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Real Time IoT and Sensor Based Pipeline Inspection Robot

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Abstract— Pipelines are used to transport water, oil, and gas so regular inspection is important to avoid cracks, corrosion, leakage and blockages. Manual inspection is slow, risky and cannot always detect internal damage. This paper presents a Real time IoT based pipeline inspection robot which can move inside pipelines and monitor their condition. The robot uses ultrasonic sensors to identify the defects and 360° camera to capture internal images of the pipe. An Arduino controls the movement and sensing the pipe as an ESP8266 module sends data wirelessly for remote monitoring. The system is powered by a rechargeable LiPo battery and designed to be simple, low cost and easy to use. The proposed robot helps in early fault detection reduces human effort and supports safer pipeline maintenance.

1 Introduction

Pipelines are widely used in industries to transport water oil gas chemicals and other fluids from one place to another. They are an essential part of infrastructure in sectors such as oil and gas water distribution sewage treatment and manufacturing plants. That pipelines often run for long distances and is to be placed underground or inside closed environments it becomes difficult to monitor their condition regularly. The problems that pipelines can develop over a period of time include cracks corrosion leakages as well as blockages caused by aging material due to high pressure temperature change in pipelines and environmental influences. Unless these problems are identified during the initial phases that may result into severe mishaps environmental pollution loss of products and high repair expenses. That is why pipelines also have to be checked and properly maintained in order to provide safe and continuous work.

The traditional ways of inspecting pipelines relies more on manual inspection or external observation. Most of the instances workers must go into closed spaces or block the pipeline in order to inspect whether it is damaged. It is a complicated and time able process that is also not safe particularly in risky conditions like oil and gas conduits. Manual inspection is also ineffective in giving around-the-clock oversight and minute flaws within the pipe will never be realized until they transform into serious malfunctions. The limitations pose the necessity to have an automated inspection system that has the ability to work within pipelines and offer real time information that is accurate and does not jeopardise the safety of human beings.

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New trends in embedded systems sensors, Internet of Things technology have enabled the creation of smart inspection tools with the ability to gather and send data over distance. IoT based monitoring that could enable the operators to monitor the conditions of the systems in real time and take preventative measures before failure. With the addition of sensors communication modules and compact controllers, it is possible to design a mobile robotic system that will move within pipelines and check the inside of the pipelines and its overall condition. These systems are eliminating the necessity of manual intervention and enhancing maintenance planning.

Considerable utilization of ultrasonic sensors that identify anomalies in the form of a crack corrosion or obstruction through analysis of reflected signals on the surface of a pipe. Real time images and video are taken by a camera module of the internal pipeline status that assists in visual detection of defects. Through built-in controllers, the data collected is analyzed and sent wirelessly by a Wi Fi module, through which the operator can easily check the inspection remotely.

Motion and sensor data is obtained using the Arduino controller where the Raspberry is used to monitor an image and process it at the most basic level. The DC motors that enable movement of the robot forward and backward as well as alternating direction within the pipe can be controlled by a motor driver. This entire system is powered by LiPo battery that is rechargeable and makes the robot small enough and fit in the field. The primary design concerns in this architecture primarily revolve around simplicity low-cost and modularity such that the extra sensors such as gas or moisture sensors can be added in future without any significant changes.

The suggested robot is expected to be a safer and more efficient substitute of the conventional method of inspection. The empowering internal monitoring and real time data transmission system is able to identify defects at early stage, it lessens maintenance time and lessen the chances of a failure of the pipeline. This method favouring preventive maintenance enhances operations safety and provides a viable manner of operation to industries where pipelines should be checked more frequently.

1.1 Need for Automated pipeline Inspection

Pipelines must be inspected regularly to prevent failures caused by cracks corrosion or leakage. Manual inspection is time consuming unsafe and not suitable for frequent monitoring. The automated inspection system can move inside the pipelines can detect defects early and provides a real time information to the operator. This improves the safety reduces a maintenance cost and avoids the unexpected shutdowns.

1.2 Design and Development

This project develops a compact IoT based pipeline inspection robot which can move inside pipelines and monitor their condition. Ultrasonic sensors are used to detect internal defects while a camera provides a visual inspection of the pipe surface. This data is transmitted wirelessly using a Wi Fi module so that the operators can observe the pipeline remotely. This system is designed to be modular robot so additional sensors can be added easily for future applications.

