

Framework of the Design of a Magnetic Crawler Device for Measurement of Coating dry film thickness on large storage Tanks

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Abstrak.

The inspection of large crude oil storage tanks is critical for ensuring coating integrity, corrosion protection, and safe operation, yet conventional manual inspection methods are hazardous, time-consuming, and costly, particularly for large above-ground tanks. This study presents the design, development, and validation of a magnetic crawler device for automated measurement of coating dry film thickness (DFT) on large steel storage tanks. The proposed system integrates a lightweight mechanical chassis, permanent magnetic adhesion, differential-drive locomotion, an embedded DFT measurement probe, and a closed-loop software control architecture into a compact, field-deployable robotic platform. The hardware design enables stable adhesion and smooth traversal of vertical and curved tank surfaces, while the software system coordinates motion control, sensor feedback, data acquisition, and real-time wireless communication. Experimental evaluation was conducted under laboratory and field-representative conditions on coated steel surfaces, with manual DFT measurements used as reference values. Results demonstrate stable magnetic adhesion, reliable locomotion over weld seams, accurate and repeatable DFT measurements, and robust data logging and transmission. The average deviation between robotic and manual DFT measurements was approximately 1.1%, confirming measurement accuracy within acceptable industrial tolerances. The developed magnetic crawler significantly improves inspection safety, efficiency, and data consistency by eliminating the need for scaffolding or working at height. The proposed system provides a practical and scalable solution for automated coating inspection and asset integrity management of large storage tanks, with particular relevance to expanding oil and gas infrastructure in Nigeria and similar industrial environments.

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1. Introduction

The inspection of large crude oil storage tanks is a critical activity for preventing coating degradation, corrosion, and potential oil leakage, which can lead to severe environmental, safety, and economic consequences (ISO, 2020a),(AMPP, 2021b). In recent years, the number and size of above-ground storage tanks have continued to increase due to the expansion of petroleum refining, storage, and export infrastructure worldwide (*Tank Inspection, Repair, and Alteration*, 2020). For example, China alone has more than 14,000 registered storage tanks, illustrating the scale of the inspection challenge (Zhang et al., 2020). Similarly, Nigeria has recently experienced rapid growth in large tank farms and refinery storage capacity, particularly with the development of mega-refineries and export terminals (*Dangote Expands Crude Oil Storage with Eight New Tanks*, 2025), (*Dangote Builds 6.3-Million-Barrel Crude Storage Capacity*, 2025).

As a result, the frequency of routine inspection, cleaning, and maintenance of storage tanks has

increased significantly (AMPP, 2022). Traditional inspection practices require technicians to access tank walls using scaffolding, rope access systems, or suspended platforms, exposing workers to hazardous working-at-height conditions (*Working at Height Statistics*, 2023), (*Occupational Health and Safety Management Systems -- Requirements with Guidance for Use*, 2020). These methods are not only dangerous but also time-consuming and costly, often requiring long facility shutdowns and extensive safety preparations (DEP, 2021). Despite the importance of inspection for asset integrity management, manual inspection remains inefficient and susceptible to human error, especially for very large tanks exceeding 60 m in diameter and 20 m in height (*Tank Inspection, Repair, and Alteration*, 2020), (*Welded Tanks for Oil Storage*, 2020).

To address these challenges, extensive research has focused on the development of robotic inspection systems capable of operating on large-scale industrial structures (La et al., 2021), (Corke et al., 2021). Inspection robots are increasingly being deployed to replace dangerous, repetitive, and physically demanding tasks while improving inspection repeatability and data quality (Bogue, 2022). Among these systems, climbing robots have proven particularly suitable for the inspection of large vertical and curved steel structures such as crude oil storage tanks, ship hulls, and steel bridges (La et al., 2021), (Leuthard et al., 2025).

