

Opportunities from Digital Transition for Integrity Inspection and Control of Major Accident Hazard

Paolo Bragatto^a, Elisabetta Bemporad^b, Romualdo Marrazzo^c, Maria Rosaria Vallerotonda^b

^a Università Campus Bio-Medico. Via Álvaro del Portillo, 21, 00128 Roma

^b INAIL DIT via Ferruzzi, 38, 00143 Roma

^c ISPRA VAL-RTEC Viale Cesare Pavese, 305, 00144 Roma

p.bragatto@unicampus.it

In the process industry, equipment integrity control has always been an essential activity to prevent accidents, avoid unwanted interruptions and product losses, and extend the useful life of the plants over time. In this context, non-destructive test NDT methods have been widely used for decades to detect different forms of deterioration of materials, before they can lead to failure or ruptures. The measurement technologies used are different, depending on the types of expected damage. In many cases, by maintaining the same measurement technology, it is possible to considerably increase the effectiveness and frequency of measurements, using innovative digital techniques, including wireless communication (e.g. Wi-Fi, BLE, RFID, etc.), shared storage (cloud), machine learning ML techniques and autonomous motion systems (e.g. robots, drones).

This paper reviews the main innovative solutions that allow to significantly enhance integrity measurements, including robotic inspections inside and outside equipment, pervasive systems for monitoring critical equipment, and augmented vision.

Digital technologies for integrity inspections have already reached a good degree of maturity and are rapidly spreading. In this paper Strength Weakness Opportunity and Threats (SWOT) analysis is used to investigate the potential of these technologies, and a possible standardization in the future. Concerning the major accident hazard, the paper includes a discussion on how to quantify the contribution that these systems make to reduce the likelihood of accidental scenarios related to equipment failures at industrial establishments.

1. Introduction

In recent years, the digital transition has had a strong impact on the integrity management of process plants. The sensors, small-sized and low-cost, can be distributed pervasively in many elements of the plant, both on primary containment systems (e.g. pressure vessels and pipes, atmospheric tanks) and dynamic systems (e.g. pumps, compressors). The use of distributed sensors has become a way to supply a sort of “nervous system” to the equipment, adequate to monitor its health condition. A further step forward it is the use of technological solutions born in robotics. In process plants, integrity inspections require direct or close contact with the surfaces of the item to inspect. Thus, inspection systems with autonomous movement capabilities have been developed to reach points where no human operator could ever go. Technological research in this area is indeed very lively and, while it may still be premature to define standards, it is important to provide all interested parties (e.g. plant managers, service providers, control bodies, and competent authorities) with a common technical basis to guide choices and evaluations and thus benefit from technological developments.

2. Pervasive Monitoring Systems

Monitoring systems, in general terms, include one or more sensors and subsystems that provide services for identification, data gathering, processing and transmission. In process plants, they can be used to monitor the integrity and operability of critical equipment, including vessels, pipes, and rotating machinery. These monitoring systems are required to be cost-effective, non-invasive, flexible, and scalable. These solutions use existing NDT

techniques, which are miniaturized, automated, and connected to systems featuring local processing and communication capabilities so that the data collected over time can be transmitted to the control room to provide updated information on equipment conditions. Well-known examples are vibration monitoring on rotating machinery and thickness monitoring by ultrasound testing (UT) on critical pipes.

The rotating machinery has been the subject of specific control activities for decades, but in recent years these activities have highly improved, using permanent sensors connected via wi-fi to the control room and exploiting the potential of advanced ML techniques for signal processing, feature recognition, and detailed diagnosis (Tiboni et al. 2022). The benefits are remarkable, defects are detected much earlier and there is a significant reduction in risk for operators, who no longer have to go around spotting machines in difficult areas (Bragatto & Ansaldi 2022).

