AERIAL ROBOTS FOR CONTACT-BASED ULTRASONIC THICKNESS MEASUREMENTS FOR FIELD INSPECTIONS

ЛІТАЮЧІ РОБОТИЗОВАНІ КОНТАКТНІ УЛЬТРАЗВУКОВІ ТОВЩИНОМІРИ ДЛЯ ТЕХНІЧНИХ ОБСТЕЖЕНЬ В ПОЛЬОВИХ УМОВАХ

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Aerial robotic systems, also referred to as drones, enable the collection of data on a scale and scope heretofore unimaginable. Field inspections at industrial sites using an aerial robotic inspection system that makes physical contact with a structure or asset as part of a nondestructive testing (NDT) or nondestructive evaluation (NDE) routine is safer than placing humans at elevation and enables more data to be gathered in less time. These aerial robotic systems are highly extensible and agile enabling safer, faster, and better inspections. Robotic inspection systems are forecast to grow exponentially this decade and beyond, as asset owners and service providers realize their economic value creation, increased data collection, and safety contributions. One early use case of these aerial robotic systems measures wall thickness (in other words, the thickness of a substrate) with a handheld electronic ultrasonic testing (UT) measurement device (see Figure 1). Selected and implemented properly, these systems positively impact safety, time, analytics, access, and cost. Companies looking to keep personnel out of danger at height or in potentially hazardous locations can adopt aerial robotic systems. What is measured is known and we can make predictions based on these measurements. These UT thickness measuring aerial robotic systems enable companies to improve the UT thickness measurement process and gather data that didn't exist before, thus adding to the body of knowledge. The systems can also bring massive efficiencies to the job, including a full auditable data record and information for digital implementation plans, allowing focus on the overall picture to plan and budget accordingly. Further, they help achieve substantial cost savings, particularly when they prevent an asset from being taken out of service or enabling an asset to be returned to service sooner. Finally, they are an elegant safety solution, moving workers from harm's way and potentially saving lives.

Літаючі роботизовані системи, також відомі як дрони, забезпечують можливість збору даних для кола застосувань і обсягів, які досі були неможливими. Виконання польових обстежень промислових об'єктів з використанням літаючої роботизованої системи контролю, здатної забезпечити фізичний контакт з конструкцією або об'єктом під час виконання процедур неруйнівного контролю (NDT) або обстежень технічного стану (NDT), є безпечнішим, ніж розміщення людей на висоті, і дозволяє зібрати більше даних за менший час. Ці повітряні роботизовані системи є універсальними, розширюваними та гнучкими, що дає змогу здійснювати безпечніші, швидші та якісніші вимірювання. У цьому десятиріччі і в подальшому очікується еспоненціальне зростання роботизованих систем контролю, оскільки власники активів і постачальники послуг усвідомлюють їх економічну рентабельність, вкладу в розширення інформаційних ресурсів, а також у підвищення безпеки. Один з перших випадків використання цих повітряних робототехнічних систем дозволяв вимірювати товщину стінки (точніше, товщину підкладки) за допомогою портативного електронного ультразвукового вимірювального пристрою (UT). Вибрані та впроваджені належним чином, ці системи позитивно впливають на безпеку, час, аналітику, доступ та вартість. Вимірювання надають відомості, які є основою наших прогнозів. Ці повітряні роботизовані системи для вимірювання товщини UT дозволяють компаніям удосконалювати процес вимірювання товщини UT і збирати дані, яких раніше не існувало, таким чином доповнюючи знання. Системи також здатні підвищити ефективність роботи, включаючи повністю контрольовані протоколи та інформацію для цифровізації планів впровадження, дозволяючи зосередитися на загальній картині для планування та відповідного бюджету. Крім того, вони допомагають досягти значної економії витрат, особливо коли вони запобігають виведенню активу з експлуатації або сприяють скорішому поверненню активу в експлуатацію. Нарешті, вони є елегантним рішенням щодо безпеки, яке захищає працівників від небезпеки та потенційно рятує життя.

