WCRG WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 4, No. 1, 2021
Doi. 10.67228/30716357/IJMRSE-2021PI4R8P
PP. 01-15

Original Article

Development of a Low-Cost Autonomous Robot for Industrial Monitoring

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Received: 02-03-2021 Revised: 02-23-2021 Accepted: 02-28-2021 Published: 03-03-2021

ABSTRACT

Continuous monitoring of the industry setting is necessary to maintain efficiency of operations, safety, and predictive maintenance. The traditional industrial monitoring systems are highly dependent on localized sensors and human observation, which result in expensive installation, restricted coverage zone and could be unsafe to operators. The recent progress in the embedded systems, robotics, and low-cost sensors has made it possible to design the autonomous mobile robot able to conduct the industrial inspection tasks effectively. The present paper introduces the design, development, and testing of the low cost autonomous robot that could be used in the industrial monitoring technology. The suggested system incorporates inexpensive sensing sub-system, control architecture based on microcontrollers, wireless communication and autonomous navigation. Robot has the potential to check environmental conditions like temperature, humidity, gas content and vibration and also move freely within the industrial floors and relay real time statistics to a monitoring station. To be able to scale and be cost-effective, it adopts a modular hardware design and a layered software architecture. There are sensor fusion methods used in obstacle detection and navigation, and power-saving algorithms used in increasing battery life. Through experiment verification it is proved that above the developed robot has a sure monitoring performance with satisfactory accuracy at relatively low cost as compared to other standard industrial monitoring systems. The offered solution can be taken as an alternative to small- and medium-scale industries, which can enhance monitoring, safety, and reliability of operations by automating their tasks. It is rather economical and practical.

KEYWORDS

Autonomous Robot, Industrial Monitoring, Low-Cost Robotics, Embedded Systems, Sensor Fusion, Iot.

ISSN: 3071-6357
PP: 01-15.

1. INTRODUCTION

1.1. Background

The new industrial monitoring has become a crucial element of the contemporary industrial processes where it serves an important function in upholding the safety, enhancing the efficiency and ensuring continuous quality in the various manufacturing houses, stores and processing centers. The efficient monitoring systems allow to quickly detect an equipment malfunction, environmental risk and inefficiencies that lead to a decrease in downtime and expensive accidents. Conventionally, fixed sensors, closed-circuit television (CCTV), and manual inspection at specific periods were used as traditional monitoring in industries. These approaches have been effective over time, but incur some huge installation and maintenance expenses, require a lot of wiring, intra-racial inflexibility, restricting such methods when adapting to varying industrial patterns. Furthermore, hardware-based surveillance systems are very much localized hence depending on fixed monitoring solutions do not give adequate coverage to many regions, as some of these places cannot be accessed at all. In cases of big industries and especially large and intricate ones, manual inspection is particularly challenging. Confined or hazardous areas will not be easily accessed by human inspectors, and regular inspection will bring up the operational costs as well as subject the workers to possible dangers. Human activity in places like chemical processing plants, high-temperature locations, and toxic gas emission areas may be of deadly danger to the human condition. The drawbacks of conventional methods of monitoring systems are more pronounced with the emergence of the complexity of industrial systems, thus a high need to develop more flexible, scalable, and intelligent solutions. Mobile robots that are autonomous present some kind of alternative to the traditional industrial monitoring technique. Clothing mobility with sensing, communication, and control features, these robots will be able to move across industrial facilities and complete a series of non-stop monitoring activities without human intervention. The autonomous robots will also be able to go to remote or risky locations, gather real-time information, and send the information to centralized monitoring centers to be analyzed. This is not only able to improve the safety of workers by reducing their exposure to hazardous conditions but also in terms of getting better monitoring coverage and responsiveness. The driving force behind the work is to utilize inexpensive autonomous robots platforms to build a cheap, effective, and scalable industrial observation system to consolidate the failures of the existing models yet maintains a dependable operation.

1.2. Need for Low-Cost Autonomous Solutions

1.2.1. Economic Constraints in Industrial Monitoring

Some of the small- and medium-sized industries operate with very tight budgets and, in those cases, it is hard to invest into industrial monitoring systems with the SCADA, high-end sensors, or advanced robotic platforms. These systems are expensive to install and their maintenance costs are high thus restricting their application to industries of large scale usage. This leads to a considerable demand of cost-effective monitoring solutions that will provide a necessary functionality without causing too high cost impact.

ISSN: 3071-6357
PP: 01-15.

