UNIVERSITEIT TWENTE.

OVERVIEW OF POTENTIAL METHODS FOR CORROSION MONITORING

Part of deliverable D1 of the NTP “Development of Sensor Technology and Maintenance Concepts for Corrosion-related Maintenance”

COLOFON

DATUM
11 November 2020

VERSIE
1.2

STATUS
draft

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SUMMARY

In this report, a technology assessment on non-destructive material testing techniques is given while focusing on evaluation capability of corrosion related deterioration processes and integrity losses. A comprehensive literature survey is made on currently available methods and techniques which can be suitable to assess instantaneous rate of corrosion processes and/or cumulative impact structural integrity losses, applied by either monitoring or inspection use case. Then methods are categorized and compared to each other by the means of a summary sheet, using variety and a range of criteria. Finally, relying on stakeholder requirements, a short list of suitable techniques are derived.

LIST OF SYMBOLS AND ABBREVIATIONS

A	Asymmetric
AC	Alternating Current
AE	Acoustic Emission
AMR	Anisotropic Magnetic-Resistance
A-Ws	Acoustic Waves
CF	Corrosion Fatigue
CGV	Constant Group Velocity
CUI	Corrosion Under Insulation
CV	Cyclic Voltammetry
DC	Direct Current
DPV	Differential Pulse Voltammetry
EC	Eddy Current
ECh	Electrochemical
ECdl	Electrochemical Double Layer
ECN	Electrochemical Noise
Ecorr	Electrode, Corrosion Potential
EIS	Electrochemical Impedance Spectroscopy
EM-AT	Electromagnetic Acoustic Transducer
ER	Electrical Resistance
FM-EIS	Frequency Modulated Electrochemical Impedance Spectroscopy
FSM	Field-Signature Method
GD	Galvano-Dynamic Electrochemical Impedance Spectroscopy
GMR	Magneto-Resistance
GPR	Ground Penetrating Radar
GWM	Guided Wave Method
HF	High Frequency
IRTg	Infrared Thermography
KPI	Key Performance Indicator
LF	Low Frequency
LPR	Linear Polarisation Resistance
LSV	Linear Sweep Voltammetry
LW	Longitudinal Wave
MAE	Magneto-Acoustic Emission
MBN	Magnetic Barkhausen Noise
MD	Magneto-Diode (or Transistor)
MF	Magnetic Flux
MFL	Magnetic Flux Leakage
MIC	Microbiologically Influenced Corrosion
MMM	Metal Magnetic Memory
NOCS	No Connection To Substrate
MW	Microwave
NDT	Non-Destructive Technique
NERSE	Near Electrical Resonance Signal Enhancement
NPV	Normal Pulse Voltammetry
OCP	Open Circuit Potential
ORP	Odd Random Phase Electrochemical Impedance Spectroscopy
PD	Potential Dynamic
PEC	Pulse Eddy Current
PZT	Piezo Transducer
PWR	Pressurised Water Reactor

RE	Reference Electrode
RF	Radio Frequency
RFID	Radio Frequency Identification Tag
S	Symmetric
SCC	Stress Corrosion
SF-EIS	Single Frequency Electrochemical Impedance Spectroscopy
SH	Shear Horizontal
SHM	Structural Health Monitoring
SHW	Shear Horizontal Wave
SNR	Signal To Noise Ratio
SQUID	Superconducting Quantum Interference Device
SB	Salt-Bridge
SC	Single Cell
SS	Single Substrate
SW	Shear Wave
T	Torsional
TECO	Transient Eddy Current Oscillation
TEM	Transverse electromagnetic mode
ToF	Time of Flight
Tx & Rx	Transmit And Receive (Signal Levels)
UWB	Ultra-Wideband
WE	Work Electrode
WL	Weight Loss
ZGV	Zero Group Velocity

1 INTRODUCTION

This Defence Technology Program (DTP) entitled as "Development of Sensor Technology and Maintenance Concepts for Corrosion-related Maintenance" aims to develop a concept to monitor corrosion in military, i.e., naval and aerospace systems. The following entities worked closely on achieving project goals. Project coordinator the Netherlands Aerospace Centre (hereafter referenced as the NLR), independent expert contractor the Endures B.V., from academic groups the Delft University of Technology (herewith referenced as the TUDelft) and the University of Twente (further referred to as the UTwente) collaborated in the DTP. Role of the latter was closely supervised by expert representatives at the Netherlands Défense Academy (furthermore referred to as the NLDA). Detailed goals of the DTP were described in the project proposal and plan.

Deliverable one or D1 of the DTP is aimed at obtaining a "Corrosion and monitoring technology assessment" with a certain level of detail. Thus, the present report addresses this technological overview by focusing on the currently most developed technologies and providing all necessary information on the potential methods which could provide proper functionality sought in this project. This overview was created by cooperation of the NLDA and UTwente. To contribute to compilation of this report, the NLR and Endures BV identified the most critical corrosion related integrity risks and phenomena along with the worst affect structural and local areas of military assets at the RNL Airforce and the RNL Navy, respectively. These insights, together with an overview of the methods presented in this report, form the requested technology assessment (D1).

In section 2, the methodology followed to assess a variety of structural health and corrosion monitoring technologies is described. Then in Section 3, the actual overview is presented. Finally, in section 4 inferences and some conclusions are drawn.

2 METHODOLOGY

A comprehensive literature survey was made to explore available and technological feasible non-destructive techniques (unprotected by patent applications) which could potentially enable condition assessment of structures and evaluation of corrosion processes and/or the consequences, i.e., degradation of coatings, reduction of plate thickness, the formation of corrosion products under insulation (coatings) or pits and cracks, by the use case of either monitoring or inspection. Methods were arranged into a number of main categories then listed in a summary sheet in a MS Excel format (see section 3). Based on the value engineering principles, techniques were evaluated in line with numbers of criteria, then a short list of suitable technologies was obtained. In this section, first different technology categories are concisely introduced. Thereafter, the set of various criteria is delineated. Readers are assumed to have in background material science with basic understanding, knowledge in interaction of electromagnetic radiations and fields with materials, as DTP members were known of, since the following section is exempt of basic introduction to fundamental physics of the phenomena on which all herewith discussed material testing techniques are based on. Since, the current review and selection of the NDT techniques are restrained to discussion of state-of-the-art and recent advancements.

2.1 Categorization of NDT techniques

For a 1st stage overview, techniques with acceptable degree of condition monitoring capabilities were selected and listed in a table sheet (MS Excel format) with attention to the maritime and partly to aerospace applications. This table sheet contains rudimentary information and recent key performance indicators on the following methods:

