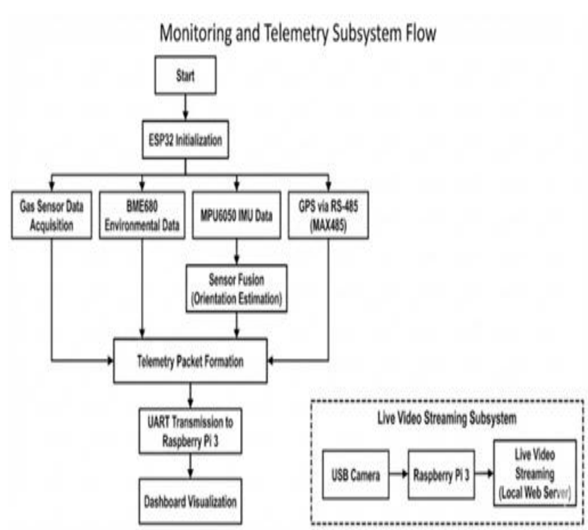


Fig. 4. Flowchart of the monitoring and telemetry subsystem.

## VI. DATA PROCESSING AND COMPUTATION

To achieve reliable and correct measurements, the proposed system converts raw sensor data with a standard signal conditioning and calibration process. The analog sensor data are brought to the correct voltage range and digitized with the ESP32 in-built ADC. The environmental parameters (gas concentration, temperature, and humidity) are obtained by means of manufacturer-specified calibration models. The inertial data of the MPU6050 is analyzed to approximate the orientation through a complementary filtering algorithm, a fusion of the accelerator and gyroscopic data, to suppress noise and drift. The GPS module records positional data, which is then translated into useful coordinate formats to be used in real time tracking. All processed parameters such as environment data, orientation and location data are structured into telemetry packets. These packets are sent through UART to the Raspberry Pi where they are decoded and shown on a web-based dashboard to monitor and visualize in real-time.

## VII. RESULTS AND DISCUSSION

The proposed robotic system was tested in controlled indoor and semi-confined environments to evaluate its performance in real-time monitoring, communication reliability, and manual navigation. The motion control subsystem demonstrated responsive behavior with minimal latency between joystick input and motor actuation due to the low-overhead ESP-NOW communication protocol. Smooth directional control and speed variation were achieved using PWM-based motor control through the BTS7960 driver.

The monitoring subsystem successfully acquired environmental parameters including gas concentrations, temperature, humidity, orientation, and positional data. Sensor readings were transmitted reliably to the Raspberry Pi 3 via UART and displayed on the web-based dashboard in real time. The live video stream provided continuous visual feedback synchronized with sensor telemetry, enabling effective situational awareness.

Inertial measurements obtained from the MPU6050 showed stable orientation estimation after applying sensor fusion techniques. GPS data parsing via the RS-485 interface yielded accurate positional information in open environments, while limited signal availability was observed indoors. Overall, the experimental results validate the system's ability to perform remote environmental monitoring and visual inspection while maintaining architectural separation between control and monitoring subsystems.

## VIII. FUTURE SCOPE

Future enhancements may include the integration of autonomous navigation algorithms and obstacle detection using LIDAR or depth cameras. Machine learning techniques can be employed for anomaly detection and intelligent decision making based on sensor data. Cloud based data logging and remote access can extend monitoring capabilities beyond local networks. Power optimization and battery management system can improve operational duration. The system may also be extended for swarn based exploration or deployment in real disaster response scenarios.

## IX. CONCLUSION

This paper presents the design and implementation of a wheel-based multi-sensor robotic platform for remote exploration and environmental monitoring. The system integrates real time sensing, live video streaming, and wireless control while maintaining a modular and scalable architecture. Experimental evaluation demonstrates reliable performance in manual navigation, telemetry acquisition, and unified dashboard visualization. By separating actuation and monitoring subsystem, the proposal design enhances system robustness and operational safety. The developed platform provides a cost effective and practical solution for exploration in hazardous or inaccessible environments.

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