Introduction

For corrosion or other engineers to take UT thickness measurements at height they may need to utilize a lift, scaffolding, ladders, inspection trucks with elevated baskets, rope work, catwalks, or other solutions. Companies looking to keep personnel out of danger at height or in potentially hazardous locations can adopt aerial robotic systems. However, as with many things, choosing the right system for the job is essential for optimal results.

While NDT field inspection programs can dramatically increase the safety and integrity of assets, access requirements in performing these inspections in elevated areas introduces risk. Working at height is dangerous, due to the possibility of falls, as well as being time-consuming due to access setup. In certain instances, it may also require taking an asset, such as a flare stack, offline so it can be accessed to take measurement readings. Utilizing an aerial robotic system for UT thickness measurements can mitigate these risks and potentially eliminate asset downtime.

Drones are commonly used for visual inspections, but it is rare to find them used for contact-based inspections. Researchers have investigated using drones for contact-based NDT (Skaga 2017; Mattar 2018), yet these studies tend to be theoretical and conceptual. The contact-based UT thickness measurement drone system presented in this paper is in commercial use and differs from those in the literature in its computer-controlled precision flight while making contact with a structure (using no human pilot/operator), and in that it utilizes the same handheld UT electronic measurement devices that a corrosion or other engineer uses in the field integrated onboard the aircraft with the data streamed live to the engineer or observer on the ground.

Further, because these systems are «flying computer» and data-gathering machines, they collect a large amount of data for NDT/NDE. This data can feed NDE 4.0, which is a force multiplier for inspecting, testing, and evaluating industrial assets for their safety, operational effectiveness, and efficacy. NDE 4.0 uses the tools of Industry 4.0–machine learning, artificial intelligence (AI), the Internet of Things (IoT), big data, and so on–to expand and generate knowledge, insights, and understandings that turn data gathered from industrial field inspections, into actionable information to enhance and extend knowledge-based information-driven decision making. These aerial robotic systems help with both the increasing importance of digitalization of assets and data and the use of NDE 4.0 by making it easier to collect information.

Aerial Robotic Measurement Collection Methodology

Having a computer-controlled heavy-lift multirotor drone outfitted with various sensors and functions to allow precisely controlled flight close to structures is critical in taking contact-based UT thickness measurements (see Figure 2). Manual control of such systems is unable to accomplish the precise flying and maneuvers required; thus, software-controlled flight is crucial. The aerial robotic system in this paper utilizes existing UT electronics and digital probes to gather measurements. The handheld electronic UT thickness measurement device onboard the aircraft streams all the data (not just what is displayed on the LED view screen) to the computer onboard the aircraft and the pilot and corrosion engineer on the ground.

The system works as follows:

The tethered (for power and data transfer) or untethered (battery power and wireless data) aerial robotic system is located close to the structure where UT thickness measurements are to be taken.

The corrosion engineer, using a computer tablet, opens the software interface to begin the test and enters the job information (operator, job name, upper and lower limits for measurements, etc.) and standardizes the handheld UT thickness measurement device that is mounted onboard the aircraft, as per the definition of standardization provided by ASTM 1316 (ASTM 2021).

Photo credit: DeFelsko Corp.

Figure 1. An example of a handheld electronic UT measurement device with a single-element 5 MHz contact transducer.

Рис. 1. Приклад портативного електронного вимірювального пристрою UT з одноелементним контактним перетворювачем 5 МГц

