ROBOTIC VISUAL INSPECTION IN CONFINED SPACES

BY EKKEHARD ZWICKER, BRANDON DEBOER, MARKUS WEISSMANN, AND ANTOINE CHEVALEYRE

Robotic visual inspection presents a promising solution to the challenges posed by confined space inspection, offering enhanced efficiency, accuracy, and safety.

Introduction

The latest advancements in robotic visual inspection technology—including the generation of digital twins, the tagging of inspection data within asset models, and the implementation of semi-autonomous control—demonstrate how robotics can effectively tackle the challenges of inspecting confined spaces. Localization technologies such as lidar (light detection and ranging) and 3D modeling are key for effective confined-space navigation. Maintaining image quality in robotic visual inspections is also important, to ensure compliance with industry standards.

The experimental validation that follows evaluates the technical capabilities of robotics and pole cameras for confined space inspection. This includes visual examination, ultrasonic thickness readings, and 3D surface scans. The integration of digital twin technology streamlines data management and facilitates post-inspection analysis.

Robotic visual inspection ultimately offers numerous benefits, including high-quality and reproducible data, reduced outage time and costs, process improvement through automation, and increased safety by minimizing human entry into confined spaces.

Challenges with Confined Space Inspection

Inspecting confined spaces presents several challenges and risks due to the unique nature of the environment, including [1, 2]:

- **Limited access.** Confined spaces are typically difficult to reach and may have restricted entry points, making it challenging for inspectors to thoroughly examine the area.
- **Poor visibility.** Many confined spaces have limited lighting or may be completely dark, hindering the ability to see potential hazards or defects.
- **Restricted movement.** Inspectors may face difficulties maneuvering within confined spaces due to narrow passages, obstacles, or equipment obstructions.
- **Communication challenges.** Communication between workers inside a confined space and those outside can be challenging due to physical barriers or poor reception, increasing the risk of accidents or delays in emergency response.
- **Time constraints.** Inspections in confined spaces often require careful planning and coordination to ensure the safety of personnel. Time constraints may arise due to limited availability of access or the need to complete inspections quickly to minimize disruption to operations.
- **Training requirements.** Inspecting confined spaces requires specialized training and expertise to identify potential hazards and implement safety protocols effectively. Lack of proper training can increase the likelihood of accidents or errors during inspections.
- **Documentation and reporting.** Proper documentation of confined space inspections is crucial for regulatory compliance and risk management. However, maintaining accurate records can be difficult, especially in remote or hazardous environments.
- **Emergency preparedness.** In the event of an accident or emergency inside a confined space, rescuing workers can be complex and time-consuming. Inspectors must be adequately trained in emergency procedures and have access to the appropriate rescue equipment.
- **Regulatory compliance.** Confined space inspection must adhere to stringent safety regulations set by authorities such as OSHA (the Occupational Safety and Health Administration) in the US. Failure to comply with these regulations can result in legal repercussions and jeopardize worker safety.

Addressing these challenges requires careful planning, appropriate training, and the use of advanced technologies and safety measures to ensure the effectiveness and safety of confined space inspections.

Limitations of Remote Visual Inspection

Remote visual inspection (RVI) conducted in confined spaces such as pressure vessels, reactors, and boilers, whether using a remote-controlled crawler or a camera mounted on a pole, often relies heavily on manual control. The crawlers are piloted remotely, data is captured manually, and reports are subsequently created by transferring this information into predesigned templates. This disconnected approach presents several challenges. First, there is no direct link between the captured data and its specific location within the asset. Second, this manual process (Figure 1) demands significant additional effort to leverage the data for internal processes and integrate it with the digitalization strategies of asset owners and operators.

