Tethered Robotics for Unpiggable Pipelines: the Development and Field Deployment of TRITON

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Abstract

Ensuring the integrity of pipeline systems is critical for optimizing operational efficiency, minimizing environmental impact, and safeguarding personnel and public safety. Neglecting pipeline maintenance can lead to reduced production and, in the worst cases, catastrophic failures due to undetected cracks or corrosion.

Traditionally, pipeline operators rely on in-line inspection (ILI) pigging solutions, which require specific pig launching and receiving facilities. When such facilities are unavailable, pipelines are often deemed unpiggable or challenging to inspect. In these cases, external surface inspection becomes the alternative, although this approach is not always feasible due to pipeline material or external obstructions.

This paper introduces two case studies that showcase the evolution of a new crawler-based inspection delivery method. This method enables targeted inspections using remotely operated scanning technologies and represents the next step toward full integration with ILI scanner systems for comprehensive pipeline inspection.

Introduction

Integrity management of pipeline systems is crucial for optimizing efficiency and production rates while minimizing environmental impact and ensuring the safety of personnel and the public. Neglecting the maintenance of pipelines can result in decreased production and, in the worst-case scenario, lead to catastrophic failures due to unidentified cracks or corrosion.

Traditional ILI technologies, such as pigging, are widely employed to assess pipeline condition. A pig is typically a cylindrical tool that fits tightly inside a pipeline and is equipped with sensors to gather data about its internal condition. The pig is propelled through the pipeline by the flow of the product, such as oil, gas, or water. Once a run has been completed, the recorded data is removed and analyzed to assess the pipeline's structural integrity and identify issues requiring repairs.

However, pipelines without pig launching and receiving facilities or with geometric complexities, limited access points, or operational constraints often fall outside the scope of these conventional methods, rendering them unpiggable. External inspection techniques, while sometimes viable, are often impractical for pipelines due to location or expense.

Tethered inspection solutions have emerged as a viable alternative for pipelines that cannot be inspected using traditional ILI technologies. These systems rely on robotic crawlers or probes connected via a tether, which provides power, data transmission, and retrieval capabilities. Tethered systems are often deployed in scenarios where limited access points, single-entry designs, or complex geometries prevent the use of free-floating tools like pigs.

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Current tethered solutions are equipped with a range of inspection technologies, including high-resolution cameras, ultrasonic testing (UT) tools, and laser scanning systems. These technologies enable the detection of internal anomalies, corrosion mapping, and wall thickness measurements. Many tethered systems are designed for bidirectional navigation, allowing them to operate in both forward and reverse directions.

Despite these advancements, existing tethered solutions face significant challenges. Their operational range is often constrained by the length and weight of the tether, which can limit their applicability in longer pipelines. Navigating sharp bends or vertical sections can also be problematic, as many systems lack the flexibility or precision required to handle such features. Furthermore, some tethered tools are limited to single inspection modalities, which may not provide comprehensive data for a complete assessment of pipeline integrity.

The limitations of current tethered solutions highlight the need for more advanced systems capable of overcoming these challenges. Enhanced mobility, improved robotics, tether management capabilities, and, most importantly, multi-modal inspection capabilities are critical areas for development to expand the applicability of tethered inspection technologies.
The Triton tethered robotic inspection system was engineered to overcome the challenges of inspecting unpiggable risers and pipelines. Initially developed to navigate complex pipeline geometries and perform precise, targeted assessments, Triton combines state-of-the-art robotics with advanced Non-Destructive Testing (NDT) technologies. In November 2024, a project commenced to integrate NDT Global's in-line inspection (ILI) tooling with Triton. This advancement transforms Triton from a solution focused solely on localized inspection into a comprehensive full-line inspection system, equipped to deploy an extensive suite of ILI tools and technologies.
This paper examines the system's technical capabilities and operational performance, supported by field results from two distinct inspection campaigns. It also details the first Triton integration with NDT Global's ART Scan technology and explores the future potential of advancing pipeline inspection solutions.

Case Study 1: Internal Riser Inspection of an Offshore Riser for bp.