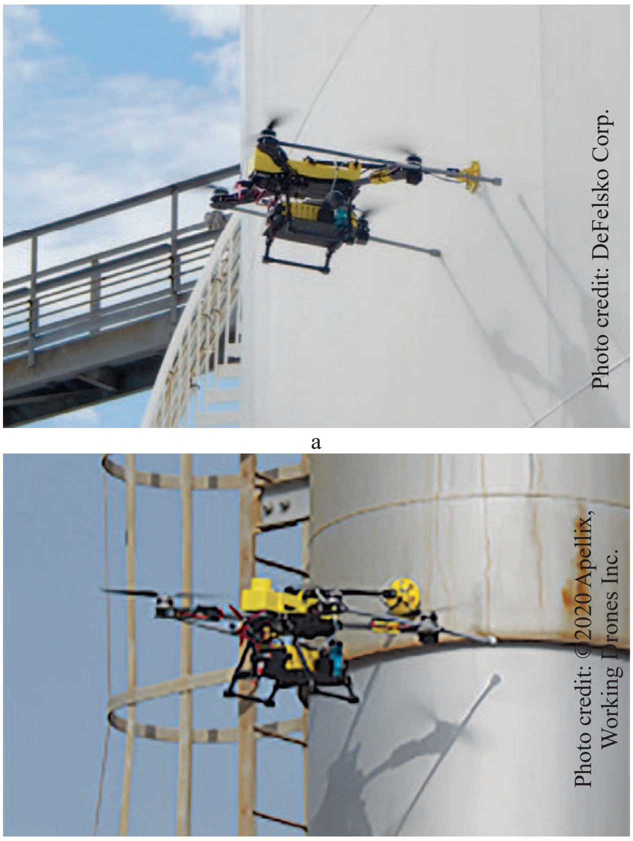

a

Photo credit: DeFelsko Corp.

b

Photo credit: ©2020 Apellix, Working Drones Inc.

Figure 2. Ultrasonic thickness measurement system in action: (a) on an in-service aboveground storage tank; (b) on an in-service active flare stack.

Рис. 2. Робота ультразвукової системи товщинометрії на діючому обладнанні: (a) наземний резервуар; (b) активна факельна труба

The pilot engages the aerial robotic system's software and the system takes off vertically to approximately 2 m (6.5 ft) in height, hovers, and completes self-checks.

The pilot then uses a standard handheld radio frequency transmitter to manually fly the system close to the where the UT thickness measurement is to be taken (the «gate» or «window»). (The radio transmitter is the standard operations control for the aircraft. Its sole use in this case is for positioning the aircraft close to the area where the thickness measurements are to be taken. It is also on standby in case manual operational flight controls are needed; for example, in case of a failure of the software).

Once the aerial robotic system is within the «gate» (~2 m [6.5 ft] from the target part of the structure), the pilot selects «start» on the software interface.

The system then operates under full computer control (no manual input). It flies in (while dispensing couplant gel onto the probe), touches the surface, and takes a UT thickness measurement reading, typically taking 1 to 4 s. The aircraft then backs away, and the pilot repositions the system at the next location and repeats the process for additional measurements at different corrosion monitoring locations (CMLs).

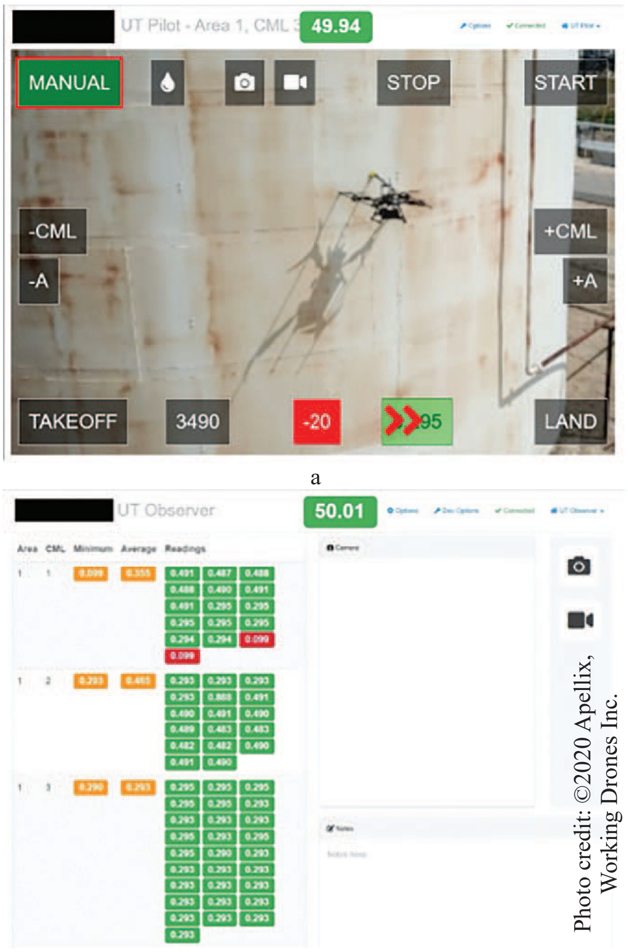
The corrosion engineer sees the data on their computer tablet in real time.

