ENT1099EE01 - Design, Development and Control of a Reconfigurable Magnetic Crawler Robot for Safe Inspection of Oil Storage Tanks and Large-Diameter Pipelines

Principal Investigator

Dr. Belal Ahmed Elsayed	belal.elsayed@polytechnic.bh
Polytechnic ID: 12010828	**Department/School**: Engineering

Programme	ENT1099 PhD in Engineering
Research Area and Specialization:	Inspection Robotics
Company Endorsement	Bapco
Industry mentor	Dr. Ismaeel Husain - VP - Health, Safety, Security, & Environment (HSSE) ismail.ahmed@bapcoenergies.com Dr. Hazem Hasan-Manager - Offsites & Utilities Engineering hazem.hasan@bapcoenergies.com

Background of the problem

The oil-and-gas and petrochemical sectors depend on reliable storage and transfer infrastructure, including storage tanks, pipe racks, large external pipelines and other related metallic structures. Storage tanks commonly hold crude oil, refined products, chemicals, and other process fluids. Failure, leakage, corrosion or deformation in these assets can lead to safety, environmental, production and reputational consequences. This makes inspection essential during both routine maintenance and emergency response.

Current inspection practices, such as API 653, are necessary but can be time-consuming and hazardous. External access may require scaffolding, manlifts or rope access, while internal tank inspection may require draining, cleaning, gas testing, ventilation and confined-space entry. These requirements increase inspection cost, preparation time, operational interruption, and direct human exposure to hazardous or uncertain environments.

Robotic inspection has been increasingly considered as a practical solution for improving safety and data collection in difficult environments. Disaster robotics literature shows the value of robots as tools for data collection and decision support in environments that are unsafe or

inaccessible for humans. For example, in Fukushima Daiichi decommissioning, robotic systems have been reported for radiation-source investigation and decontamination in reactor buildings.

However, inspection of oil tanks and large-diameter pipelines still presents practical challenges, including magnetic adhesion, traction, stability on vertical and curved surfaces, obstacle crossing, sensor integration, and reliable human-machine interaction. Therefore, there is a need for a reconfigurable magnetic crawler robot that can climb ferromagnetic tank and pipeline surfaces, carry inspection payloads, and support teleoperated and semi-autonomous inspection.

List of publications related to the field

Belal A. Elsayed, Tatsuya Takemori, and Fumitoshi Matsuno, “Gait Recovery for a Snake Robot With Multiple Failed Joints,” IEEE/ASME Transactions on Mechatronics, 2024. https://doi.org/10.1109/TMECH.2023.3334481

Belal A. Elsayed, Tatsuya Takemori, Motoyasu Tanaka, and Fumitoshi Matsuno, “Mobile Manipulation Using a Snake Robot in a Helical Gait,” IEEE/ASME Transactions on Mechatronics, 2022. https://doi.org/10.1109/TMECH.2021.3114168

Belal A. Elsayed, Tatsuya Takemori, and Fumitoshi Matsuno, “Joint failure recovery for snake robot locomotion using a shape-based approach,” Artificial Life and Robotics, 2022. https://doi.org/10.1007/s10015-022-00742-1

Samuel Wild, Belal A. Elsayed, Hongshen Shi, Brian Jones, Tianyi Zeng, Ahmed Mohammad, Dragos Axinte, and Xin Dong, “Unified Neural Network-Based Shape Sensing for Continuum Robots Using Fiber Bragg Gratings,” IEEE Sensors Journal, 2025

Jie Li, Xiang Zhou, Chao Gui, Mingxing Yang, Fengyu Xu, and Xingsong Wang, “Adaptive climbing and automatic inspection robot for variable curvature walls of industrial storage tank facilities,” Automation in Construction, 2025.

Yuki Nishimura, Cheng Wang, and Wei Song, “Metal Thickness Measurement Using an Ultrasonic Probe with a Linear Actuator for a Magnet-Type Climbing Robot: Design and Development,” Actuators, 2025.

Chaojie Xu, Wenming Jiang, Hongzhang Ma, Yang Liu, Huiyun Men, Xining Xu, and Zhixin Li, “A Review: Research and Application of Pipeline Robots in the Oil and Gas Industry,” Journal of Pipeline Science and Engineering, 2025.

Research Objectives and Expected Outcomes:

Aim

The main aim of this PhD research is to develop and validate the modelling, adaptive locomotion, and decision-support methods required to transform a reconfigurable magnetic crawler from a teleoperated prototype into an intelligent inspection platform for tanks, pipelines, and ship hull structures.

The core PhD project objectives are:

O1: Develop and experimentally identify a coupled dynamic model of magnetic adhesion, traction, reconfigurable locomotion, payload effects, curvature variation on representative ferromagnetic surfaces.

O2: Develop robust and adaptive motion-control methods that maintain adhesion, stability, and trajectory tracking under uncertainty in curvature and local discontinuities.

O3: Develop robot localization and autonomous or semi-autonomous coverage-planning methods for large tank, pipeline, and ship-hull surfaces.

O4: Develop a spatial inspection-data framework that fuses robot pose with camera and selected NDT measurements.

O5: Develop and validate repair-oriented decision-support methods for inspection completeness, anomaly prioritization, and repeat inspection.