In the process industries, during routine planned maintenance shutdowns primary containment systems (vessels and pipelines) are inspected to control the effects of deterioration mechanisms (e.g. corrosion, erosion, fatigue, etc.) and, consequently, prevent failures and accidents. These inspections are complemented, if possible, by several measurements during operation time. For a few years now there have also been pervasive systems for the continuous monitoring of items, difficult to measure in other ways. The solution consists of a network of miniaturized sensors distributed in critical positions, aimed to early detect anomalous thinning. A significant example is corrosion under insulation, which is always an insidious problem because, in common practice, the detection requires the removal, at least partially, of the insulation of the pipes or tanks involved, with a significant impact on activities. The installation of ultrasonic sensors on a few critical positions under the insulation, connected via wifi, allows continuous monitoring of thinning and prevents corrosion and through-hole formation (Bragatto et al. 2018). Advanced AI defect detection is currently under development. By leveraging deep learning, machines can learn to recognize the defects detected by automated visual inspection or other NCD through examples while managing vast amounts of data (Schmedemann et al., 2022).

The combined use of distributed sensors contributes significantly to improving the performance of the plant integrity management system, increases reliability and availability, and reduces costs, as well as occupational hazard exposure for workers.

3. Inspection Systems with Autonomous Movement Capability

When possible, the use of pervasive sensors is the best way to monitor health conditions. Permanent sensors, anyway, cannot control too many points and, for many phenomena, localized measurements are inadequate to detect defects. For many situations, rather than continuous monitoring, it would be necessary to increase the frequency of inspections. That could be hindered by the costs as well as by the occupational risks for operators, including working at height (e.g. on elevating platforms), confined or polluted environments, oxygen deficiency, and thermal extremes. To overcome these limitations, special measurement systems have been developed, suitable for operating even in environments inaccessible to human beings. These systems take advantage of recent achievements in robotics and self-driving ground and air vehicles, transferring these possibilities to inspection activities. These systems can overcome the physical barriers that stand between the operator and the object to be measured. They can bring the sensor into contact with the equipment to be measured. It is a large family of systems, but they have some common characteristics, which we summarize below.

3.1 Features

The first and fundamental characteristic is that they carry out a "mission". Thus, these systems are activated for a relatively short period and must reach the required positions and perform all the necessary measurements. The systems must complete the mission without causing damage to the system itself, to the instrumentation transported, to the equipment being measured, to people, machines, structures, and any other objects along the way.

These systems have parts that allow movement in a particular environment, which can be terrestrial, aerial, or liquid. Movement can be outside or inside the equipment, even in operation. Depending on the need, the systems will be specialized to move in cramped, high-altitude, remote, or hostile environments for various reasons, such as extreme temperatures, lack of oxygen, or pollution. If the system moves on the ground, to control the equipment from the outside, it is called a "rover" or more generally of unmanned vehicle. If it moves in the air, it is called a "drone" or better UAV (Unmanned Aerial Vehicle). A drone can move outside equipment or even inside particularly large equipment when it is not in operation. The same term is used for systems that move in the sea or similar water bodies to inspect equipment from the outside, typically underwater pipelines (Yu et al. 2019).

There is also a large group of systems that move inside the pipes in operation and control the condition of the internal walls. This group includes common systems such as PIGs (Pipeline Inspection Gauges), which have long been used in pipelines, as well as robots specialized for missions within more complex and difficult plants.

Possible moving organs include wheels, multi-segment articulated legs, and. Systems can be divided into passive and active systems. The passive systems are dragged by the flow and as they move forward and rotate autonomously, verifying wall thicknesses with ultrasonic sensors. It is an effective system, but not very versatile, because it has many limitations, including tube size, angles, and bend radii. Systems with autonomous movement (e.g. caterpillar) are made with various segments connected by bellows that inflate and deflate (Rusu and Tatar, 2022). A further evolution of the PIGS is the robot systems that can be submersed into the liquid inside large tanks. Thanks to wheels, they have moving capabilities all around the bottom. Energy is provided through a cable connecting the moving system to the external.

