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AI-Driven Autonomous Pipeline Inspection and Maintenance Robot Using IoT and Smart Sensors

J. Antony Robinson[1], M. Suman[2], M. Nithesh kumar[3], S. Selva Rajesh[4], M.S. Mohamed Thoufeeq[5]

[1]Assistant Professor, Department of Electrical and Electronics Engineering, Francis Xavier Engineering College, Tirunelveli - 627003, India.
[2,3,4,5]UG scholar, Department of Electrical and Electronics Engineering, Francis Xavier Engineering College, Tirunelveli - 627003, India.

ABSTRACT

The increasing complexity and scale of pipeline infrastructure demand effective and efficient methods for inspection and maintenance. Traditional manual methods for pipeline inspection are often hazardous, time-consuming, and prone to errors. To address these challenges, an AI-driven autonomous pipeline inspection and maintenance robot integrated with Internet of Things (IoT) and smart sensors is proposed. This system aims to revolutionize pipeline management by offering real-time, precise, and continuous monitoring of pipeline conditions, reducing human intervention and ensuring proactive maintenance. The ESP32 Camera is a microcontroller board equipped with an ESP32 chip, which is a highly versatile and powerful microcontroller that integrates Wi-Fi and Bluetooth capabilities, along with support for external peripherals like cameras. Further, an ultrasonic sensor is a device that uses ultrasound to measure distance to an object. These sensors transmit data in real-time to a cloud-based system via IoT technology, allowing for remote monitoring, diagnostics, and predictive maintenance. This robot's capabilities ensure that it operates in hazardous or hard-to-reach areas without human assistance, improving safety and operational efficiency. Overall, this system enables early detection of potential failures, and extending the overall lifespan of the pipeline.

Keywords: ESP32 Camera Microcontroller, IoT, Node MCU, Ultrasonic Sensor, Servo Motor and Robot.

1. Introduction

Underwater pipelines are essential infrastructure for the transportation of oil and gas. Owing to the quick advancements in autonomous system technology, researchers are actively exploring the many uses of autonomous vehicles, such as surveillance and undersea exploration [1–2]. One of the most significant applications of these technologies is in the inspection and maintenance of pipelines, a critical infrastructure for industries such as oil, gas, water distribution, and more. Pipelines, often located in remote or hard-to-reach areas, require constant monitoring to ensure their structural integrity and to prevent costly leaks, environmental hazards, and failures [3]. Traditional methods of pipeline inspection typically rely on manual labour or stationary sensors, which are often expensive, and perhaps to human error. Additionally, these methods are not always providing real-time data or sufficient insights into the pipeline's safety. In response to these challenges, autonomous robots, equipped with IoT are emerging as an effective solution to streamline the pipeline inspection and maintenance process [4-5]. Robotic gadgets are diverse and very relevant. The creation of such tools is also crucial for the education of upcoming scientists and engineers. It is crucial that students be able to build robots on their own, starting with basic models and utilizing inexpensive sensors and motors. As the smart industry has grown, robots particularly robotic arms are being employed in a variety of settings, including multi-robot cooperative systems and commercial settings [6]. Thus, robots are becoming more and more important. Because of its effectiveness, precision, and longevity, a robot is a need in many industrial facilities [7]. One of the primary parts of the robot is the servo motor, which controls the robot's rated load and rotation angle precision. Because of their high torque, compact size, and precise control, servo motors in particular appear frequently in industrial robots [8-9]. However, high torque, transformation stress, cyclic load, and impact load cause a lot of failures in robots. A number of problems, including misalignment, broken rotor bars, and bearing failure, happen after a given amount of use. These malfunctions lower productivity and result in manufacturing mishaps. Additionally, the entire robot and manufacturing are susceptible to unforeseen costs if one of the robot's components fails [10-11].

Traditional pipeline inspection often requires teams of workers to conduct manual inspections, which involves travel, setup, and potential hazardous work environments. Workers involved in pipeline inspections are often exposed to dangerous conditions, such as toxic gas leaks, extreme temperatures, high-pressure areas, or remote and hard-to-reach locations. Human inspectors make mistakes or overlook critical signs of damage or wear, especially when under pressure or working with limited data. This fatigue is further increasing the likelihood of errors, which could compromise the safety and integrity of the pipeline. Above the downsides are require to recovered; so, a robot with IoT technology is essential for immediate analysis and decision-making. By connecting different sensors and devices throughout the pipeline, the IoT makes it possible to continuously and instantly monitor the pipeline's status [12-14]. To gather crucial data, smart sensors such as gas, temperature, pressure, and ultrasonic detectors are integrated into the pipeline or the robot itself. These sensors allow for quick decision-making and increase inspection accuracy by feeding data to the robot and cloud-based platforms for analysis [15]. Hence, this work an AI-driven autonomous pipeline inspection and maintenance robot using IoT is implemented for enhanced efficiency, safety, and predictive maintenance to cost savings and improved environmental impact.

