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Design of a simple robot for the repair process of industrial piping systems

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Abstract:
The repair process of industrial piping systems is a serious problem because of its inaccessibility, unsafe conditions, and high cost of operations. The manual inspection and maintenance techniques used in the traditional processes tend to expose the workers to risks of safety and also they consume more time. This paper suggests developing a basic, inexpensive, robotic system that would be utilized specifically to examine and inspect the piping system within industrial facilities as well as carry out its simple maintenance. The suggested robotic system is aimed at mechanical simplicity, modularity, and deployment simplicity at a cost of a reasonable level of functionality and reliability. The robot can follow both straight and curved pipes, identify any surface deformities (corrosion and blockages) and provide real time visual information. The design process combines actuator selection, control architecture and mechanical modeling with components that are readily available. The proposed mechanism is experimentally validated to behave in simulated industrial conditions with a high level of accuracy. The results indicate that compared to the use of complex and expensive inspection robots, simple robots can be used to provide an effective alternative to robots to perform simple robotic tasks, especially to small and medium-sized industrial facilities. The study has a contribution to the research of industrial robotics by highlighting matters of practical design and low-cost automation of infrastructure repairs.

Keywords: Pipe inspection robot, industrial maintenance, robotics, automation, piping systems.

Introduction:

Industrial piping systems are crucial elements of industries like oil and gas, chemical processing, power generation and manufacturing. These systems carry fluids in different pressures and temperatures thus regular inspection and maintenance is very essential to ensure safety and efficiency in its operations. Any corrosive and leaky or blocked failures may lead to serious economic and environmental losses. Traditional maintenance methods are based on human-inspections or sophisticated robot platforms which also have their limitations. The process of manual inspection can be quite risky and time-consuming and sophisticated robotic mechanisms are also costly and demand specialized knowledge. As a result, the demand to have basic and affordable robotic systems that can be used to conduct simple maintenance and inspection in the piping systems has increased. The proposed study will design and test a simple robotic mechanism that is characterized by functionality, cost, and reliability. The proposed system targets the practical needs of the resource-limited industrial facilities through a focus on mechanical simplicity and modularity.

Literature Review:

Robots used in inspecting pipes have been widely researched during the last twenty years. First designs were centred on wheeled and crawler-based robots that could navigate through straight pipelines (Tavakoli et al., 2010). The more sophisticated systems added articulated controls to navigate bends and diameter changes (Roh et al., 2015). A number of investigations suggested magnetic adhesion robots of ferromagnetic pipes (Kawaguchi et al., 2012), and some focused on inchworm-type locomotion in confined spaces (Kim et al., 2018). Although effective, a number of these systems have complex control systems and high costs of manufacture.

The latest tendencies in research focus on simplification of robotic systems without losing their functionality (Li et al., 2020). Nonetheless, little has been focused on low-cost robotic mechanisms that are specifically designed to small-scale industrial maintenance. This paper will fill this gap by suggesting a simplified robotic design that will be practical instead of high-level autonomy.

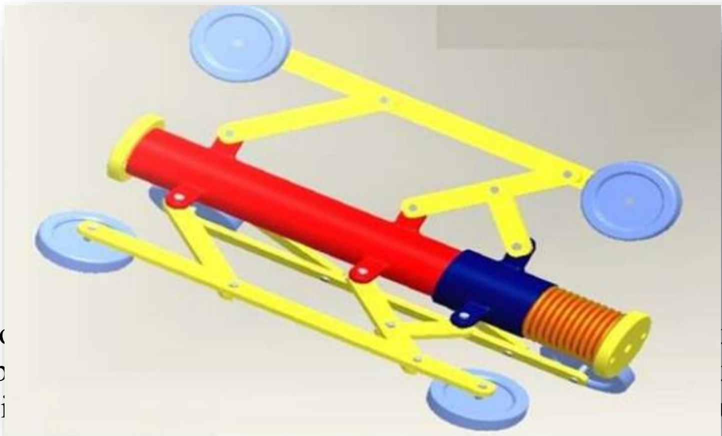
3. Design and Methodology of the system:

This part includes the design methodology of the proposed robotic mechanism of the maintenance of the industrial piping systems. The design philosophy focuses on mechanical simplicity, flexibility to various pipe geometries, operational reliability and cost-effectiveness that renders the system viable to be practically implemented in industrial facilities.