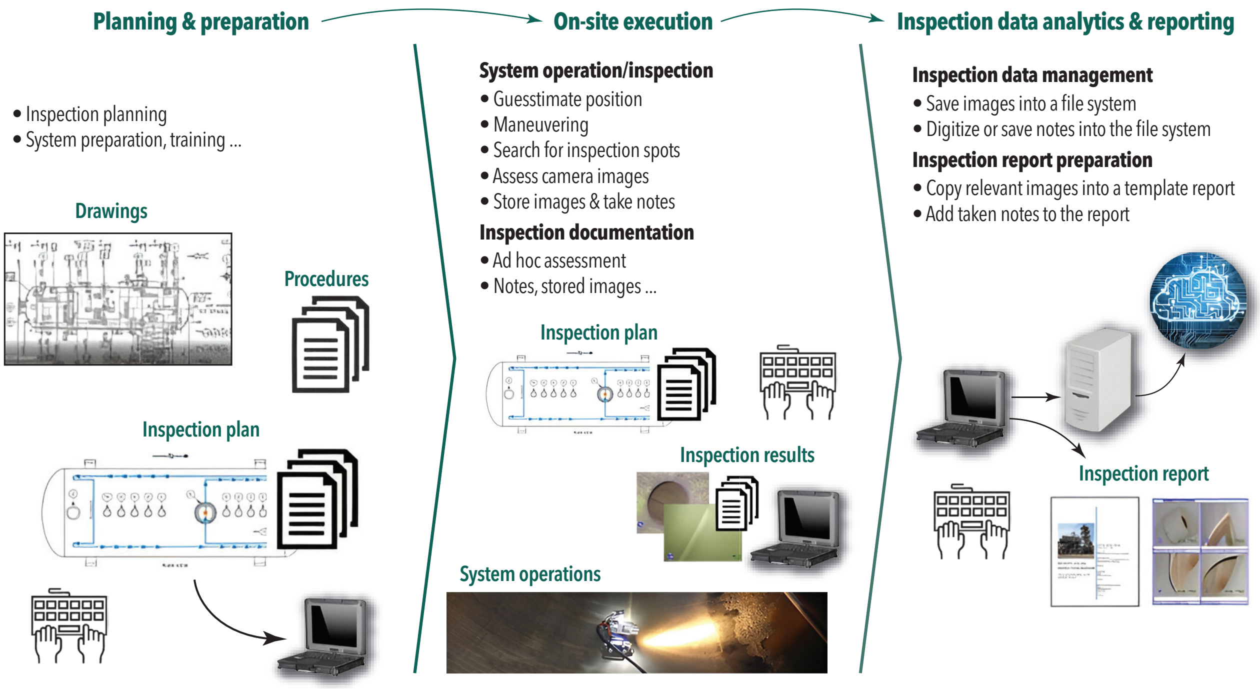


Figure 1. Remote visual inspection (RVI) process involving manual preparation, inspection, and documentation.

Advantages of Robotic Visual Inspection

The latest state-of-the-art robots create digital twins, tag inspection data positions within the asset model, and provide 3D semi-autonomous control. These robots then generate inspection reports automatically and directly upload the data into asset performance management systems. Recent technology is moving toward refining this new process of robotic visual inspection while supporting a seamless integration into asset owners' digital strategy. By using the latest robotic technology, inspections are now semi-automated, data is automatically stored, and asset inspections can be compared over time.

Robotics visual inspection offers several compelling advantages for inspecting confined spaces, including:

- **Enhanced visibility.** Robotic systems equipped with high-definition cameras can provide superior visual inspection capabilities compared to human inspectors. These cameras can capture detailed images and videos of the interior of confined spaces, allowing for thorough examination of equipment, structures, and components. The enhanced visibility offered by robotic visual inspection ensures that potential defects, damage, or anomalies are detected with precision.
- **Consistency in inspection.** Robotic visual inspection systems can follow predefined inspection paths and parameters consistently, ensuring uniform coverage of the entire confined space. Unlike human inspectors, robots do not suffer from fatigue or distractions, which can compromise the thoroughness and accuracy of inspections. This consistency in inspection results in high-quality data for analysis and decision-making.
- **Safe accessibility to hazardous environments.** With the use of robotics, human entry into confined spaces can be eliminated, and the related efforts and challenges as previously described (limited access, restricted movement, communication challenges, required confined space training, emergency planning and measures) are reduced.
- **Real-time monitoring and feedback.** Robotic visual inspection systems can provide real-time monitoring and feedback during inspections. As the robot navigates through the confined space, operators can view live video feeds and data from onboard sensors, allowing them to assess the condition of assets immediately. Any abnormalities or issues identified can be addressed promptly, minimizing downtime and reducing the risk of potential failures.
- **Comprehensive documentation and reporting.** Robotic visual inspection systems can automatically capture and store visual data, creating comprehensive documentation of inspections. These records can include images, videos, timestamps, and annotations, providing a detailed history of the condition of assets over time. Additionally, automated reporting features enable the quick and accurate generation of inspection reports, facilitating compliance with regulatory requirements and internal quality standards.

- **Integration with data analysis tools.** Visual data captured by robotic inspection systems can be integrated with data analysis tools and software for further analysis. Advanced image-processing algorithms can detect patterns, anomalies, or defects in visual data, supporting predictive maintenance and asset management strategies. By leveraging the power of data analytics, companies can optimize maintenance schedules, extend asset lifespan, and reduce operational costs.

These advantages make robotic visual inspection a valuable solution for industries seeking efficient, accurate, and safe methods of assessing confined spaces and maintaining critical assets.