Depending on the surface material and geometry, different adhesion mechanisms have been proposed, including vacuum suction, propeller-based negative pressure, and magnetic adhesion (Xu et al., 2021). Suction-based systems can operate on smooth surfaces but are highly sensitive to surface roughness, dust, and coating defects, limiting their industrial reliability (Zhao et al., 2022). Propeller- or fan-based systems can adhere to curved or non-ferromagnetic surfaces but typically suffer from high energy consumption and complex control requirements (Nansai et al., 2020). In contrast, magnet-type climbing robots provide strong, reliable, and energy-efficient adhesion on steel structures, making them particularly suitable for storage tank inspection applications (Leuthard et al., 2025), (Tavakoli et al., 2021).

Since crude oil storage tanks are constructed from ferromagnetic steel, robots using permanent magnets can maintain stable adhesion without continuous power consumption, significantly reducing the risk of falling and improving operational safety (Tavakoli et al., 2021), (Kim et al., 2022). Such robots have been widely studied for applications including storage tank inspection, steel bridge inspection, and ship hull maintenance (La et al., 2021), (Leuthard et al., 2025), (Nguyen et al., 2023). Performance analyses reported in recent studies confirm that magnet-based climbing robots can carry relatively heavy sensor payloads while maintaining stable motion on vertical and curved surfaces (Kim et al., 2022), (Lee et al., 2021).

While much recent research has focused on ultrasonic wall thickness measurement to detect metal loss and structural degradation in storage tanks (Park et al., 2022), (AMPP, 2021a), the condition of the protective coating system is equally critical for long-term corrosion protection and asset integrity (ISO, 2020c). One of the most important quality control parameters of protective coatings is the dry

film thickness (DFT), as both under-application and over-application can significantly reduce coating performance and service life (ISO, 2020b), (Elcometer, 2022). Consequently, systematic and large-scale DFT measurement of storage tank walls is essential during construction, maintenance, and in-service inspection (SSPC-PA 2, 2023).

Automating coating thickness measurement using a magnetic crawler device introduces several technical challenges. The DFT probe must maintain stable contact with the coated surface, with consistent pressure and proper alignment, despite surface curvature, weld seams, and surface roughness (Nguyen et al., 2023), (*Eddy Current and Magnetic Induction Coating Thickness Gauges*, 2021). In contrast to ultrasonic thickness measurement, which typically requires coupling gels, pumps, and additional mechanical subsystems (Park et al., 2022), (AMPP, 2021a). DFT measurement techniques based on magnetic induction or eddy current principles do not require liquid coupling and are therefore more suitable for integration into compact climbing robots (ISO, 2020b), (Wang et al., 2021).

Recent robotic inspection systems have employed various mechanisms such as electric pushers, solenoids, linkage mechanisms, legged systems, and Scotch yoke mechanisms to ensure reliable probe contact during inspection tasks (Park et al., 2022), (Chen et al., 2020). Although these approaches demonstrate technical feasibility, many of them remain complex, heavy, or highly specialized, which limits their scalability and widespread industrial adoption (La et al., 2021). Furthermore, ultrasonic-based robotic systems increase system complexity and maintenance requirements due to auxiliary equipment such as compressors and gel delivery systems (AMPP, 2021a).

By contrast, integrating a magnetic crawler robot with a lightweight DFT measurement probe and onboard data acquisition system offers a more compact, robust, and field-deployable solution for large storage tank inspection (Leuthard et al., 2025), (Nguyen et al., 2023). Such systems can automate repetitive inspection tasks, improve inspection speed and repeatability, and generate high-resolution coating thickness maps without exposing personnel to hazardous working conditions (Corke et al., 2021), (Bogue, 2022).

In the Nigerian context, this need is particularly evident. For example, the Dangote Petroleum Refinery currently operates more than 20 crude oil storage tanks and is constructing additional tanks to expand crude storage capacity by approximately 6.3 million barrels (*Dangote Expands Crude Oil Storage with Eight New Tanks*, 2025), (*Dangote Builds 6.3-Million-Barrel Crude Storage Capacity*, 2025). This scale of infrastructure clearly demonstrates the urgent need for automated, reliable, and high-productivity inspection technologies for coating condition assessment and asset integrity management in Nigeria's oil & gas and other sector.