2 Literature Survey

Robotic automation has advanced tremendously particularly in the fields of assistive technology and in industrial applications. It is shown that considerable numbers of Presented an overview of pipeline inspection robots for detecting leaks, damages, and blockages. Introduced a 120° wheel-mounted design to navigate curved pipelines effectively. (2022) [1] Proposed a screw-drive wall-press robot with a 15° helix wheel angle, modeled in UGNX, tested for smooth vertical, horizontal, and elbowed pipe navigation. (2014) [2] Designed an optimized three-wheel IPIR with angles 120°, 104.88°, and 135.12° to avoid wheel slip. Validated through simulations and 3D-printed prototypes. (2022) [3] Compared various in-pipe robots and proposed a simple steering mechanism enabling smooth navigation through elbows, reducers, and branches. (2016) [4] Developed the PLIERS system using IoT, swarm robotics, and CNNs for image-based crack detection with 80–90% accuracy and 95% precision. (2024) [5]

Reviewed in-pipe robots and sensors like ultrasonic, magnetic, laser, and X-ray for flaw detection, guiding optimal robot design selection. (2016) [6] Reinched amphibious robots to enhance versatility, wrote about the wheel-driven robots, track-driven robots, pig-type robots, and bio-inspired robots with wireless communication and autopilot. (2024) [7] Discussed leak detecting amphibious robots with a CD and wearable cameras, sensors and DC motors, and elbows along with inclined pipes. (2022) [8] Discussed amphibious robots sensing leaks, corrosion, and internal obstruction; a device would use

Developed a bio-inspired caterpillar robot that requires compliant mechanisms to navigate narrow, curved pipes effectively. (2018) [9] introduced a mobile robot that has a design enabling it to detect corrosion and cracks as well as welding defects and navigate pipelines when conditions become dangerous, such as nuclear plants.

Engineered an inspection robot on a wheel type in pipes based on a continuously variable transmission (CVT) system. The CVT system assists the robot in changing speed and gripping force automatically based on pipe varying diameter. The design provides easy movement of horizontal, vertical and curved pipes. Its primary objective was to enhance the stability, flexibility, and general efficiency of the inspection process within pipelines. (2024) [10] Recommended the implementation of Industry 4.0 related technologies like IoT, cloud technology, and intelligent sensors into pipeline inspection robots. Concentrated on remote monitoring and collection of data in real time to take care of the pipeline. Enhanced accuracy in fault detection with the use of digital communication systems. The primary focus was on creating a smarter, automated, and efficient in-pipe inspection system. (2024) [11] Provided an in-depth overview of the various in-pipe inspection robot designs and mechanisms. Moved, tracked and wall-press type robots an compared based on performance and movement. Discussed the advantages, limitations, and challenges of each design. The paper mainly guides researchers in selecting suitable robot structures for effective pipeline inspection. (2012) [12]

Designed and developed a robotic system specifically for sewage pipe inspection. The robot can travel inside narrow and contaminated pipelines using a wheeled mechanism. Integrated a camera system to capture images and detect blockages or damages. The main objective was to improve safety by reducing human entry into hazardous sewage environments. (2017) [13]

Integrated guided acoustic wave sensors with a mobile inspection robot for pipeline monitoring. The system detects internal cracks and structural defects using non-destructive testing methods. The robot moves along the pipeline while collecting and transmitting inspection data. The main aim was to improve defect detection accuracy, especially in long-distance pipelines. (2023).

3 Challenges in Existing System

Many of the existing pipeline inspection systems still have several practical limitations that affect their performance and reliability. In some methods, detecting very small cracks is difficult, these small issues become serious damage if not find early. Others have low-resolution cameras, and it captures blurred photographs and it becomes difficult to detect cracks, corrosion, or leakages appropriately. Lot of real-time monitoring is another similar issue. In others, there is the limited storage of the collected data locally so that access is impossible remotely, causing delays in the analysis and making decisions. Advanced inspection robots and imaging technologies are also expensive, and thus small industries and large network of pipelines are limited by their cost. The use of IoT in a few systems also influences the sphere of wireless communication decreasing the efficiency of remote monitoring and control moreover, most of the currently existing systems are not fully automated, which makes people spend more labor and provides the opportunity of technological malfunctions.