2. Proposed Methodology

The paper develops an AI-driven autonomous pipeline inspection and maintenance robot using IoT to improve efficiency. The developed block diagram is presented in Figure 1.

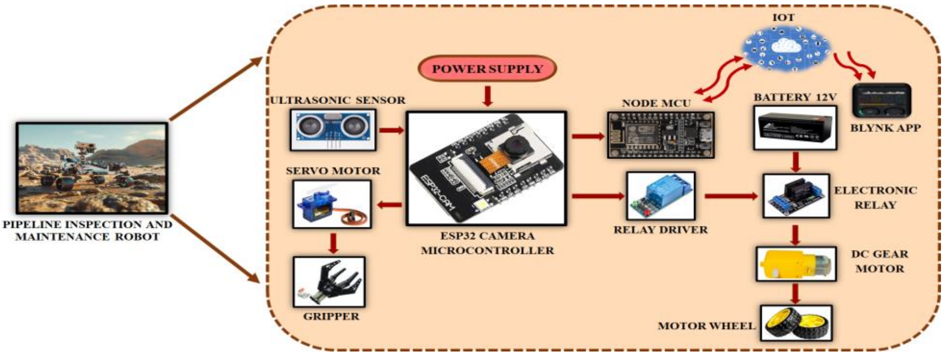


Figure 1 Developed Block Diagram

The system consists of the ESP32 camera microcontroller, Node MCU, ultrasonic sensor, servo motor, gripper, electronic relay, DC gear motor, and relay. Initially, power is supplied to the ESP32 camera microcontroller. The microcontroller is mainly used to operate all of the functions. Then, the ultrasonic sensor, servo motor, Node MCU, and relay drivers are connected to the microcontroller. The ultrasonic sensor is employed to measure distances and to detect obstacles. A servo motor is used to rotate to a specific position and hold the gripper in that position with high accuracy. A gripper is used to grip and hold the manipulate objects and place items in specific locations. A 12V battery is supplied to the electronic relay for charging purposes. The relay driver is linked with an electronic relay; these are used to operate the switch and its contacts when an electrical current flows through its control circuit and it generates an electromagnetic field. The DC gear motor operates by converting electrical energy into mechanical energy. The rotation of the output shaft is transferred to the wheels in a robot. All of the collected data are uploaded to the IoT device by using Node MCU for the internet for monitoring and analysis. Finally, the IoT outcomes are displayed on the Blynk app.

2.1 ESP32 Camera Microcontroller

The ESP32 Camera microcontroller is a highly versatile and powerful development board that integrates a camera module with the ESP32 chip. This board offers Wi-Fi and Bluetooth capabilities alongside the ability to capture images and stream video, making it suitable for a variety of IoT and embedded vision devices. The schematic representation of ESP32 Camera microcontroller is displayed in Figure 2.

Figure 2 ESP32 Camera microcontroller

The ESP32 Camera typically uses the camera module, which supports image resolutions up to 2 megapixels. It captures images in JPEG format, which is suitable for web-based applications. It integrates Wi-Fi and Bluetooth capabilities, which allow seamless wireless communication for IoT devices.

2.2 Node MCU

NodeMCU is easily programmed using the Arduino IDE, making it accessible to both beginners and experienced developers. It operates at 3.3V, which is different from the standard 5V of many Arduino boards, so careful attention is paid when interfacing with other components. NodeMCU is notable for its integration of Wi-Fi connectivity, its compatibility with the Arduino IDE, and its powerful ESP8266 microcontroller. Figure 3 is presented in the NodeMCU device.

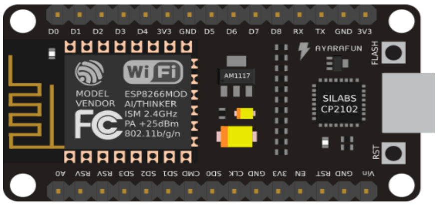


Figure 3 NodeMCU

It quickly connects devices to the internet and takes advantage of Node MCU's capabilities with the suitable libraries. Further, it is perfect for building sensor networks where data from various environmental sensors is collected and sent over the internet for monitoring and analysis.