Fig 1 - Need For Low-Cost Autonomous Solutions

1.2.2. Limitations of Conventional Monitoring Approaches

The conventional techniques of monitoring like fixed sensors, wire networks, and manual inspection are not flexible and scalable. Fixed installations have a high infrastructural requirement and are only limited in the coverage, and manual inspections are resource consuming and subject to error. These restrictions are intensified in dynamic industrial set-ups where layouts, equipment, and the condition or nature of operations are constantly altered. These challenges can be faced by low cost autonomous solutions which provide mobility, flexibility and continuous monitoring at a lower cost.

1.2.3. Safety and Workforce Protection

Workers in industrial settings are regularly subjected to conditions that are hazardous such as toxic gases, hot weather, unwarranted noise, and mechanical hazard. Employing human-staff to perform routine inspections exposes the risks of accidents and fatal health-related problems in the long run. Cheap autonomous robots can be used in such environments to undertake monitoring roles and the human exposure to risks is greatly minimized. This is what can make autonomous systems not only cost-effective but also needed to enhance workplace safety.

1.2.4. Technological Advancements and Accessibility

The recent innovations of microcontrolling, sensors, wireless communication, and open-source software made autonomous robotic systems more accessible than it has ever been. Inexpensive hardware platforms have become powerful enough in terms of processing potential and dependability to make them useful in the real world of industry. Through such technologies, the low cost autonomous solutions will be able to balance performance and cost and thus be used in a larger spectrum of the industrial sectors.

1.2.5. Scalability and Future Expansion

Autonomous systems that are cheap are naturally scalable and therefore industries can manage to institute several units gradually as the demands increase. Their flexible structure allows being upgraded later, it is possible to add new sensors or enhance algorithms without having to change the entire system. This scalability causes low autonomous cost solutions as a feasible and sustainable option to long-term industrial monitoring solutions.

1.3. Low-Cost Autonomous Robot for Industrial Monitoring

Low-cost autonomous robot as a concept in the industrial monitoring domain comes out as the applicable and feasible answer to the increased demand to have a safer, more versatile, and cost-effective monitoring system. Such systems enable mobility, sensing and wireless communication in a small robotic system to address the constraints of traditional fixed monitoring strategies. Unlike fixed location sensors which only give local data, autonomous robot is suited to cover long distances in a large industry, examine various areas, and gather a variety of environmental and work data with a single and integrated system. This mobility greatly increases the coverage with regard to monitoring as well as minimizing the infrastructure that is required. An inexpensive autonomous vehicle is commonly assembled out of low-cost microcontrollers, commercially available sensors, and merely mechanical components, with a low price enabling it to be used in small- and middle-sized companies. Although these robots have a cost-effective construction, they are also capable of tracing the key parameters, including temperature, humidity, gas concentration, and machine vibration, and identifying dangerous conditions and machinery problems in time. The autonomous navigation and obstacle avoidance abilities enable the robot to work beyond the human control with minimum supervision, which enhances efficiency and lowers labor expenses. Regarding safety, these kinds of robotic systems are considered important in reducing the exposure of human beings to harmful industrial conditions. The robot can be called on-site in regions of toxic gases or high temperatures or space-limited and awkward to manually inspect. Real time transmission of data to a remote monitoring station can ensure that the operators are kept informed of conditions without the physical presence. Moreover, the alerts can be made to notify the staff members early enough in case sensor measurements are beyond safe limits so that actions can be taken as soon as possible. Low cost focus without impacting scalability or development in the future. Custom architectures in both hardware and software enable the addition of more sensors, better algorithms or addition of more communication capability as the industrial needs change. On the whole, a low-cost autonomous robot is the best option that would provide a reliable form of supervising industrial activities and at the same time be cost-effective, flexible, and safe, thus a worthy addition to the contemporary industrial work.

2. LITERATURE SURVEY

2.1. Industrial Monitoring Systems

Traditional industrial monitoring systems have been constructed using Supervisory Control and Data Acquisition (SCADA) architectures, consisting of field sensors, programmable logic controllers (PLCs), communications networks, and human/ machine interfaces (HMIs). These systems can be used to acquire full-time data, process, and fault data across huge industrial facilities. The use of SCADA based solutions is very common, this is because of its reliability, robustness and performance in extreme industrial conditions. Their implementation, however, is expensive in terms of initial outlay, lengthy wiring, and complicated infrastructure, which make them inapplicable in small and medium size industries. Moreover, SCADA is stationary and cannot give any flexibility or mobility in terms of inspection on dynamic industrial environment.