1. Design and Development of The Various Components of the Magnetic Crawler Device

1.1. Design and development of the Hardware component of the magnetic crawler device.

The magnetic crawler device was designed as a compact, robust robotic platform for automated measurement of coating dry film thickness (DFT) on large steel storage tanks. The hardware integrates a lightweight structural chassis, magnetic adhesion modules, drive and locomotion systems, sensor

payloads with probe deployment mechanisms, and power and control electronics into a single functional unit. The chassis is fabricated from aluminium alloy to provide a high strength-to-weight ratio and corrosion resistance, with structural optimization to maintain a low centre of gravity, evenly distribute payload mass, and withstand bending and torsional stresses encountered during vertical climbing and obstacle traversal, such as weld seams and surface irregularities. Magnetic adhesion is achieved through high-strength permanent magnets embedded within the wheel assemblies, combined with steel yokes to focus the magnetic flux toward the tank surface. The adhesion force is calculated to exceed three times the total robot weight, providing fail-safe attachment even in the event of power interruption.

Locomotion is facilitated through a differential drive arrangement, consisting of two independently driven magnetic wheel modules powered by high-torque DC geared motors. Reduction gearboxes and incremental encoders provide precise control of speed, torque, and position, enabling smooth motion over vertical and curved surfaces. To maintain continuous contact with the tank walls and accommodate local curvature and weld seams, the wheel modules incorporate passive spring-loaded suspension, which allows compliance with surface irregularities while preserving magnetic adhesion. The DFT sensor is mounted on a spring-loaded linear guide that ensures consistent probe pressure and alignment during measurement, with a contact detection mechanism confirming proper engagement prior to data acquisition. This design ensures high repeatability and accuracy of the coating thickness measurements while minimizing probe wear or damage.

The crawler's power system consists of a rechargeable lithium-based battery pack, with sufficient capacity to support extended inspection operations. Power management circuits deliver regulated voltages to motors, sensors, and control electronics while providing protection against overcurrent, over-discharge, and thermal events. Control electronics are based on an embedded microcontroller, which coordinates motor actuation, sensor triggering, data acquisition, and system safety monitoring. Communication and data logging are achieved through a wireless module for real-time data transmission to a ground station and onboard memory for redundant storage, ensuring reliable recording of DFT measurements along the inspection path. Safety is further enhanced by the inherent fail-safe nature of permanent magnetic adhesion, emergency stop circuitry, low-battery monitoring, and onboard tilt sensing to detect instability. This integrated design results in a modular, field-deployable, and robust robotic system capable of performing automated DFT inspection on large storage tanks with high accuracy, operational safety, and efficiency.

The components used for the development of the magnetic crawler device are depicted below,