- Short- and long-range **ultrasonic techniques**, based on time of flight, variation in group and phase velocity of propagating or standing ultrasonic waves. Short-range ultrasonic is excellent for spot area testing to gauge uniform wall thickness loss, at a rate of 0.15 mm/year within 1.5 hours [1] if applicable on easily accessible areas with low geometrical complexity. In a protected environment, very low thinning rates at a 10 μm/year can be accurately defined over sufficiently long periods, i.e., 15 days to achieve uncertainty of ±1.5 μm/year [2] . The 15 relative percent error is regarded as good in the viewpoint of other well performing techniques. Most of the industry solutions are well established and mature. It is often combined with electrochemical techniques, the qualitative open circuit potential measurement. The **long-range guided waves** offers complementary benefits in condition assessment over inaccessible areas. Such techniques are readily advised by international standard guidelines [3] for detection of corrosion at inaccessible locations [4]. Complex behaviour of guided waves is the susceptibility to mode conversion from fundamental to first harmonic at non-continuous structural sections with abrupt increase plate thickness, while insensitive for smooth and continuous cross-section changes [5]. Total reflection of harmonic modes can be observed at cut-off plate thickness. In a reversed manner, first harmonic can converse into fundamental mode when damage section suddenly features cross-section of smaller than cut-off thickness. Wavenumber changes according to decreasing plate thickness and reaches minimum at cut-off thickness while group velocity becomes minimum and phase velocity maximum. Low frequency guided wave inspection is employed for large area testing from a single transducer position. However, detection becomes insensitive and problematic at inaccessible regions like pipe supports or beyond T-joints since low frequency guided waves cannot effectively propagate rather reflect from those geometrical sections, hence severely limiting detection performance of damages. Thus, higher frequencies help to increase sensitivity to small damages like pits and cracks, and to minimise reflections from complex structures. Guided wave techniques used for corrosion inspection involve symmetrical and asymmetrical Lamb waves fundamental mode at ~1.5 MHz mm (wide-area gradual thinning) [6–9], shear horizontal waves of fundamental mode sensitive for shallow sharp edges and grooves [10,11] and the first harmonic mode (~3 MHz mm) for gradual thinning detected in transmission mode [12], CHIME [13,14] and multi-skip (highly surface sensitive) and the A1 mode at ~18 MHz mm [15–17] (highly affected by surface dissipation factors like liquid loading, coatings and welded T-joints). Based on electromagnetic induction, variety of ultrasonic waves can be preferentially excited [18]. Shear horizontal waves are preferably used in pitch-catch mode [19], featuring low error range (±10 μm) at uniform plate thickness reduction rate of 0.9 mm/year by temperature fluctuations between 20 and 200°C. The most typical shortage of necessary use of couplant materials can be overcome by using rectangular waveguides with varied aspect ratios. Thus, effective transmission of shear horizontal waves can be achieved via dry-coupling between piezoelectric transducer and investigated areas. Average wall thickness loss of as low as 0.1 mm can be consistently defined in plate thickness range between 3 and 25 mm based on Hanning windowing, even at relatively high temperatures [20]. The creeping head wave inspection method was developed for condition monitoring of parallel or near-parallel wall metallic plates. This patented technique known as CHIME [21,22] is a lateral surface skimming compression waves generated by probes at a critical angle. The multiple-skip testing is an intermediate-range condition assessment inspection technique suited for pipes with diameter of >30 mm and wall thickness of above 10 mm [23–25]. In the aspect of detection sensitivity, small uniform thickness variation of around 0.2 mm can be detected, owing to the high frequency of propagating waves (~2 MHz mm plate thickness), multiple reflections from internal surface and the moderate range of propagation. Unfortunately, due to its exceptionally high sensitivity to the surface condition, this technique is not feasible to substrates with thick paint coatings and over large corroded areas with rough surfaces (strong scattering). Although it was in research phase, corrosion monitoring of submerged plates and differentiation from notch sections was attainable along with assessing stress–strain behaviour and tensile strength of plates [26]. Even submerged and layer structured materials were successfully investigated by guided waves for damage assessment [27] but no quantification obtained. Sharp surface near damage profiles like cracks and gradual plate thickness reductions can be provenly assessed in reflection and transmission modes [28], respectively. Interestingly, short and long-range guided waves are combined with electrochemical techniques to achieve monitoring onset of corrosion [29]. In the aspects of implement-ability on naval vessels, inspection of uniform plate thickness over large areas can be obtained by testing with Lamb waves at increased frequencies in combination with constant group velocity over a wide range of wall thickness, then shift of the phase velocity becomes indicative via dispersion, allowing accurate wall thickness assessment with easy temperature correction [30]. Although testing with guided waves can be indicative to identify and localize subsurface cracks in welded stiffener sections, the use of this technique is restrained to some distinct industrial fields [31].

- Using active and passive **magnetic characterization techniques**, electrically conductive, ferromagnetic and ferrimagnetic materials can be characterised. Active magnetic techniques with sufficient NDT potential can be further categorised as type of arising secondary effect such as orientational change and eddy current arousal via perturbation and saturation with magnetic fluxes and inductive coupling of randomly oriented eddy current of magnetic domains in the investigated materials. In fact, there are further categorizations into sub-classes of magnetic measure modes, this set could only be valuable in a further stage of revision for development of detailed design. Subdivision relates to three main categories such as magnetic flux leakage , eddy current [32,33] and pulsed eddy current [34] testing (can be automated [35]) and magnetic memory method. Thus, **magnetic flux leakage** can be defined as secondary-passive and eddy current method as secondary-active methods. The former (**MFL**) utilises strong magnets, preferably electromagnets to set strength of the magnetic fields to the level required to type of investigated materials [36]. As soon as high density magnetic fluxes saturate investigated material, flux leakage arise at all defects and damages from the bulk and near surface regions from depth ranges of around 20 and 12 mm, respectively. Concentration ability of magnetic fluxes is deflected by geometrical discontinuities such inclusions, voids and corrosion affected regions, everything which features different permeability. Generally, strong permanent magnets, large yokes with coils are used for excitation and multiple coils or array of Hall effect sensors for detection of distribution of magnetic fluxes. Generally the magnetisation power must be high, whereas the leakage signals are rather weak and must clearly be separated from the background noise. So, pick-up sensor coils must be located close to the investigated sections (very low lift-off preferable [37]) to be able to explore location and possibly orientation of damage sections. Flux density hysteresis curves are representative to degradation but usually insensitive to small defects, whereas flux distribution is sensitive to small defects [38]. In the aspect of NDT, MFL is widely used at many engineering fields, despite the fact of its commonly known limitations. For damage characterisation, inverse determination of defects is usually difficult solely from the recorded MFL signals [39] but solvable based on mathematical methods [40], i.e., wavelet, artificial neutral network [41] and genetic algorithm [42,43]. In addition, this technique is rather slow and impractical due to several reasons such as plastic deformation related damages with impact on flux leakage not well understood, a highly regular macroscopic structure of the tested material required, the probes and the equipment bulky and requires high power supply. To sense leakage of magnetic fields, array of pick-up coils, Hall effect sensors, anisotropic magnetoresistive (AMR), giant magnetoresistive (GMR) and tunnelling magnetoresistive (TMR) sensors are utilized [44]. Coil sensors are mode of multi-turn loops around high permeability core to increases sensing performance by collecting leakage field [45]. It features low power consumption and operate at frequencies up to 1 MHz. Coil sensors are not sensitive for low frequency fields and more sensitive to rate of field change rather than its strength. The response signal is affected by thermal and electrical noise. Therefore, for low frequency scanning coil sensors are advised to use for MFL testing. The higher sensitivity and more stable Hall effect sensors are built from thin plates of good conductors fitted with four electrical contacts, measuring field variations in vicinity of damages. Due to moderate sensitivity and wide range linearity of sensing response, Hall effect sensors are suited for detection of strong magnetic fields. On the other hand, magnetoresistive type AMR [46], GMR [47] and TMR sensors are made of thin films, which enables higher sensitivity expressed in MR ratio increasing in the aforementioned order. Due to high sensitivity and non-linear response (<1.5 mT), these sensors are only advised to apply for weak magnetic fields when high accuracy, output and stability with restrained temperature drift required. **Eddy current technique** is the most widespread, deeply investigated and still actively researched area of NDTs. This group of methods includes great variety of active testing modes of electrically conductive ferromagnetic [48] and non-ferromagnetic materials and detection modes which summarised in the Excel sheet. In general, eddy current is rather surface sensitive to the effects of chemical state [49], anisotropy of conductivity [50], phase transformation in near and somewhat in bulk phase [51] due to exponential decay of magnetising and arousing field signals from a maximum analysis depth of ~6 mm which depends on signal types, testing frequency, material properties like conductivity [52,53], magnetic permeability and lateral size of the probe. Defect localisation and identification works with austenitic steels and non-ferromagnetic alloys. Mainly cracks [54,55], anisotropic defects and damages can be readily identified close to surface, e.g., damage size of 0.2 mm in depth of ~1.2 mm [56]. The presence of coatings with thickness of up to 1 mm can easily be overcome [57]. Defects and damages can be identified via lift-off correction (practical advantage of sensitive detection under insulations) or alternatively pulsed mode can be used to define coating thickness accurately [58]. Pulsed eddy current is provenly capable to characterise layers of corroded phase [59]. Thus, this is complementary to the ultrasonic techniques which more suited for bulk phase testing. Qualitative and quantitative capabilities with 3D aligned probes cover localisation, size and orientation identification, indication of uniform and local integrity losses, i.e., cracks possibly in all three directions depending on number and orientation of the magnetic field flux gate sensors [60]. Most recent development involves diversity geometries of the sensor probes [61–66], array variants [67–70] with flexibility [71–73]. band selection to pulse testing modes [74], combination with TMR sensing [75], thickness assessment of metal layers via apparent eddy current conductivity spectroscopy [76], applicable to strain sensing [77] based on implementation of simulation [78,79] and modern signal-processing algorithms [80]. No magnetic NDT survey would be complete without mentioning the meandering winding magnetometer (MWM) developed by the JENTEK Sensors Inc. Although, it may not fit directly into either of the aforementioned categories, active magnetization with MWM probes and MWM-arrays are proven to effective inductive sensing mode dedicated to condition assessment, evaluation of material properties such as electrical conductivity and magnetic permeability [81,82]. Performance of the MWM array sensors is moderate for small size cracks but it can be customised for the targeted damage size range [83–86]. The passive **magnetic memory method** (**MMM**) came under consideration due to sensitive detection of self-leakage of residual magnetic fields [87,88] from ferromagnetic materials affected by anisotropic magnetic field and physical load. Qualitative information can be obtained from a depth of up to 7 mm [89] with detection sensitivity of ~1 nT with flux gate sensors and hand-held device with scanning at a speed of >100 m/hour. Only this technique is to assess pitting corrosion in a depth of 6 mm. The flux leakage signal is proportional with extent of deformation of magnetic domains in elastic part of the stress-strain curves [90] both in tensile and compression modes. In addition, the effect of fatigue can be assessed [91–93]. This could be valuable to use on ship hulls, ballast tanks and deck plates. Applicability is related to areas where elastic to plastic transition and permanent shift of dislocations take place. Nevertheless, in general the large difficulty in obtaining quantitative data for maintenance experts precludes taking it further to conceptual and detailed design development [94–97].