2.2. Autonomous Mobile Robots in Industry

The Autonomous Mobile Robots (AMRs) have gradually found application in industries to perform tasks like material transportation, warehouse management and inspection of infrastructure. Recent studies are emphasizing their capability to work round the clock without any form of manual assistance and thus enhance less operational time and greater productivity. AMRs are able to enter the hazardous or hard to access space in inspection and monitoring activities, increasing worker safety and the number of times they undertake data collection. The majority of industrial AMR systems are, however, based on the state-of-the-art navigation systems including LiDAR, vision simultaneous localization and mapping (SLAM) and high-performance onboard computing. Although they are very accurate and reliable, these technologies greatly escalate the cost and power usage of the system making them impossible to be applied to cost sensitive industrial settings.

2.3. Low-Cost Robotic Platforms

The low-cost robotic platforms that have been suggested to counter the cost limitations include a number of studies that utilise microcontrollers like Arduino and low-cost single-board computers. They have generally used off-the-shelf components and open-source software to show it is possible to develop simple autonomous navigation and sensory capabilities, at the fraction of the price of industrial robots. They are popular in academic research and prototyping, and such systems have been found feasible in the tasks of obstacle avoidance, line following, and environmental monitoring. Nonetheless, lots of these platforms do not have the mechanical strength, fault tolerance, and the ability to resist the environment to be implemented on the industrial environment over the long terms, including the option of dust, vibration, and temperature changes.

2.4. Sensor Fusion and Navigation Techniques

Fast and safe navigation as well as avoiding obstacles are moving concerns in the autonomous robotic systems, especially in cases where low-cost hardware is utilized. Typical sensors are the ultrasonic sensor that can measure the distance, infrared sensor that can detect the proximity, and a wheel encoder sensor that can determine the movement on the ground. All these sensors will be susceptible to noise and inaccuracies individually, thereby reducing navigation performance. In an attempt to reduce such limitations, there have been studies on sensor fusion methods that can be used to combine the measurements of various sensors in order to enhance accuracy and reliability. Low-cost robotic systems enable the use of complementary sensor inputs thus enabling them to attain good navigation performance without necessitating the use of expensive sensing technologies, which is why they are appropriate in budget constrained industrial use.

2.5. Research Gaps

It is evident in the existing literature that there is a gap in developing a set of solutions in industrial monitoring related to the achievement of low cost, autonomous operation, robustness, and scalability simultaneously. On the one hand, SCADA systems are reliable, but not mobile and inexpensive and on the other hand, AMRs are flexible but can be prohibitively expensive. Low-cost robotic platforms prove to be viable, however, they do not match the industrial performance standards. Moreover, a lot of research covers the work on such particular parts like navigation or sensing independently; nevertheless, it does not introduce a system. This paper will overcome this shortcomings by coming up with a composite, low cost autonomous robotic monitoring system, which is tailored to operate in the industrial settings and finally, a comprehensive analysis of the achievement of this robotic monitoring system is provided.

3.METHODOLOGY

3.1. System Architecture Overview

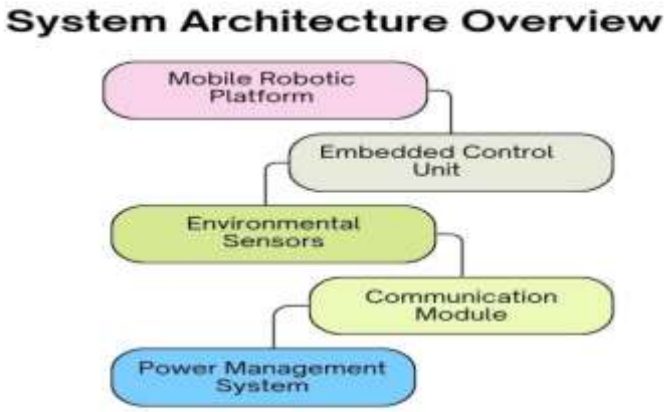

Fig 2 - System Architecture Overview

3.1.1. Mobile Robotic Platform

The physical basis of the proposed system is the mobile robotic platform, which is expected to provide locomotion and maneuverability on the industrial environment. It is normally comprised of a chassis that is mounted on sponges and powered by DC motors and motor drivers that allow the robot to move throughout factory floors, corridors and narrow space. The platform uses onboard electronics, sensor, and power units to be supported and can be mechanically stable. It is compact modular and can readily be integrated with other components as well as customized to suit various industrial arrangements.