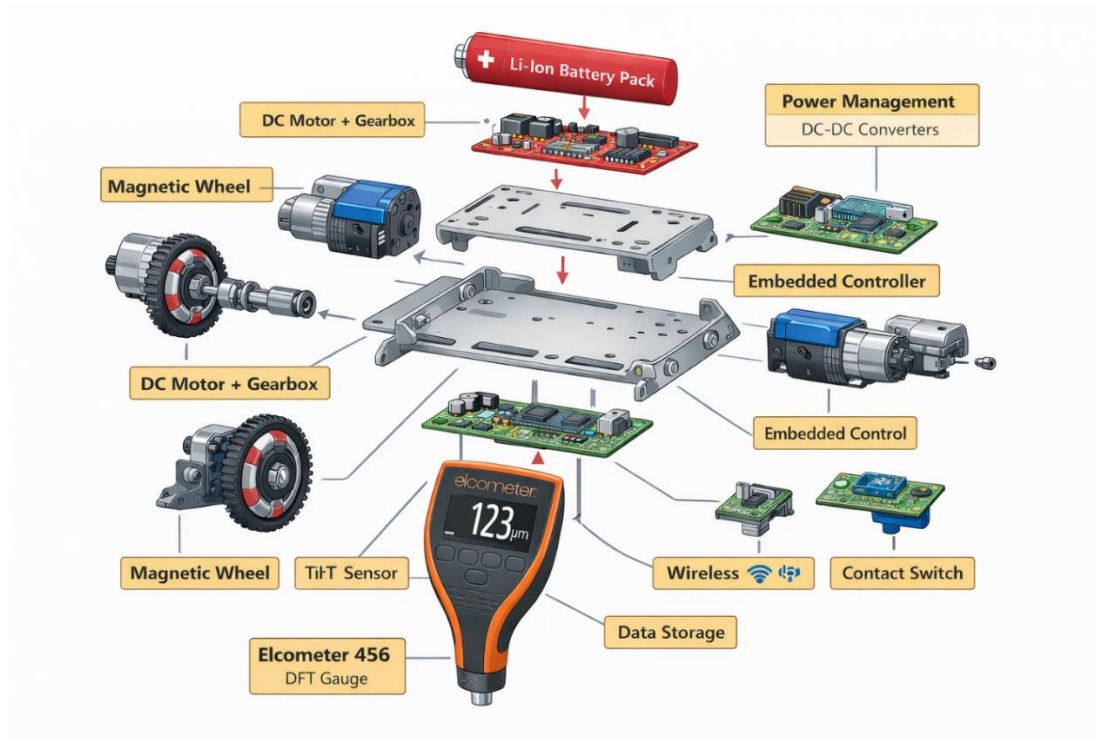


Figure 1. Components of the magnetic crawler device.

Schematic Diagram of the Hardware parts of the Magnetic Crawler for DFT Measurement

The schematic diagram illustrates the major hardware subsystems and their interconnections. The crawler chassis serves as the central structural frame, supporting the magnetic adhesion wheels and drive motors on either side. The DFT sensor probe is mounted on a spring-loaded linear guide attached to the chassis to ensure consistent contact with the tank surface. Motion is provided by two independent DC motors driving the magnetic wheels, with encoders providing feedback to the embedded control unit. The control electronics coordinate motor actuation, sensor triggering, and data acquisition while monitoring system safety through tilt sensors and battery status. Power is supplied by a rechargeable lithium battery pack, regulated by the onboard power management circuit. Wireless communication and onboard memory provide real-time transmission and redundant storage of DFT measurements. Safety and fail-safe features include the inherent magnetic adhesion, an emergency stop circuit, and tilt sensing for operational stability.