2.3 Ultrasonic Sensor

An ultrasonic sensor is a type of sensor that uses ultrasonic waves to measure distances. Ultrasonic sensors are commonly used in robots to help detect obstacles and navigate by measuring the distance to the nearest object. The sensor provides information about the time required for sound waves to go from the sensor to the object and back after reflecting off its surface and returning to the receiver. The ultrasonic sensor is shown in Figure 4.

Figure 4 Ultrasonic Sensor

Using the speed of sound in air, the sensor calculates the distance to the object using the formula,

$$Distance = \frac{Speed\ of\ Sound \times Time\ Taken}{2} \qquad (1)$$

It is difficult to measure the distance to microscopic or fluffy objects since ultrasonic waves are reflected from nearly any surface, even clear ones. Furthermore, the angle at which the wave occurs has an impact on the measurements. The measurements are most precise if the sensor is oriented perpendicular to the item. Furthermore, an inaccurate measurement results from the wave reflected from the object not entering the receiver if the angle of incidence is too great.

2.4 Servo Motor

Servo motors are made to rotate to a precise position and maintain it with extreme precision. This makes them ideal for applications that require precision control, such as in robotics. Vector control in synchronous coordinates is a widely used technique for controlling the servo motors in industrial robots. Figure 5 shows the servo motor device.

Figure 5 Servo Motor

The servo motor test system included electronics and converters for machinery control, a DC machine connected to the servo motor shaft via a torque transducer, and electronics for measuring the torque and winding resistance of the servo motor. One of the primary parts of the robot is the servo motor, which controls the robot's maximum weight and rotational precision.

2.5 DC Gear Motor

A DC gear motor has a gearbox attached to its output shaft. The purpose of the gearbox is to convert the high speed and low torque of the DC motor into low speed and higher torque, which makes it ideal for applications where precise movement and higher force are required. It operates by converting electrical energy into mechanical energy. The DC gear motor device is displayed in Figure 6.

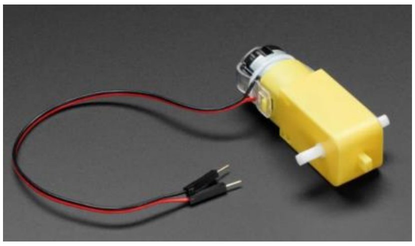


Figure 6 DC gear motor

The motor generates an electric current that passes through the armature windings when a DC voltage is generated. The gears work together to reduce the motor's high rotational speed and increase the torque, making it suitable for specific applications. The rotation of the output shaft is transferred to the wheels in a robot.

2.6 Electronic Relay

An electronic relay is an electrical switch that opens or closes its contacts when an electrical current flows through its control circuit. Relays are switch high-current or high-voltage devices using a low-power signal. In Figure 7, the electronic relay is shown.

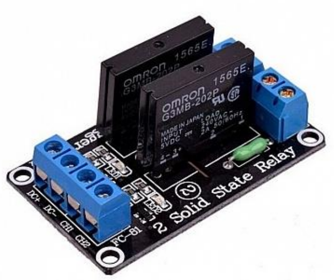


Figure 7 Electronic Relay

When a control signal is supplied to the coil of a relay, it generates an electromagnetic field. The magnetic field generated by the current flowing through the coil attracts a metal armature, which is connected to the switching contacts. When the relay is unpowered, the contacts are open. The relay will close the contacts when powered, allowing current to flow. Once the control current is turned off, the electromagnetic field collapses, and the armature is returned to its default position by a spring.

3. Results and Discussions

In this work, an AI-driven autonomous pipeline inspection and maintenance robot using IoT is developed for enhanced efficiency, safety, and maintenance. Figure 8 shows the hardware setup of the pipeline inspection robot system.