- There are two types of **Infrared thermography** techniques such as active and passive infrared thermography. Both types offer sensitive temperature distribution mapping of monitored surfaces. The former utilises external source of radiation to increase thermal energy of investigated objects, which local heat accumulation translates into increasing temperature. The most common active infrared technique is the pulse phase thermography with short temperature ramp-up phases [98] due to its strength in sensitivity [99], ease of use and rapid application. Damage affected zones like integrity disrupted volume ranges exhibit lower rate of cooling. There are numerous implementations such as lock-in thermography with oscillating heating, long-pulse or stepped heating thermography with continuous low power heat source (focusing on the cooling phase). Furthermore, vibrothermography uses mechanical energy of vibrations and its conversion to heat and measure altered rate of energy dissipation and conduction through cracks, voids, or other damages. On the other hand, passive infrared thermography does not utilise external heat source instead infrared radiation emitted by the investigated object and so more suitable for industries with moderate and high temperature and materials featuring slow or moderate rate of heat dissipation. As an example, carbon fibre reinforced polymers are widely used in lightweight engineering structures and despite their mechanical strength, these are susceptible for damages like delamination, buckling and cracking [100]. Thermography techniques generally offers solution to investigate such composites, e.g., in aerospace components [101] for characterization of delamination, impact damage and porosity [102]. What is more, condition assessment of civil structures [103] like concrete is achievable detecting damages up to 8 cm below the surface [104]. In cases, thermographic techniques was stated as capable of detecting cracks in metallic components beneath thermal barrier coatings with thickness of 0.6 mm [105]. The highest sensitivity of detection was reached with pulse eddy current (PEC) excitation coupled thermography. The inspection time is usually between a second for PEC and 50 ms or even less (with short laser pulse). Tested size area may vary between ~20 mm in diameter (PEC) and some millimetres (laser pulse heating). Reliability and reproducibility are generally adequate for high industrial standard.
- **Radio frequency resonators** have been recently developed to detect uniform and localised corrosion phenomena [106] in transmission lines via measuring decreasing degree of absorption by the metallic conductor between the receiver and transmitter [107], transmission and reflection of the electromagnetic waves in thin strip line sensing element [108]. To monitor atmospheric corrosion events and measure level of liquids, strip and stub resonators are regarded potential candidates, respectively. Nevertheless, there are number of shortages limiting implement-ability to high risk assets, such as sensitivity of substrates for radiation losses affected by temperature variation of the environment, low accuracy of permittivity of materials at high frequencies, different wave propagation or conductor loss in top and bottom layers (frequency dependent), overestimation of dielectric loss by inaccurate and non-homogeneous permittivity of materials, rare stability due to non-parallel geometry of the resonators (physical embodiment limitations) and high sensitivity to increasing surface roughness affected by the skin depth leading to strong attenuation of signals. **Microwave testing** offers condition assessment of

dielectrics in non-contact mode in the form of volumetric size [109] and porosity [110]. By the former case, detection is achieved by measuring reflection from the metallic substrates at certain frequencies where magnitude of reflected waves vary largely besides nearly zero phase variation or opposite. This allows accurate determination of volumetric size of dielectrics on the metal specimens. The accuracy is high with error of around only 1%. Similarly, porosity of dielectrics is evaluated by phase variation of the reflected waves.

