Robotic Inspection System Intended to Work in Extreme Environment

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Abstract: A serious challenge for designers of inspection robots is their adaptation to work in often difficult and extreme environments. This paper presents possible solutions for a mobile inspection robot intended for operation in an environment where locomotion is difficult because the tested object is relatively large and, moreover, in order to carry out diagnostic tests, it is required to move on vertical surfaces. Since the tested surfaces are ferromagnetic, the solution was to use magnetic wheels to ensure effective traction of the robot. In addition, thanks to the solutions used, the robot can be adapted and used to carry out inspections at high temperatures, in which people cannot stay and work. The inspection system can use both vision and ultrasonic measurements. The applied interface and the operator's panel provide the presentation and visualization of the results, including the prediction of detected damage.

Key-Words: Mobile robot, Magnetic wheel, User interface, Non-destructive testing, Inspection system, Control software

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1 Introduction

In order to ensure safe operation of industrial facilities, it is important to carry out periodic inspections. The resulting downtime causes significant costs. To reduce these costs, a number of robotic solutions have been proposed to help shorten this time.

The American company General Electric has developed an automated, robotic solution for cleaning and controlling water-tube boilers [1]. The system is able to reach any point of interest inside the boiler from a given starting point. It is fully remotely controlled, allowing the operator to remain in a safe place during operations. The basic element of the system is a tracked robot with four magnetic rollers. The rollers allow movement from one wall to the other at an angle of 90 degrees. It can carry one jet of water, fed by a pump outside the boiler. A dedicated robot insertion tool allows the team of operators to securely place an 80 kg device inside the unit. The feedback needed for remote robot navigation is provided by several cameras connected on the platform. A dedicated pan-tilt-zoom inspection camera can be mounted at the front of the track to allow for a more accurate, flexible inspection of the boiler. To control the wall thickness, it is possible to install an ultrasonic probe, collecting and processing target data. The robot's track system automatically detects eroded pipes, recognizes unevenness in the path and automatically corrects it. For the operator, this means that he can focus only on checking the condition of the boiler walls and analyzing measurement data on an ongoing basis. Considering the possibility of analyzing a large area in a relatively short time, its savings thanks to automatic cleaning and remote inspection are enormous.

Guardian S is another example of an inspection device, developed by Sarcos Robotics. It is a solid, multi-functional platform carrying the measurement sensor system, ensuring real-time information processing while protecting the operator from potential danger. The robot is optimized for unstructured and unpredictable working environments and designed specifically to navigate uneven, difficult terrain in a small, confined space. Thanks to the possibility of remote control, Guardian S reaches where people cannot or should not work.

The robot is ideal for commercial, industrial and public safety (SWAT, EOD, HAZMAT), mining, oil and gas processing, marine, petrochemical and power generation applications [2].

Guardian S system functions:

• Cloud computing with the Sarcos 'command center'

• Authorization of access to robot control data and data from the measurement system
• Tracking the position and condition of the robot
• Configuration, execution and postoperative review
• Easy-to-use data analysis tools

The Crawler is a compact, versatile and handy robot equipped with tracks or magnetic wheels. Built-in magnets in the wheels or tracks allow the device to move vertically, horizontally, and over the ceiling on ferrous metal surfaces such as tanks, pipes or channels. It is also perfect for inspecting ship hulls.

The magnetic caterpillar can be equipped with the world's smallest industrial pan-tilt camera VT 34 PT or many other inspection cameras, as well as UT devices for non-destructive testing. Thanks to the built-in lighting and the rear camera, the robot is very easy to operate.

Shihe Technology is a company dedicated to the development of robotic platforms, whose goal is to use mobile robots to replace people in large-scale work. The company implements its solutions in the shipbuilding industry, heat energy, chemical industry and construction. Currently, devices for derusting ship hulls are produced in small batches, while inspection and cleaning robots are at the stage of implementation into serial production.