Key Technology: Localization and Data Geotagging

Robotic localization technology for autonomous operation and reporting is available and is used by both drones and mobile robots on the plant level. However, most modern localization technology cannot be applied to confined spaces due to the lack of GPS reception, weakly textured surfaces, asset size, and complex geometries.

Current robotic practice in GPS-restrictive areas is simultaneous localization and mapping with lidar remote sensing technology. By using a lidar, a point cloud of the environment is created, and a mesh is stitched together simultaneously while the robot is moving. By comparing the point clouds and mesh, the absolute distance between positions can be computed, and the robot can be located within an asset.

Another much simpler approach is to provide a 3D model of the asset as input, measure the distance from the robot to a specific point on the asset, and compare this with the distance calculated using the corresponding position in the 3D model. To increase accuracy and repeatability, additional navigation sensors are integrated into the localization process. These include an inertia measurement unit (IMU), odometry (distance measured by the driving wheels), and kinematic constraints. All this data is combined using a particle filter and/or a Kalman filter. This allows for the calculation of the robot's 3D pose (position and orientation within the asset) and the specific location in the 3D model where the inspection camera is directed (Figure 2).

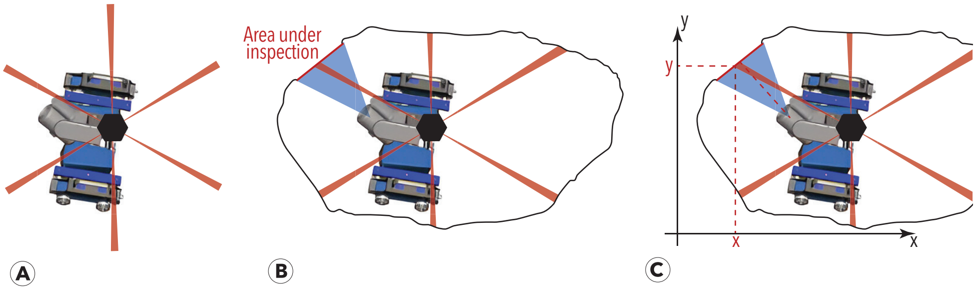
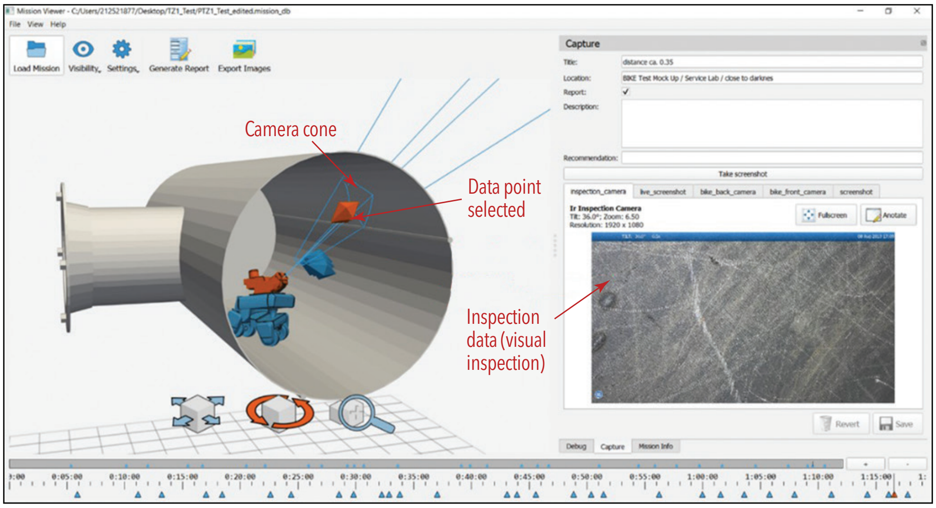


Figure 2. The approach to calculate the 3D pose of a robotic system in a confined space and to localize the inspection camera view on the asset being observed: (a) robot with distance sensors (lidar), IMU, and odometry; (b) confined environment; (c) localization of robot and inspection data.

As a result, the system can geotag all images to the 3D model and store them in a database along with the camera settings at the time of capture, such as zoom level, lighting, and resolution (Figure 3).



Title: distance ca. 0.35
Location: BIKE Test Mock Up / Service Lab / close to darknes
Report: ✓
Description:
Recommendation:

Ir Inspection Camera
Tilt: 36.0°; Zoom: 6.50
Resolution: 1920 x 1080

Figure 3. 3D digital twin software calculates the view cone of an inspection camera and automatically links the captured image with the correct asset coordinates. The data can be edited and amended with comments and sketches.

Notes—either as text or created with a drawing editor—can be added to the images during the inspection or later when creating the documentation. These annotated images are then stored in the database. The inspection report can be generated automatically using templates (Figure 4).