A further group of systems includes the robots that climb on the outside of equipment. Climbing robots are equipped with four or more independent mechanical limbs, equipped with adhesion devices. Adhesion devices can be mechanical, magnetic, or pneumatic. Essential elements are three-dimensional vision devices, with related image processing software, which make it possible to identify obstacles and find the safest route. To control movements, systems at the entry-level have just a few sensors on board that warn of obstacles and interference and remote control is required. In more sophisticated systems there are many sensors on board to perceive the environment as a whole and autonomous computing resources to process the perceived signals and move autonomously in the environment to find the target and carry out the mission (Dejian Li, 2017). It is essential to have robust software on board, which can adapt movement in various situations, taking advantage of the learning possibilities provided by artificial intelligence (Devold et al. 2019). For sensors and motion actuators, the systems need power, which is supplied by an internal rechargeable battery. Less frequent are the alternatives of cable-powered, solar panel-powered, or other energy-harvesting systems.

All systems have one or more specific measurement sensors on board for assessing the status of the equipment to be measured. Drones typically stay at a minimum distance from the target and, therefore, install HD cameras for examination in the field of visible or IR. In a few cases, a light is provided to illuminate the target. If direct contact with the target is possible, ultrasonic thickness gauges, eddy current (ET) or magnetic flux loss (MFL) sensors can be mounted. The measurements require the availability of specific resources for data acquisition, pre-processing storage, and communication.

3.2 Examples from Process Industries

A few cases are discussed here, just to give an idea of the benefits of digital transition for inspection practice. For measurements of points at height on internal surfaces of boilers and furnaces, scaffolding or equivalent equipment would need to be erected and dismantled to allow the operator safe access to the locations to be duly inspected during periodical shutdowns. Using drones flying inside, the entire interior walls are covered. Alternatively climbing robots may be used. Thickness measurements on distillation columns and cooling towers, even in operation, are effectively carried out by climbing robots, which avoid dangers for inspectors.

Flares are an essential system for the safety of process plants and are subject to various forms of deterioration, including corrosion and cracks that can cause service interruptions with serious consequences. Inspections have always been problematic, both because of the difficulty of access, because of the height, and because of the very high temperature, which is maintained for a few days even after the shutdown. For flares, which are in relatively free areas, it is effective to use drones, which mount high-resolution video cameras and allow a very detailed visual examination, keeping the operator in a safe position (Sabry 2017). Chimneys are also subject to deterioration due to temperature and effluent chemical composition and need periodical inspections requiring, complex scaffoldings, which are expensive and time-wasting. Drones provide a valuable alternative to that, cutting costs and time.

Measurements of major pipelines connecting terminals, depots, and refineries are regularly performed by PIGs. Active piping inspection systems, discussed in §3.1, are much more versatile and suitable also for lines featuring minor diameters or tight curves in sequence.

In the oil industry, a periodical of atmospheric storage tanks is required by technical regulations to prevent losses. In current practice, internal inspection is possible just for empty and reclaimed tanks. Submersive robot inspection is a new technique that allows in-service tank inspection. Through a roof opening, they are dropped inside into the full tank until they reach the bottom, which is the most critical part. They are equipped with MFL (Magnetic Flux Loss) sensors, that measure the local corrosion phenomena. These systems reduce inspection costs, environmental impacts, and occupational risks (Shamsi et al. 2022).

In gas and oil pipelines, external interference, including unintentional and intentional acts, are major causes of accidents, as demonstrated by the periodical reports (EGIG 2020) and, consequently, surveillance is an essential duty of operators. It's a difficult activity due to the great distances involved and the normal obstacles of natural environments. Drones flying along the pipeline are valuable for early detection of leaks and potential interferences (Jordan et al. 2018). The drones are also assumed to be a deterrent for any malicious people.