The operational integrity of subsea assets is essential to ensure safe and efficient offshore production. The North Sea presents unique challenges for offshore platforms, with extreme environmental conditions such as high winds, freezing temperatures, and rough seas. These conditions, combined with the corrosive subsea environment, demand rigorous inspection and maintenance protocols for critical infrastructure such as risers and pipelines.

Figure 1 Offshore riser

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bp faced a significant challenge with a 14-inch (365 mm) duplex riser on one of their offshore platforms in the North Sea. Initially installed as a spare, the riser had remained unused.

As part of a new development project, bp planned to commission the riser but required a comprehensive internal inspection to confirm its integrity. The inspection specifically targeted cracks in the circumferential welds and areas of possible corrosion. It was critical to determining whether the riser could be safely integrated into the project timeline and operational framework.
The duplex riser's unique design presented considerable challenges for conventional inspection methods. With a single entry and exit point, it measured 328 ft (100 m) in length with a wall thickness of 1.9 in (48.8 mm) and included recessed welds every 32 ft (10m) as well as three complex 90-degree bends with a radius of 3D. An external inspection was deemed infeasible due to geometric and environmental constraints, while the internal inspection was further complicated by the riser being partially flooded with anti-corrosion fluid, which was maintained at elevated temperatures.

From Challenge to Custom Robotic Solution

To address these challenges, bp engaged TSC Subsea to design and develop a tethered robotic inspection system specifically designed for internal pipeline and riser inspections in scenarios where traditional ILI tools were unsuitable. Its bidirectional mobility, combined with its ability to navigate vertical sections and complex bends, made it an ideal solution for this project.
The robotic crawler was designed with a custom-built scanning system capable of a full 360-degree axial rotation to ensure full circumferential coverage of the welds while maintaining consistent probe pressure, ensuring the quality of the inspection data. Additionally, TSC Subsea engineers developed a custom umbilical management system to accommodate the riser's length and geometry.
The sensor carriage was developed for probe interchangeability so that suitable technologies could be utilized in the same delivery system.

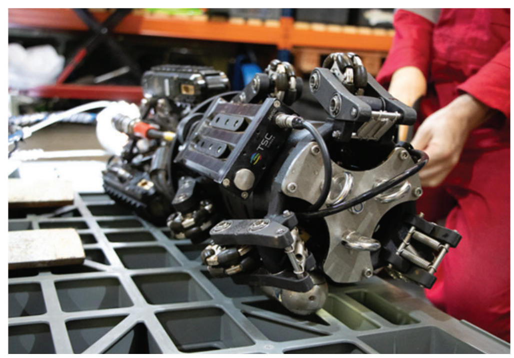

Figure 2 TRITON robotic internal pipe crawler

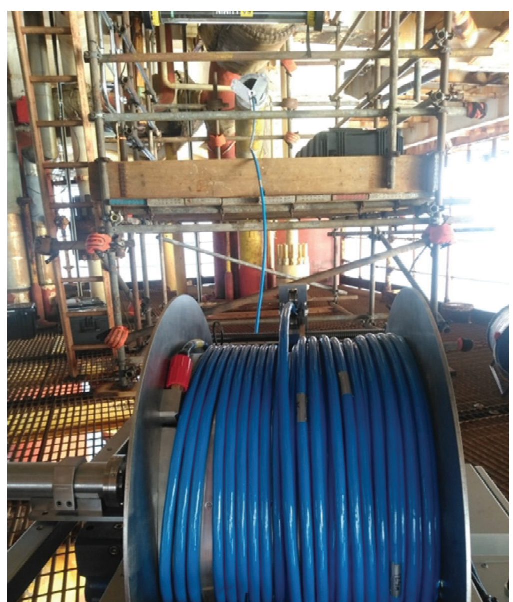

Figure 3 Umbilical management and winch system

NDT Technology Selection
bp faced several specific challenges with the unused 14-inch duplex riser, which directly influenced the inspection technology selection:

1. Complex Weld Geometry: The riser featured recessed welds every 10 meters. These areas,

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critical for structural integrity, required a precise inspection method capable of detecting surface-breaking cracks and providing volumetric assessments.