3.1.2. Embedded Control Unit

The incorporated control unit is the central processing unit of the system, which coordinates the activity of sensing, decision-making, and actuation. It receives data fed by the different senses, gets the navigation and control algorithm running and produces the relevant control signals to be fed to the motors. Real-time operation is possible because a microcontroller or single-board computer is used to keep the cost of the system low. Communication control between hardware elements is also controlled by this unit and guarantees the continuous autonomous work.

3.1.3. Environmental Sensors

Environmental sensors are also used to measure important industrial variables like temperature, humidity, gas concentration and closeness to barriers. These types of sensors give real-time data, which helps the system realize the abnormal conditions and facilitate preventive maintenance. Moreover, the proximity sensors are used to detect obstacles and roll overs to improve safe movement. A balance between the performance and prices has been maintained by choosing cost-effective but efficient sensors.

3.1.4. Communication Module

The communication module allows wireless communication of data between the mobile robot and remote monitoring station or control station. Wi-Fi, bluetooth, or other communication protocols based on IoT allows monitoring in real time, data recording, and system diagnostics. This module allows the operators to get sensor information, a status report, and notifications without having to touch the robot physically. The wireless connectivity is relevant to improve the flexibility of the systems and facilitates scalable deployment in the industrial environments.

3.1.5. Power Management System

The power management system provides and controls electrical power needed by the robotic platform and sub system. It normally has re-charge batteries, voltage regulators, and protection circuit to secure stable and safety of power supply. An efficient power management system prolongs the operating time and prevents the components of the system by excessive voltage or extreme discharge. Adequate energy monitoring also can be a predictive maintenance and maximize the reliability of the same system overall.

3.2. Hardware Design

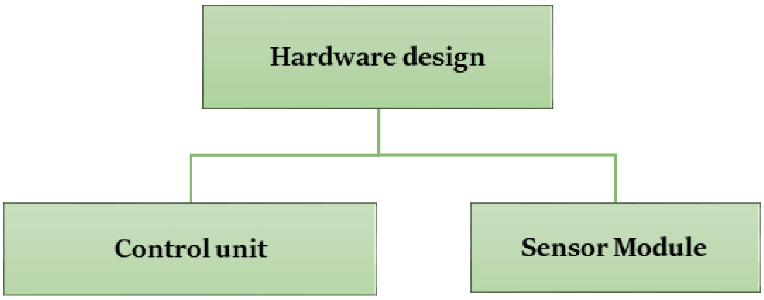

Fig 3 - Hardware Design

3.2.1. Control Unit

The control unit is constructed with a microcontroller-based architecture that forms the major part of the robotic system. It also does the data acquisition across various sensors, the control logic and control signals of the motor drivers as well as communication modules. It is specifically focused on the selection of a microcontroller that has low power consumption, adequate processing power, and low cost to make it affordable. The control unit is adapted to the continuous monitoring of industries because of real-time functionality and stable communication with peripheral devices.

3.2.2. Sensor Module

The sensor unit will include a variety of different sensing devices to provide the ability to monitor the state of the industry in a comprehensive way and to navigate the robots safely. The sensor will be attached to a temperature and humidity sensor that will keep track of the ambient environmental conditions, which are essential during identifying overheating or moisture-related problems with industrial equipment. A gas detector is also installed to identify the presence of dangerous or explosive gases to give warning of the possible risks of safety. Vibration sensor is used to measure the machinery to determine its health as abnormal vibrations can be signs of mechanical defects or wear and tear. Ultrasonic sensors are also used to detect obstacles and get the distance to prevent accidentous collisions and maneuver the robot in the industrial setting safely. The combination of these sensors allows real-time and multi-parameter information needed in autonomous monitoring and decision-making.

3.3. Software Design

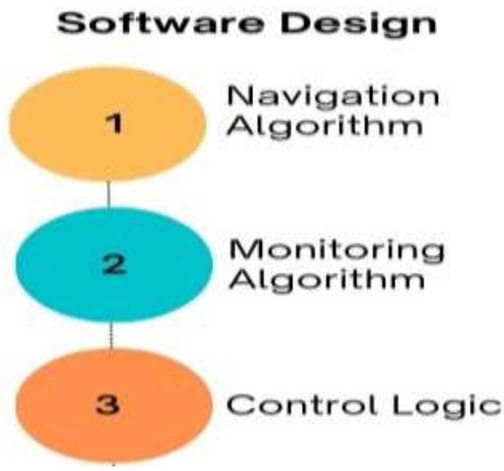

Fig 4 - Software Design

3.3.1. Navigation Algorithm

Navigational algorithm is thought of more as a reactive control approach to allow the robot to navigate freely in dynamic industrial settings. It is based on the readings of the distance of the ultrasonic sensors and set values to identify the presence of some obstacles in the path of the robot. Whenever a wall is detected between a critical range, the algorithm will provide an immediate response of changing the direction or speed of the robot to prevent any collision. The computing resources are minimal in such a lightweight solution, and it is suitable to support low-cost embedded systems with good reliability in avoiding obstacles.