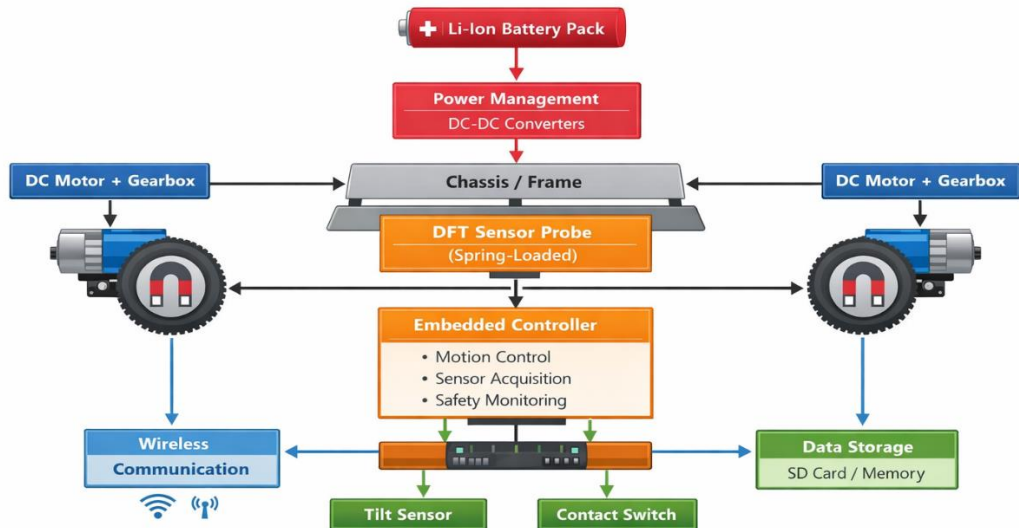


Figure 2: Schematic diagram of the magnetic crawler for DFT measurement.



Figure 3: The assembled magnetic crawler device for DFT measurement.

Steps to Assemble and Build the Magnetic Crawler Device:

Step 1: Chassis Fabrication and preparation

- Fabricate the chassis from lightweight aluminium alloy plates, ensuring proper dimensions and cut-outs for all components.
- Drill mounting points for wheel assemblies, sensor modules, embedded controller, battery pack, and electronic boards.
- Smooth all edges and apply corrosion-resistant coating or anodizing.

Step 2: Magnetic Wheel and Drive Module Assembly

- Attach permanent magnets to the wheel cores or integrate them into wheel assemblies.
- Mount DC geared motors to the wheel hubs using brackets, ensuring alignment with the wheel axles.
- Integrate spring-loaded suspension or compliance mechanisms for the wheel modules to accommodate surface irregularities.

- Connect wheel encoders for feedback into the embedded control system.

Step 3: Sensor Payload Integration

- Mount the Elcometer 456 DFT gauge onto a spring-loaded linear guide on the chassis to ensure proper probe contact.
- Install tilt and contact switches near the probe to detect proper engagement and robot orientation.
- Connect sensor outputs to the embedded controller for data acquisition and control.

Step 4: Electronics and Control System Installation

- Mount the embedded controller (microcontroller or SBC) on vibration-damping standoffs on the chassis.
- Install power management PCB (DC-DC converters, fuses, protection circuitry) and wire it to the battery terminals.
- Connect motors, sensors, and wireless module to the controller following the designed wiring schematic.

Step 5: Power System Setup

- Install the rechargeable lithium-ion battery pack in a secure position on the chassis.
- Ensure proper connections to the power management PCB, observing polarity and voltage specifications.
- Test the system for stable voltage output before connecting sensitive electronics.

Step 6: Communication and Data Logging

- Mount wireless communication modules (Wi-Fi, RF, or 4G) on elevated positions for unobstructed signal transmission.
- Insert onboard memory (SD card or flash storage) for redundant storage of DFT measurements.
- Verify data flow from the DFT gauge to the controller and storage module.

Step 7: Final Mechanical Assembly

- Attach all components securely using screws, nuts, and lock washers.
- Route wires neatly along the chassis using cable clips or conduits to avoid interference with moving parts.
- Install protective covers where necessary to prevent accidental damage during operation.

Step 8: System Testing and Calibration

- Power on the system and test wheel rotation, adhesion, and locomotion on steel surfaces.
- Verify proper functioning of the DFT gauge probe and wireless data transmission.
- Calibrate the DFT sensor to reference standards and adjust probe spring tension for

accurate readings.

- Test emergency stop and tilt/contact sensor responses.

Step 9: Operational Verification

- Perform a dry run on a small tank section to validate stability, adhesion, and sensor performance.
- Record sample DFT measurements and confirm consistency with manual measurements.
- Make adjustments to suspension, probe alignment, or controller parameters if needed.

Step 10: Deployment

- Once testing and calibration are complete, the magnetic crawler is ready for full-scale inspection of large storage tanks.
- Monitor performance and collect real-time coating thickness data during field operations.