- Despite **ground penetrating radar** techniques have been long-time used in civil engineering, developed over 30 years realising ultra-wideband devices scanning from 10 MHz up to 10-50 GHz (typically used above 1 GHz), ground penetrating radar is relatively newly utilised for non-destructive material testing [111]. This is highly sensitive detection of uniform and local loss of metallic phases covered within large volume of dielectric materials like concrete and other dielectrics like coatings and polymer laminates. It is capable to inspect tunnel linings as it was stated in a report "Mapping voids, debonding, delaminations, moisture, and other defects behind or within tunnel linings" [112]. Further development is related to tomographic multi-offset advanced scalar imaging, 2 & 3 D ray-tracing and borehole radar function. As an example for corrosion related condition assessment, in experiment conducted over 10 years, uniform and localised events of rebars were identified and differentiated by the means of altered intensity of reflection of incident radar signals between the 1.5 and 2.6 GHz range [113]. Detection mechanism and sensitivity is based on the principle of dielectric polarisation change and Debye relaxation [114] for water at ~10 GHz [115], distribution for composites by Cole−Cole dispersion attenuation in time-domain reflectometry [116,117]. This method was involved in the survey, owing to its marked ability to detect emerging distinct porous phase materials such as corrosion products on surface of metallic substrates, although it was not accepted as one of the most applicable for the DTP, nor compatible with the maritime application field (similarly to many other techniques).
- The **weight loss method** dates back the longest history of corrosion research and engineering [118] and still currently used in laboratories [119−122] with various types of coupons for validation purposes in case of well-defined and measurable integrity losses such as uniform corrosion proceeding at moderate rates compared to the exposure time. Benefits include generally good definition of corrosion rate with ≤5% error in reproducibility with high reliability. It can be performed in any media, so electrical conductivity is not a limiting factor under wide conditions up to 450°C and to 350 bar in case of retrievable holders without restrictions on fixed probes. Detailed examination, observation of the coupon surface can be performed to identify corrosion products and explore mechanism of processes. Materials and coupons can be customised for crevice examination (disc coupons), for SCC (stressed coupons), for erosion testing (rod coupons), welded coupons for variance between corrosion behaviour between welded and heat affected zones compared to non-welded areas, gauze coupon for collection of biofouling. The method is highly economical at low scale and for over short-term testing. Limitations include the number of parallel samples needed to obtain reliable reference data. The rate of experimentation is usually low, may easily cover hundreds and thousands of days if the loss rate is around 1 μm/year. General and average data serve as cumulative data over specified periods. Treatment of the coupons takes long-time with preparation, cleaning, weighing, etc. WLM does not apply regarding corrosion of nonferrous alloys, e.g., copper alloys in water and selection of corrosion inhibitors. Sensitivity and accuracy with metals like copper is generally low in aqueous phase in the presence of corrosion inhibitors. The main drawback is usually the difficult installation and change of coupons on a regular period. It is labour intensive and cost a lot of time for all steps in the procedure leading to extraordinary long processing times. On top of that, this provides historical data, retrospective information and not real-time cumulative losses and estimated, deducted actual rates. Furthermore, this method is ineffective at assessment of all other corrosion phenomena and the most importantly the implementation of current interest due to incapability of real-time monitoring and inspection. Originally, benefits were comparable with shortages but in recent times this method is regarded as obsolete. Thus, it is excluded from a highly sustainable, maintainable maritime implementation unless local environment and geometrical variation of corrosion impact would necessitate validation assessment by the means of well-arranged specimens (including

coatings) as shown in Figure 1 (defence intended research on corrosion impact on a naval vessel, the USN CVN74).

FIGURE 1. SPECIMENS FITTED ON EXPOSURE RACK ON DECK OF THE USN CVN 74 (NIMITZ-CLASS NUCLEAR-POWERED SUPERCARRIER) TO PERFORM CORROSION RATE ASSESSMENT OF THE MARITIME ENVIRONMENT [123].

- **Electrical techniques** were subdivided into subcategories as follows.

  The **electrical resistance (ER) [124] and multiple electrical resistance or field-signature methods (FSM) [125], the direct potential difference (**DCPD**) [126] and alternating current potential drop (**ACPD**) [127] methods**. The electrical resistance measurement is specified and descried by standards [128–130] existing in many practical implementations such as the two and four-point measurement [131–134] (dating back more than 100 years) [135], strips, various concentric sensor probes and arrays for material characterisation. Any realisation of the technique provides real-time monitoring full cross-sectional impact of both uniform and localised atmospheric corrosion events. The object of subject to monitor can be the targeted structure or modelling materials. The former realises real-time condition assessment via fitted electrodes, and the latter achieves estimation of environment corrosivity using miniaturised substrates [136–138,]. Continuous monitoring of indoor and outdoor atmosphere lies on the measurement of electrical resistance of thin strips made of zinc, iron, copper and nickel modelling superficial cumulative loss of intended structural materials exposed to the same environment and the unprotected sensor part (resistance measured in comparison with a reference). Material loss in cross-section translates into decreasing conductivity, increasing resistance of the transmission line [139]. Sensitivity is more than sufficient varying between 1 and 10 nm depending on type and thickness of the active sensor area. Fast response time of sensing is expressed in changes in corrosivity detected within hours or even few minutes [140]. Reproducibility described STD is within ±20% or lower for metals experiencing uniform corrosion. In addition, automation of such corrosion loggers was an industrial routine [141]. Direct current potential drop techniques were implemented to achieve penetration over full cross-section, thickness of plates [142]. The four-point ACPD is typically employed in NDE of material properties [143–145]. The ACPD is considered as extension of DCPD to estimate depths of defects based on varied scanning frequencies due to the skin effect. Thus, low currents can produce large potential difference [146] for characterization [147,148]. Latest development at the field is the non-linear difference imaging based crack estimation, which tolerates spatial variation of the sensing skin background conductivity [149]. The electrical resistance tomography develops imaging of complex structural crack patterns. To increase sensing area for large-scale monitoring and to detect internal corrosion, DCPD arrays or the FSM was developed based on potential-matrix measurement [150] using electrode pairs [151,152]. FSM provides information on location dependent resistance changing caused by local voltage drops along current lines and so, it suited for sensing uniform plate thickness loss. The reason for low accuracy sensing of pitting corrosion is in distribution of potential field between electrode pairs highly affected, altered by the size, depth and lateral distribution of corrosion pits. Nevertheless, subdivision to resistor network and mathematical modelling may offer sufficient solution to this shortage [153]. The error and inaccuracy source drag effect in evaluation of pitting, welding corrosion and erosion has been properly addressed [154]. Field of application of FSM is mainly restrained to land-based oil and gas transmission pipes and containers [155], fatigue crack monitoring on steel bridges [156]. Limitations are the following. Low amount of salt deposition, corrosion products filled or unfilled with electrolyte on the substrate and sensor surface certainly lead to error due to high degree of shunting leakage current (if no grounded electrodes used for draining). Preliminary information is needed to select correct probe array matching target resistance range while sensitivity reverse proportional with lifetime of the probes. So, usually weight loss method is needed prior to define proper selection of the ER probes with suitable sensitivity and lifetime. This group of techniques is suited to condition monitoring in the presence of insulator and low conductivity environment like air and organic fluids (no valuable contribution from the ionic regime). This selection does not include non-contacting type resistance or capacitive measure modes, which is a state-of the-art characterisation of metals and dielectric materials. Based on the recent developments, the inductive coupling based magnetic techniques present competitive alternatives to assess condition of metallic substrates and ferromagnetic steel plates.

- The work function to sense permittivity of materials in non-contact mode offers **capacitive sensing, imaging** [157]. Despite the fact this is a relatively newly developed industrial area, there are variety and number of applications like mass [158], pressure [159], humidity [160] and proximity measure [161–163], soil moisture sensors are undoubtedly the most widespread [164]. Detection or material testing mode utilises bending electrical fields outreaching in normal direction from the coplanar electrode configurations while the field concentrates in the near volume range of the electrode plane to obtain fringe capacitance. In reality, the electrical field always concentrates in between the electrode edges and tends to scarce in inner electrode regions, so these are also known as edge-coupled electrode strip-lines . High frequency electronic devices require low dissipation factor of the boards expressed in permittivity and electrical conductivity of the host platform materials (to conductor tracks) which are very similar to electrical testing, monitoring of high resistance maritime coatings. Nevertheless, what is the worst in electronics, i.e., strong interaction of the electrical field with track-nearby materials. Then it is the best for electrical sensing, material testing for NDT and condition monitoring, to obtain valuable information on electrical properties reflecting state of the materials. The usual configuration is in-plane honey-comb alignment (interdigitated) electrodes, although there are multiple variations for touch sensing [165]. Permittivity changes in the near field perpendicular to the electrodes is sensitively defined for liquids [166] and moderately for solids [167–170]. In this case, the penetration depth into the materials depends highly on frequency of the electric field [171]. As for effectivity of the work function, 'shunted mode' sensing provides deeper penetration depth into the tested materials than transmission mode [172]. The reason is behind alteration of the sensing electrical field (provided by the driver or counter electrodes) by the grounded back-plate electrodes before arrival at the ground-balanced sensing or working electrodes. When useful signal is low compared to base signal and background noise besides with delicate shielding [173], then capacitive sensing is technically not feasible. Nevertheless, it is successful maritime implementation of the technique to detect corrosion of rebars in dockyard concrete structures [174].