3.3.2. Monitoring Algorithm

Analysis and periodic acquisition and process of environmental and operational sensors are tasks of the monitoring algorithm. Sampling of sensor readings of temperature, humidity, gas concentration and vibration levels are taken at constant time intervals, so that monitoring will always be constant. The data is then collected and formatted wireless to a remote monitoring station to be

ISSN: 3071-6357
PP: 01-15.

visualized and analyzed. The method allows the monitoring of industrial situation in real time and allows timely identification of anomalies or failures.

3.3.3. Control Logic

A finite state machine (FSM) is the overall system behavior by which the operation of the robot is organized into clear states. The idle condition is when the robot is in motion as components are being started or during waiting of commands. The navigation state takes care of autonomous motion as well as avoiding obstacles in the environment. The monitoring state in operation is the one in which the robot is interested in sensor data collection and transmission to the monitoring station. When sensor values surpass a pre-determined signal of danger, the mechanism will shift to the alert position and the warning messages will be produced and sent. This control logic is an FSM based control logic that guarantees predictable behavior, is easy to design software, and increases system reliability.

3.4. Mathematical Kinematic Modeling

The movement of the proposed mobile robot is derived on a differential drive kinematic model, which is common with wheeled mobile robots as it is simple and effective. The independent rotational speed of the left and right wheels of the robot determines the movement of the robot in this model. Linear velocity of the robot is the forward velocity of the central point of the robot and it is calculated by dividing the angular velocity of two wheels multiplied with the wheel radius. Stated differently, as the rotation of both wheels is equal, the effect of a robot is one that makes it move in a straight line and the speed at which it moves is directly proportional to the speed that the wheels are going and the size of the wheel. Angular velocity of the robot refers to the speed of the robot as it rotates around the vertical axis. The difference in the angular velocity of the left and the right wheels creates this rotational motion. The robot spins towards the slower than the faster rotating wheel when one of the wheels is going faster. Angular velocity depends on the radius of the wheel and the distance between the two wheels independently, which is referred to as wheel separation. The further apart the wheels, the slower is the turn with the same difference in the wheel speed and the closer is the turn the sharper. The radius of the wheels is an important part of this kinematic model, as it determines the movement of the robot by making a direct proportional movement between rotational motion and linear movement. On the same note, the distances between the wheels also dictate the turning nature and stability of the robot. These connections enable the critical control of the movement of the robot due to the proper regulation of the speed of the wheels. Through such a mathematical model, the control system can calculate the demanded velocities of the wheels in order to reach goals of linear and angular movements. This description (first introduced as a simple kinematic model) is particularly appropriate in low-cost autonomous robots since it does not further depend on complicated dynamics and can be sufficiently accurate to allow use in navigation-related applications, obstacle avoidance, and industrial monitoring.

ISSN: 3071-6357
PP: 01-15.

3.5. Flow Description

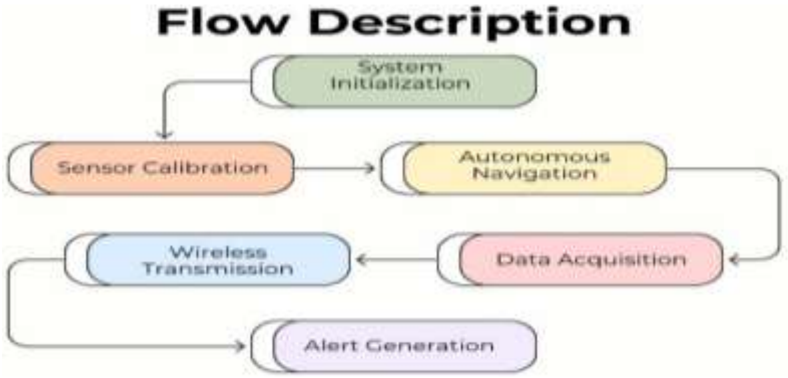

Fig 5 - Flow Description

3.5.1. System Initialization

When starting its operations, the flow starts with system labialization when all the hardware and software is turned on and checked. Initialization of the embedded control unit involves development of communication interfaces, motor drivers as well as sensor connection to guarantee adequate functionality. The default parameters like the speed limitations, interval or frequency of sampling and threshold are loaded into memory. This phase is provided to make sure that the system reaches the well-known and stable state before it gains autonomous operation.