2. Material Properties: The riser was constructed from duplex steel, a material known for its high strength and corrosion resistance. However, its unique properties, such as a tendency for certain types of cracking under stress or corrosion, demanded inspection methods capable of addressing both surface and volumetric defect risk.
3. Precision Requirements: BP required both surface and volumetric data to validate the riser's integrity. The inspection needed to identify cracks, corrosion, and other anomalies with high accuracy and reliability.
4. Environmental and Operational Constraints: The riser contained anti-corrosion fluid and was maintained at elevated temperatures. These conditions required inspection technologies capable of functioning effectively in flooded environments and at non-ambient temperatures.

For this scope, Alternating Field Measurement (ACFM) was chosen to be employed for surface-breaking crack detection and sizing within the circumferential welds, and Subsea Phased Array (SPA) was selected to be utilized for volumetric weld inspection, corrosion detection, and comprehensive mapping of areas of interest.

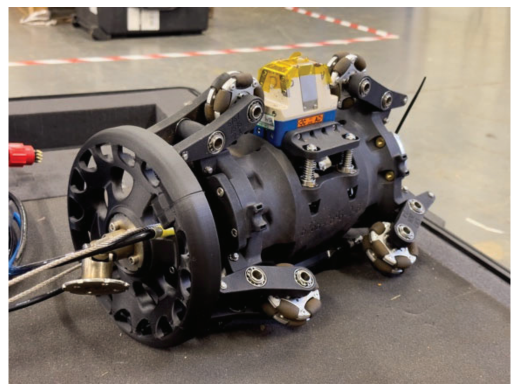

Figure 4 Sensor carriage module mounted with ACFM array probe

Alternating Field Measurement (ACFM):

ACFM is an advanced electromagnetic inspection technology widely recognized and certified by authoritative bodies such as DNV, ABS, BV, and Lloyds. It has a proven track record in detecting and sizing subsea surface-breaking cracks in welds, effectively replacing traditional non-computerized methods like Magnetic Particle Inspection (MPI).

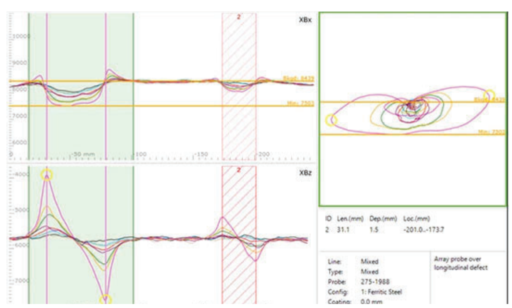

Figure 5 Sample ACFM data

Originally designed to assist divers in identifying and sizing fatigue cracking in jacket structures, ACFM has evolved into a recommended NDT technique for detecting and sizing subsea cracks. The technology works by introducing an alternating current into the surface of a component. When a surface-breaking crack is present, it disturbs the electromagnetic field. Advanced mathematical techniques then instantaneously convert the return signal, alerting operators to the presence of defects.

One of the major benefits of ACFM is its ability to provide immediate defect sizing and recording. Independent testing has shown that ACFM matches the performance of MPI in inspecting underwater structural welds, with significantly fewer missed or spurious signals compared to MPI and conventional eddy current testing. Additionally, ACFM requires less cleaning and generates fewer

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false calls, which significantly shortens inspection times and maximizes inspection campaign efficiency.

Subsea Phased Array (SPA):
Phased Array Ultrasonic Testing (PAUT) technology, initially established for high-resolution corrosion mapping and crack assessment in topside operations, was extended by TSC Subsea to subsea inspections, resulting in the SPA system. This system incorporates conventional PAUT and utilizes advanced applications with Total Focusing Method (TFM) technology.
PAUT probes comprise multiple piezoelectric crystals that can independently transmit and receive signals at different times. Time delays are applied to the elements to create constructive interference of the wavefronts, allowing the ultrasonic beam to be focused at any depth in the test specimen undergoing inspection.