After landing, the operator has the option to download the full data record which includes all the UT thickness readings, high-definition (HD) video, and additional information such as locational coordinates and weather and environmental data (see Figure 3). The data is also made available in a secure data repository accessible via the Internet. The system is agile and motile, enabling it to take a lot of readings in a short amount of time. Depending on the condition and geometric complexity of the asset being measured as well as environmental and weather conditions, the system can take measurements at up to a few hundred contact locations per hour.

Aerial Robotic System UT Thickness Measurement Technology

UT thickness measurements require the application of a couplant gel to the measurement probe tip prior to taking a reading. Thus, the end effector at the terminus of the robotic arm has a mechanism to dispense the couplant prior to each contact with a structure (see Figure 4). There is a reservoir of couplant gel on the aircraft with a pump and motor connected to a small-diameter tube that runs the length of the robotic arm and attaches to the end effector. The onboard computer, via the embedded software programming, signals the pump to push the couplant to the couplant injection point at a short time interval prior to making contact with a structure to take a UT thickness measurement.

Onboard the aircraft is also the handheld electronic UT thickness measurement device with a single- or dual-element contact transducer capable of taking echo-to-echo ultrasonic thickness measurements. The device is plugged into the onboard computer for power and data transfer. The full data record is transmitted during its use, not just what is set to display



a

Area	CML	Minimum	Average	Readings
1	1	0.099	0.355	0.491 0.487 0.488 0.488 0.490 0.491 0.491 0.295 0.295 0.295 0.295 0.295 0.294 0.294 0.099 0.099
1	2	0.293	0.483	0.293 0.293 0.293 0.293 0.888 0.491 0.490 0.491 0.490 0.489 0.483 0.483 0.482 0.482 0.490 0.491 0.490
1	3	0.290	0.293	0.295 0.295 0.295 0.295 0.295 0.293 0.293 0.293 0.293 0.295 0.293 0.295 0.295 0.290 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293 0.293

b

Photo credit: ©2020 Apellix, Working Drones Inc.

Figure 3. An example of the screen views that are streamed live to the computer tablets held by the pilot/system operator and observer (corrosion engineer or NDT technician): (a) live video stream; (b) data report.

Рис. 3. Приклад скріншотів з відео в реальному часі на комп'ютерних планшетах пілота/оператора системи та спостерігача (інженер-корозіоніст або технік НК): (а) відео в режимі онлайн; (b) протокол вимірювань

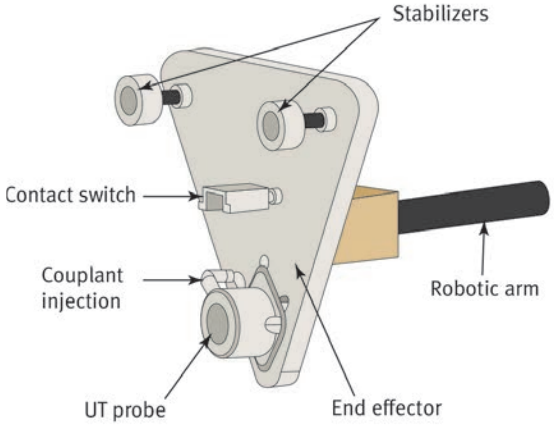


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Figure 4. The robotic end effector that disperses the couplant gel.