- Both **passive and active DC polarisation techniques** are extensively used for corrosion rate assessment both in laboratories and at field applications. For monitoring, open-circuit (electrode) potential or corrosion electrode potential and **electrochemical noise measurement** are well suited for qualitative condition evaluation of protectiveness and corrosion of systems such as most of the engineering alloys, concrete and coated specimens. Noise measurement does not provide instantaneous rate assessment unless DC based resistive slopes are defined both in the anodic and cathodic ranges. Generally, both techniques are compatible with marine environment due to the high conductivity of the surrounding fluid phase. Probably, these are the reasons for such methods actively used at the US Navy for monitoring condition of seawater ballast tanks [175]. Electrochemical noise measurement was listed for its universality by the ‘no connection to substrate’ configuration along with other appliable configurations and set-ups suitable for laboratory and field implementations for inspection and monitoring use cases. Latest industrial developments in open circuit potential measurements are informative [176,177] for condition assessment [178,179] and time saving for inspection and for maintenance organisation [180]. This is to define effectiveness of barrier coatings and cathodic protection systems [181] (regardless of impressed or sacrificial types) on ballast tanks [182]. Embedded solid state reference electrodes offers real-time monitoring of metallic components for over medium long periods. Nowadays embedded reference electrodes are advised to use for corrosion monitoring in reinforced concrete, which can be composed of graphite [183] and manganese oxide [184] for cathodic protecting systems [185,186] reinforced concrete structures [187,188], platinum [189] and silver/silver chloride electrodes [190] for coatings existing in stable thin-layer forms [191] favourable due to reliable stability in environment of high chlorite concentration [192].
- To investigate the impact of surface events, **active DC techniques** provide results with acceptable accuracy on instantaneous loss rate of metallic structures at the surface via interfacial resistance also known as the polarisation resistance. Although polarisation resistance is directly coupled and greatly affected by mass transport of the chemical components in case of macro-size electrodes and relatively large electrolysing currents, micron-size linear polarisation resistance or LPR sensors [193] are exempt of this characteristic. Thus, such sensors features mainly charge-transfer limitation which can be accurately defined by electrochemical techniques along with correction to surface properties. There are successful civil engineering [194,195] and military applications [196–201] with proven validity for atmospheric corrosion evaluation. Despite the fact, there were lots of advancements at this field and many convincing applications appeared as market ready solutions, some validation procedures drew doubt on true accuracy (validity) of this sensing mode despite the introduction of many meticulous corrections.
- In cases when DC results would be noise affected at field and the impact of mass transport processes unknown at extent to couple with superficial electrochemistry events, i.e., Faraday processes, then a large variety of **AC techniques** offer remedy for laboratory and field applications. **Impedance testing** is a powerful tool to distinct time constant based resistance contributions so as to analyse reaction mechanism [202], to define charge-transfer resistance and interfacial pseudo-capacitance. This is listed due to exceptionally highly sensitivity in characterisation of surface and bulk phase events, genuinely suited for corrosion assessment at solid-liquid interphases, biofilms [203] and dielectrics such as paint coatings [204–208]. Surface condition characterisation is expressed in the charge-transfer resistance and interfacial pseudo-capacitance. Although multi-sine [209–215], electrochemical frequency modulation [216,217] and non-linear [218,219] techniques work well under laboratory condition with reference set-ups and materials, there are regarded still in research phase and so further customisation needed to enable effective implementation at fields. Intensity of harmonic responses are at least an order of magnitude lower than fundamental signals. Therefore, implementation of such methods to high resistive maritime coatings and

materials may look more than questionable. This partly means optimal set of potentiostat-galvanostat coupled with frequency analyser might not be possible in current state and so underperform in comparison with single-sine impedance analysis. Furthermore, non-linear EIS is usually problematic as it requires more time to scan in frequency ranges than traditional linear EIS, and it is for good a reason to improve SNR of collected data [218]. Top of that, the response signal can be very complex and difficult for corrosion reactions to interpret. Therefore, traditional linear impedance testing is still considered to be a reference in characterisation of material properties.

- Owing to severely limited timeframe of the DTP, the final section of column A (bottom part) is not continued in detail with coupled micro-electrode arrays, despite the fact miniaturised electrodes work reliably under environment with wide range of conductivity without marked limitation by impact of the electrical double layer.

2.2 Selection criteria

After categorization as described in the previous section, a table was created to provide information in the following manner. The first column is assigned to technique parameters and key performance metrics. Some extraordinary features of each technique are included both on technical and programmatic parameters. In the consecutive columns, other important information is provided on capabilities, characteristics, preparation of the materials prior to testing, geometrical factors of the investigated structures and probes with supplementary equipment, strengths and shortcomings, limitations in the subsequent sections, besides economic terms in the forms of investment related capital and consumable type regular costs.

3 OVERVIEW OF METHODS

Methods and the related criteria are combined in a MS Excel sheet (25 columns x 93 rows). Some screenshots are shown below in Figure 2. By applying filters to the most relevant criteria, a short list of suitable methods can be obtained. Abbreviations used in the data sheet are given in initial section of this report under the title of “List of symbols and abbreviations”.