A primary goal is to minimize the time spent on-site and inspecting the asset. The planning of the inspection, based on the inspection plan, can be completed before the mission by utilizing a 3D model and a virtual representation of the robot and inspection camera system. This can be achieved through a sophisticated simulation tool, which enables running the inspection scenario to assess technical feasibility

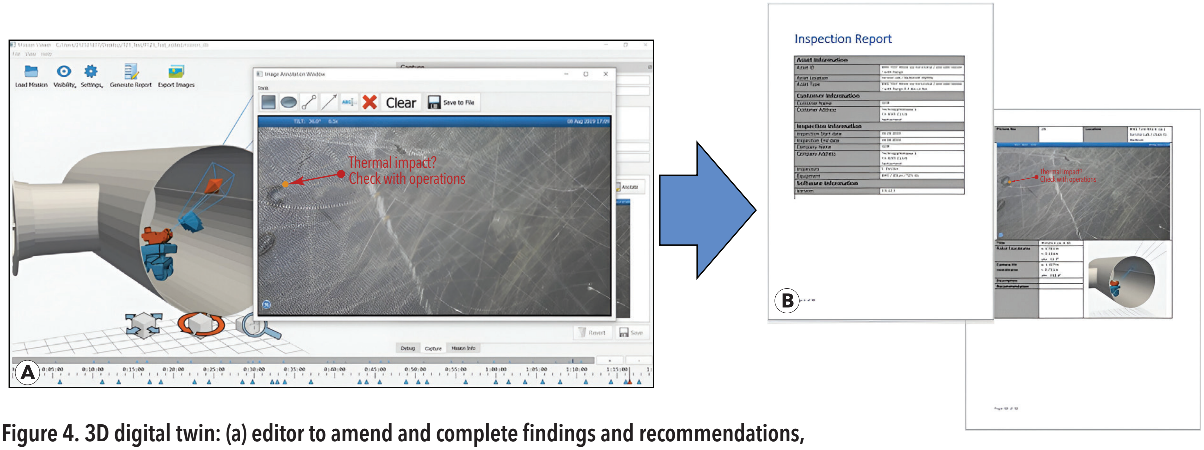


Figure 4. 3D digital twin: (a) editor to amend and complete findings and recommendations, possibility to annotate inspection data; (b) automatically generated inspection report.

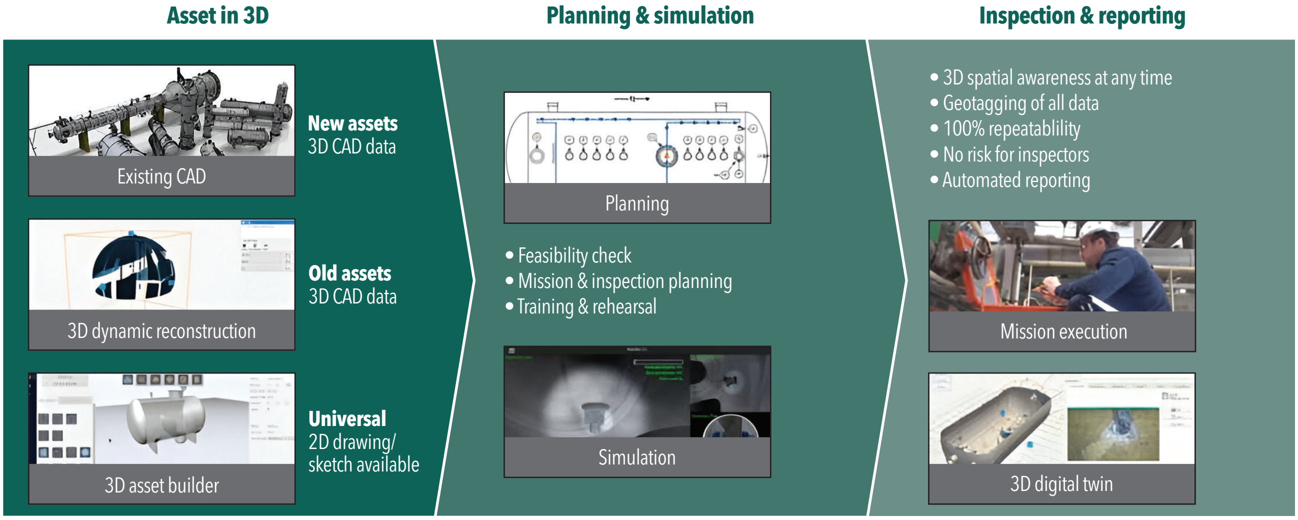


Figure 5. Integrating planning and simulation, using the 3D virtual representation of the asset and the kinematic representation of the robot with the camera and the cables.

and provides an opportunity to train and rehearse the inspection (Figure 5).

