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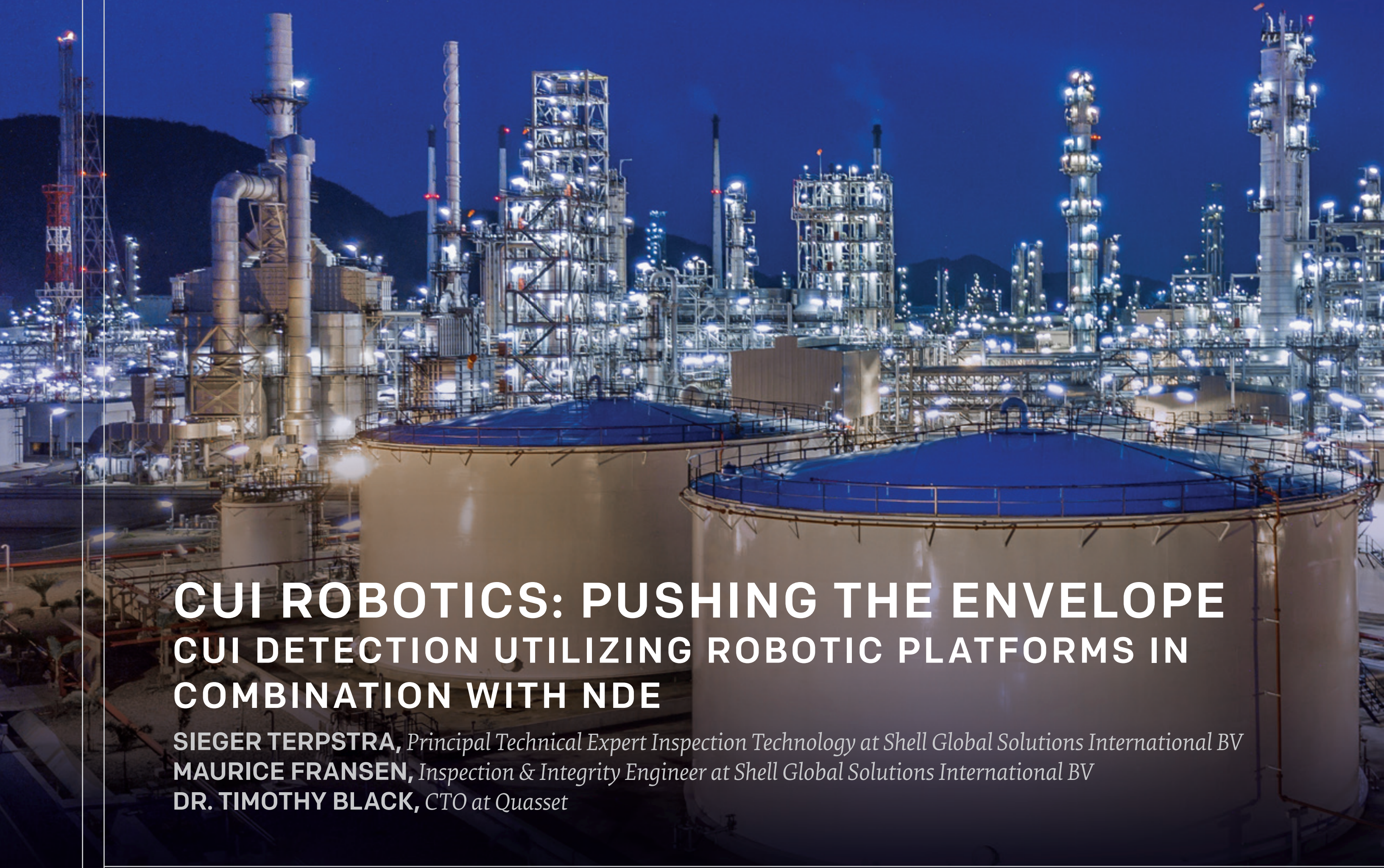

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INTRODUCTION

Detection and repair of Corrosion Under Insulation (CUI) cost the petroleum and petrochemical industry an estimated $3-4 Billion USD per year. Key focuses in CUI detection are safety and the reduction of Loss of Primary Containment (LoPC). LoPC due to CUI not only has safety implications, but also substantial financial ones. Production loss and costs related to fitness-for-service, including inspection, repair/replacement, fabrication and installation costs can arise, as well as carrying high environmental impacts if LoPC occurs.

The current CUI inspection and maintenance practice with scaffolding and full de-lagging is highly inefficient. This is done predominantly due to uncertainties associated with low accuracy of detection and sizing of damage associated with current inspection technologies. High-cost savings can be realized if the approaches to CUI inspections are optimized. For example, a conservative estimate of a 5% efficiency increase would result in benefits in excess of $150 Million USD.