4 Proposed System Overview

The proposed system is an innovative and realistic method of real-time pipeline inspection. Its primary role is to locate cracks, corrosions and other issues that may arise within the pipe. The robot traverses the pipeline with the assistance of a motor and gathers the information with the help of sensors and a camera. This information is then transmitted wirelessly through the ESP8266 in which the remote monitoring of the condition of the pipeline can be obtained. Majority of the concluded IoT empowered in pipe robots concentrate solely on rudimentary surveillance. One of the significant research gaps is the unification of real-time multi sensor architecture which combines ultrasonic sensing, vision based crack detection and live transmission of IoT that only provides a possibility to improve the efficiency of the work conducted by the whole inspection. On top of this OpenCV is employed to process the images that have been taken, a concept that aids in detecting cracks on the surface of surfaces more precisely. Consequently this system enhances safety saves time and enhances efficiency of inspections at large due to less manual checking.

4.1 System Architecture

The robot that will be used to inspect our pipeline system architecture is created in a simple and practical manner to monitor the state of the pipelines on-the-fly. The robot has been fitted with sensors including an ultrasonic sensor to trace the cracks or obstacles and a camera to take visual inspection of the inside surface of the pipeline. All the information obtained is transmitted to the central controller the ESP8266, which serves as a brain of the robot. It works with the sensor information, regulates the movement of motors, and regulates wireless communication.

The information and pictures are relayed via Wi-Fi in order that the checking of the pipeline state should be made remotely. OpenCV is used in providing image analysis that aids in determining the cracks and surface defects. This whole system will work on a rechargeable battery, such that the robot can travel in the pipeline and carry out inspection effectively without the daily engagement of the human being.

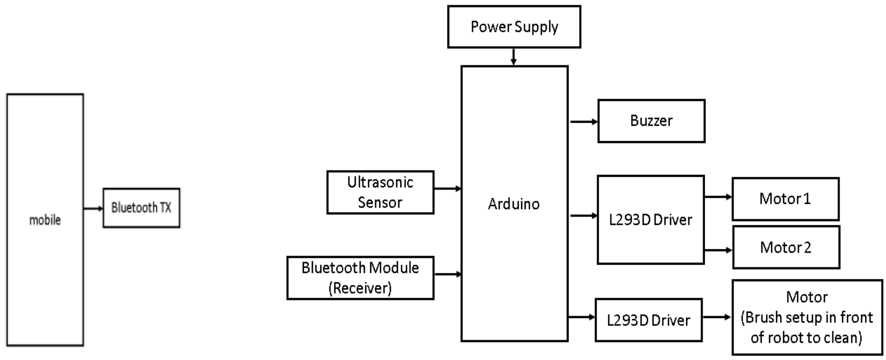

Fig. 1. Frame of Crack Detection

4.2 Hardware Components

The physical structure of the pipeline inspection robot is made of the hardware components. These in combination control movement, data collection, and transfer to enable real time monitoring. The system is modular in design and can easily have other sensors like gas, moisture or pressure sensors added to it.

4.2.1 Microcontroller

The brain of the robot is the microcontroller. It gets the signal of the sensors and interprets the data. It is also in charge of the motors which assist the robot to navigate along the pipeline. The ESP8266 will also have WiFi built in that will enable real time monitoring of the data being sent by the robot wirelessly. This allows inspection remotely without involving the human touch.

4.2.2 Ultrasonic Sensor

The ultrasonic sensor detects cracks, obstacles and blockage within the pipeline. It operates by producing sound on sending the sound waves and reflecting the signal back to measure the distance. In case of any form of flaw or object in front of the sensor it notices it in a short time. This will assist in tracking any internal damages before they get severe. It enhances security and early failure identification.

4.2.3 Camera Module

The camera module records pictures taken of the inside of the pipeline. Cracks, corrosion, and surface defects are inspected visually by using these images. The camera also aids in getting to know the precise state of the pipe. The images taken are aided by analysis to find tiny damages as evidently. This enhances accuracy of inspection hence improvement when compared to manual checking.