Recommended Practices for Robotics-Based Remote Visual Inspection

Close visual inspection is a top priority for robotic applications, but there are discussions about whether robotics-based remote visual inspection (RVI) can fully replace close visual inspection (CVI) performed by a human. Several RVI limitations have been identified, including the robot's distance from the inspection surface, limited viewing angles, lack of tactile feedback, absence of surface preparation or deployment of inspection aids, and challenges with artificial lighting. Due to these limitations, it is advised not to claim robotics-based RVI as a complete replacement for human CVI. Instead, robotic inspection should complement conventional CVI by identifying areas that require further examination.

Standards such as ASME V Article 9 [6] and BS EN 17637 [7] specify spatial resolution requirements for CVI and direct visual inspection (DVI), typically around 3 line pairs per millimeter (lp/mm) under optimal viewing conditions, based on human eye acuity. Although ASME V Article 9 also references the visibility of fine lines, this is not considered a reliable measure of spatial resolution. To comply with ASME V Article 9, robotics-based RVI images should demonstrate a spatial resolution of approximately 3 lp/mm, equivalent to that of CVI and DVI.

The "HOIS Guidance on Image Quality for UAV/UAS–Based External Remote Visual Inspection in the Oil & Gas Industry" [5] provides detailed guidance on maintaining image quality during uncrewed aerial vehicle (UAV) inspections within the oil and gas sector. Its goal is to ensure that the images obtained are of sufficient quality for engineering assessments of component integrity, aiding asset operators in making critical decisions about continued operation. While the HOIS guidance focuses exclusively on

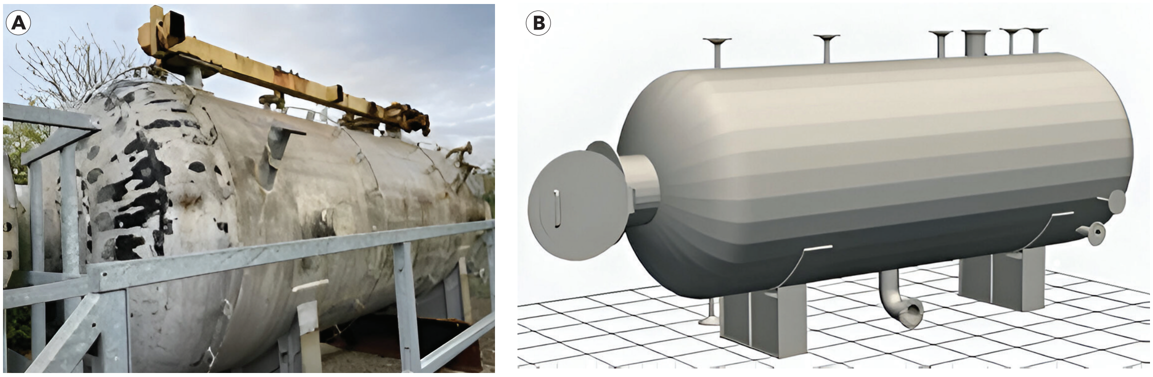


Figure 6. Digital twin created from asset drawings: (a) photo of asset; (b) digital twin.

image quality, it does not address safety and operational aspects of UAV deployment, which are covered in separate publications.

The same guidelines for an UAV-based visual inspection can be applied to robotic crawlers.

The guidance identifies three priority applications for UAV and robotics-based RVI among members of the HOIS organization [8]: achieving CVI resolution, assessing coatings to ISO 4628 standards, and inspecting flare tips/stacks. While both still images and videos are considered, the document places more emphasis on still images, as they are typically more common in final inspection reports.

Specific guidance is also provided regarding spatial resolution requirements for each of the priority applications, along with methods for verifying that the achieved resolution meets these standards. Additionally, the importance of image signal-to-noise ratio (SNR) is highlighted as a critical quality criterion, with recommendations for minimum SNR values and maximum ISO settings for cameras. Information on these settings can often be obtained from resources such as the DxOMark website or estimated based on the camera's sensor element area.

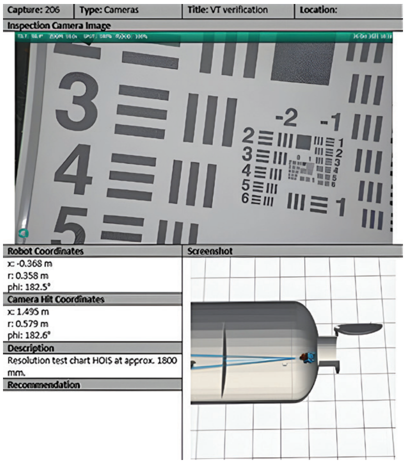
General advice covers various aspects of UAV and robotics-based RVI, including considerations for viewing direction, ambient light levels, and camera settings. It also addresses file formats and post-processing software for both still images and videos.