Global oil and gas operator, Shell, contracted Dutch-based consultancy, Quasset, to evaluate and verify the current state-of-the-art approaches in CUI robotics on non-magnetic cladding materials (i.e. insulation weather barrier) and perform a series of validation trials to determine which robotic systems are ready or close to release for deploying non-destructive examination (NDE) for CUI detection. This multidisciplinary project presented the opportunity to explore whether inspection of CUI could be performed at a significantly lower cost by leveraging innovative robotic equipment in combination with NDE.

Currently, the initiative for development in CUI inspection is almost exclusively left to the developers of inspection technology. This requires these often-small companies to make high investments and seek cooperation with providers of complementary techniques, such as robotics. Business/commercial risks are high, as practical, effective CUI inspection is a challenging matter.

REPLACING TRADITIONAL CUI INSPECTION METHODS WITH ROBOTICS

Robotic systems are increasingly considered to improve the safety and efficiency of inspection and maintenance activities. In the petrochemical industry, many critical assets such as vessels, piping and tanks are insulated with non-magnetic materials that are in intermittent service, curved and often irregular and therefore are at risk of CUI. These assets require frequent inspections, meaning there is a strong drive in the industry to replace traditional CUI inspection—done by removing insulation—with

Figure 1. Phase 1 - Robotic platform testing at Quasset Test Facility

inspection techniques that can detect CUI damage through the insulation. Traditional CUI inspection methods with scaffolding and full de-lagging are manual, labor intensive, and expensive; as such, there is a need for versatile robotic systems that can integrate NDE equipment for the detection of corrosion under insulation and other asset defects.

THE TESTING PROGRAM

The scope of this program was to provide an initial assessment of the current capabilities of commercially available robots for non-magnetic surfaces by demonstrating their capabilities on a pressure vessel (decommissioned), and with a typical set-up of a vessel covered in insulation with a weather barrier that mimic real world conditions within the petrochemical industry.

Two main questions were asked:

1. Are there robotics solutions on the market that can work on non-magnetic surfaces?
2. Can these robotic systems perform successful detection of defects in combination with NDE technology?

The testing program was split into two phases: Phase 1 - Robotic platform testing, and Phase 2 - NDE Integration testing. Performed between 2017 and 2018, the two phases entailed testing the robotic systems on different non-magnetic surfaces with small curvatures, as well as the general robustness of the robotic systems. While the tests were not intended to be a full demonstration of the robot's ability to perform inspection activities, the tests focused on investigating the capability of the robotic system to carry and integrate potential NDE technologies, with the secondary investigation on how the system works as a whole when combined. Hence, these experiments create an accurate picture of the state of the technology and the existing gaps to deployment in the petrochemical industry.

Phase 1: Robotic platform testing

Phase 1 focused on the general capability of four different robotic systems. The robots of interest to these trials were made available by technology providers from a variety of sectors. Each of these robotic systems employed different adhesion and mobility mechanisms, including flexible rolling seal vacuum systems, vortex wheeled suction, tracked passive seal suction, and a combination thereof. The objective of the tests was to establish the current capabilities and limitations of the robots and their operation. This consisted of performing measurements of the systems' characteristics, such as the mobility of the robot, the robustness of the system, the adhesion mechanism, the ability to integrate NDE equipment, and the use of the robot on real-life practical surfaces.

There were some key criteria used to assess the robotic systems. These criteria are summed up in the following categories:

Table 1 - Key criteria used to assess the robotic systems

Mobility	Adhesion	System Capability	Safety
Speed & Movement Obstacles Scanning Patterns Transitioning Surface Movement	Surface Adhesion Payload Capacity Fall off Angle Surface Traction	Deployability Autonomy System Robustness Hardware Review NDE Integration	Electric Circuits Fall Protection Umbilical Management ATEX

The test object used was a decommissioned pressure vessel, which was cladded with three different types of non-magnetic materials often used in the petrochemical industry: aluminium, galvanised (carbon) steel, and stainless steel. The vessel was uniquely created to test different kinds of surface shapes. The body of the vessel was shaped as a 2.5m wide cylinder and provided a challenging curvature. Furthermore, the top and bottom of the vessel were cladded in a dome and conical shape respectively. This was to provide a challenge for the robots, not only with respect to the small curvatures, but also in the transitioning from the body to the top and bottom surfaces, as well as handling the different number of seams and bolts that form a part of the insulation.