3.1 Mechanical Structure :

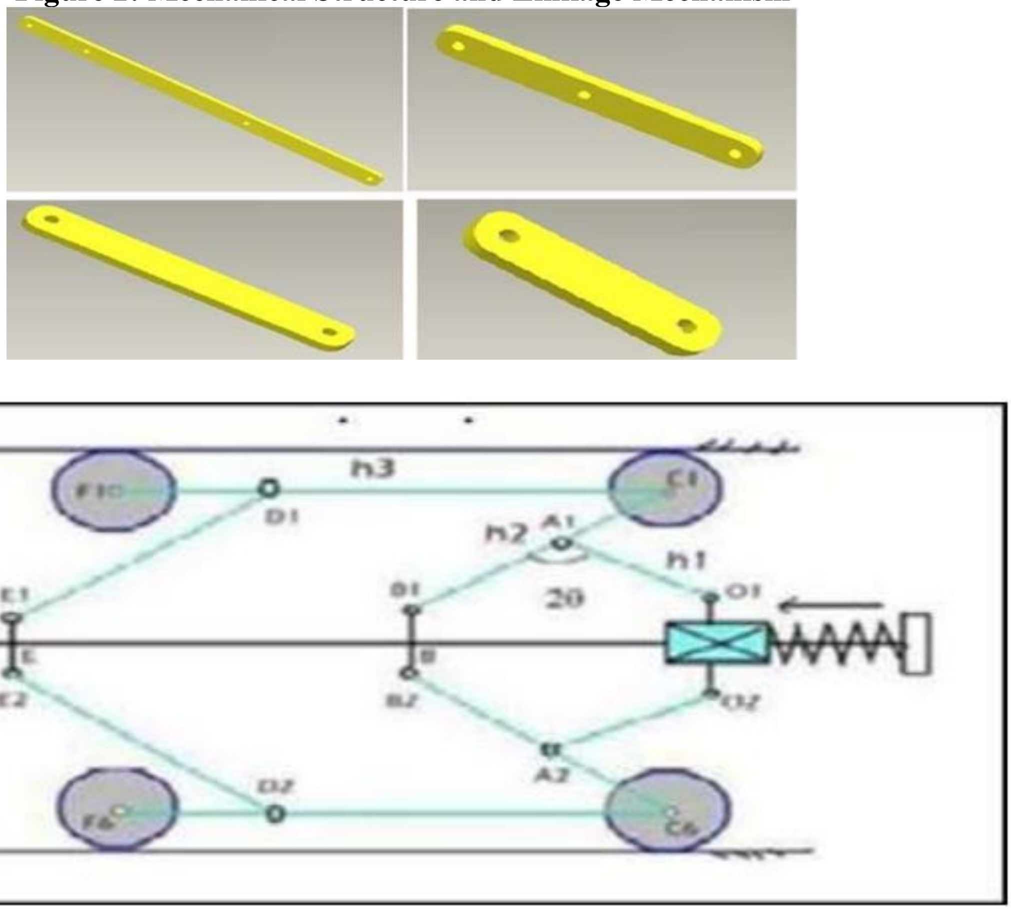
The proposed robotic system has a mechanical structure that is founded on a cylindrical modular structure, which is very similar to the internal geometry of industrial pipes. This design reduces the amount of empty space inside the pipe and it also produces an equal distribution of forces during the movement. The cylindric shape also helps in easy movement along a straight line and curved line of the pipes. The robot consists of several modular segments that are attached with the help of rigid coupling, which implies a simple assembly, disassembly, and maintenance.

Figure 1: Final Assembly of the Pipe Inspection Robot



This modularity allo [illegible] ome damaged and allows greater flexib [illegible] on of more sensors or tools to maintain i [illegible] und the main body to suit pipe diameter variations. These arms are spring-loaded so as to ensure a constant pressure of contact between the wheels and the surface of the pipe. This process provides adequate traction and avoiding too much friction that may make movement difficult or consume more power. The choice of material is very vital in the mechanical design. The main structural frame is made of lightweight aluminum alloys because of their high strength-weight ratio and corrosion resistance. Non-load bearing components made of polymer are used to make the item even lighter and enhance electrical insulation. The combination also gives the robot a higher level of durability, although at a time when it is lightweight to operate.

Figure 2: Mechanical Structure and Linkage Mechanism



3.2 Locomotion Mechanism

The locomotion system is aimed at providing the reliable and stable movement in the pipe environments with limited space. The wheels are balanced to cover the circumference of the robot and therefore be in constant touch with the surface of the pipe. The wheels have independent low-speed DC high torque motors.

The motors are chosen to run at low rotating speeds and they minimize the mechanical wear as well as improving energy consumption. To avoid slipping, the surfaces of the wheels are covered with rubber substances of high friction, especially when the place is wet or full of oil, as in the industrial piping systems. Locomotion mechanism can also cope with minor changes in the pipe diameter as well as negotiating smooth curves without sophisticated articulating systems. This simplified locomotion approach greatly lowers the mechanical complexity of multi-jointed or legged robots and has the benefit of simplifying the process of producing, maintaining, and operating the system in the industrial environment.