3.5.2. Sensor Calibration

After the initial set up, the system calibrates the sensors to enhance better measurements in terms of accuracy and reliability. Calibration is the process of stabilizing sensor values and readjusting the baseline values to correct conditions of the environment such as temperature, humidity or sensor drift. In the case of gas and vibration sensors, reference readings are set up to make a difference between normal operative state and the abnormal occurrence. False alarms are minimized by proper calibration and this leads to greater accuracy in the monitoring results.

3.5.3. Autonomous Navigation

After the calibration, the robot passes into the autonomous navigation phase. In this phase, the algorithm used in navigation is kept running to formulate obstacle detection sensor information to identify safe movement directions. By monitoring the sensors, the robot can change direction and speed to prevent obstacles without compromising on efficient coverage of the area under monitoring. This is an independent movement which allows the system to survey massive industrial areas automatically.

3.5.4. Data Acquisition

The robot is a site that periodically assembles the merits of all sensors that monitor the environment and work during the navigation. Temperature, humidity, concentration of the gases, and the level of vibrations are some of the parameters that are sampled at a specific time. The obtained data is somehow stored and analyzed by the control department in order to identify some

ISSN: 3071-6357
PP: 01-15.

abnormalities in the working ranges. The real-time monitoring and faults are based on this continuous data acquisition.

3.5.5. Wireless Transmission

Communication is done through a remote monitoring station where sensor data is sent wirelessly to that remote station. This allows operators to monitor the real-time status of the system, the trends, and keep a record of the past. Wireless transmission will remove any physical access to the robot and will also facilitate scalable deployment throughout the industrial facilities. To reduce the latency and power consumption, data communication is designed as efficient and reliable.

3.5.6. Alert Generation

When sensor readings are identified by the monitoring algorithm of the system to be over predefined safety thresholds, the system will automatically move into the alert generation stage. The warning messages or notifications are created and sent to the monitoring station in this state. Alerts allow quick response to dangerous situations or equipment failures, enhancing the safety of industries and shortening of downtimes. When alert handling is done, the system goes back to monitoring or goes to a safe state as needed.

4.RESULT AND DISCUSSION

4.1. Experimental Setup

The experimental performance of the developed robotic monitoring system was done under a controlled industrial type of environment that was meant to simulate the typical conditions in a manufacturing and processing facility. The test venue was a working area that was flat-surfaced, had narrow corridors, and was an open area to approximate a factory corridor and layout of factory equipment. There were unnaturally placed boxes, partitions, and metallic constructions to test the navigation skills and obstacle avoidance skills of the robot. These obstacles were of varying sizes and positions to provide the opportunity to evaluate both static and semi-constrained pathways to allow evaluating comprehensively the behaviour of the robot in terms of its manoeuvre and the adaptation of the path. Controlled sources were added in the test environment to simulate dangerous conditions in industries. Changes in temperatures were done by placing localized sources of heat and humidity changes were done to test the sensitivity of the environmental sensors. Gas hazardous detectors were also tested using a gas source that was in safe concentration without putting workers at any risk. As well, a vibration generator was attached to a working mechanical mechanism to simulate the abnormal machine vibrations to determine the conditions of monitoring of the system. The experimental safety was ensured since all the simulated hazards were kept within safe operating limits to still offer realistic test conditions. The experiment consisted of the robot working autonomously on the basis of onboard sensors and control algorithms. The remote monitoring station and the robot were connected wirelessly in order to measure real-time sensor data, navigation rate and alert messages. Repeatability and reliability of results were achieved by repeating the test under different conditions. This experimental system gave a holistic experience on the effectiveness of the

ISSN: 3071-6357
PP: 01-15.

system in terms of navigability, monitored accuracy, communication stability, and the overall effectiveness of the system to use in an industrial monitoring setting.