4.2.3 DC Motors

The robot has four DC motors that are mounted on wheels. The motors assist the moving of the robot along the pipeline and changes the direction where necessary. The four wheels help achieve stability and balance wherein the wheels manage to navigate smoothly through the curve or bends in the pipeline which is uneven.

4.2.4 Motor Driver and Locomotion System

The speed and direction of the motors is controlled by the motor driver. It aids the movement of the robot either forward or backward or even to turn within the pipeline. The locomotion system provides easy movement even in sloping corners that are more or less curved. Controlled movement ensures that the robot scouts through various regions without being trapped. This makes the process of inspection to be continuous and efficient.

4.2.3 Raspberry Pi

Raspberry Pi is a mini-computer used in the system. It accesses the image information through the 360 degree camera and process it through image processing method. Raspberry Pi assists in detecting visible defects and transferring the processed output to a display unit so that it can be observed easily by the operator. A robot is able to travel in curvature pipelines with light curved pipelines but vertical and different pipeline diameter pipelines demand an extra gripping system.

4.2.5 ESP8266 WIFI Module

ESP8266 is a miniature and inexpensive Wi-Fi board that is employed in wireless communication. It enables the robot to transmit data and pictures of sensors to a distant device via the internet. It is possible to monitor in real time without cables. It also assists in the remote control of the robot in case of necessity.

4.2.6 LIPO Battery

The LiPo battery aims at providing power to the whole robot system. It provides power to the microcontroller, sensors and motors as well as the communication module. LiPo batteries are light and can be recharged hence suitable in the use of mobile robots. They enable the robot to work continuously over some time, without the provision of a direct power connection.

4.2.6 Rotating Dust Cleaning Brush

The robot has a small rotating dust cleaning brush, which is fitted at the front to clean the inside of the pipeline during movement. It assists in the elimination of dust, mud and tiny particles which may compromise the camera view or sensor readings. It enhances the quality of detecting the cracks by washing the surface before making the inspection. Such a mere addition allows obtaining clearer images and more confident inspection results.

4.3 Software and IoT Integration

The robot can be smarter and real-time communicating, and this is possible due to the software and IoT integration. The sensors and motors are controlled by the programmed software and the wireless sensors can transmit data to the IoT module where it can be remotely monitored. This incorporation enables the user to monitor the state of the pipes without the need to be physically present anywhere in the place.

4.3.1 Open CV

It is applied in the processing of images. It aids in image processing of the captured image and detecting cracks or defects on the pipeline surface with the help of the OpenCV. It performs well in regards to suitable lighting. Poor lighting, heavy dust or muddy floors, could however diminish performance in detection. Robustness can be enhanced by adding more light and filtering of images.

4.3.1 Arduino IDE

The Arduino IDE is used to write and upload the program to the ESP8266. It helps control sensors, motors and WiFi communication.

Fig. 2. Arduino IDE Software

5 Performance Parameters and Evaluation Basis

This paragraph determines the ways of measuring the performance of the proposed pipeline inspection robot. The parameters assist reliable comprehension of how well, effective and steady the system performs when put under test conditions. It was tested in terms of the percentage detection, response time and inspection speed to achieve quantitative validation.

5.1 Crack Detection Accuracy

Accuracy of crack detection is the correct way the system detects cracks and corrosion within the pipeline. The test of the system with known defects was done with sample pipeline parts which were known to have certain defects.The system gave about 85 to 90% accuracy in detecting cracks in normal light conditions and controlled conditions.

5.2 Minimum Detectable Crack Size

This is a parameter that determines the size of the smallest crack that the system can be able to detect with the ultrasonic sensor. It assists in testing the sensitivity of the inspection system. The smallest detectable size of a crack was about 1 to 2 mm when the testing was controlled.

5.3 Inspection Speed

Inspection speed This is the velocity at which the robot travels along the pipeline when gathering information. It has an influence on the overall duration of inspection of long pipelines. The robot works at the speed of about 0.2 0.3 meters per second, decreasing the time spent on manual inspection.