Shihe Technology has been operating on the inspection equipment market for several decades. Initially, robots using spiders, additional scaffolding or hanging baskets were developed, but such solutions were burdened with a high risk of loss of safety, low efficiency, and the need for additional control by the operator or the eventual use of manual operation. In the context of rising labor costs and the shortage of devices operating at high altitudes, magnetic wheels have started to be used [3]. Shihe products are devices with an optimized design, equipped with adaptive suspension, modular drive unit, positioning and navigation algorithms, thanks to which they are distinguished by a high ratio of maximum load to empty weight and the ability to adapt to relatively complex surfaces.

The robot can be equipped with a detector, flaw detector, cleaning head, spray gun or ultrasonic sensors. After an initial inspection of the test area, it can perform specific tasks related to defect detection, cleaning, rust removal, spraying, polishing and collecting accurate data about the working environment.

Average operating efficiency can reach 3-5 times the workforce, while the total cost drops by 30 % and the payback period is 1-3 years.

The RPP-LW-TED thermal boiler rapid inspection robot developed independently by Beijing TimeRiver Technology measures the erosion of the boiler screen wall tubes using the EMAT electromagnetic ultrasonic thickness gauge. The robot is relatively small and light, so it can be carried and operated by one person. It can be widely used to control heating units located in power plants and is the right assistant for temporary maintenance and emergency repairs [4].

Basic features of the device:
• relatively low weight in relation to the dimensions
• quick detection and alerting of a dangerous situation
• receiving, transmitting and visualizing measurement data in real time
• various detection methods, including high-resolution macro functionality
• excellent efficiency in negotiating obstacles, the ability to adapt to the terrain
• safe, reliable and easy to use
• reliable adsorption and stable cooling.

2 Robot Design

Meeting the challenge of building a robotic inspection system intended to work in extreme environment requires the use of components that enable operation in elevated temperatures and the development of a cooling system for the remaining components [5] [6]. The developed unit allows for quick transport of the measuring system, which enables the monitoring of large surfaces of the boiler walls in a relatively short time, and as a result, the assessment of the current technical condition of the unit on the basis of the map of eroded places.

The assumed measurement conditions (increased temperature), limited access to the boiler and the location of the tested elements (vertical walls) as well as certain technical limitations of the measuring system to be used, especially electronic systems, make it necessary to solve a number of technical challenges.

Before starting the design process, certain elements of equipment that should be characteristic of the final robot model were determined:
• a modular four-wheel platform with a ground clearance enabling it to overcome potential obstacles without the chassis coming into contact with the road surface
• magnetic wheels containing a set of radially distributed permanent magnets with a Curie temperature enabling movement in a temperature of up to 200 °C, with a structure ensuring an even distribution of the magnetic flux with a width enabling contact with two adjacent pipes of the boiler screen wall while driving

• the surface of the wheels is covered with a thin layer of heat-resistant rubber for increased traction
• drive consisting of four electric motors adapted to work in high temperatures
• thermally insulated compartment with a cooling system based on a coolant supplied from the outside, equipped with additional windows for optical systems, in which there are electronic systems with a control unit to ensure their correct operation at high temperatures in dusty rooms
• permanent power supply with a cable adapted to work in high temperatures
• data transmission ensuring the throughput of robot-computer communication at the level of 100 Mb/s realized through the power line in the Power Line Communication technology
• navigation and communication systems, adaptation to the robot's movement on vertical surfaces, equipped with an operator support system with elements of autonomy based on sensor systems adapted to work in high temperatures.

It is important to note that the robot has not been tested under failure conditions during vertical traversal. By design, the system includes safeguards to immediately halt operation upon detection of critical faults, such as loss of traction, communication, or power. This safety-oriented approach aims to prevent uncontrolled movement or further damage in hazardous environments, and therefore excludes intentional endurance testing under failure scenarios.