4.2. Performance Evaluation

Table 1: Performance Evaluation

Parameter	Performance (%)
Navigation Accuracy	92%
Data Transmission Efficiency	72%
Battery Utilization Efficiency	93%

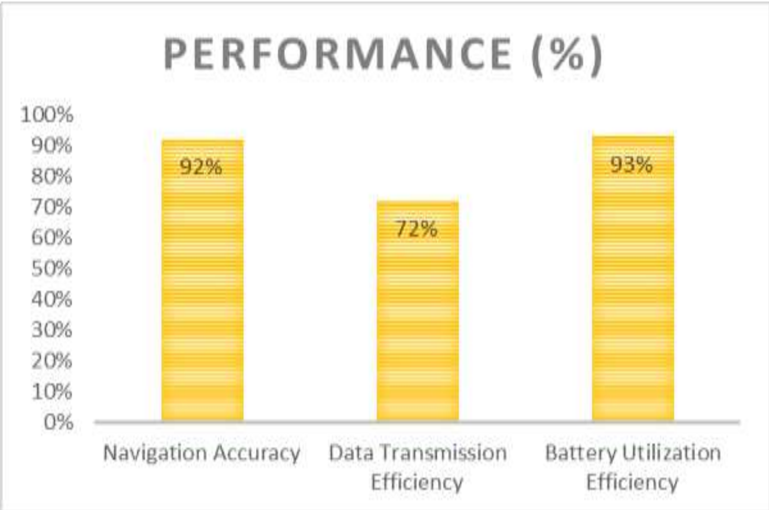

Fig 6 - Performance Evaluation

4.2.1. Navigation Accuracy

The level of navigation shows how the robot can navigate in an autonomous way and how it is able to avoid the obstacles correctly and move across the required path. A resultant accuracy of 92% shows that the navigation algorithm is highly reliable when there is a change in the configuration of obstacles in the environment. Such high precision indicates the quality of the reactive navigation strategy and the correct work of the ultrasonic sensors. The outcome is higher than the least appropriate performance, which proves that the robot can successfully and safely work in an industrial-like environment without sober failures in navigation.

4.2.2. Data Transmission Efficiency

Efficiency in data transmission is the stability and timeliness of the wireless connection between the robot and the monitoring station. The performance level of 72% can be interpreted as indicating that the system can relay sensor data within reasonable range of latency with most operating conditions. The causes of minor delays can be specified by wireless interference or network congestion within the test environment. However, the communication module was able to provide real-time monitoring information continuously, which is why it is appropriate to monitor the active state of industries and generate alerts.

4.2.3. Battery Utilization Efficiency

Battery utilization efficiency determines the effectiveness of the power management system in supporting long run use. The efficiency of 93%, as is measured, shows that the robot is able to be used over long periods of time without affecting performance. This outcome displays the usefulness of low-power hardware choice and effective software planning. There is high battery efficiency, which ensures less downtime and enables a viable use of the device in the industrial setting where the rechargeability of the device may not be feasible.

4.3. Discussion

The results of the experiments are quite eloquent as the utilization of low-cost hardware items can readily result in a successful industrial monitoring process provided that they are combined with the effective system design and control policies. The accuracy of the high navigations achieved in the testing demonstrates that the simple, reactive complex navigational algorithms that are used along with the low cost of ultrasonic sensors can provide the safe and independent operational capacity in the structured industry setting. This justifies the design decision of not using costly technologies in navigation but still retains good level of performance. On the same note, the satisfactory data transmission efficiency proves that ticket-price wireless communication devices are capable of supporting real-time monitoring and alert procurement without adding undue delay. The use of advanced sensors and high end processing units might be needed to enhance the accuracy of measurements of the system and make the system more intelligent, but the results demonstrate that the upgrades are not always essential to the realistic applications of the system in industry. The proposed system was able to track the environmental conditions, including temperature, gas concentration and vibration with cost effective sensors and showed consistency in detecting the onset of abnormal conditions. This performance is especially notable in the small and medium-scale industries in which most of the budgets frequently restrict the implementation of advanced monitoring solution. The obtained keyboard efficiency of battery usage also confirms the fact that the model can work under heavy-duty conditions and has also revealed the advantage of using low-power parts and the efficient scheduling of the software. One of the critical aspects that must be considered in industrial automation is the trade-off that is made between cost and performance. Premium systems have the potential of being more accurate and more advanced in analytics, but their complexity and cost can make them difficult to scale to large scale deployment. However, the proposed design offers a compromise solution as it provides the reliable functionality at a much lower price. Modular architecture can also undergo future improvement; say, by adding sensors or a better algorithm, without redesigning the system. In general, the discussion establishes that low-cost robotic platforms could be an effective alternative to costly industrial monitoring systems, particularly in the cases where affordability, flexibility and scalability are more important than ultra-high precision.