4. Innovative Inspection Technologies in Risk Analysis

In a nutshell, it can be said that the systems described in the previous sections are all aimed at increasing the probability of detecting damages and defects long before they lead to ruptures and consequent containment losses. The leading parameter for any inspection system is the probability of detection PoD, which is a function of the size of the minimal defect s_d

$$PoD = f(s_d) \quad (1)$$

The risk analysis should quantitatively consider the contribution that these systems can make to safety. To this purpose, it is very useful FMEA/FMECA analysis, which identifies, for each element, the possible failure modes (in this case damage), the mechanisms that produce them, the severity of the consequences S, the probability of damage occurrence O; and D the probability of damage detection. According to the standard code that defines the method (EN 2006), both S and O are ranking numbers rather than the actual measures. The higher the number the higher the severity or the likelihood of occurrence. D is, instead, ranked in reverse order: the higher the PoD the lower the D factor.

To get a quantitative determination of criticality the three factors are combined to have the Risk Priority Number RPN, defined as follows:

$$RPN = S \times O \times D \quad (2)$$

RPN determines the criticality of each item. Different types of FMECA assign different scales for the values of S, O, and D; but the standard code provides ranking tables ranging from 1 to 10 and the combination gives RPN ranging from 1 to 1000. Risk priority numbers may then be used for prioritization in addressing the mitigation of risk. Pervasive monitoring systems or autonomous motion inspection systems will be adopted to lower the RPN. They act on D number, which decreases, whilst S and O will remain the same. The higher the PoD associated with the inspection system, the lower the D number. Thus, the establishment operator will be able to decide the adoption of innovative technologies for the items having the highest RPNs. To give a quantitative idea of the expected benefits, some typical items have been imagined and RPNs pre and post-adoption have been calculated, using the above-mentioned ranking tables. Results are shown in table 1.

Table FMECA analysis for a few critical items in a typical refinery

Item	Failure mode	Cause	Effect	S	O	D	RPN pre	Action taken	S	O	D	RPN post
Compressor	blockage	fatigue wear	loss of material, discontinuity	4	8	4	96	Vibration Monitoring	4	8	1	32
8 inches Insulated pipeline	casual rupture	CUI corrosion	loss of a material major accident	8	5	9	360	UT pervasive sensors on a critical point	8	5	3	120
40 inches crude oil external pipeline	casual rupture	erosion-corrosion	loss of a material major accident	6	5	8	240	PIG periodical inspections	6	5	2	60
Furnace	cracking creep	thermal fatigue stress corrosion	rupture explosion	9	4	8	288	EC sensors + Climbing Robot	9	4	2	72
Atmospheric Distillation Tower	casual rupture	sulfidation stress corrosion	rupture major accident	9	3	7	189	EC sensors + Climbing Robot	9	2	1	36
Atmospheric Storage Tank (bottom)	casual rupture	pit corrosion trough-holes	loss of material major accident	4	8	7	224	MFL sensors + Tank Inspection Rover	4	8	1	32
Flare	misfunction	thermal fatigue, fouling	accident in emergency	6	5	8	240	IR camera + drone	6	5	2	60

For those who prefer to reason with the fault tree analysis FTA, the approach is similar. For each critical item for which an innovative technology is adopted, the probability of failure reported in the literature data should be divided by a factor related to the probability of detection of the defects. Of course, the higher the POD, the higher the reduction factor. Typical reduction values could range about one order of magnitude. In a very critical situation, the monitoring system itself, with its reliability, could even be included in the fault tree.

5. SWOT Analysis

A SWOT analysis has been conducted here to better address the application of inspection technologies in the process industries.

5.1 Strengths

Mobile autonomous systems and continuous monitoring pervasive systems provide great improvements in inspection practices, as discussed in previous sections. The expected advantages include higher efficiency in preventing failures and a reduction of occupational risks and inspection costs. The investment costs, which in most cases are not very high, are compensated by the reduction of losses due to accidents and unwanted shutdowns and by the extension of equipment's useful life, as emerges from the analysis of the operational experience conducted during inspection activities on the safety management system.