PAUT can simultaneously collect A-scan data at multiple angles. This unique feature produces a volumetric beam, allowing operators to distinguish between geometric reflectors and defect signals, thus increasing the likelihood of detection. Additionally, this capability improves flexibility on complex geometries, as the beam can be steered to suit the inspection requirements. In contrast, conventional ultrasound inspection methods rely on fixed-angle probes, which can be severely restrictive when inspecting parts with unfavorable oriented discontinuities.
Further advantages of Phased Array technology include saving data sets and utilizing visual aids, making the inspection fully auditable, and allowing clients to review data sets as they are collected.

Tethered Inspection Robot Development (TRITON)

The Triton system was designed as a bidirectional tethered robotic crawler, engineered to conduct advanced inspection of pipelines and risers with complex geometries and operational constraints.
Its modular design incorporates three independently driven tracks arranged in an adaptable tripod chassis. This configuration enables Triton to navigate a wide range of pipeline orientations, including horizontal, vertical, and multiple bend sections, with the capability to handle multiple 90-degree turns seamlessly. The system is designed for use in both dry and wet conditions, including water, inhibitors, or petroleum products.


Figure 6 TRITON Crawler

Constructed from anodized aluminum and stainless steel, Triton was built to endure harsh environments, including those requiring resistance to high pressures and corrosive conditions. The system is pressure-rated for deepwater operations, ensuring reliable performance in subsea deployments.

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A suite of real-time sensors monitors pipeline dimensions and crawler expansion forces, optimizing its contact pressure for stable traction and precise maneuverability through pipelines of varying diameters.

Inspection areas are illuminated (when possible) with high-power LED lighting, while onboard cameras capture high-resolution video.

The tool was built with future integrations in mind. All of TSC Subsea's technologies can be interchangeably used with the Triton system, including Acoustic Resonance Technology (ART), Alternating Current Field Measurement (ACFM), Pulsed Eddy Current (PEC), Subsea Phased Array (SPA) and laser scanning technologies allowing TRITON to detect surface-breaking cracks, perform volumetric weld inspections, ovality and map corrosion with high resolution. These capabilities are complemented by the system's ability to perform 360-degree circumferential scans, ensuring thorough coverage of critical areas.

Factory Acceptance Testing (FAT)

Prior to deployment, a rigorous Factory Acceptance Test (FAT) was conducted to validate TRITON's capabilities. A full-scale mockup of the riser, complete with recessed welds and complex bends, was fabricated. Additionally, bp provided a duplex test sample containing hidden defects to evaluate the detection accuracy of the NDT technologies.

The FAT was conducted in two phases:

1. Detection Validation: Both ACFM and SPA successfully detected and sized all engineered defects within bp's strict engineering tolerances.
2. Navigation Testing: TRITON demonstrated seamless mobility through the riser's bends and transitions. Trials were conducted in dry and flooded pipe conditions to simulate on-site conditions. The system's integrated high-resolution cameras ensured controlled navigation, even under low-visibility conditions in the flooded environment.

Figure 7 Full-size mock-up of the riser used to demonstrate TRITON's navigation

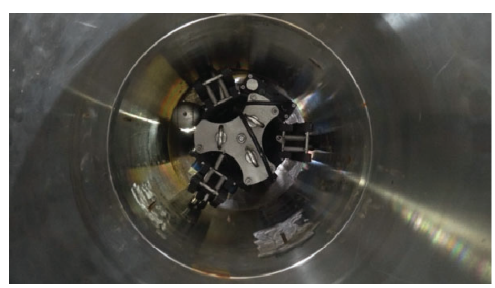

Figure 8 TRITON undergoing ACFM detection capabilities assessment.

Offshore Inspection Campaign

Following the successful FAT, TRITON was mobilized to bp's offshore platform. The inspection campaign was conducted over a five-day period and involved a multidisciplinary team of four experts, including robotic engineers and NDT specialists.

Figure 9 Offshore operation showing TRITON entering the riser.