	Key Performance Indicators (KPIs)	*Availability*		*Size of inspected materials*	*Preconditon of application*	*Spatial requirement*	*Test parameters & material*
		Public	*Patented*		*Set-up, size of probe & equipment*	*Sensitivity to surface state & structure complexity*	*Target /electrode/ materials (WE,CE,RE) probe arrangement, alignment*
Experimental techniques							
	NDTs must measure in the range of around 0.05 mm						
Short-range acoustic techniques							
Principles of all ultrasonic techniques	Mobile testing, scanning over large areas with materilal thickness of (3)5–150 mm			reproducibility: 0.1 mm	High mobility (specific feature)	Moderate or high	Steels & other alloys & via coatings (no composites)
PZT-Td (piezoelectric transducer) point-to-point in single pulse-echo (or echo-echo mode)	Sensitive & accurate	free applicable	also patented	Wall thickness range: 1-40 mm	NA		via coatings of up to 6 mm
PZT-Td (bonded-array) in single-pusle-echo (or echo-echo mode)	Sensitive & accurate continously	free applicable	also patented	Wall thickness range: 1-40 mm	NA		
PZT-Td AUT-TOFD (semi automted time-of flight deflection)	Faster & good resolution	free applicable	also patented	Wall thickness >6 mm	NA		
PZT-Td (single- or multiple-array focused probes / phased array)	Fast (at least an order of magnitude) & high resolution & sensitivity	free applicable	also patented	Wall thickness: 1-25 mm	NA		
PZT-Td (single- or multiple- L or SV-waves / phased array)	Fast (at least an order of magnitude) & high resolution & sensitivity	free applicable	also patented	Wall thickness: 6-25 mm	NA		
EM-AT (electromagnetic transducers)	Good detection near surface range & in thin bulk phases without couplant, SH & SV angle-beam probes by segmented phased-arrays with high bandwidth & resolution (!)	free applicable	also patented	Wall thickness: 0.6–3.0 mm	NA		Electrical conductivity for magnetic excitation
Laser pulse (ps or fs) excited A-Ws	Fast, good for macro- & micro-cracks along with strain & temperature detection, airplane, aerospace & marine materials (combination of techniques based on feature of the SHM equipment), promising military-aircraft application	free applicable			NA	No (bulky equipment if detection is by laser interferometry (!?))	sensitive to cracks in composites & submerged metals by non-linear acoustics
AE (acoustic emission)	Early & global, real-time mechanism sensitive & locate using 3 sensors	free applicable		Wall thickness >1 mm, detection range up to 25 m	NA	Moderate	Steels & Ti alloys, composites, coatings & insulations
Long-range acoustic techniques	Immobile testing over large, bulky structures & sheets above thickness of				Immobile use (specific feature, not shortage)	Moderate	Steels & Ti alloys, scanning through coatings, but no composites
GWM (guided-wave method) with PZT-Td & dry couplant	Fast & global screening of the surface & bulk phase	free applicable	also patented	Wall thickness >1 mm, max. length: <30 m,	NA	moderate, axi-symmetric L(0,2) & T(0,1) mode for pipes,	same
GWM with magnetostrictive sensor	Fast & global screening of bulk phase	free applicable	also patented	Wall thickness >1 mm, max. length: <30 m,	NA	moderate	same
GWM-SH (shear-horizontal-wave mode, y) with EM excitation	Fast & global screening of bulk phase, low sensitivity to viscous environment (conversion between S0 & Sh0, to L0,1 & L0,2; T0,1 modes)	free applicable	also patented	Wall thickness 1–15 mm, max. length: <10 m,	NA	moderate	same
Lamb waves (acoustic S0 & A0 - phase & group velocities, x - z) excited by PiEz or EM-AT	High sensitivity due to phase dispersion (at CGV point), locate damages over long distances (in pipes) up to 50 m (with EM-AT excitation), thickness by fr. shift at ZGV (in pipes),	free applicable	also patented	Asymmetric (AN) modes at L & HFs (LF-S0 modes not disturbed by soil & water), S0 modes not preferred	NA	asymmetric (N) mode at LFs (pipe walls over long distances), usually	same

Time & parameters of measurement			*Type of corrosion detected*	*Local*					*Capability of monitoring*	*Instantenous reaction rate*
Physical-chemical factors	*short period*	*long period*	*Uniform*	*Pitting*	*Crevice*	*Stress corrosion cracking (SCC)*	*Corrosion fatigue (CF)*	*Coatings (& passivated metals in stable condition)*	*Actual state (static, integral)*	*Actual rate of loss (dynamic, differential)*
Wide temperature & pressure range	Yes, real-time area-state assessment	no	Absolute measure of wall-thickness (10 µm year^{-1} over 15 days)							
			optimal		optimal	planar cracks (between 0.1-2 mm) with depth,		(flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
			optimal		optimal	planar cracks with depth		adhesion test (flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
			optimal			planar cracks with depth		(flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
			optimal			planar cracks with depth		(flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
			optimal			optimal		(flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
			optimal		optimal	optimal	optimal	(flaws, flakes & laminations, detachment, inclusions, cavities & porosity)	yes	no
				readily feasible		proven feasible to defect defects in size range of 20-110 µm, by laser excitation & piezoE detection	cracks in length: 15 mm & width: 50 or even <10 µm, by single & dual laser excitation (non-lin. ultrasonic modulation), life-cycle assessment	delamination testing (by damage reflection) in GFRP (wind turbine blade composite)	yes	
	Yes, real-time area testing, assessment of progression	no		possible & feasible	optimal	optimal (qualitative indication of stages)	optimal		no	yes
Wide temperature & pressure range								Moderate size flaws detected of any sort in transmission (attenuation) & in reflection modes, but locate them exactly impossible		
	Almost real-time testing, state assessment	no	optimal	optimal by L(0,7) at 1 MHz bulk sensitive mode	optimal	optimal by L(0,7) at 1 MHz bulk sensitive mode	optimal	possible by L(0,1) at 0.1 MHz surface sensitive mode	yes	no
			optimal		optimal	optimal	optimal		yes	no
			optimal by A1 mode in transmission	optimal by S0 & S1 in refl. &/or transmission	optimal by A1 mode in transmission	optimal by S0 & S1 in refl. &/or transmission, or SH waves by phased-array angle deam probe EM-AT	optimal by S0 & S1 in refl. &/or transmission, or SH waves by phased-array angle deam probe EM-AT		yes	no
			optimal by A0 mode	optimal by A0 mode	optimal (for surface behaving E_n adsorbers)	optimal by A0 mode	optimal by A0 mode	Waves sensitive to radial gradient of wall thickness variation, detection by trasmission & reflection with pitch(pulse)–catch(echo) mode should be selected accordingly	yes	no

Specific feature(s) of the method				*Investment cost of method*	*Maintenance cost of method*
Strength(s) - Advantage(s)	***Representative nature***	***Applicability***	***Shortcoming(s) - Disadvantage(s)***		
Locating imperfections in pulse-echo mode, usually 1st to apply because of its afford-ability			No real-time detection of surface near imperfections & small voids, size of cavity & orientation of cracks, reflections from grain boundaries & inappropriate for inhomogenous materials, calibration & couplant required on clean & smooth surface, probe alignment critical on the surface, skill & training	Affordable	affordable
Sensitive & accurate at very low rates, only one-side access without coating removal, cheap & easy to deploy	Surface & sub-surface	Structure (probe)	Slow & laborious, calibration & couplant required for single-echo, coating removal if thicker than 6 mm in echo-to-echo mode	Very affordable	affordable
Sensitive & accurate at very low rates, only one-side access without coating removal, cheap & easy to deploy	Surface & sub-surface	Structure (probe array)	Slow & laborious, calibration & good surface mounting, bonding of flexible transducer strip required, coating removal	Very affordable	affordable
Fast & good resolution	Erosion - general corrosion losses		Coating removal	Affordable	affordable
Fast & high resolution & sensitivity	Surface & sub-surface		Coating removal	Affordable	still affordable
Fast & high resolution & sensitivity	Surface & sub-surface		Coating removal (riser open)	Affordable	still affordable
Good detection near surface range & in thin bulk phases, without couplant (but constant spacing required), magnet clearence can be up to 25 mm (by magneto-strictive mech., but is highly material dependent)	Surface & sub-surface		Strong interaction with ferromagnetic maters (attraction force) leading to hard measure & scanning (linear coils), good SNR ratio if probe within distance of 5 mm from sample surface (to close in normal direction), lower SNR than by PZTs, no application on complex surface, geometries (distance depended sensitivity)	Affordable	affordable
Rapid scan & well repeatable (excitation) without baseline, no direct mounting, identify & locate macro damages in pulse-echo mode (based on CWT - selection of *a (scale)* & *b (shift)* parameters), laser pulse power (high amplitude & bandwidth) – piezoelectric echo detection (high sensitivity) = good SNR			Only macro defects detected so far (in the size of some mm), only metals stands only incidence of High Power (HP), sensitive to weather conditions (surface of exposure), impact of crack orientation unknown yet,	High (but depends on set-up; PL-PZT, PL-PL; good SNR)	affordable
Early real-time detection of bulk events, identify stages (micro-cracking), some quantification of extent of damage, (frequently & successfully combined with ECN), (good resolution with ASK clustering algorithm)	Surface & bulk (sensitive to rupture of passive layers & plastic deformation)	Structure	Qualitative nature (no quantification), only for simple structures (no attached surfaces, bolts, rivets, etc), often required to couple with other techniques, sensitive to wave patterns from environment, (more material sensitive)	Affordable	affordable
Less material sensitivity			High geometry (& macro-structure / noise) sensitivity		
Fast & gobal screening of bulk phase	Surface & sub-surface	Structure (probe)	Requires couplant, sensitive to internal & external damage, no adsolute measurement	Affordable	affordable
Fast & gobal screening of bulk phase, without coupling material,	Surface & sub-surface		Sensitive to internal & external damage, no adsolute measurement	Affordable	affordable
Fast & gobal screening of bulk phase, without coupling material, not disperison sensitive	Surface, sub-surface & bulk events		Sensitive to internal & external damage, SH0 & SH1 mode changes & frequency shifts depending on investigated geometry (may be hard to intepret!), no adsolute measurement	Affordable	affordable
Phase velocity dispersive to flaws & wall thickness at HFs over CGV* (simple temperaure correction), damage location in thin plates over long distances, dry-coupled only inclination angle must be set properly, baseline usually not required,	Surface, sub-surface & bulk events		Damage detection highly depend on type of waves, array sensor needed to exact detection, sensitive to surface events - (A0 mode sensitive but leaks (?)), high-sempling rate required (over 1 MHz),	Affordable	affordable