5.2 Weakness

For all moving systems, the problem of interference with structures, machinery, and workers is critical. For ground systems, it is essential to have intelligent reliable devices that prevent the robot from causing damage to things or people, as well as adequate procedures compliant with occupational safety regulations. This issue is more complex for drones, which have more freedom degrees. They should be operated in areas that are not too congested and possibly free of inconspicuous objects, such as power lines. In any case, it should be remembered that the use of drones is subject to air navigation regulations, with an increasing series of obligations and authorizations depending on different parameters, including size, power, and altitude. The formation of potentially explosive atmospheres is a hazard present in many areas within chemical and oil plants. For aerial systems, that can be a major limitation. As far as drones are concerned, there is no possibility of having systems compatible with ATEX regulations. Permit-to-work procedures may allow the use just in open environments away from points of emission of flammable vapours, to exclude any possibility of explosive atmospheres. In the case of the use of drones in indoor environments, such as boilers and furnaces, their use is only possible after certified remediation (*gas-free*) of the internal environment.

Inspection digital systems are highly interconnected and, consequently, prone to cyberattacks, as every digital system. In process industries, many attacks on industrial digital systems, even with severe consequences for property, workers, and the environment, have been reported in recent years (Iaiani et al. 2021) and it is essential to improve security readiness and resilience of such infrastructures (Iaiani et al. 2022). Underestimating these aspects can also affect negatively the spread of digital inspection technologies.

5.3 Opportunities

The measurements coming from distributed sensors will feed continuously the equipment integrity database. Further updating will come from mobile autonomous inspections, as well as from conventional inspections. Adequate software will combine all measurements coming continuously from different sources to understand the equipment's "health" condition and to guarantee the safe extension of its useful lifetime. To support operation, inspection, and maintenance, the software should include a platform for communication, a sound database, and models for equipment condition prediction. For this last point, advanced algorithms are preferred, including "Bayesian" networks, which allow the likelihood of failure to be continuously adapted, exploiting the large amount of data received (Ancione et al. 2023).

Data collected by monitoring and mobile systems and prognostic evaluation may be used to update the plant's digital representation coming from computer-aided design/engineering CAD/CAE systems, to have a living digital representation or, in other words, a "digital twin" of the plant. Digital twins may be used in combination with augmented reality systems, which allow, for example, walking around the real plant by seeing the real present and future conditions superimposed on a pair of special glasses (smart glass), thus multiplying the potential of conventional inspection activities. Particularly interesting is also the combination of the data acquired with mobile measurements within inaccessible areas and the CAD-based digital model of the equipment itself (Ancione et al. 2022).

5.4 Treats

There is still a lack of recognized practices to assist decision-makers in digital innovation and plant safety. The investment in sensors and instrumentation must be accompanied by investments in software, including "prognostic", which is essential to transform data into knowledge and decisions. If management fails to find a balance between all of this, it risks underperforming investments.

A further critical issue is represented by the authorities and control bodies that have not had the opportunity to keep up to date with the rapid evolution of control technologies and do not take them into account in the assessment phase, hindering the adoption of new technologies.

6. Conclusions

To respond to the exponential growth of remote measurement systems, the Italian Thermo-Technical Committee of the Italian Standards Body (UNI) is developing a guideline, to support operators in making effective choices in this field and adopting the most appropriate systems, avoiding those errors discussed in §5.4. The guideline will also be useful to system builders and integrators, who will be more confident in proposing the systems themselves to operators. Regulators will have a shared tool to understand the improvement in safety conditions induced by these new solutions, adequately taking into account in the various steps required by safety regulations, including authorization, derogations, recommendations, and requirements, in a flexible manner depending on the conditions. To transfer proven research results to industrial practice, the role of standardization is essential (Radauer et al. 2022). At an early stage, the guideline can play an essential role in directing the market, but without entangling it too much in rigid rules that could be overcome in a short time. Thanks to the support of an official document, even conservative companies will be encouraged; authorities and control bodies will overcome qualms and mistrust, which are obstacles to the development of technologies.