5.4 Communication Delay

Communication delay is the time spent in transmitting sensor information on the robot to the remote monitoring device. This must be significant in real time monitoring.Delay during normal network conditions The ESP8266-based WiFi transmission exhibited a latency of approximately 200-500 milliseconds.

5.5 Battery Performance

Battery performance will provide information on the duration that the robot can perform before it requires re-charging. It should be noted that it is important in terms of uninterrupted inspection. Work The robot can work up to about 1.5 to 2 hours with a fully charged LiPo battery.

6 Result and Discussion

The results of the suggested real time IoT and sensor-based pipeline inspection robot are compared in this section. The test system was conducted to examine checking the accuracy of crack detection, inspection speed, delay, and battery performance in communication. The outcomes indicate the level of efficiency of the robot in detecting cracks, corrosion, and obstacles within pipelines. System performance is also in comparison to the traditional manual inspection systems and the existing systems under robots. Lastly there is the discussion on the strengths, limitations and the area of improvement on the system.

The proposed pipeline inspection robot was established to minimize the workforce of manual inspection and enhance safety. The robot was able to manoeuvre within the pipeline and inspect cracks and obstacles through ultrasound and camera inspection of the pipe. In controlled lighting conditions, the accuracy of detection of cracks was approximately 85 to 90%. During testing, the system could identify cracks with a size of about 1 to 2 mm.

The sensor information of the robot was sent wirelessly with the ESP8266 and took approximately 200 to 500 milliseconds to reply. This was a suitable delay with real time monitoring. With a fully charged LiPo battery, the robot was continuous in an approximate time of 1.5 to 2 hours.

The proposed system will lower the amount of human effort and enhance safety since it will allow monitoring remotely compared to manual one. It is also a quicker and more reliable method as opposed to hand checking. There is however a possibility that performance may decrease with poor light or muddy pipeline condition. This can be enhanced in the future by adding better lighting, gripping devices to the vertical pipelines, and increasing the amount of battery.

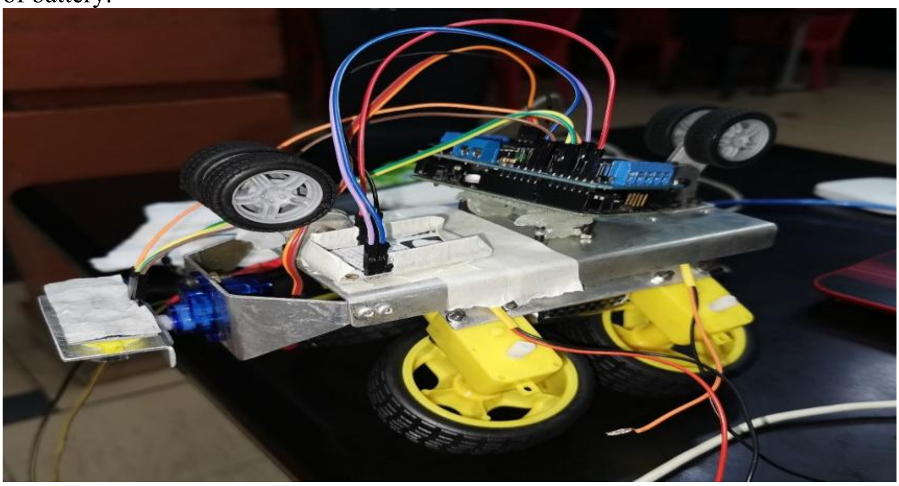

Fig. 3. Hardware Setup

6.1 Simulation

The proposed pipeline inspection robot was simulated on the Proteus software. Proteus is a computer-based simulator, which enables us to create and simulate circuits in real-life construction without necessarily creating the hardware. This was used to test the circuit design, check during connections and detect any errors in the circuit to be implemented in the real time. Simulation decreases the risk of hardware breakages and saves money as well as enhances the system reliability.