FIGURE 2. OVERVIEW OF ACOUSTIC METHODS / TECHNIQUES AND THE VARIOUS SELECTION CRITERIA (THIS IS UPPER PART OF THE COMPLETE TABLE).

4 SELECTION OF SUITABLE TECHNIQUES

This section specifies requirements on expected capability and features of the corrosion sensor. Then, closer overview and evaluation of the anticipated techniques suitable for maritime industry is given which leads to the final selection.

4.1 Main criteria to select suitable technique(s)

Techniques were assessed by matching with a set of requirements delineated by experts in the DTP and expectations of the stakeholders and future customers. To ensure favourable outcome on behalf of the clients, the general procedure of value engineering was followed for prioritization and well-established selection based on the following set of core criteria.

- Technical parameters
  - Integrity deterioration of paint coatings are aimed at sensitive detection along with emerge and accumulation of corrosion products under the insulating around 1 mm thick dielectric layers.
  - Sensitivity of detection to degree of coating deterioration and accumulation of corrosion products must deviate no more than 2 times in comparison with data obtained with the traditionally employed reference technique and its implementations both in the lab and at field, with and without direct wire connection to steel substrates, respectively.
  - Reliability and repeatability of detection of uniform must be comparable with the traditional reference methods.
  - Lateral size area of testing is expected to be between ~10×10 and 30×30 cm to assess by the prototype(s) via a single testing procedure.
  - The type of information provided by techniques must be real-time, instantaneous data and feature condition assessment (cumulative information), integrity loss of the bulk (mostly) phase.
  - Applicability of techniques on varied complexity of the structures. As an example, usually OCP (E_{corr}) and ECN are unlimited in use on structures of complex geometries but EIS, thermography and acoustic techniques could be hindered for routine application, limited with increasing complexity of target locations.
  - Few number, preferably one probe of moderate lateral size is to be fixed on tested location and coupled with mobile testing equipment.
  - Low power supply (<1W) is required for continuous operation.

- Programmatic and organisational aspects:
  - low maintenance need, good maintainability of the sensor hardware,
  - full safety of the crew and maintenance users whilst engaging with activity with the sensor hardware,
  - the ease of use with installation, operation and maintenance of the sensor, including lifetime support,
  - the ease of use for monitoring and inspection by the marine crew, maintenance experts and expert representatives of the asset management,
  - the ease for interpretation of measurement results/sensor data, evaluated information, the ease of making justified decisions on maintenance actions,
  - compliance with international standards and regulations, i.e., fully closed and sealed structure, safe operation, low power consumption, no emission, full recycle-ability.

- Although the economical range of naval assets is far not comparable with development and implementation of the corrosion sensors, an important economic aspect of the requirement set was the cost over lifetime (similarly to maintenance need of the sensors) not to outweigh expected economic turn-over by application of the sensor(s). Main features of the most frequently used inspection techniques for fatigue crack assessment are provided in Table 1. In terms of the most favourable selection, although the design space with fourteen different parameters of capabilities and requirements can be optimised in a straightforward manner, in practice only a subset, around one third of these parameters are regarded as pivotal and so to use for selection of the most suited material testing techniques for further concept and detailed design development then implementation.

TABLE 1. MAIN FEATURES OF THE MOST FREQUENT INSPECTION TECHNIQUES USED FOR FATIGUE CRACK ASSESSMENT

	Ultrasonics	X-ray	Eddy current	Magnetic particles	Liquid penetrant
Capabilities & requirements	Thickness gauge	Thickness gauge	Thickness gauge	Defect & damages	Defect & damages
Relative sensitivity	High	Medium	High	Low	Low
Rate of testing, time of results	Immediate	Delayed	Immediate	Short delay	Short delay
Type of damage & defect	Internal	Most	External	External	Superficial, surface located
Dependent of material composition	High	High	High	Magnetic only	Little
Effect of geometry	Important	Important	Important	Less important	Less important
Access limitations	Important	Important	Important	Important	Important
Formal record	Expensive	Standard	Expensive	Unusual	Unusual
Operator skill	High	High	Medium	Low	Low
Operator training	Important	Important	Important	Important	Medium
Training need	Intense	Intense	Intense	Low	Low
Portability of equipment	High	Low (no)	High to medium	High to medium	High
Ability to automate	Good	Fair	Good	Fair	Fair
Capital cost	Medium to high	High	Low to medium	Medium	Low
Consumables cost	Very low	High	Low	Medium	Medium

- <u>Extended set of criteria to select material testing techniques involves the items with basic information and explanation:</u>
  - An important criteria is consistency of the experimental data in determination of damages at the interested size range, deterioration rate. Thus, technologies must be mature and feature sufficient level of performance to consider as applicable for corrosion assessment of naval assets by inspection and monitoring use cases. This information is included in column ‘B’ entitled as ‘KPIs’ , in column ‘T’ and ‘W’ with the main title headings of “Specific feature(s) of methods”, subtitle headings of “Strength(s) – Advantage(s)” and “Shortcoming(s) & limitation(s)”.
  - In case of required coating removal and/or additional surface preparation prior to application of techniques, the column entitled as ‘Shortcoming(s) & limitation(s)’ provides proper information. In this viewpoint, short range ultrasonic and eddy current techniques [220] are suited for seamless monitoring application. Informative use of these methods does

not require expert hands and laborious work for coating removal and meticulous surface preparation. Furthermore, electrochemical techniques like impedance and noise measurements are inherently suitable for characterisation of resistance and pseudo-capacitive of surface properties, less limited by condition of the substrate materials. Other techniques are comparably highly sensitive to surface condition of materials but correction of measurement data obtained with the electrochemical techniques usually less difficult and do not require coating removal for excitation and detection.