Overall, the document serves as a comprehensive guide for ensuring adequate image quality in UAV-based RVI within the oil and gas industry. It offers specific recommendations for key quality criteria and priority applications while providing general guidance on related aspects.

Experimental Validation

To validate the technical capabilities of both robotics and pole cameras for confined space inspection, we conducted an extensive visual examination of a test vessel. In addition to visual inspection, we took ultrasonic thickness readings at designated spots on the hull and conducted 3D surface scans on sections affected by corrosive pitting. All this data was geotagged (localized) in a digital twin optimized for inspection, which was built from customer drawings (Figure 6).

The test was conducted using an ultra-mobile robotic platform that allows it to climb over obstacles [8]. The robot is equipped with a visual inspection camera, an ultrasonic probe, and a structured white light–based surface scanning system. Utilizing 3DLOC technology, it can calculate the robot's pose within the vessel and geotag the images to the 3D virtual model (as described previously in the "Key Technology: Localization and Data Geotagging" section).



Capture: 206 | Type: Cameras | Title: VT verification | Location:

Robot Coordinates

x: -0.368 m
r: 0.358 m
phi: 182.5°

Camera Hit Coordinates

x: 1.495 m
r: 0.579 m
phi: 182.6°

Description

Resolution test chart HOIS at approx. 1800 mm.

Recommendation

Figure 7. USAF test chart at 1.8 m distance and typical reporting structure.

To assess image quality, an USAF 1951 resolution chart was utilized within the vessel, with measurements taken from a distance of 1.8 m. Figure 7 depicts the camera's capabilities, serving as an example of the output obtained from the localization data, images, and other key notes from the inspection. Typically, a report of this nature would include:

- a picture captured with the HD camera
- the coordinates of the robot within the 3D model
- the coordinates of the camera hit point on the surface
- a screenshot of the crawler's position and stance at the time the image was captured
- descriptions and recommendations as necessary.

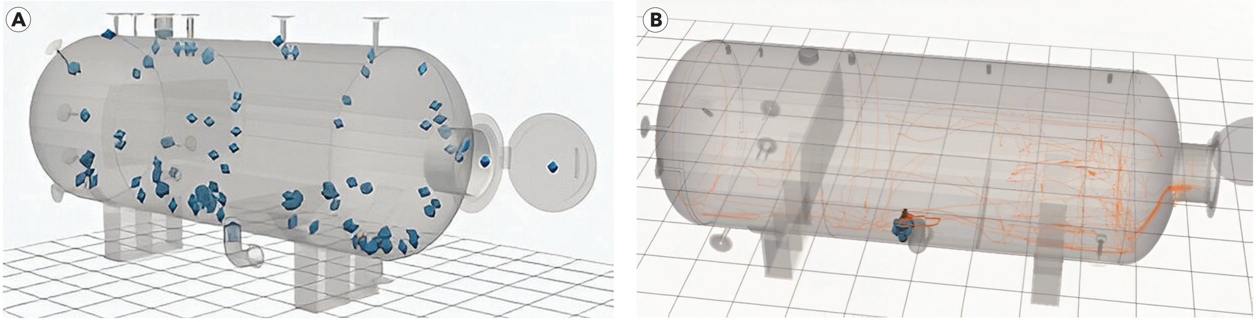


Figure 8. Overview of the (a) complete inspection locations and (b) path driven by the robotic crawler.

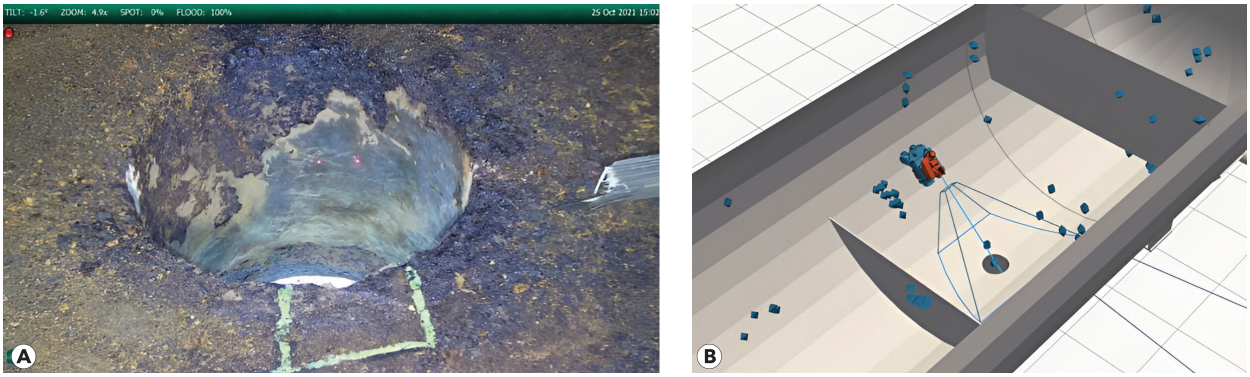


Figure 9. Close-up of (a) nozzle and (b) its positioning in the digital twin.