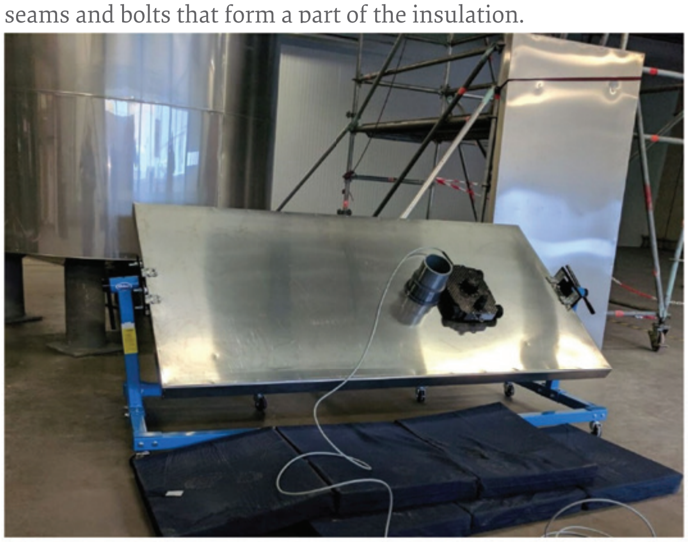

Figure 2. As part of Phase 1 - testing on an inclined surface

[...] it is unlikely one solution will fill all needs of inspection activities. The nature of CUI will require different robotic technologies complementing each other with a combination of solutions to tackle the huge CUI challenge.

Phase 1: Results

Overall, the Phase 1 trials demonstrated that all tested systems have potential to be deployed for CUI inspection activities in the petrochemical industry. The fact that the robotic systems came from various industry sectors and their design and operation were intended for different purposes did have an impact on some of the robot's performances. Nevertheless, all robotic systems tested in Phase 1 proved valid potential for deployment in the petrochemical industry. Areas of needed improvement were identified.

For the development of robots for CUI inspection, it is unlikely one solution will fill all needs of inspection activities. The nature of CUI will require different robotic technologies complementing each other with a combination of solutions to tackle the huge CUI challenge.

Key takeaways included:

- Due to the uniqueness of each insulation system design, the performance varied during the trials.
- Each solution demonstrated advantages and disadvantages while simulating inspection activities.
- All robots possess potential for deployment in the petrochemical industry. Areas for improvement were identified.
- Performing these trials provided an invaluable learning opportunity for all parties and saved months of R&D for the robot providers.
- Each robot provider could benefit from implementing minor technological changes (quick gains) that justify longer term technology development (e.g., towards ATEX certification, inspection reliability, and low-cost deployment).

Phase 2: NDE Integration testing

Phase 2 focused on the ability to integrate NDE equipment with a robotic system. This phase was a blind trial which combined the most capable robotic system from Phase 1 with commercially available Pulsed Eddy Current (PEC) probes from two separate companies in order to gauge the feasibility of combining existing technologies for CUI detection.

An independent service provider was contracted. The trials were structured similarly to an on-site inspection. The service provider oversaw the integration of the robotic platform with the NDE technology and leading the scanning operations during the trials.

The aims of Phase 2 were as follows:

1. Evaluate a robot platform in combination with an NDE sensor for CUI detection
2. Assess the ability for defect detection
3. Assess the ability of the integrated system to locate a defect in reference to the asset
4. Evaluate the effectiveness of the scanning methodologies and the extent of coverage

Figure 3. Phase 2 - NDE Integration testing with PEC system and robot

The test object was the same pressure vessel from Phase 1 with three different kinds of cladding and defects manufactured under the insulation to mimic real world wall loss through corrosion. The vessel contained defects scattered in areas that would allow us to assess the extent to which the defects could be detected and sized. The defects were placed in areas where corrosion would typically occur, around complex curvatures on the vessel where moisture could seep through and collect. Once the defects were machined, it was important to precisely localize each defect on the vessel and their geometries to compare with the inspection reports provided at the end of the trial. For this, the vessel was fully 3D scanned and modelled into a digital twin.

The aims of these trials were not only to assess the detection capabilities of a sensor mounted to a robot, but also to test whether an integrated system could locate defects in reference to an asset and perform scanning methodologies to achieve (near) 100% coverage. Hence, this was not a probability of detection (POD) trial, but rather an evaluation of the location and sizing abilities of the sensors along with optimal scanning efficiencies. Both hardware and software elements of the robot and sensor components needed to be integrated and assessed in order to perform this effectively. This approach was chosen to better determine the kind of improvements necessary to join the separate technologies into a commercial CUI detection solution.

Figure 4. As part of Phase 2 - testing robot near manway

Phase 2: Results

Determining if the combination of robot technology and NDE technology could be integrated together was the major aim of this project. In general, the trial was a successful indication that using the robotic approach integrated with a PEC tool is possible for CUI inspection. It also proved that this combination was available in the market and did provide more stable results in dynamic scan mode compared to manual scanning due to the stable movement of the robot on the vessel. However, it was evident that insufficient attention was paid towards integrating the systems. When the systems were used together, they did not perform as expected, causing the overall technology readiness level to drop.