Рис. 4. Кінцева насадка робота для подачі контактного гелю on the device LED screen. The system uses a Wi-Fi router to connect with the onboard computer which, among other things, allows the aircraft to communicate with the pilot and the corrosion engineer on the ground, enabling it to display data in real time. The aircraft also has an onboard HD camera and may include a «gas sniffer», which records concentrations of various gas levels and notifies the system operators if certain thresholds of gas are detected. All the data from the onboard computer is saved to a memory card/USB flash drive. The data is also made available in a secure cloud-based repository with the ability to create charts, graphs, download data, and so on.

Example Use Case

Recently the aerial robotic system described in this paper was utilized at an in-service gas refinery in the southwestern United States. The NDT engineering company provided guidance as to the areas of concern where UT thickness measurements were required on behalf of the asset owner. These CMLs were pointed out to the aircraft system pilot by the NDT engineering company personnel. Representatives of the asset owner were onsite during the flights. The job was completed without tethered ground power to the aircraft. The total time from initial takeoff to final landing, including landings to change batteries, was under 90 min and multiple readings were obtained from more than 100 separate content monitoring locations. Weather on the date of testing was partly cloudy with winds ranging from 5 to 15 mph, generally from the east/northeast. The system is not recommended for use in winds over 20 mph (15 knots). The ambient temperature ranged from 80 to 90 °F (26 to 32 °C) over the course of the morning. The UT thickness measurements would have been postponed had there been weather conditions such as high winds or rain.

A total of 104 CMLs were successfully sampled from 112 attempts. In eight of the 112 instances, no valid data was obtained, typically because of a wind gust or other disruption to the flight. In almost all the successful locations, multiple measurements were obtained. From the total of 535 measurements at 104 locations, the minimum (lowest) recorded wall thickness measurement is reported for the individual location. Data is stored in the onboard computer and relayed in real time to the computer tablet of the engineers on the ground. A separate simplified data stream is presented to the aircraft pilot. Location data is tracked using cameras located on the ground and on the aircraft. During flight, an HD video was recorded for post-flight analysis and use. Referring to Figure 5 showing an annotated photo of one side of the flare stack, you will notice there is a cluster of readings in a section approximately twothirds of the way up and to the left. This section was an area of concern to the asset owner and engineering NDT company. It was theorized the metal thickness in this area might have been thinner than the other areas of the stack, indicating it was corroding more quickly than the asset in general. Multiple UT thickness readings were taken at this area. Due to privacy issues, the thickness readings cannot be shared or published. That said, thickness measurement data was consistent with previously obtained measurements taken by engineers using handheld electronic measurement devices utilizing lifts while the asset was out of service (Dahlstrom 2020).

The flare is approximately 68 ft (20.7 m) tall with a catwalk at about 55 ft (16.8 m). Sections from approximately 8 ft (2.4 m) above the ground to approximately 4 ft (1.2 m) below the catwalk were tested. A ladder obstructed the ability to take measurements on the southwest and west side of the stack, and a vertical pipe rack obstructed measurements on the northeast corner of the stack. During the course of the flights, the engineers had access to the user interface that streamed the UT thickness reading measurements in real time.