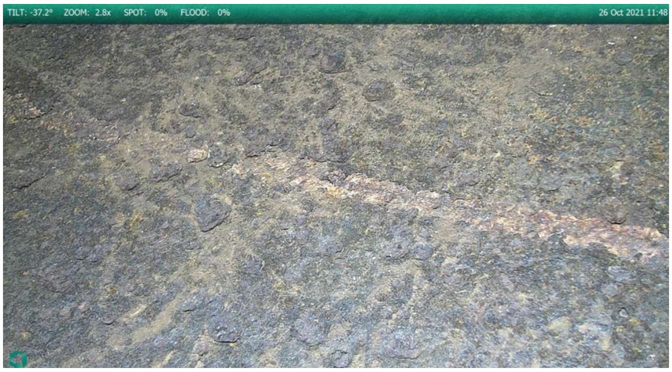


Figure 10. Close-up of the shell surface.

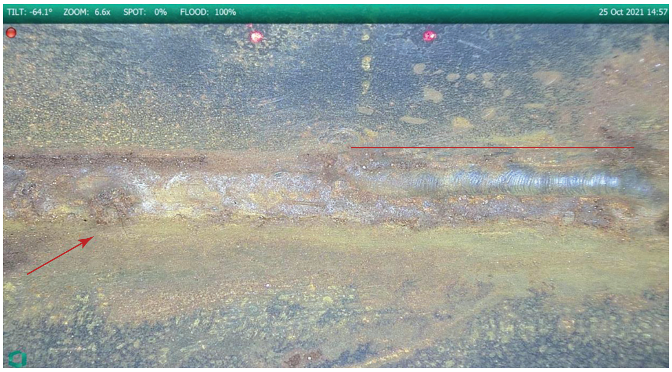


Figure 11. Close-up of a support weld with some annotations. Note the two laser dots that allow a rough dimension of findings.

The comprehensive examination of this vessel involved a detailed focus on crucial zones such as nozzles, supports, and welds (Figure 8). Each photograph captured during the inspection has been precisely marked within the 3D model, indicating their specific positions (Figure 9). Additionally, a complete video feed of the inspection was recorded.

During the meticulous examination of the vessel, significant internal corrosion and clusters of pits were identified (Figures 10 and 11). Relevant findings were recorded in the report, prompting further investigation using 3D surface scanning techniques to accurately determine the dimensions and depths of the affected areas (Figure 12).

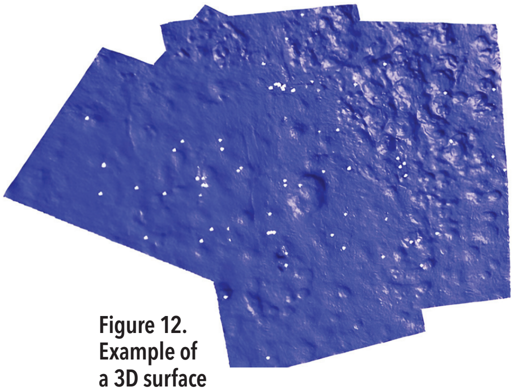


Figure 12. Example of a 3D surface scan of the shell.

Results and Discussion

The comprehensive test conducted on the vessel, coupled with a direct comparison with a manual inspection carried out by an inspector entering the vessel, met the requested standards for inspection quality. The creation of a digital twin streamlined the handling and management of inspection data, facilitating easier analysis post-mission. The automatic generation of the inspection report also significantly reduced the time required for post-inspection tasks.

The trials demonstrated that robotics-based RVI can effectively detect various damage mechanisms in vessel shells and internal structures. However, factors such as lighting angles, camera positions, and automated settings can impact image quality and the detectability of pitting. Localized pitting detection with zero-degree ultrasonic inspection proves ineffective in heavily corroded vessels, with external ultrasonic testing showing greater success. RVI, structured light, and stereoscopic imaging can measure anomaly width, length, and depth, although the accuracy may vary depending on inspection conditions.

Vessel cleanliness plays a crucial role in achieving optimal inspection results, and while high coverage is attainable, it relies on the inspector's estimation. Although calibration charts may aid in assessing camera performance, their direct correlation with overall inspection effectiveness remains unclear. Utilizing a plastic test piece offers a cost-effective method to validate RVI capabilities, and the integration of 3D mini-digital twins enhances reporting compared to traditional PDF formats.