- The time for measurement over a spot-size area can vary from milliseconds up to hours. In this aspect, short and long range ultrasonic techniques are sufficiently fast featuring time-scales of seconds with measurement parallels and scanning at other various frequencies. Nevertheless, when long range ultrasonic techniques are applied to surface areas of some cubic metres and over large pipe sections, then complete measurement time can increase up to the scale of hours. This feature itself is not a factor to deter from selection because most of the maritime applications spread over years and majority of the corrosion processes are slow. Thus, such a detection time over a critical area at a certain ship location is not a limiting factor but in comparison, eddy current techniques can be up to 10 times faster than ultrasonic ones in case of a spot-size area investigation. In real-world maritime application, the difference between seconds, milli- or micro-seconds makes almost no difference. In addition, magnetic memory method monitors effectively the leakage of traces of remnant magnetisation of ferromagnetic materials in the surface near region, with a lateral scan rate of up to some metres per second, but this performance requires proper mechanic systems for full exploitation. Just like radar and resonator implementations, experimentation and data collection with electromagnetic techniques are blazing fast, with the usual detection time far below than a second even for many parallel scans. Detection with infrared thermography also ranges over some seconds which only slows down in comparison with the electromagnetic techniques owing to time of certain level of heat accumulation in the inspected zone and to obtain a steady temperature for radiation. Resistivity and field signature measurement requires only seconds to perform but their usually much less or completely immobile. Slower detection techniques start with the DC and AC electrochemical techniques featuring measurement times from some minutes up to hours depending on the excitation frequency, the number of cycles for integration to average measured signals. This statement also applies to the open-circuit electrode potential and electrochemical noise measurement. The slowest technique is the weight loss method. This requires a time-scale for measurements from at least days, or rather weeks and months, may even up to years depending on the rate of processes, which makes this approach completely unfeasible. It is extremely labours way to work with, it is still not exempt from possible experimental artefacts.
- For the last by not least, economic aspects of the methods was divided into two main parameters such as investment related capital cost and operation related consumables. Price of the equipment and consumables is graded by the means of similar relative scales with some absolute difference between the two. Thus, the term of ‘expensive‘ collocates with tens of thousands of Euros, expressed as ‘high cost‘. The term of ‘moderate expensive’ is assigned to the range of thousands of Euros. In comparison, there is only slight difference with the somewhat less expensive, more affordable category referred as ‘moderately economic’ cover the range between thousands and hundreds of Euros. The range of ten and hundreds of Euros is associated with the ‘low’ cost category. The category of ‘very low’ capital and maintenance cost ranges from hundreds and tens of Euros down to one or even less than a Euro (like in the case of disposable RFID tags).

Organisational and operational needs along with technical and programmatic requirements were defined as smart based on the LEAN engineering approach**Fout! Verwijzingsbron niet gevonden.**. The summary is presented in Table 2 (next page).

TABLE 2. OVERVIEW ON STAKEHOLDER NEEDS AND REQUIREMENTS

Levels of customer, stakeholders' interests	**Needs**	**Requirements of the corrosion sensor**
Organisation (MoD & Navy)	High availability & efficient naval operation (economics) Full compliance with international standards & regulations	Regular condition assessment data to MM No emission from device & pollution of the environment Full recycle-ability
Maintenance experts & asset management	Long-time Navy service (without frequent service need) Ability to plan, schedule & execute maintenance according to condition of the vessels	Continuous operability over device lifetime (≥3 years) Condition assessment data regularly & on request Condition assessment data enable maintenance planning & schedule
Operation	Safe & reliable operation No regular maintenance need (until depot maintenance after a period of 3 years) Sensitive & reliable detection of corrosion processes General applicability, ese of use Easy decision making on maintenance actions based on corrosion sensor data	Closed & sealed structure, fully compatible with maritime environment Continuous power supply Sensing onset, deterioration & breakdown of coatings (*p* of detection uniform events ≥95%) Process & evaluate raw measure data autonomously Net weight ≤1 kg Ease of interpretation of evaluated data by maintenance experts & asset management

4.2 Result: final selection of the sensor techniques

Based on the assessment made by the panel of DTP members, recommendation and proposal for corrosion sensing and structural health monitoring, **EIS** was selected for sensing deterioration of paint coatings and **eddy current type magnetic techniques** were taken to monitoring corrosion of aerospace aluminium alloys. The most important stakeholders and their needs and requirements are summarised in TABLE 3.

TABLE 3. EXPLORATION & DEFINITION OF DESIGN SOLUTIONS BASED ON THE VALUE ENGIEERING METHOD

	Ultrasonic Techniques		Magnetic techniques	Electrical resistance	Electrochemical techniques	
Evaluation factors	Short-range	Long-range	EC, MFL, BHN, MMM	ER & FSM	Active (LPR & PD) & passive (OCP & ECN) DC methods	AC (EIS) methods
Type of detection	Uniform superficial & localised bulk	Uniform & localised bulk events	All	Uniform & cracking	Uniform (& localised events)	Uniform & localised events
Materials	Metals & alloys	Metals, alloys & composites	Metals, alloys & composites	Metals & alloys	Metals & alloys	Metals & alloys
Depth of info (wall thickness)	1-25(40) mm	1-15 mm	Up to 6 mm	Any	Superficial	Superficial

Investment (capital)	Medium/high	Medium/high	Low/medium	Highly economic	Low/moderate	Low/moderate
Consumables	Very low	Low	Low/medium	Low	Low	Low
Advantages	Fast, sensitive, high resolution	Fast global (up to ~2 m) screening	Real time measure, no coating removal	Fast & real time measure	Fast & real time, directly to the structure	High sensitivity & accuracy (moderate sensitivity)
Shortages	Coating removal, no real time measurements	High geometry sensitivity of complex geometries	Difficult quantification (or calibration required)	Low sensitivity to localised events	Moderate accuracy (H_2 evolutions)	Slow scan, sensitivity to instability
Marine compatibility	yes	no	yes/no	yes/no	yes	yes

5 CONCLUSIONS

Based on a set of criteria, electric field sensors based on electrochemical impedance spectroscopy and the magnetic sensors type eddy current techniques (based on inductive coupling) were selected as for further development to the maritime and aerospace implementations, respectively, for the following reasons.

Similarity of the techniques in regard with type of the application, sensitive characterisation of materials, i.e., deterioration and damage accumulation is directly related to electrical permittivity and magnetic permeability which affected by the varying electrical conductivity of the tested materials. By utilising proper sensor probe geometry and electrical settings, these techniques are able to detect little changes of material properties in dielectrics and electrical conductors. Thus, damages in coatings and substrates can be defined at sub-millimetre size and indication of relative permittivity changes of around 0.1. Impedance spectroscopy is devoted to characterise dielectric materials and so to assess deterioration of coatings from the very early phase, i.e., water and electrolyte uptake then diffusion after initial non-diffusive moisture ingress of the linings. Strength of the eddy current techniques lies in the numerous electrical testing modes, 3D oriented and flexible array sensors probes allowing detailed lateral mapping, exploration of orientation of defects and damages in a depth range of up to 6 mm. These features are accompanied with a large variety of technical realisations featuring moderate and small size, multiple complexity, customisation to possible installation on variety of structures, and the generally low power requirement of the probes, electric and magnetic sensors. The seemingly major shortfall of both of these techniques especially the electrical testing mode, namely the very localised, point detection mode can easily be circumvented by definition of the most critically affected areas on the assets for inspection and/or monitoring. This would ensure high probability of survival of the unmonitored remaining part of the assets.

Rest of the techniques, although there are several mature solutions, these certainly fall short on many of the aforementioned aspects. Therefore, those were not taken to the further stage of development of the detail design.

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