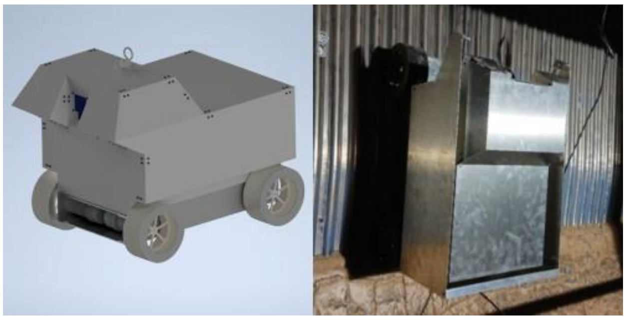

Fig. 1. Visualization of a robotic inspection system (left), device during testing (right)

One of the main features of the presented solution is the ability to move on ferromagnetic surfaces. These surfaces may have humps or protrusions. The robot must be able to run on longitudinal humps, no more than 30 mm long and not more than 60 mm apart. In addition, it is required to be able to pass between walls that meet at an angle of 90°. Permanent magnets are the source of the force that attracts the robot to the wall.

In order to scan correctly, it is necessary to maintain the known orientation of the profilometers in relation to the tested surface. The wheel falling between the humps while driving along them may cause the profilometers to skew against the surface. To prevent this from happening, the wheels are designed so that they always run on at least one top of the hump. The magnetic holding force must be ensured in the most demanding situation where the wheel is in contact with only one hump.

The required force of attraction was determined for extreme situations, i.e. the highest possible temperature and the most unfavorable position. The occurrence of such a situation is extremely unlikely, for example, the robot will not enter the facility if there is a risk of exceeding 200°C. So the working temperature of the magnets is actually lower. Magnets in the shape of a fragment of a ring, magnetized diagonally, were used. As a result, the force of attraction is always directed normal to the ground, regardless of where the wheel contacts the surface.

Although full experimental testing of the magnetic adhesion system at elevated temperatures was not conducted due to the lack of a suitable adjustable-temperature testing facility, the design was informed by theoretical calculations and preliminary tests carried out at ambient conditions [7]. These tests confirmed that the magnetic holding force exceeds 200 N per wheel, providing sufficient traction for vertical movement. The selection of neodymium magnets with a high Curie temperature, combined with a titanium wheel core, was based on these evaluations and ensured thermal stability of the system up to 180–200°C.

The novelty of this work lies in the integration of a magnetic-climbing robotic platform with a non-contact ultrasonic diagnostic system (EMAT), designed to operate in high-temperature industrial environments. Unlike previous studies that focused either on mobile platforms or on EMAT techniques in isolation, this paper presents a unified, thermally protected prototype capable of autonomous diagnostics in constrained areas. To the best of the authors' knowledge, no prior work has combined these elements in a system intended for harsh boiler inspection tasks.

6 magnets with alternating magnetization were used. This creates a magnetic circuit that runs between two adjacent magnets through the substrate material. The magnets are made of sintered neodymium as it has the highest magnetic force. Due to the fragility of the magnets, they were placed in a core made of durable metal. The core rolls on the ground, hence the need for high mechanical and

temperature resistance. In order to avoid the closing of the magnetic circuit between the magnets by the core material, a titanium alloy with a magnetic permeability similar to air was used. Titanium is additionally characterized by a high coefficient of static friction on steel and cast iron surfaces, amounting to 0.65. The coefficient of friction can be further increased by nitriding the surface or coating the wheel with a thin layer of synthetic rubber. In the described solution, it was decided to use fluoro rubber.

Unlike existing inspection robots such as Guardian S or Shihe systems—which are primarily designed for standard environments and visual or surface-level diagnostics—the presented platform is tailored for operation in high-temperature, confined industrial spaces such as boiler interiors. Its key distinguishing features include a compact magnetic drive system, a thermal protection assembly, and an integrated non-contact EMAT-based diagnostic module. This configuration allows for structural thickness evaluation without requiring access from both sides or couplant media, setting it apart from previously reported mobile NDT solutions.

3 Diagnostic system concept

The extreme working environment imposes certain requirements on the diagnostic systems that can be implemented in the robot. One of the basic requirements is that diagnostic systems should operate in a non-contact manner without the need for consumables. This requirement limits application of penetrant methods and also hinders using the ultrasonic fluid-coupled techniques.

