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Using Robots to Achieve Full Coverage CUI Inspections

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Introduction

Corrosion under insulation (CUI) continues to be one of the most challenging damage mechanisms facing asset integrity professionals. While inspection programs have evolved significantly over time, many operators still rely on stripping and reinstalling insulation, or a combination of visual assessment, risk-based prioritization, and targeted inspections of susceptible areas. This approach is limited by partial inspection coverage and the difficulty of finding the localized, hidden threat of CUI.

This article examines these challenges in current CUI inspection programs and explores how advances in robotics create an opportunity to collect more data, expand the inspection coverage, and reduce inspection risks. It compares different robotic architectures and their applicability to CUI inspections. The author also considers how robotic solutions can be combined with each other and/or with manual methods in a hybrid approach.

Current CUI Inspection Programs

Despite decades of industry focus and established inspection practices, CUI continues to drive high maintenance costs, unplanned outages, and safety risks. A key reason is not just the prevalence of the damage mechanism itself, but how difficult it is to detect reliably with conventional inspection approaches.

CUI is a localized damage mechanism. It occurs where moisture gets trapped beneath insulation and creates conditions for corrosion, often combined with contaminants such as chlorides. The damage tends to appear in isolated areas where water accumulates and where coatings have broken down. Adding to the challenge, the external condition of the insulation does not always give insight into what is happening underneath. Moisture can travel within the insulation system, allowing corrosion to develop far from where the water originally entered. As a result, areas that look fine from the outside may still contain damage, while visually degraded insulation does not always indicate severe corrosion.

This combination of being both hidden and localized can contribute to uncertainty in inspection programs, as the condition of the pipe cannot be evaluated without either removing insulation or using nondestructive testing (NDT). NDT through the existing insulation is typically a more cost-effective approach.

Current inspection methods have several limitations. Many piping systems are located at elevated heights and in congested pipe racks—areas that require scaffolding or rope access. This means that access can account for a large share of inspection cost and effort. Once inspectors gain access to the pipe, the length of pipe that they can inspect per hour or day is limited by how quickly they can safely move along the pipe, while ensuring that they are collecting repeatable and high-quality inspection data, with sufficient coverage. Due to these limitations, CUI inspection scope is driven as much by what is accessible and affordable as by what is technically desirable.

These limitations must be considered when using risk-based inspection (RBI) programs to prioritize inspections based on probability of detection, failure, and consequence of failure. For traditional CUI programs, this takes the shape of visual inspections, determination of susceptible areas, and inspection coverage in those susceptible areas. The inspections are constrained by the limitations of access, human operators, and the tools currently available, and due to the hidden and localized nature of CUI, we are left with a big challenge. The advent of new inspection robots presents an opportunity to rethink our approach.

How Robots Can Impact CUI Inspections

Robotic inspection systems are not new to the industry, but their capabilities have improved significantly in the last decade. Earlier generations of automated systems were often limited by their mobility, power requirements, or what sensors they could carry. Today, progress in mechanical design, battery technology, sensor miniaturization, and software advancements have made it possible to deploy more effective robots for inspection of piping assets. Newer systems can reach harder-to-access areas, inspect more piping per unit time, and enable greater confidence through more complete inspections, with a range of non-destructive evaluation tools.

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One of the most important changes is in mobility. Modern robotic platforms can move along both horizontal and vertical piping, insulated and uninsulated, and rotate 360 degrees around the pipe to reach any point for inspection purposes (barring any obstructions). In many cases, the latest robots can operate within congested pipe racks where traditional access methods may be difficult or costly, and they can allow inspections to be performed from fewer access points, thereby reducing the need for scaffolding and minimizing the amount of work at height. As a result, a greater proportion of the assets can be inspected within the same time and budget constraints. That said, access and congested piping may still preclude some robotic inspections, so it is critical that these limitations are understood up front.