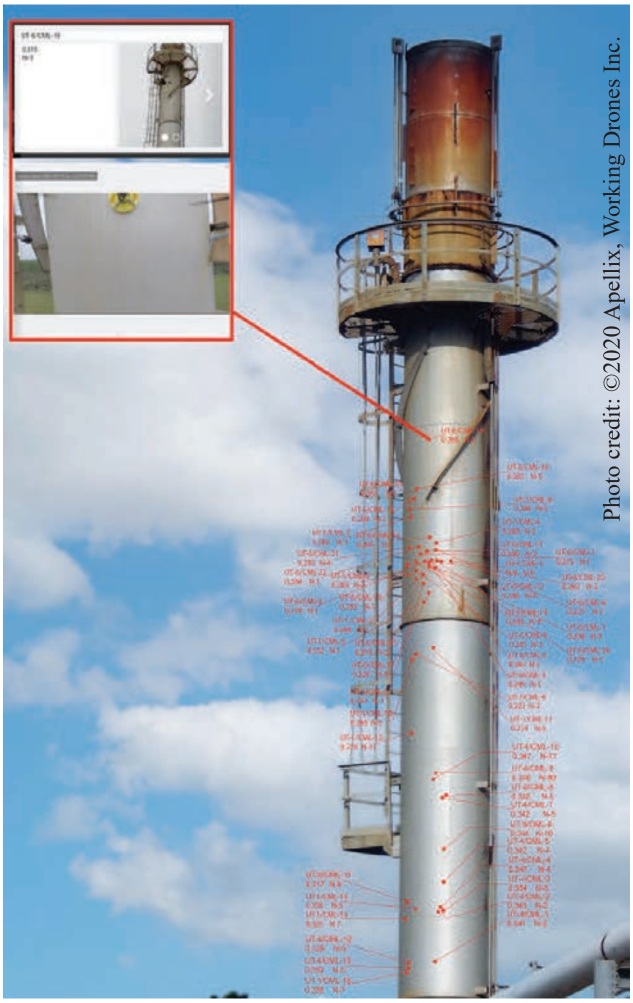
Photo credit: ©2020 Apellix, Working Drones Inc.

Figure 5. An example of the data obtained from a section of an in-service flare stack (note all numbers and values are illustrative).

Рис. 5. Приклад візуалізації даних, отриманих на секції діючої активної факельної труби (примітка: всі числа та значення є ілюстративними)

Additional Data

In addition to the UT thickness data collected during the flight of the aerial robotic UT system, HD video was recorded, as were still photos of the UT probe tip in contact with the flare stack as the UT thickness reading was being collected (see Figure 6).

In addition to the snapshot photos taken for each measurement location from onboard the aircraft and the snapshot of the aerial robotic system making contact with the flare stack from the camera on the ground, a full HD video from onboard the aircraft was recorded. This video is provided to the client for their use; for example, to review it for visual areas of corrosion or to look for surface areas of concern. Localization data is included; however, as GPS signals are not accurate, especially when flying close to structures, it is not precise enough for use to match CMLs on the physical geometry of the structure.

Data gathered from HD cameras can include visual, multispectral, and other imaging data. Further, additional information can be collected from sensors and devices placed in physical contact with surfaces. As NDE 4.0 is data driven, industrial inspection robotic systems are perfect for enabling it and affording its benefits.

Capabilities that these aerial robotic systems make available for NDE 4.0 include aerographic services that utilize 3D and other computer vision; various AI, machine vision, computational geometry, simultaneous localization and mapping (SLAM); live 3D point clouds; stereoscopic real-time video photogrammetry; and other technology innovations. This would include mature and emerging technologies such as the use of AI, machine learning, machine vision, deep learning, big data and smart data processing and visualization, cloud computing, augmented/virtual/mixed reality, blockchains, 5G, quantum computers, special data formats and data storage, and more (Vrana 2020). These aerial robotic systems excel at gathering the data needed to unlock the potential of NDE 4.0.

Visual inspection can also enable a look at the air density and detect gas leakage using optical gas imagery camera-based systems. Similar «bolt on» technologies to robotic systems can enhance the data collection component of NDE 4.0, thereby augmenting the UT thickness data collected. Outfitting a drone with an array of multimodal sensory devices collecting a plethora of data and information will enable the best success and use of NDE 4.0 as these systems provide more and better data for analysis.