This PhD project will run concurrently with the related MSc project. While the MSc focuses on prototype development and baseline testing, the PhD will deliver distinct contributions in modelling, autonomous control, localization, inspection mapping, and decision support.

Expected Outcomes:

The expected outcome of this project is to establish a practical and research-driven robotic inspection solution with value for Bahrain Polytechnic and industrial partners. For Bahrain Polytechnic, the project will create a showcase of applied robotics theme that can support postgraduate research, student training, publications, prototype development, and future externally funded projects. For industrial partners, it will provide an opportunity to be part of designing and testing a locally-developed inspection technology that can support safer inspection of oil tanks, large pipelines, and related metallic infrastructure. The project will also allow industry partners to be involved from the early stages of technology development, ensuring that the proposed system responds to real inspection needs. At the national level, the project supports Bahrain's direction toward industrial digitalization, resilient infrastructure inspection, and local capacity building in robotics, and autonomous systems.

Research Design/Methodology

The proposed robot will consist of serially connected crawler modules with magnetic adhesion. The unites will also have motors for active traction. The modular body will allow the platform to adapt to flat tank walls, curved tank shells, large external pipes, weld regions and interconnecting structures. The design will be guided by industrial partner requirements to maximize the practical relevance. The key subsystems are:

• Mechanical platform: magnetic crawler modules, reconfigurable joints. The research will be focused on magnetic adhesion, stability, traction force and curvature adaptation.

• Sensing and inspection: camera, lighting, IMU, and encoders, in addition to optional thermal, ultrasonic-thickness or gas sensors. The practical outcome is readable information for inspectors and maintenance teams.

• Control and autonomy: teleoperation, assisted maneuvering, stabilization and slip detection. The main value lies in reducing operator burden while maintaining human authority.

• Human-machine interface: live video, digital twin visualization of the robot status, and sensor data display. The value lies in enabling safe and reliable inspection through an easy-to-use and intuitive interaction interface.

The work will follow an applied engineering research methodology: Defining the requirements, modelling, design, simulation, prototype development, control implementation, laboratory validation and industry partner supervised demonstration. The proposed work packages are as follows:

• WP1 - Industrial requirements: partner meetings, asset selection, safety constraints, inspection standards and test scenarios. Output: requirement specification and validation metrics.

• WP2 - Modelling and design: adhesion/traction/stability modelling, CAD, magnetic layout, payload design and joint design. Output: optimized concept and detailed design files.

• WP3 - Prototype development: fabrication, electronics, embedded control, sensor mounting and user interface. Output: first integrated robotic platform.

• WP4 - Control system development: teleoperation, assisted driving, slip/stability monitoring, coverage planning and emergency-stop/fail-safe logic. Output: tested control software.

• WP5 - Validation and demonstration: vertical and curved mock-ups, obstacle/discontinuity tests, payload tests, inspection-data capture and partner review. Output: validation dataset and demonstration report.

Significance and potential impact of research in Bahrain

Failure, leakage, corrosion or deformation in these assets can lead to safety, environmental, production and reputational consequences. This makes inspection essential during both routine maintenance and emergency response.

The expected outcome of this project is to establish a practical and research-driven robotic inspection solution with value for Bahrain Polytechnic and industrial partners. For Bahrain Polytechnic, the project will create a showcase of applied robotics theme that can support postgraduate research, student training, publications, prototype development, and future externally funded projects. For industrial partners, it will provide an opportunity to be part of designing and testing a locally-developed inspection technology that can support safer inspection of oil tanks, large pipelines, and related metallic infrastructure. The project will also allow industry partners to be involved from the early stages of technology development, ensuring

that the proposed system responds to real inspection needs. At the national level, the project supports Bahrain's direction toward industrial digitalization, resilient infrastructure inspection, and local capacity building in robotics, and autonomous systems.

Alignment with Bahrain's national research strategy

Contribution to Bahrain Society:

This project contributes to Bahrain society by supporting safer inspection of oil tanks, large pipelines, and related metallic infrastructure. By reducing direct human exposure to hazardous, high, confined, or uncertain environments, the project can improve worker safety, emergency response capability, and environmental protection. It also supports local capacity building in robotics, autonomous systems, and applied engineering research.

Alignment with Industry:

The project is directly aligned with the needs of the oil, gas, petrochemical, and industrial sectors in Bahrain. These sectors depend on reliable storage and transfer infrastructure, where failure, leakage, corrosion, or deformation can lead to serious safety, environmental, and production consequences. The involvement of industrial partners from the early stages will ensure that the proposed robotic system responds to real inspection requirements.

Alignment with National Research Priorities / Strategy:

The project supports Bahrain's direction toward industrial digitalization, resilient infrastructure inspection, and local capacity building in robotics and autonomous systems. It is also aligned with Bahrain's Industrial Sector Strategy 2022–2026, which aims to develop a sustainable industry based on innovative and advanced initiatives.

Alignment with EDB Policies:

The project is aligned with Bahrain EDB's focus on innovation, technology, and Industry 4.0 in the manufacturing sector. Bahrain EDB highlights the role of collaboration, forward-looking regulation, skills building, smart factories, automation, and AI-driven efficiency in transforming Bahrain's manufacturing sector.

This project supports these directions by developing a locally relevant robotic inspection technology for industrial applications.