References

- Ancione, G., Saitta, R., Bragatto, P., Fiumara, G., & Milazzo, M.F. 2022. An Advanced System for the Visualisation and Prediction of Equipment Ageing. *Sustainability*, 14(10), 6156.
- Ancione, G., Bartolozzi, V., Bragatto, P., & Milazzo, M. F. (2023). Monitoring Equipment Corrosion due to Sour Crude Oils: a Bayesian Approach. *Chemical Engineering Transactions*, 99, 337-342.
- Bergman, J., Chung, H., Janapati, V., Li, I., Kumar, A., Kumar-Yadav, S., Chapman, D., Nissan, A., Sarrafi-Nour, R. 2016. Evaluation of the Real-Time Active Pipeline Integrity Detection System for Corrosion Quantification. *NACE – Int. Corrosion Conference Series*, 4, 2674 - 2685
- Bragatto, P., Ansaldi, S.M. 2022. Cyber physical systems for occupational safety at industrial sites: opportunities and challenges. *Serbian Journal of Management*, 17(2), 451-461.
- Bragatto, P., Ansaldi, S.M., Mennuti, C. 2018 Improving safety of process plants, through smart systems for critical equipment monitoring *Chemical Engineering Transactions*, 67, 49-54.
- Dejian Li, (2017), Machine design of robot for detecting oil pipeline, *Chemical Engineering Transactions*, 62, 691-696
- Devold, H., Fjellheim, R. Artificial intelligence in autonomous operation of oil and gas facilities 2019 Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference, ADIP 2019
- EGIG. 2020. 11th Report of the European Gas Pipeline Incident Data Group, 1970-2019. <https://www.egig.eu/>.
- Jordan, S., Moore, J., Hovet, S., Box, J., Perry, J., Kirsche, K., Lewis, D., Tse, Z.T.H. (2018) State-of-the-art technologies for UAV inspections. *IET Radar, Sonar and Navigation*, 12, 151-164.
- EN (2006) Analysis techniques for system reliability – procedure for failure mode and effects analysis FMEA (IEC 60812) CENELEC Brussel, BE.
- Iaiani, M., Tugnoli, A., Bonvicini, S., & Cozzani, V. 2021. Analysis of cybersecurity-related incidents in the process industry. *Reliability Engineering & System Safety*, 209, 107485.
- Iaiani M., Tugnoli A., Cozzani V., 2022, A Bow-Tie Approach for the Identification of Scenarios Induced by Physical Intentional Attacks to Chemical and Process Plants. *Chemical Engineering Transactions*, 90, 403-408.
- Radauer, A., Baronowski, S., Yeghyan, M., 2022 Scoping study for supporting the development of a code of practice for researchers on standardization: European Commission, Directorate-General for Research and Innovation, Final Report, Tardos, G.(editor), Publication Office of the European Union.
- Rusu, C. Tatar, M.O. 2022 Adapting Mechanisms for In-Pipe Inspection Robots: a Review. *Applied Science*, 12, 6191
- Sabry, H. 2017. Integrity of LNG flare systems. Society of Petroleum Engineers (SPE). In Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE. Paper# SPE-188307-MS.
- Schmedemann, O.; Baaß, M.; Schoepflin, D.; Schüppstuhl, T. (2022). Procedural synthetic training data generation for AI-based defect detection in industrial surface inspection. *Procedia CIRP*, 107, 1101–1106
- Shamsi, A., Humaid, A., Castelino, S.M. 2022 Online Robotic Inspection of Above Ground Storage Tanks without Outage. Paper presented at the ADIPEC, Abu Dhabi, UAE
- Tiboni, M., Remino, C., Bussola, R., & Amici, C. 2022. A review on vibration-based condition monitoring of rotating machinery. *Applied Sciences*, 12(3), 972.
- Yu, L., Yang, E., Ren, P., Luo, C., Dobie, G., Gu, D., Yan, X. 2019 Inspection robots in oil and gas industry: A review of current solutions and future trends 25th IEEE Int. Conf. on Automation & Computing, 8895089