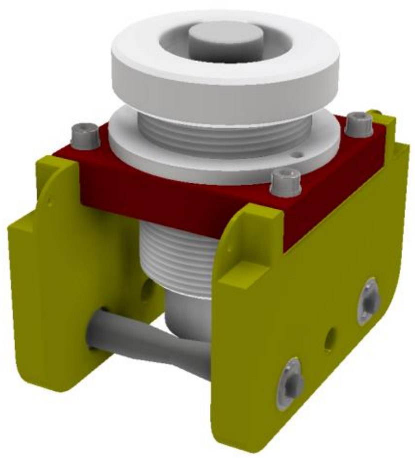

Fig. 2. Close-up of the mechanical structure designed to carry and stabilize the EMAT sensor during operation.

One of the possible solutions for metallic wall thickness measurement is application of electromagnetic transducers (EMAT). The measurement of the pipe wall thickness using the EMAT technique is an ultrasonic measurement carried out in the echo mode, using access to only one side of the tested structure. Thickness measurement can be performed using both elastic longitudinal and shear waves; however, the use of shear waves, due to their slower velocity, is more advantageous as it reduces the requirements for the accuracy of the timing. The EMAT head with an appropriately shaped coil can generate shear waves normal to the tested surface.

A structural element supporting the EMAT probe is shown in Fig. 2. This part of the platform was designed to ensure correct positioning and stability of the sensor when traversing vertically oriented surfaces. Although it represents only a portion of the full system, it plays a crucial role in the effective deployment of diagnostic equipment.

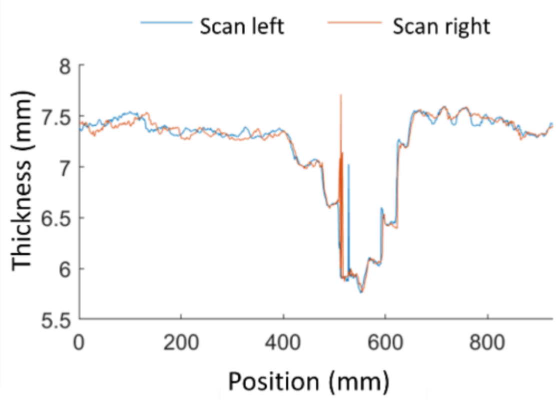

Fig. 3. Comparison of wall thickness evaluated with EMAT probe during scanning in two directions.

The results illustrated in Fig. 3 represent one of several partial experiments conducted in the target working environment to verify the performance and repeatability of the EMAT-based wall thickness measurements. Multiple scans were performed under varying orientations and motion directions on actual boiler surfaces, consistently yielding reliable signal profiles. These field tests confirmed the diagnostic feasibility of the EMAT probe and supported its integration into the final inspection system.

4 Control software and user interface

The complexity of the systems installed on the mobile robot required the creation of appropriate software both for its operation and for processing the collected data. The main requirement for this software was simplicity of use. The diagnostic system should be operable by a single person who does not have any programming skills. It was decided to separate the tasks related to robot control and data acquisition from the data processing system (Fig. 4).

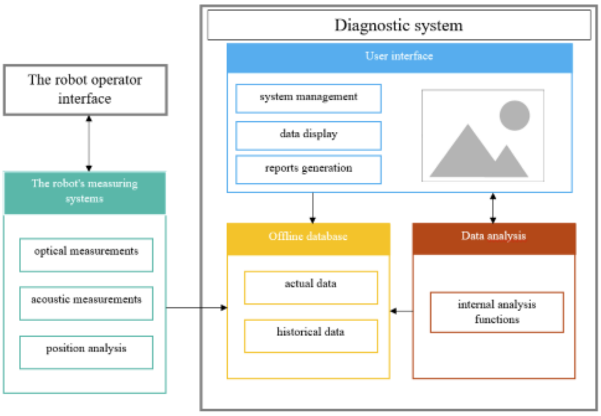

Fig. 4. Software architecture scheme

The robot is driven with the use of a game pad. The developed software converts the movements of the control knobs on the pad into the appropriate movement of individual motors in such a way as to enable both straight-line driving and driving through curves. The operator of the control console is able to monitor the position of the robot thanks to the installed sensors.