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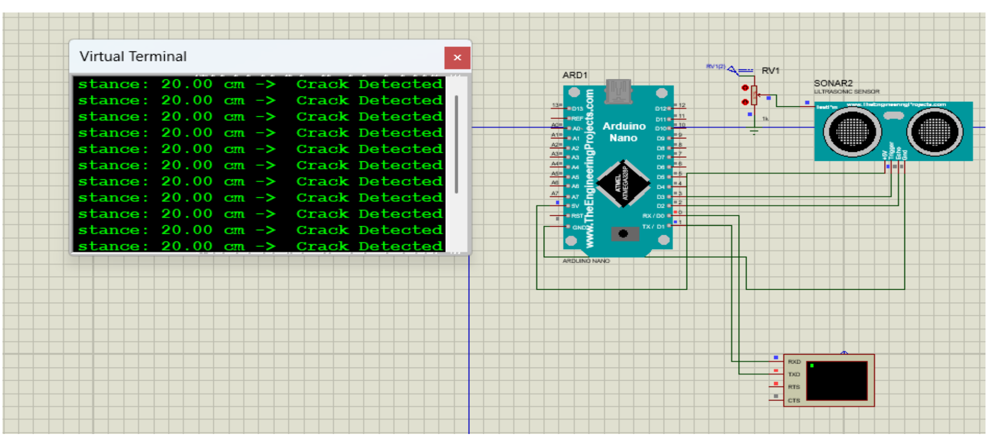

Fig. 4. Software Simulation

7 Conclusion

To sum up, The proposed real-time IoT and sensor based pipeline inspection robot was designed successfully, simulated and tested to observe the internal state of pipelines. The system incorporates ultrasonic measurement and observation in order to identify cracks, corrosion, and objects. With the ESP8266, the robot can transmit data wirelessly such that it can be monitored real time by being in a remote place. This saves the importance of being manually inspected as well as enhancing safety particularly in dangerous or inaccessible places in testing, the robot demonstrated an acceptable level of crack visualization and high-quality wireless communication with less delay. The image processing was additionally enhanced by the use of OpenCV to detect defects on surfaces. The system also exhibited easy flow within horizontal pipelines and lasted longer in work as per the acceptable battery life. Even though the prototype is quite efficient even in usual conditions its efficiency can be improved with the help of several improvements like improved lighting, improved battery life and increased capability to move vertically. In general, the present project demonstrates that the combination of sensors and IoT technology with robots mobility can offer a stable, safe and inexpensive solution toward the further pipeline inspection systems.

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7.1 Future Improvements

This project can greatly be practical in the years to come. The ability to extend the quantity of batteries can be extended such that the robot is capable of working longer without having to have a frequent stop and start. Motor and gripping system can also be enhanced to assist the robot in maneuvering through vertical rounded or irregular pipelines. With the inclusion of brighter LED lights and a sharper camera with high resolution the robot will be able to identify cracks more easily even at dark or dusty places. The accuracy of defects can be further enhanced by the utilization of better image processing techniques. The testing uncovered small problems of wheel slippage and temporary loss of signal and I corrected the situation by enhancing grip and ensuring communication stability.

An enhancement in the range of the wireless communication will assist in monitoring the robot over a greater distance. When testing, cases of services like wheels slipping and loss of signals briefly were recorded and managed through better grip modulation and control of communication. This can be done by reducing the overall design to be smaller, stronger, and waterproof to enable them to work under harsh and difficult environments. The introduction of such features as automatic alerts and transferring data to a cloud is going to simplify data monitoring and maintenance. Comparing the robot with the oil and gas pipeline inspections, all that will be required is to prepare the robot explosion proof and industry approved in the future.

8 Scope Limitations

There are still a number of practical limitations involved in the project at this level. This means that the robot is yet to experience real-world pipeline conditions, which include water leaking, rust forming, heavy dirt, and blockages as the robot has only been put through a simulation. Due to this fact, the actual performance will have some slight variation in case it is applied to actual industrial cases. The battery life is also restricted and this implies that the robot is not able to work on a long-term basis without being charged. During testing, the operational problems were briefly noticed, such as the wheel slippage and temporary signal losses, that were reduced by enhancing the grip and stabilizing the communication. addition, the performance of the crack detection is not as effective in very dark or dusty pipelines with poor visibility. The robot also may have difficulties with moving through the extremely narrow or sharp-curved pipes. What is more, in case we want to upgrade the system with more sophisticated sensors and quality cameras the cost of the project might grow as well.

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