The final solution featured a robotic crawler equipped with high-resolution cameras for navigation and visual inspections. An additional module contained the ACFM array and SPA probes, followed by a technology bottle containing the electronic circuitry. A custom winch system was used to handle the system's weight and ensure a fail-safe in case of crawler immobility.

The inspection process was executed in two stages:

- ACFM Inspections: Focused on the recessed welds, including the top toe, root, and bottom toe. All 13 welds were thoroughly examined, and no reportable defects above the minimum threshold of 0.8 in (20 mm) in length and 0.08 in (2 mm) in depth were identified.
- SPA Inspections: Performed using both water and perspex wedges to determine the optimal ultrasonic responses. The water wedge provided superior results, enabling the detection and detailed analysis of any potential volumetric anomalies. No defects were found beyond the reporting threshold.

Figure 10 TRITON exiting the riser

TRITON's bidirectional capabilities allowed it to navigate the riser's challenging geometry, including its vertical sections and bends, with precision. The inspection confirmed the riser's integrity, enabling bp to proceed with commissioning and integrating it into its development project.

Results of Triton Inspection

The successful completion of the inspection provided bp with the necessary assurance to proceed with their project. Without TRITON's innovative capabilities, bp would have faced significant delays and potential operational disruptions. This inspection not only demonstrated the effectiveness of bidirectional crawlers but also highlighted the critical role of advanced robotics and NDT technologies in addressing complex inspection challenges.

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Case Study 2: Onshore Pipeline Inspection

Shortly after the completion of the first tethered project, a request was fielded from an onshore pipeline operator (confidential).

The second application involved the inspection of a 16-inch (406 mm) onshore pipeline in the United States. Following an incident that resulted in a shutdown, the operator required confirmation of the pipeline's integrity, specifically any mechanical damage or ovality deformation, before resuming operations.

The pipeline extended 1968 ft (600 m) and featured a single entry and retrieval point, necessitating a tethered solution.

For this inspection, the robotic tethered solution was instrumented with high-definition visual and laser scanning technologies to provide a high-quality visual inspection of the inspection locations. Laser scanning was to be used to determine pipe ovality and follow up on any locations where visual inspection anomalies were found.

Figure 11 Onshore tethered pipeline inspection

The system identified and mapped internal anomalies, providing the operator with detailed data to support their decision-making process. The inspection was completed within a four-week mobilization timeline, allowing the operator to resume operations safely and without significant delays.

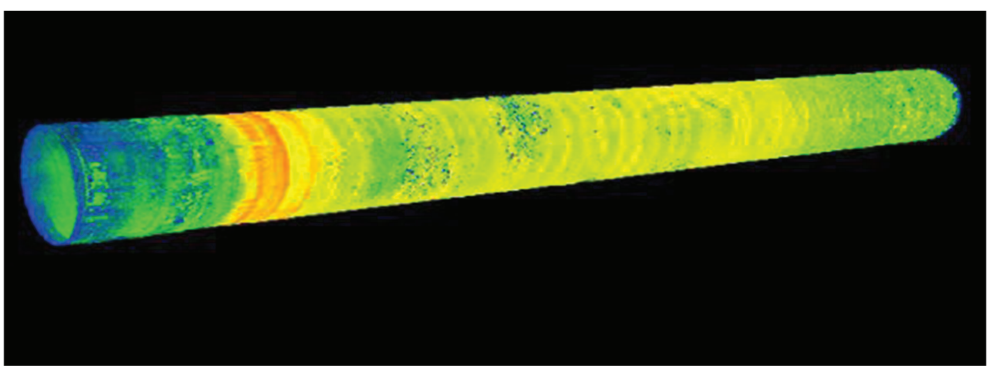

Figure 12 Laser scanning data

Case Study: Triton + ART Scan Integration

Building on the success of previous field applications, a client operating a marine terminal sought to utilize the Triton for a critical line inspection. The client required a tethered solution to address the challenges posed by their pipeline, which lacked the infrastructure for traditional pigging methods. However, TSC Subsea's existing targeted scanning capabilities were insufficient to meet the project's requirements. The inspection demanded a full volumetric scan of the entire pipeline to provide a comprehensive assessment of its integrity.