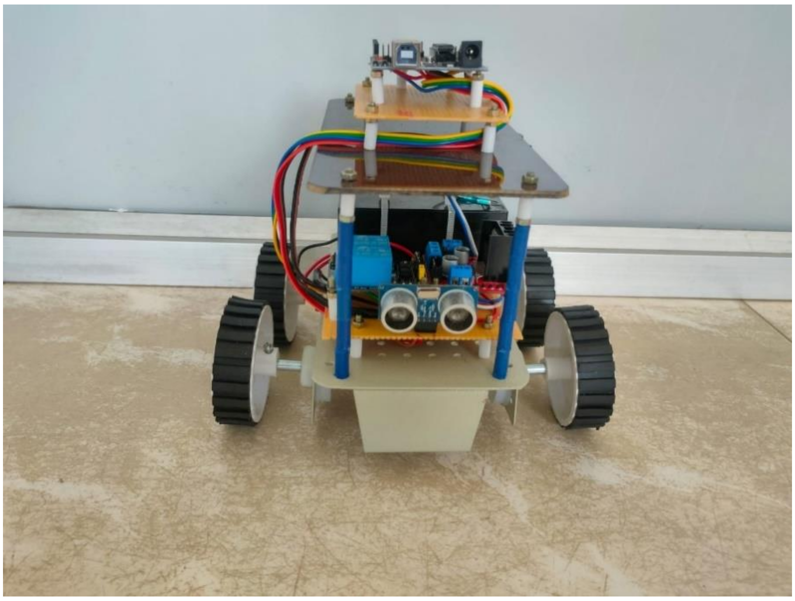
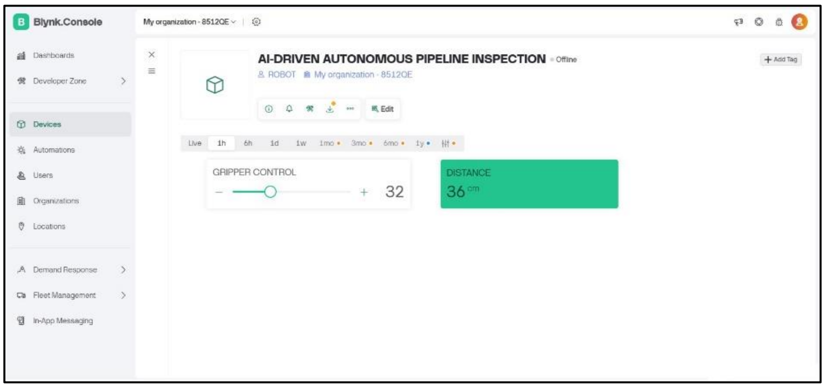


Figure 8 Hardware Setup of The Pipeline Inspection Robot System

The ESP32 Camera microcontroller, which combines the Node MCU and IoT, is integrated inside the robot, and it also supports external gadgets like cameras. Moreover, an ultrasonic sensor is a tool that measures an object's distance using ultrasonic waves. Through the use of IoT technology, this robot provides data in real time to a cloud-based system, enabling remote monitoring, diagnostics, and predictive maintenance.



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GRIPPER CONTROL 32

DISTANCE 36 cm

Figure 9 BLYNK App Outcome of the Pipeline Inspection Robot System

The BLYNK app outcome is presented in Figure 9. In this figure, the distance of 36 cm is measured using an ultrasonic sensor, and the gripper values are monitored and demonstrated in this system.

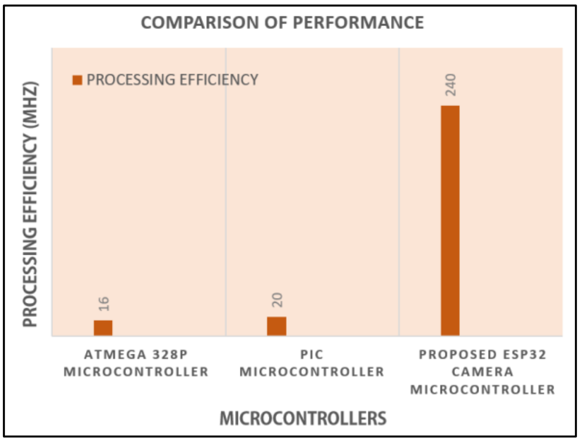

Figure 10 Comparison of Performance

Figure 9 illustrates a comparison of different microcontrollers of processing efficiency. In the graph, the proposed ESP32 Camera microcontroller of 240 MHz is attained. Previous controllers of the ATMega-328 microcontroller of 16 MHz and the Peripheral Interface Controller (PIC) of 20 MHz are attained based on processing efficiency.

4 Conclusion

The purpose of this works an AI-driven autonomous pipeline inspection and maintenance robot using IoT is developed for enhanced efficiency, safety, and predictive maintenance. Consequently, the gripper values are tracked and perfectly demonstrated, and the distance is determined using an ultrasonic sensor. Further, sensors, cameras, and AI-driven analysis pipeline inspection robots provide real-time data, allowing for prompt decision-making and minimizing the need for costly manual inspections. Their ability to access confined spaces and operate autonomously also reduces downtime and improves overall pipeline reliability. This work demonstrates the decreasing risk of undetected issues or failures and predicts potential failures. Further, this system transforms pipeline management by offering real-time, accurate insights and automated solutions that significantly improve operational efficiency and reduce risks.

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