Improvements in data acquisition and processing have also played

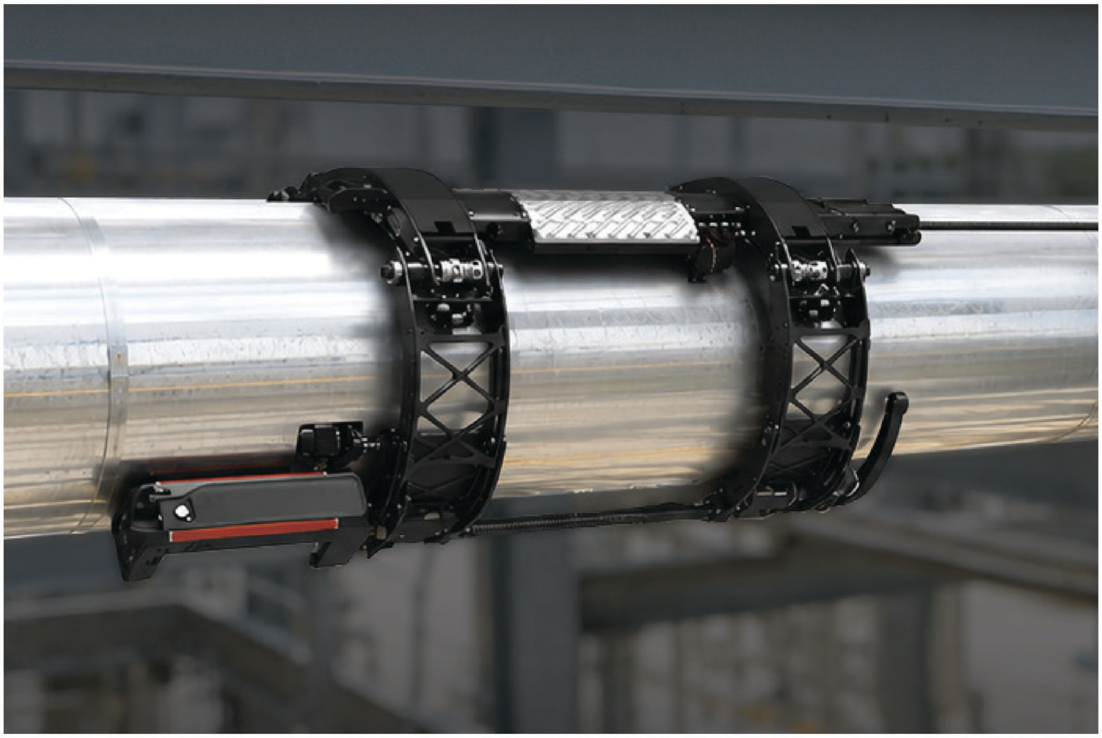

Figure 1. Example of a clamping robot. Image courtesy of ARIX Technologies, Inc.

an important role. Robotic systems can now record inspection data continuously, along with position information that allows each data point to be tied to a specific location on the pipe. This creates a structured dataset that can be reviewed, analyzed, and compared over time. In contrast to manual inspections, the robotic approach can often provide a more thorough and traceable record of what was inspected.

Another key development in recent years has been the ability to combine multiple inspection techniques on a single platform. For example, real-time radiography (RTR) can be used as a screening method to identify moisture within the insulation and provide a direct visualization of degraded coatings and corrosion, while pulsed eddy current (PEC) qualitatively measures the remaining wall loss and provides a more quantitative estimate of the severity of the corrosion than is possible with RTR alone.

Instead of focusing only on selected "susceptible" areas, it becomes more practical to scan larger portions of the piping system, and in many cases, entire piping circuits. This does not eliminate the need for risk-based prioritization, but it may change how the effectiveness of the inspections is credited due to increased coverage and, therefore, an increased probability of detection. Inaccessible areas must, however, still be considered to account for obstructions or hard-to-inspect areas (e.g., close proximity of equipment and appurtenances such as supports).

Robotics for Piping CUI Inspection

Different types of robotic systems have been developed to address specific CUI inspection challenges. Some are designed to clamp onto the pipe and move along its surface, attempting to maintain constant contact while carrying inspection sensors. Others operate as balancing crawlers that can move along horizontal piping. Robotic arms and drones offer newfound flexibility, allowing inspectors to reach areas that are difficult to access with surface-mounted systems. Each approach has its own strengths and limitations, depending on factors such as pipe geometry, accessibility, and the type of inspection being performed.