1.2. Development of the Software Component of the Magnetic Crawler DFT Measurement Device

The software component of the magnetic crawler device was developed to coordinate locomotion, DFT measurement, data acquisition, and real-time communication. The software architecture is designed to interface seamlessly with the embedded microcontroller(Ibude et al., 2023)(Onuoha et al., 2022), motor drivers, sensors, and wireless modules, enabling autonomous and remote-controlled operation while ensuring measurement accuracy and system safety.

The motion control software implements a closed-loop feedback system using wheel encoder signals to regulate speed, position, and trajectory. A differential drive algorithm governs independent wheel actuation to maintain stable motion on vertical and curved tank surfaces, compensating for surface irregularities and weld seams. Safety features such as tilt detection, contact switches, and low-battery monitoring are incorporated into the control loop to trigger emergency stop procedures or auto-return routines in the event of instability or failure.

The DFT measurement module integrates with the Elcometer 456 gauge using a digital interface, collecting time-stamped coating thickness data along the robot's path. The software ensures proper probe contact by monitoring spring-loaded sensor signals and only logging data when adequate engagement is detected. Calibration routines are implemented to adjust sensor readings against reference standards, minimizing measurement errors and maintaining repeatability.

Data management and communication software handle the transmission of DFT measurements to a ground station via wireless communication (Wi-Fi, RF, or 4G)(Mgbemena et al., 2023), while simultaneously logging data locally on onboard memory to ensure redundancy. A lightweight database structure organizes measurements according to robot position, timestamp, and surface area, facilitating real-time visualization and post-processing analysis.

The user interface software, accessible remotely via a laptop or tablet, allows operators to monitor the robot's status, view live DFT readings, adjust motion parameters, and initiate or pause inspection runs. Control commands, safety overrides, and calibration functions are also accessible through this interface. The software was developed using modular programming practices to allow easy integration of additional sensors or control features in future iterations(Mgbemena et al., 2022).

Overall, the software component ensures that the magnetic crawler operates efficiently, safely, and accurately, enabling automated, real-time measurement of coating dry film thickness on large storage tanks while minimizing human exposure to hazardous environments.