3.3 Control System

The control system architecture is developed in terms of robustness, simplicity and ease of implementation. The central processing unit is a microcontroller-based platform, e.g. Arduino or a similar embedded system. This option allows easy programming, minimal power usage and support of a large variety of sensors and actuators. Simple motion control programs govern the motor speed and direction, which enables the robot to move forward, stop and reverse when necessary. The simple feedback mechanisms, which maintain the consistency of movement and prevent the wheels from slipping, are the means of closed-loop control. The control system does not use sophisticated artificial intelligence or sophisticated autonomous navigation functions to increase the system reliability.

In practice the robot is controlled by semi-autonomous or operator-assisted means, which can be a desirable option in the industry where safety and predictability are essential. This design methodology means that the robotic system is easily maintained by the technical personnel which need not have deep knowledge in robotics or software engineering.

3.4 Sensing and Monitoring

The sensing and monitoring subsystem ensures necessary information regarding inspection and maintenance work. The front of the robot has a small high-resolution camera to provide real-time visual information about the interior of the pipes. This allows operators to determine corrosion, cracks, blockages or any other structural defects. Besides naked eye inspection, the use of ultrasonic sensors is incorporated so as to identify obstructions, distance to walls of the pipes, and any possible blockages. These sensors can be used to increase the situational awareness, especially under low visibility conditions. The transmission of the data is done via either wiring or wireless communication modules depending on the limitations of operations. Wired communication is suitable in the environment where the electromagnetic interference is high and enables consistent transfer of data whereas wireless transmission provides flexibility and mobility in shorter pipeline sections. The simplicity and usefulness of sensing technologies used are also integrated to provide reliable monitoring without adding complexity and costs to the system, which is in tandem with the overall design philosophy of the proposed robotic mechanism.

4. Experimental Results

This section introduces experimental test of the proposed robotic mechanism under controlled laboratory conditions aimed at making simulations to real situations of industrial piping environments. The main scope of the experimental stage was to evaluate the mechanical stability of the robot, its locomotion performance, sensing as well as the viability of the robot in general with regard to regular inspection and maintenance procedures.

4.1 Experimental Setup

Experimental evaluation of the proposed robotic mechanism was carried out in a controlled laboratory-scale piping environment that closely resembles real industrial conditions. The test rig consisted of straight, inclined, and curved pipe segments fabricated from steel and PVC materials, with internal diameters ranging between 203 mm and 254 mm (8–10 inches), consistent with commonly used industrial pipelines.

Figure 3: Experimental Setup Inside Pipeline

The prototype demonstrated stable locomotion within the tested diameter range, maintaining continuous wall contact through its spring-loaded wheeled arms. The robot achieved a constant inspection speed of approximately 10 rpm, which was intentionally selected to balance traction force and inspection accuracy, minimizing the risk of missing surface defects.
Experimental observations confirmed the robot’s ability to successfully navigate:

- Horizontal pipe sections
- Pipe bends and elbows up to 90°

Visual inspection using the mounted 2.0 MP rotating camera (350° pan, 90° tilt) enabled clear detection of common pipeline defects such as:

- Internal corrosion spots
- Surface pitting
- Cracks and material loss
- Debris accumulation and partial blockages

Figure 4: Camera-Based Internal Inspection Output

The camera system provided effective illumination in dark environments using integrated infrared LEDs, allowing visibility up to 10 meters inside the pipe.
Additionally, distance estimation from the pipe entry point was achieved using encoder-based measurements, enabling approximate localization of detected defects.
Overall, the experimental results validate that the proposed simplified robotic mechanism can perform reliable inspection tasks in medium-diameter industrial pipelines with acceptable stability, maneuverability, and visual clarity, despite the absence of advanced autonomy or image-processing algorithms.