Data acquisition is carried out in real time via a wired Ethernet link, which also provides continuous communication with the robot. Data from the optical sensors are saved as binary files on the workstation's storage disk, from where they are then transferred to the database. Each file contains a registration of the profile captured by the sensors at a frequency of 1 mm, however, due to cache performance limitations, it was decided to limit the capacity of a single file to 200 profiles. This approach makes it necessary to merge a series of files together before proceeding to the actual processing.

The first step in processing the optical data is to correct the inclination of the profilometers mounted on the robot. Due to the limited space, they have been installed in such a way that the angle of their inclination with respect to the analysed surface is about 30 degrees. This adjustment is carried out using simple trigonometric functions, but due to the complexity of the reproduced surface, it is carried out on a point cloud in three-dimensional space. The corrected data are then segmented for further stages of analysis to be carried out on a single tube.

One of the most important stages of data processing is the transformation of the information gathered by the optical sensors into information about the thickness of the pipe. This is performed with the use of the author's geometrical method, using the dependence of the profile shape on the position in relation to the peak point. Thanks to this approach, from indirect information and with the knowledge of internal diameter of the analysed pipe one can obtain a direct value that constitutes its thickness. These measurements are very dense and subject to some uncertainty error, therefore the final results are subject to Savitzky-Golay filtering. After this step, integration with the data from the position sensors takes place for the precise determination of the location of a possible anomaly in the expected thickness. The accuracy of the position determination was defined on a regular grid with a mesh no smaller than 5 cm.

According to the designed layered architecture of the diagnostic system (data layer, logic layer, presentation layer), the received data are then transferred to the user interface for display (Fig. 3). Depending on the adopted accuracy, the screen area is divided into appropriate fragments, each of which is assigned an adequate colour, determined by the thickness of the pipe in a given place, selected from a twelve-grade scale. This allows a quick visual estimation of the damage on the analysed surface. In addition, these values can be compared with historical data stored in a database, allowing the degradation rate of structures at specific points to be estimated, and thus allowing repair measures to be planned accordingly.

5 Conclusions

The above considerations show the important problems of designing a four-wheeled mobile robot intended for inspection in high temperature environments. Development of a fully functional robotized system requires an interdisciplinary approach and the use of knowledge from various fields of science, such as: strength of materials, thermodynamics, electronics and programming. In the design process, certain technological assumptions should be taken into account together with the limitations resulting from the characteristics of the target work-place.

The device designed as a result can be considered a relatively innovative solution, characterized by a highly personalized specification due to the strict dependence of the technical parameters of the device on the requirements im-posed by its operating environment. One of such conditions is undoubtedly high temperature, the requirement of which resulted not only in the implementation of one of the title features of the designed device, but also limited the selection of other elements, such as the construction material of the robot body or the method of transmission. By adapting the mechanical structure to new tasks or a slightly different working environment, it is possible to expand the functionality of the robot. The system can be perfect for measuring structures that are unilaterally accessible with similar characteristics, such as: ship hulls, pipelines, tank walls, cisterns, other kinds of industrial structures. Future developments will consider the integration of advanced predictive maintenance tools to enhance diagnostic capabilities [8].

Due to the prototype stage of the current platform, full environmental testing — such as long-term operation under continuous high-temperature exposure — has not yet been conducted. While initial mechanical and diagnostic validation was successfully performed on representative surfaces, complete integration and endurance testing are planned for the final stage of development. The current results nevertheless confirm the feasibility of the system concept and its core components.

Future research in this field could focus on improving the autonomy and fault tolerance of inspection robots operating in extreme environments. Key directions include the use of machine learning for defect recognition, enhanced navigation in unstructured spaces, and the development of adaptive magnetic adhesion systems for variable geometries. Moreover, standardized testing protocols for evaluating performance under thermal and mechanical stress would help compare solutions across platforms and ensure broader industrial applicability.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.