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To meet these demands, Triton is being integrated with NDT Global's ART Scan module. The integration of the ART Scan module with the Triton system is pivotal in meeting the client's need for a full volumetric assessment of their oil pipeline. The pipeline's known challenges, including the presence of paraffin deposits and the lack of pigging infrastructure, made a traditional inline inspection unsuitable. The ART Scan tool was specifically chosen for its ability to provide precise wall thickness measurements and its proven performance in overcoming wax-related issues in similar applications.

ART Scan Integration: Enabling Comprehensive Inspection for a Challenging Oil Pipeline

ART Scan employs an advanced acoustic resonance technology designed to deliver sub-millimeter wall thickness measurements with an accuracy of +/-0.4mm (+/-0.2in). This level of precision is critical for detecting corrosion, internal/external metal loss, and laminations that can compromise pipeline integrity. The tool's ability to simultaneously gather data on geometric anomalies, such as dents or ovality, further enhances its value for comprehensive integrity management.

Because the lines are not able to be fully cleaned before inspection, a key factor in the tool's selection was its effectiveness in addressing paraffin and wax deposits, which were known to affect this pipeline. Traditional ILI methods often fail to provide reliable data in the presence of such deposits due to sensor interference, as sound attenuation in the ultrasonic frequency range can interfere with accurate data collection. ART Scan, however, operates within a frequency range (400 kHz to 1.2 MHz)) where sound attenuation in paraffin is minimal, enabling reliable wall thickness measurements, even with the presence of wax.

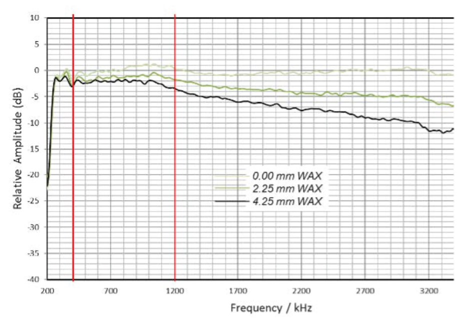

Figure 13 Chart showing absorption spectrum of ultrasound in paraffin.

In November of 2024, the project was officially sanctioned. Engineering and development are ongoing.

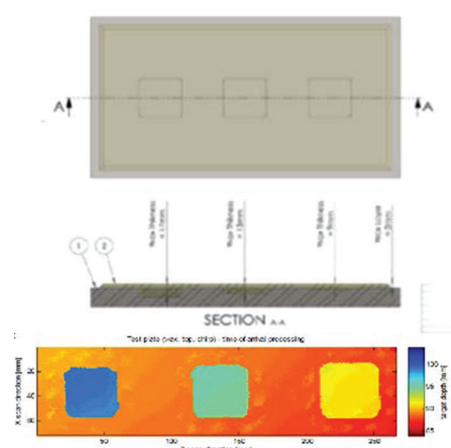

Figure 14 Feature depth sizing through layer of paraffin

Engineering & Development

Integrating the ART Scan module with the TRITON tethered robotic crawler required significant engineering innovation to adapt the functionality of a traditional ILI tool for a tethered deployment scenario. Unlike free-floating ILI tools, which rely on pipeline flow for propulsion, a tethered system must ensure precise control, consistent positioning, and stable operation throughout the inspection process. This involved addressing key challenges in mechanical integration, power management, and data acquisition.

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Mechanical Design and Integration:
A tethered solution allowed for significant weight reduction by removing the need for ART Scan's battery assemblies since the system would be powered through the cable. However, the pull calculations, which take into account the system's weight, the tether's friction coefficient, and the pull weight when traversing the riser, clearly showed that a single Triton would not have the pull force to traverse the entire pipeline. Because of this, a dual Triton configuration was chosen.

Figure 15 Dual TRITON crawler with ART Scan module

TRITON's crawler system was also upgraded with enhanced traction mechanisms to counteract increased drag from the tether and maintain precise positioning. The system's bidirectional capabilities were retained, allowing for controlled navigation in and out of the pipeline.