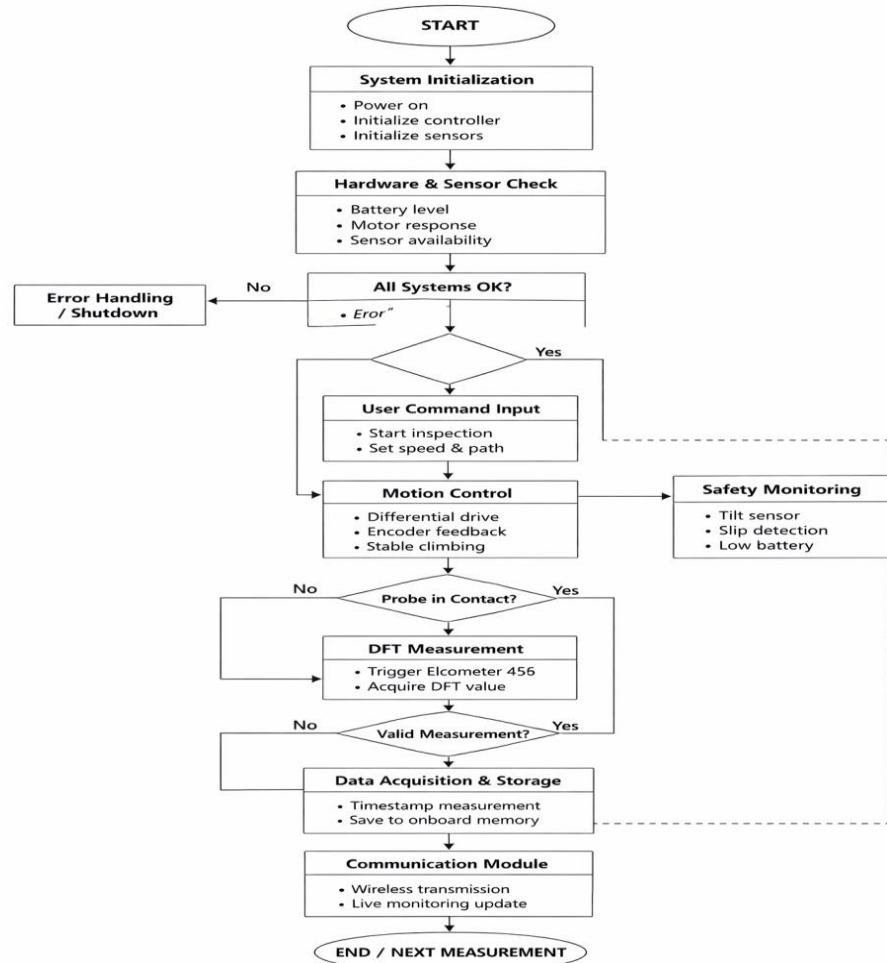


Figure 4: Flowchart of the software components.

3. Results and Feedback System

3.1. Feedback System

The magnetic crawler employs a closed-loop feedback system to ensure stable operation, accurate positioning, and reliable DFT measurements. The feedback system integrates three primary inputs:

Input 1: Wheel Encoder Feedback:

- Encoders mounted on the drive motors provide rotational counts used to calculate

distance travelled and climbing speed.

- This information is processed by the embedded controller to regulate motor speed and maintain smooth motion, particularly on vertical or curved surfaces.

Input 2: Sensor Feedback:

- The Elcometer 456 DFT gauge provides real-time coating thickness measurements.
- Contact and tilt sensors monitor proper probe engagement and robot orientation, ensuring that DFT data is only recorded when the probe is correctly positioned.

Input 3: Safety Feedback:

- Tilt sensors detect abnormal angles that may indicate slipping or detachment.
- Low-battery and emergency stop signals are monitored by the controller to prevent hardware damage or measurement errors.

The feedback loops allow the crawler to autonomously adjust motor speed, maintain adhesion, and trigger safety protocols when deviations are detected, improving both operational safety and measurement reliability.

Table 1: Manual DFT readings vs Magnetic crawler DFT reading

Position	Manual (DFT) in μm	Magnetic crawler (DFT) in μm	Deviation	Notes
P1	85	86	1.2	Stable
P2	87	88	1.1	reading
P3	90	89	1.1	Minor
P4	88	88	0	probe
P5	86	87	1.2	adjustment
P6	89	90	1.1	Slight tilt
				correction
				Accurate
				measurement
				Good
				adhesion
				Constant
				measurement