Clamping Robots

Clamping robots use a mechanical design that "hugs" the pipe and uses a multitude of wheels with rubber tires to propel itself along the surface of the pipe. The design allows them to be used on both horizontal and vertical pipes (or any orientation in between). With steerable wheels, the robot can drive along the pipe, rotate around it, or any combination thereof, to execute the most optimal scan pattern for full coverage 360° inspections. A limitation of the clamping robots is that they are designed for specific pipe diameters and that they need to be manually moved around some fittings, such as flanges, valves, and elbows. The length of the robot along the pipe also places a limitation on the minimum required pipe section length, between two obstacles, that can be inspected.

Balancing Crawlers

Another common architecture is balancing crawlers, which balance and propel themselves along the top of horizontal pipes, usually with a set of tracks. The tracks that propel these robots are effective for driving over damaged or uneven insulation cladding, as they distribute the weight over a larger area. Due to the balancing nature of this design, they are limited to horizontal pipes, and their inspection payload is mounted to inspect one or more fixed angles (azimuths) of the pipe, such as the bottom (6 o'clock) position where water is most likely to accumulate. Similar to clamping robots,

Table 1. Comparing strengths and weaknesses of architectures.

	Clamping Robot	Balancing Crawler	Robotic Arm	UAV/Drone
Pipe orientation	Any orientation	Horizontal only	Any orientation	Any orientation
Inspection Coverage	360° full coverage	Fixed angles of the pipe	360° full coverage	360° (spot measurements)
NDT payloads for CUI	PEC+RTR (simultaneously)	RTR	PEC or RTR (not simultaneously)	PEC
Obstacle traversal	Partial - can drive over some pipe supports. Needs to be moved around some fittings.	Partial. Needs to be moved around some fittings.	N/A – not limited by obstacles along the pipe	N/A – not limited by obstacles along the pipe
Clearance needed around the pipe	Low clearance all around	Low clearance on the sides, more on top of the pipe	Needs a clear path from the inspection point to the base of the arm	Needs significant clearance in direction of approach towards the pipe
Typical productivity	Higher - hundreds of feet per day, thousands of PEC data points	Higher - hundreds of feet per day	Lower	Hundreds of PEC spot readings per day
Operational complexity	Lower	Lower	Higher, due to system complexity	Higher, due to weather, safety, & regulatory
Inspectable assets	Piping only. Limited to specific diameters.	Piping only. Limited to specific diameters	Piping of any diameter. Vessels and other assets.	Piping of any diameter. Vessels and other assets.

balancing crawlers can move along the pipe relatively quickly, and the two types are typically the most productive pipe inspection robots. But unlike clamping robots, balancing crawlers cannot rotate around the pipe to perform inspections with a variable number of scan lines (as required in PEC inspections, for example) or achieve true full coverage inspections. Balancing crawlers are also limited to specific pipe diameters, and they also need to be manually moved around the same fittings. They also have a minimum inspectable pipe section length between obstacles, based on the length of the robot.

Robotic Arms

The third architecture of note is the robotic arm. A multi-linkage robotic arm, typically powered by a combination of electric and pneumatic power, provides a tool to reach piping from ground level, with a variety of inspection methods. Since the arm does not attach to the pipe itself, this provides the flexibility to inspect pipes in any orientation, as well as fittings. The arm can be manipulated to reach around the pipe from multiple angles and achieve full inspection coverage. They may also be used to inspect non-piping assets. This flexibility comes at the cost of higher operational complexity and generally lower inspection productivity compared to the previous two architectures. The robots themselves are significantly larger, have higher power demands, and are more complex to program and control. The inspection needs to be planned out carefully, for example, to decide how to place and move around the base of the robotic arm to provide a clear path to the inspection object without interfering with other nearby equipment.

Drones

The last architecture to mention is the aerial inspection drone, also known as an unmanned aerial vehicle (UAV). UAVs are often placed in their own category, but they are effectively flying robots. They do not attach to the piping in any way, which provides flexibility to approach the piping from any accessible direction or orientation, as well as the ability to inspect non-piping assets. Some designs developed in recent years have enabled inspection UAVs to effectively pivot in mid-air and reach any accessible point on the pipe, for example with a PEC probe. This feature improves their ability to inspect any portion of the piping, but it does require significant room to maneuver, so may be limited in congested areas, such as pipe racks. Other NDT equipment, such as RTR, is typically too heavy to be deployed by UAVs. UAVs are more susceptible to weather conditions, and their motion control makes them more suitable for collecting point measurements at discrete locations, rather than providing full (scanning) coverage. UAVs also introduce other safety and regulatory requirements – for example, unlike the other designs, a UAV cannot be safely powered down on immediate notice in an emergency, such as a gas leak.