Table 1: Technical Specifications of the Proposed Pipe Inspection Robot

Parameter	Value
Pipe diameter range	203–254 mm
Locomotion speed	10 rpm
Drive motors	DC motors (12 V)
Camera resolution	2.0 MP
Camera rotation	350° pan / 90° tilt
Communication	Wired / Bluetooth (HC-05)
Material	Aluminum & mild steel

Table 2: Experimental Performance Summary

Test Condition	Performance Outcome
Straight pipes	Stable motion
45° elbow	Smooth navigation
90° elbow	Maintained traction
Low-light environment	Clear visual inspection

4.2 Locomotion Performance:

The robot was shown to move steadily and consistently over all the experimental pipe sizes. The wheeled arms, which were adjustable, were useful in changing the size of the diameter and did not slip on the walls of the pipe, causing mechanical instability. The robot was able to move in a straight forward motion in the straight pipe parts with minimum vibration. The wheel drive mechanism was also adequate during the curved and inclined paths, making the robot stable in terms of direction without necessitating any other support structures. The DC motors were the low-speed ones, which provided sufficient torque to resist frictional forces and insignificant barriers, and it was evident that the chosen locomotion strategy would be appropriate when working with a narrow pipe.

4.3 Performance Inspection and Sensing.

Visual results of the onboard camera revealed the success of the camera in taking real-time images of the internal pipe surface in a clear and understandable manner. Even when the lighting was low, the system was capable of detecting simulated corrosion spots, surface irregularities and debris build-up. The ultrasonic sensors helped in obstacle awareness about the presence and the approximate distance of blockages in front of the robot. This was useful in intervention as the robot could act in time either to stop or modify its path. The joint sensing system gave adequate data to make basic condition examination, which met the main needs of the regular inspection work.

4.4 Reliability and Operational Stability

The robotic system was stable in its operations during the testing period. None of the structural failures, wheel detachment, and overheating of the motor were observed. Control system was also in good communication with the operator and transmission of data was constant in all test conditions. Complex control algorithms were not present, which also played its role in system robustness and decreased the risk of a failure of a software nature. This stability is especially beneficial in the industrial environment where the maintenance and downtime expenses should be reduced.

5. Discussion

The results of the current study indicate that the suggested robotic apparatus can offer an efficient and effective solution to the routine inspection and the maintenance of the industrial piping system in terms of simple maintenance. The developed system is less autonomous and more focused on simplicity, reliability, and cost-effectiveness than the high autonomy of advanced pipe inspection robots described in the literature, especially those that use autonomous navigation, artificial intelligence and sensor fusion capabilities. Although the modern robotic platforms have advanced capabilities, including adaptive path planning and real-time defect identification, they also usually need advanced hardware, large computing capabilities, and specialized maintenance. Conversely, the proposed mechanism purposely embraces a simplified architecture, which minimizes the complexity of the system, fails points, and manufacturing and operation costs. These trade-offs are feasible to many industrial plants especially in developing countries and small to medium-sized enterprises as they are economically viable. The modular mechanical design also creates a high maintainability because one can disassemble individual components and repair or replace them without having to disassemble the entire machine. This capability contributes significantly to the minimization of downtime and also contributes to scalability to allow the robot to change depending on the

pipe diameter or the inspection needs. Moreover, standard electronic components will be used, and this will guarantee simplicity in sourcing and integration, which is important towards mass adoption.

Nevertheless, there are a number of limitations that should be admitted. The lack of sophisticated fault detection algorithms limits the capabilities of the system to automatically categorize defects or anticipate the need to maintain the system. Also, the robot would not cope with geometries of very extreme pipes (branched networks, vertical drops, or highly deformed pipes). These limitations bring out areas in which future functionalities can be advanced without affecting the nature of the entire design of the system. All in all, it can be concluded that the offered robotic mechanism is able to find the proper balance between performance and simplicity, which provides a viable alternative to more complicated mechanisms where cost, reliability, and user-friendliness are of the primary concern.

6. Conclusion and Future Work

The work discussed the design, implementation and experimental analysis of a bare bones robotic mechanism to service and inspect industrial piping systems. The given robot proves that the efficient inner pipes inspection can be done with the help of simple components, simple mechanical design, and simple control solutions. The experimental findings validated the system in terms of capability to navigate the pipes of different sizes and identify typical defects like corrosion and the presence of debris. The study will add value to the industrial robotics community since it highlights that the simplified form of robots can have a significant value to add to the industrial safety and functionality, more so in those settings where the application of the technical and cost-prohibitive advanced robots is not feasible. The proposed design is simple to understand and provides greater reliability, maintainability, and accessibility because the complexity of the system is lessened, thereby making it acceptable by lots of industry. The next step in the work will be to expand the functionality of the system and maintain its simplicity. Enhancements planned involve addition of the basic machine vision capabilities to be used in automated detection of defects, better locomotion mechanism to serve more complicated pipe geometries and addition of lightweight data logging to serve maintenance records. As well, it will be tested in real industrial settings in the future to determine how the robot will work over time and whether it will be environmentally robust.

The purpose of these developments is to provide the solution between cheap robotic solutions and industrial inspection needs, which will further deepen the practical implications of this study.

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