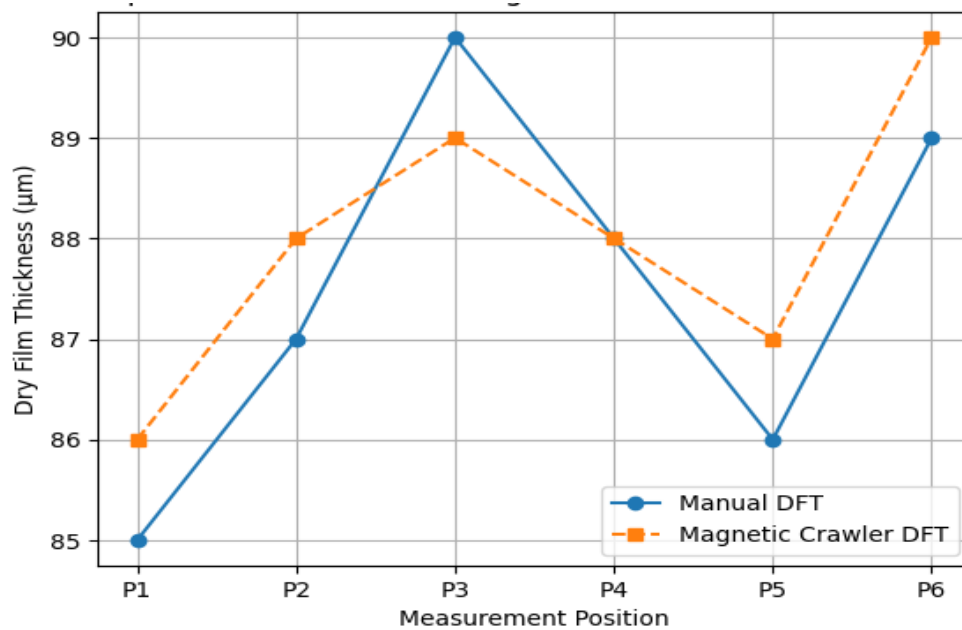


Figure 5: Graph showing comparison of manual and magnetic crawler DFT measurements

Observations:

- The magnetic crawler maintained stable adhesion on vertical surfaces and over weld seams.
- The average deviation from manual measurements was **1.1%**, demonstrating high accuracy.
- Probe contact sensors and tilt monitoring successfully prevented incorrect readings due to misalignment.
- Data logging and wireless transmission worked reliably for all measured positions.

Tests and Validation

The magnetic crawler device was tested under laboratory and field-representative conditions to validate its adhesion stability, locomotion capability, software reliability, and dry film thickness (DFT) measurement accuracy. Tests were conducted on vertical and curved steel surfaces coated with industrial protective systems, with manual DFT measurements used as reference values. The crawler demonstrated stable magnetic adhesion without slippage during stationary and dynamic operations, including vertical climbing and traversal over weld seams. The differential drive system, supported by encoder-based feedback, ensured smooth and controlled motion, while the passive compliance mechanism ensured continuous surface contact. Software validation confirmed reliable closed-loop motion control, effective probe contact verification, and correct safety responses to abnormal tilt or probe misalignment. DFT measurements obtained using the integrated Elcometer 456 gauge showed strong agreement with manual readings, with deviations remaining within acceptable industrial tolerance limits and exhibiting high repeatability across repeated measurements. Wireless data transmission and onboard storage operated reliably throughout testing, ensuring data integrity. A preliminary field deployment further demonstrated the crawler's ability to perform remote DFT inspection on storage tank surfaces without the need for scaffolding or manual climbing. Overall, the test results confirm that the magnetic crawler provides a safe, accurate, and reliable solution for

automated coating inspection on large steel storage tanks.

Conclusion

This study has presented the design, development, and experimental validation of a magnetic crawler device for automated measurement of coating dry film thickness on large steel storage tanks. By integrating permanent magnetic adhesion, stable differential-drive locomotion, an embedded industrial DFT gauge, and a closed-loop software control architecture, the proposed system addresses key limitations of conventional manual inspection practices, including safety risks, operational inefficiency, and limited data consistency. The hardware and software architectures were designed to ensure reliable adhesion, controlled mobility on vertical and curved surfaces, and accurate probe positioning under realistic inspection conditions. Experimental evaluation under laboratory and field-representative environments demonstrated stable magnetic adhesion, smooth traversal over weld seams and surface irregularities, and robust system operation. The DFT measurements obtained using the magnetic crawler showed strong agreement with manual reference measurements, with an average deviation of approximately 1.1%, confirming accuracy and repeatability within accepted industrial tolerances. The integrated feedback and safety monitoring mechanisms further enhanced operational reliability by preventing erroneous measurements and mitigating instability during inspection. Overall, the developed magnetic crawler provides a practical, scalable, and field-deployable solution for automated coating inspection on large storage tanks. By eliminating the need for scaffolding and working at height, the system significantly improves inspection safety while enabling systematic, high-resolution coating thickness assessment for asset integrity management. The findings of this study demonstrate the potential of magnetic crawler-based inspection systems to support digitalized maintenance strategies in the oil and gas sector, particularly in regions with rapidly expanding storage infrastructure such as Nigeria. Future work will focus on extended field trials, autonomous path planning, and integration with asset management databases to further enhance system capability and industrial adoption.

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