The ART Scan module was mounted onto TRITON's adaptable chassis, designed with a modular configuration to accommodate the tool's size and weight without compromising mobility. For the ART Scan module, a wheeled configuration was chosen in order to reduce friction.

A custom tether management system is also under development. Particular attention is given to minimizing drag and resistance, reducing mechanical stress, maintaining navigational accuracy, understanding loading and location, and ensuring safe retrieval. A robust tether management system is composed of several key components that work together to ensure the reliable deployment and retrieval of a tethered robotic crawler. A winch system must enable precise tether deployment and retraction based on the crawler's position and speed. At the same time, load monitoring ensures tension remains within the safe limits to protect both the tether and the crawler. Variable speed adjustment allows the system to adapt to changes in crawler speed and pipeline geometry. A well-designed cable reel supports controlled spooling to prevent tangling or overlapping and must have sufficient capacity to accommodate the long-length tethers required for extended pipeline sections.
The tether itself features high-durability sheathing to protect against abrasion and chemical exposure, multi-channel cabling for simultaneous power delivery, data transmission, and communication, and flexibility to conform to bends and diameter changes. The tether is neutrally buoyant to reduce friction within the pipeline.

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Power and Communication Systems:
The integration process required modifications to TRITON's tether to support the power and data transmission needs of the ART Scan module. Power supply systems were optimized to handle the higher energy demands of the ultrasonic probes, ensuring uninterrupted operation during extended inspections. The tether was also upgraded to include high-speed data channels, enabling real-time transmission of inspection data from the ART Scan module to surface control systems.

Testing & Offshore Mobilization
Testing is set to commence in January 2025. Following successful testing, Triton with ART Scan will be deployed in the Gulf of Mexico in February 2025 to inspect two subsea pipelines spanning over 4,025 feet each. These pipelines, which lack pigging facilities and feature complex geometries, require the advanced capabilities of the integrated system. The deployment will demonstrate Triton's potential to provide full-spectrum data for pipeline integrity management, further solidifying its role as a leading solution for unpiggable pipeline challenges.

Conclusion | The Future of Triton + ILI Integrations

The evolution of the TRITON tethered robotic inspection system demonstrates a significant leap forward in pipeline integrity management. Initially developed as a tool for targeted internal inspections, TRITON's capabilities have been progressively enhanced to meet the industry's growing demand for comprehensive inspection solutions. Through the integration of NDT Global's ART Scan module, TRITON has transformed into a full-fledged tethered ILI tool capable of delivering detailed, high-resolution data across entire pipeline lengths. This advancement underscores TRITON's adaptability and its ability to overcome the challenges posed by unpiggable pipelines.

The success of this integration highlights the collaboration between TSC Subsea and NDT Global, combining cutting-edge robotic deployment with state-of-the-art inspection technologies. The ART Scan module's ability to perform wall thickness measurements through paraffin deposits and detect corrosion beneath wax layers has already positioned TRITON as a pioneering solution for crude oil pipelines. However, this is just the beginning.

Looking to the future, TRITON's integration has been engineered to accommodate the full suite of NDT Global's ILI tooling. Whether it's crack detection, metal loss assessment, geometric profiling, or even advanced applications for emerging fuels like hydrogen, TRITON provides a tethered deployment platform capable of replicating NDT Global's existing ILI capabilities in scenarios where traditional pigging tools cannot operate. This versatility opens up opportunities to address complex pipeline configurations and restricted access environments that were previously deemed uninspectable.

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The transformation of TRITON from a localized inspection tool to a comprehensive tethered ILI system marks a paradigm shift in pipeline inspection. By bridging the gap between ILI and tethered technologies, TRITON ensures that no pipeline is beyond the reach of thorough, reliable inspection. With its scalable design and forward-looking adaptability, TRITON is poised to redefine what's possible in pipeline integrity management. It offers operators the data and insights needed to ensure safety, reliability, and efficiency across their networks.

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