The strengths and weaknesses of the four architectures described above are summarized in **Table 1**.

Table 1 provides a high-level qualitative comparison only. A more detailed quantitative analysis should be performed before selecting the appropriate technology for a given inspection project.

The Future of CUI Inspections

Advancements in robotic inspection systems highlight a shift in how CUI inspections can be performed. It is becoming more practical to move beyond limited sampling-based approaches and begin inspecting much larger portions of piping systems in a consistent and repeatable way. While the capabilities vary across different approaches, the overall direction is clear: robots expand what can be inspected and can reduce the amount of inference.

Clamping robots and robotic arms, in particular, make it possible to access the full circumference of a pipe and collect data along continuous scan paths, allowing for less limiting and less isolated sampling. Instead of inspecting a few selected locations and extrapolating the results, inspectors can directly measure the condition of a much larger portion of the asset. This fundamentally changes the level of confidence in the inspection results.

In practical terms, full coverage does not necessarily mean that every square inch of piping is inspected with the same level of detail, but it does mean that larger sections—sometimes entire circuits—can be screened in a systematic way. Areas of concern can be identified with higher confidence, while larger areas can be positively confirmed as free of damage. This reduces the need for more conservative assumptions when planning maintenance or repairs.

It is important to remember that robotic systems have constraints. Therefore, there are still areas that cannot be inspected as part of a continuous scan. Complex geometries, congested layouts, and certain pipe configurations will always introduce gaps that must be managed in other ways. From a practical standpoint, this means that robotics should not be viewed as a standalone solution, but rather as a part of a broader inspection strategy.

This leads to the concept of a hybrid approach where "full coverage" is best understood as an achievable outcome at the system level, rather than something delivered by a single tool. Robotic systems can efficiently and consistently cover the majority of accessible piping, while other methods, both robotic and manual, are used to address the remaining gaps.

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For example, a clamping robot can be used to perform continuous scans along long pipe runs, collecting data across large areas with relatively high productivity. When the robot encounters features it cannot traverse, such as valves or complex fittings, these areas may be addressed using alternative approaches. In some cases, a robotic arm may be used to inspect these features from a different approach angle. In others, a rope access team equipped with handheld inspection tools may perform targeted follow-up inspections. In both cases, the alternative approach is focused only where it is needed, rather than being the primary inspection method.

Similarly, different robotic systems can be combined to take advantage of their respective strengths. A clamping robot may be used for high-productivity, full-circumference scanning along straight pipe sections, while a UAV or robotic arm is used to access areas with limited clearance or complex geometry. By planning inspections around the capabilities of multiple systems, it is possible to significantly increase overall coverage while minimizing inefficiencies.

This shift in approach also changes how inspection programs can be designed and allows a higher confidence of finding the damage (probability of detection) over larger areas to achieve the necessary risk reduction.

Conclusion

Robotic approaches do not eliminate all challenges associated with CUI inspection, but they significantly change what is possible. By enabling broader coverage, more consistent data collection, and better integration with digital inspection systems, robotics can help to better manage risks by reducing the uncertainty that has historically defined CUI programs. When combined with complementary inspection methods, these technologies can make it possible to achieve a more complete and reliable understanding of piping integrity. ■

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

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Petter Wehlin is Co-Founder and Technical Product & Program Manager at ARIX Technologies, where he helps drive the development and commercialization of robotic inspection solutions for industrial asset integrity. A Yale University mechanical engineering graduate, Petter combines deep technical expertise with a strong product and business mindset. Since joining ARIX in 2017, he has played a key role in bridging engineering, operations, and customer needs to bring innovative inspection technologies to market. Passionate about solving complex industrial challenges, he is dedicated to improving safety, reliability, and efficiency through robotics and data-driven decision-making.