Drawbacks of Industrial Robotic UT Thickness Measurements and Inspections

The aerial robotic system described in this paper is not always the ideal solution. In many situations, the existing inspection regime and methods can be completed relatively inexpensively and safely. They provide the requisite data and information for good operations and knowledge of the current and projected future state of the asset. Aerial robots can require a relatively high upfront investment (Global Electronic Services 2021), although on a per-inspection cost basis, the robotic inspections may cost less.

These systems are aircraft with electronics onboard and are thus subject to limited operations due to weather. For example, you could not operate one in the rain unless it is specifically designed to be waterproof. Wind is also a limiting factor as gusts, the venturi effect, crosswinds, and low-velocity eddies on structures all can impact their flight and performance.

As these systems collect huge amounts of data, they provide a fantastic opportunity to add to or create a digital record of industrial field assets.

Additionally, robots do not respond well to many unexpected situations. Robots are not as versatile as people and while they may exceed at certain specif-

UT-6/CML-9

0.215
N-3

a b

Figure 6. An example of flight details: (a) a sample UT thickness measurement reading (UT-6) at condition monitoring location 9 (CML-9) showing the lowest measurement reading out of three readings (N-3); (b) photo of the aerial robotic system making contact with the flare stack from the post-flight report (note all numbers and values are illustrative).

Рис. 6. Приклад фрагментів протоколу польоту: (a) результати УЗ товщинометрії (протокол UT-6) у точці 9 (CML-9) моніторингу технічного стану – мінімальне значення товщини за трьома вимірами (N-3); (b) скріншот протоколу польоту – етап встановлення контакту повітряної роботизованої системи з факельною трубою (примітка: всі числа та значення є ілюстративними) ic tasks–especially repeated programmatic tasks–they might not be able to adapt in unexpected or unanticipated situations. Since the aerial robotic systems are not human inspectors, they may not discover some issues that an experienced human inspector might. Due to this limitation, companies supplement robotic-powered inspections and examinations with ones completed by people.

When properly selected and utilized, aerial robotic inspection systems can assist with creating safer workplaces, provide better data to manage assets, and unlock cost savings. While industrial robotic inspection systems can be highly effective when properly used, they do have limitations and, in some cases, they are the incorrect tool.

Organizational Benefits of Faster, Safer Robotic UT Thickness Measurements

Planned preventative maintenance has long been practiced as a strategy for keeping industrial field assets operating safely and efficiently. This has led to the development of standards to help asset owners maintain the integrity and fabric of their facilities and to ensure that they remain operationally safe and effective for their entire life cycle. Transformative technology such as aerial robotic UT thickness measurement and visual asset assessment systems, such as those discussed in this paper, allow customers to take a fresh look at the opportunity for conducting inspections and data-gathering operations that can help redefine a planned maintenance regime.

As these systems collect huge amounts of data, they provide a fantastic opportunity to add to or create a digital record of industrial field assets. Investment in a powerful data-collection system via an aerial robotic system is fairly simple and can be easily made purely on a financial footing. Utilizing these systems makes other visual or data inspections redundant, as the aerial robot collects UT thickness measurement data as well as HD video that can be used for visual inspection. The benefits have been clearly shown from the early adopters of this technology.

Conclusion

Given the enormous potential industrial aerial robotic field inspection systems enable, one can easily envision a future with robotic systems having more automation, functionality, and capability. This would enable more inspections as an increased number of inspection robots are placed in service and as functionality increases.

The systems presented in this paper improve efficiency due to reduced inspection times and increase efficacy by faster reporting and decision making, which adds value and creates even more value when coupled with NDE 4.0 processes. Further, they help achieve substantial cost savings, particularly when they prevent an industrial asset from being taken out of service or enabling the asset to be returned to service faster. And, finally, they are an elegant safety solution moving workers out of harm's way and potentially saving lives.

As we move toward a more automated future with robotic inspection tools becoming more advanced, affordable, and utilized, we will continue to utilize automation tools that free human inspectors from the dirty, dull, and dangerous tasks of collecting inspection data. This will enable them to spend more time on the higher value components of industrial asset operation and maintenance.

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