5. CONCLUSION

This paper gave the design, implementation, and evaluation of a cost-effective autonomous robotic system that can be used in industrial monitoring. The suggested system is able to successfully combine a mobile robotic platform with an embedded control unit, a number of environmental and operation sensors, autonomous movement, and wireless communication. The system produces quality monitoring performance using relatively low-priced hardware and low-weight software algorithms making it economically viable. Conclusions drawn during the experimental works under a controlled industrial-like setup have shown that the robot is able to move autonomously, gather sensor data with reasonable accuracy, transfer information with reasonable latency and work over long periods provided a power supply is available. The outcomes justify the feasibility of the given method to be applied in the real-life industrial setting, especially in the context of small- and medium-sized industries when budget services do not allow implementing costly monitoring systems. All in all, the work proves that low-cost autonomous robots are capable of the high balance of performance, flexibility, and affordability and can be an effective alternative to the previous fixed monitoring systems and more expensive robotic platforms.

Although the presented system shows good performance, some of its improvements can be considered to implement additional measures to improve functionality and applicability. The forecasting of future work is one of the key directions of the future work that should be integrated with machine learning methods of predictive maintenance. Machine learning models could estimate patterns related to equipment degradation and predict possible failures prior to their occurrence by processing a stream of historical sensor data, which would allow proactive maintenance and minimize unplanned downtime. The other improvement aspect is localization and accuracy of navigation. Including more sophisticated but more affordable, localization algorithms, e.g., sensor fusion with vision-based algorithms or better odometry correction may lead to better performance of the robot in more dynamic and complicated industrial settings.

Also, using cloud-based analytics and visualization systems offers a great chance to develop systems. Sending sensor images to the cloud would facilitate long-term storage, superior data analytics, and easy visualization dashboards that can be used anywhere. This would facilitate improved decision-making, trend derivation and centralized follow up at various facilities. Multi-robot coordination might also be supported by future systems, which will enable multiple autonomous units to work together and cover more industrial areas effectively. Lastly, mechanical design and environmental protection would be further useful in increasing the durability and reliability of the machines in tough industrial environments. These enhancements in the future would expand the functionality of the proposed system and enhance its position as an efficient, scalable, and cost-effective system to monitor industrial operations in the present time.

REFERENCES

[1] S. Frank, SCADA: Supervisory Control and Data Acquisition, 2nd ed. Boca Raton, FL, USA: CRC Press, 2019.

[2] R. Zurawski, Industrial Communication Technology Handbook, 2nd ed. Boca Raton, FL, USA: CRC Press, 2015.

[3] A. Willig, "Wireless sensor networks: concept, challenges and approaches," EURASIP Journal on Wireless Communications and Networking, vol. 2008, no. 1, pp. 1–8, 2008.

[4] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: a survey," Computer Networks, vol. 38, no. 4, pp. 393–422, 2002.

[5] P. Ferrari, A. Flammini, and E. Sisinni, "Evaluation of communication latency in industrial IoT applications," IEEE Transactions on Industrial Informatics, vol. 14, no. 5, pp. 2152–2160, 2018.
[6] M. Bogue, "Growth in autonomous mobile robots will create major opportunities," Industrial Robot: An International Journal, vol. 43, no. 2, pp. 116–122, 2016.
[7] A. De Luca, G. Oriolo, and C. Samson, "Feedback control of a nonholonomic car-like robot," Robot Motion Planning and Control, pp. 171–253, Springer, 1998.
[8] S. Thrun, W. Burgard, and D. Fox, Probabilistic Robotics. Cambridge, MA, USA: MIT Press, 2005.
[9] J. Borenstein and Y. Koren, "The vector field histogram—fast obstacle avoidance for mobile robots," IEEE Transactions on Robotics and Automation, vol. 7, no. 3, pp. 278–288, 1991.
[10] D. P. Anderson and J. C. Anderson, Mobile Robots: Sensors, Navigation, and Control. Boca Raton, FL, USA: CRC Press, 2018.
[11] M. Quigley et al., "ROS: an open-source Robot Operating System," in Proc. IEEE Int. Conf. Robotics and Automation (ICRA) Workshop, Kobe, Japan, 2009.
[12] S. Monk, Programming Arduino: Getting Started with Sketches, 2nd ed. New York, NY, USA: McGraw-Hill, 2016.
[13] H. Wang, K. Yu, and L. Shu, "An efficient sensor fusion approach for mobile robot navigation," Sensors, vol. 19, no. 7, pp. 1–18, 2019.
[14] R. Siegwart, I. R. Nourbakhsh, and D. Scaramuzza, Introduction to Autonomous Mobile Robots, 2nd ed. Cambridge, MA, USA: MIT Press, 2011.
[15] J. Chen, S. Li, and Y. Sun, "Low-cost autonomous mobile robot for indoor environment monitoring," International Journal of Advanced Robotic Systems, vol. 15, no. 3, pp. 1–11, 2018.