For more detailed information on the conducted test and comprehensive results analysis, refer to the HOIS report "HOIS-R-070 C20-03 RII Practical Trials Report" [3].

Conclusion

In summary, the benefits of using robotic visual inspection for confined spaces in industry include:

- **High-quality, reproducible inspection data** tagged with the asset's position and stored in a database.
- **A 3D virtual model tagged with inspection data**, known as a "digital twin," which serves as an IoT (Internet of Things) building block and supports digital integration strategies (such as asset performance management systems and data analytics). The digital twin acts as the front end for these tools, allowing for comparison of repeat inspections with previous ones to calculate trends and predictions.
- **Reduced outage time and costs** through offline preparation using virtual planning and training. Safe and simple operation of the robotic tools is supported by full 3D spatial awareness and 3D interactive control, along with automatic inspection report generation.
- **Process improvement through task automation** (such as automatically repeating missions) and autopilot functionality, enabling inspectors to focus more on the inspection and less on system operation.
- **Increased safety** by avoiding human entry into confined spaces.

These benefits apply to both asset owners and service companies.

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VISUAL TESTING METHOD PERSONNEL QUALIFICATION AND CERTIFICATION: AN OVERVIEW

BY MIKE ALLGAIER

Most major nondestructive testing (NDT) personnel qualification and certification (PQ&C) schema address visual testing (VT) as a standalone NDT method. However, there are significant differences between the details of these elements. Various codes, standards, and specifications delineate various requirements for personnel education, experience, training, and examination of the candidates for certification. This article addresses the common elements needed for PQ&C across different codes, standards, and guidelines.

Introduction

Visual testing (VT) has long been integral to other NDT methods, as it historically has served as a prerequisite for those methods. It was a prerequisite to liquid penetrant testing (PT), magnetic particle testing (MT), ultrasonic testing (UT), and radiographic testing (RT) when it was stated in those methods that "surface conditions that would interfere with the examination should be evaluated and removed." Level I/II certification took for granted that the prerequisite to PT and MT included the VT knowledge and skills.

The VT method has gained its own method status over the last 50 years. Early VT tools included the human eye, a magnifying glass, a dental mirror, a 6-in. steel scale, a 12-in. wooden ruler, and maybe a 50-ft tape measure. Today, how to examine an object has changed. The advent of digital imaging has offered a great expanse in the variety of instruments available to capture digital images and allow analysis of the part condition, including measurement techniques that are more and more sophisticated. Remote visual inspection, also known as RVI, can be used to inspect areas of infrastructure from a distance that are too dangerous, remote, or inaccessible for direct visual inspection. RVI technologies include remotely operated cameras, borescopes, videoscopes, fiberscopes, and drones.

Background

When exploring PQ&C schema for VT, we discover two major categories. The first is direct VT (DVT) and the second is indirect VT, more commonly referred to as RVI.

The DVT examination definition taken from the *ASME Boiler and Pressure Vessel Code,* Section V: *Nondestructive Examination*, Article 9, *Visual Examination,* states that the eye should be within 24 in. of the surface to be examined and at an angle not less than 30°. This can include aids such as a magnifier or mirror. The term "aid" implies that the surface can be inspected without these tools, hence the direct method of VT.

RVI is used when the above criteria for DVT cannot be met—for example, when the surface under inspection is *only* accessible with a mirror, a magnifying glass, a series of lenses in a borescope, a bundle of fibers, a charge-coupled device transmitting the image to a monitor (such as a videoscope), or a telescope for long-distance inspections.

With either category for evaluating hardware, there are three pillars, or goals:

- to acquire an acceptable image,
- to evaluate the part, component, or system test results, and
- to disposition those test results to the appropriate acceptance or recording criteria.

To perform these steps, the inspector or examiner needs to possess the core knowledge and basic skills for common applications. In addition, industry-specific knowledge and skills unique to various industries, products, or VT techniques are also required. These are called industry specific segments (ISS). When comparing various industry PQ&C requirements, we observe overlaps, omissions, and unique criteria across different programs. Some VT requirements are common across all industries, while others are unique to certain ISS.

Elements of Personnel Qualification and Certification

Proper execution and evaluation of any VT application requires the inspector or examiner to be qualified in the VT method using the applicable techniques. Compliance with those qualifications, along with written documentation and a summary sheet, is known as certification. Following are a few of the common schema for VT PQ&C used in the NDT industry.

American Society for Nondestructive Testing (ASNT)

The original recommendations for NDT PQ&C date back to 1968 with the publication of ASNT Recommended Practice No. SNT-TC-1A: *Personnel Qualification*