This was due to several different factors:

- The technology tested was designed to work as a standalone
- No ability to integrate the existing systems into a coherent solution
- Neither the NDE sensor manufacturers or the robot manufacturers have a common understanding of each other's needs to achieve success
- Some elements were not yet ready for commercial application (e.g., the location technology for positioning the robot is not proven and not ready to be deployed)

Overall detection of defects was limited. None of the NDE sensor providers could definitively locate the machined defects or accurately size the defect. The primary aim for the detection of the defect was not a probability of detection (POD) trial; rather it was to determine if the system could detect the uniform defects as an integrated system.

CUI ROBOTICS: A COLLABORATIVE EFFORT

The results from Phase 1 and 2 of these trials proved that robotics can be used to detect CUI. Firstly, robotic systems are available in the market to carry the NDE tools and work on non-magnetic surfaces. Secondly the feasibility of integrating a PEC probe onto a robotic tool for CUI detection was demonstrated.

From the integration trials we conclude that in order for commercially available NDE sensors and robotic solutions to be combined into a potential CUI solution, significant integration efforts need to be undertaken. Performing the trials uncovered a key gap to overcome: both the robot providers and NDE providers should make a concerted effort to marry the various systems into one solution that can service the market. Currently available technology needs further improvements and requires significant integration efforts on both hardware and software aspects in order to become a full-fledged robotic solution.

The main takeaways from these trials are as follows:

1. Merging existing technologies into one system for CUI detection is feasible provided the engineering hurdles are tackled collectively; an agile approach which progressively builds towards an integrated minimum viable product with stage gates can help to align the objectives of each parties.
2. The NDE sensors need to be further "robotized" for robotic inspection as they are currently only designed for human use.
3. Focus should be placed on the practicalities of deployment and a ready-to-go solution. For true cost-effective service deployments, "out-of-the-box" solutions are needed.
4. The storage and management of data should be integrated and aligned with aspects of digitalization, such as digital twinning and advanced analytics, as well as tighter coupling of data collection and locations to be applied to standard data reporting.

CONCLUSION

It is clear that there is a need to develop a technology pathway that focuses on the evolution of robotic systems capable of performing CUI inspections, which sequentially tie into specific business drivers of end-users and service and technology providers in the petrochemical industry. Indeed, the rationale for replacing conventional CUI inspection methods with robotic systems is centred around the potentially high savings generated by reducing downtime and bypassing the inefficiencies of de-lagging insulation with scaffolding and piecemeal visual inspection that is not only impractical, but also exposes personnel to the hazards of working at heights and damaging insulation weather barriers. Robotic systems could allow for CUI inspection activities to be deployed at a significantly lower cost and could reduce the maintenance scope in a targeted manner. This should begin by tackling the low hanging fruit and gradually working collectively towards technology mature enough to handle the more complex aspects of CUI inspection. ■

For more information on this subject or the author, please email us at inquiries@inspectioneering.com.

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CONTRIBUTING AUTHORS

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Dr. Timothy Black has been a part of the Quasset team since 2013. In his role as CTO, Dr. Black's primary responsibilities include Oil and Gas innovation projects, technology scouting, and innovation roadmapping, as well as leading the Quasset Test Facility (QTF) to facilitate the development of robotic solutions for inspection and maintenance activities. Dr. Black has a PhD in Robotics, Bachelors in Engineering. Prior to working for Quasset, he was Senior Research Fellow – R&D Systems at the Centre for Intelligent Systems Research (CISR) performing robotic research and development for the Australian Defense Force and Industry.

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Maurice Fransen has 4 years of experience in the Oil & Gas industry. He is an inspection engineer focusing on the midstream sector and supporting natural gas processing (LNG, GTL) assets. He received a bachelor's and master's degree in Applied Physics from the Eindhoven University of Technology in the Netherlands. Mr. Fransen also obtained a PhD from the same university in the field of chemical physics, on the topic of water nucleation. He has published and presented several research papers in this field. After obtaining his PhD, Mr. Fransen started as a flow assurance engineer with Shell in 2015.

SIEGER TERPSTRA

After graduation in 1981 in Applied Physics, Sieger Terpstra started at the Royal Dutch Shell Laboratory in Amsterdam, working on Development of NDT (Non-Destructive Testing) techniques and their deployment at Shell's Operating Units. After roles in Shell's Downstream central organization and in Upstream for structural inspection, he returned in 1998 to the central organization in Amsterdam in Inspection Technology. He is currently in a global support role as Principal Technical Expert, involved with NDT consultancy, Non-Intrusive Inspection, assessment of NDT Reliability, and involved with Research & Development of Inspection Technology, Corrosion Monitoring, and remote – robotic – deployment of inspection technology.