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Robotic inspection of ship structures: how to fill the gap between available technologies and current survey practices?

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***Abstract* –Adoption of Robotics and Autonomous Systems (RAS) in activities related to ship inspections has obvious potential advantages, but also shows some problems, ranging from ship-RAS interface to regulatory and legal viewpoints.**

The ROBINS project (ROBotics technology for INspection of Ships) is a collaborative project co-funded within the H2020 EU Research and Innovation programme call, aimed at filling the gap between current ship inspection requirements and available robotic technology. The present work aims at highlighting how human-made ship inspections can be improved using RAS, with equivalent results of the current practice, which indeed is rather satisfactory.

In such a framework, a Testing Facility (TF) has been built up and it is still under development. Hence, the features of the TF where RAS will be tested and the testing protocols during trials are presented, showing how technological and regulatory gaps can be filled. Basically, RAS target will be to carry out inspections at the same quality level of humans' ones.

I. INTRODUCTION

The introduction of Robotic and Autonomous Systems (RAS) in the field of ship hull surveys is an interdisciplinary activity requiring the expertise of naval architects and robotic developers. Surveys of ship structures usually follow an organized set of activities aimed at identifying structural defects that could compromise or reduce the vessel's seaworthiness [1-2]. Typically, corrosion, fracture and mechanical damage are the main families of ship structural defects (see Table 1).

The key features of RAS platforms, emerging from the environmental constraints and from specific requirements of the different operational scenarios of ship structures, are identified duly considering current survey practices and rule requirements. I.e. information for the condition assessment required by rules are regarded as an overall description of the key features and metrics for RAS in the context of the ship inspection activities. In practice, this links the RAS features with the end-user needs.

Quantities, methods and units aimed at providing a measure of the ability and extent to which RAS platforms are capable to provide such features are defined, possibly identifying standard measurements to check if RAS is fit for the intended purpose (i.e. carrying out ship surveys) and to which extent. Different RAS platforms already exist aimed at accomplishing a specific task. At University of Genoa, a team of cooperant climber robots for autonomous inspections inside ships and offshore platforms has been designed consisting of four units, with adhesion based on suction cups or magnets, pneumatically powered and controlled by Actuator-Sensor-interface technology (ASi). Each unit is equipped with video-camera and ultrasonic thickness measurement device; other sensors and transducers can be added and handled, depending on the survey requirements [3-9]. Other kinds of RAS include for example aerial platforms [10] or crawlers.

II. CURRENT SHIP INSPECTION RULES

Class surveys are the means by which Classification Societies verify the structural strength and the integrity of essential parts of the ship's hull and its appendages, the reliability and function of the propulsion, steering systems, power generation etc.

Classification Societies' verification process is based on the development and application of their own rules and on compliance with international and/or national statutory regulations on behalf of flag Administrations. For ships in service, each Society carries out periodic surveys to verify that the ship remains in compliance with those rules.

Even if Classification societies develop their own rules, collaboration among them is a leading guideline and uniformity in classification survey procedures is one of its main implementations, aimed at providing as much equity as possible in the application of the standards.

In Table 1, 2 and 3 the main variables of ship inspection performances and relevant inspection methods are summarized. Nowadays inspections are generally carried out by human surveyors, who must reach each ship area increasing the risk for their safety.

III. EQUIVALENCE PRINCIPLE

Ship surveys are for sure one of the most challenging, yet desirable, application of RAS assisted inspections. This because the use of RAS platforms can potentially increase surveyor safety and save time and money. It is essential to provide information and measurement data at least equivalent to those obtainable by means of traditional inspection techniques (Table 2 and 3). The actual goal is to put the surveyor in the condition of making up his/her mind about the conditions of the ship's hull, and then let him/her make informed decisions on remarks, prescriptions, or mandatory repairs, based on the information obtained by means of RAS platforms without the need of reaching in person each area especially the dangerous ones [11].

While equivalence for data obtained from simple, direct measurement of physical quantities, like thickness measurements, can be relatively easy to assess (leveraging e.g. error theory applied to measurement), many open questions remain about how visual or other complex information provided by RAS platforms can be considered equivalent to the direct sensory experience and observation in first person carried out by the surveyor. Indeed, the surveyor's direct sensory experience differs from the mediated, almost purely visual experience provided by RAS platforms (and ancillary software tools) in several substantial aspects. For example, when acting in first person, the surveyor can use tools to test more thoroughly the point of interest, e.g. by hammering, or manually removing rust scales or superficial coating, or other techniques. Moreover, he/she has an 'immersive'/ real experience of the surrounding environment and forms a cumulative impression of the overall condition of the vessel. This means that (a) the evaluation is a result of the Surveyor's memories/ experience in the field and (b) these conditions are committed to memory more vividly when experienced in first person (Fig. 1).

When in place, the human is able to acquire a large amount of visual information without the limitations of existing technology, i.e. due to limited field of view, large distortion or chromatic aberration of wide-angle lenses. And most important, he/she is able to elaborate such information, merging it with previous knowledge and skills.

Equivalent information may be provided in RAS assisted inspections as long as RAS platforms are able to:

- Operate at least in the same environmental conditions as those assumed for the inspection of a human surveyor in person, or even more severe conditions, not allowing human presence;
- Reach the points of interest in a way that allows satisfactory views, possibly different from that of a human surveyor;
- Provide visual information with level of detail, color, contrast, brightness etc., sufficient for detecting and ranking defects in a way that is comparable to the information available to the surveyor;
- Provide measurement data, e.g. for thickness, at least with the same accuracy and for the same locations as in traditional surveys, as prescribed in rules and guidelines.

It turns out that the key features of RAS platforms should be identified, and relevant metrics defined, also considering the capability of software tools to process, render and archive collected information.

Fig. 1. Human surveyor in an oil cargo tank

Table 1 - Variables affecting performance of an inspection of a ship (adapted from [13] and [2])

General variables affecting the performance of an inspection in ship and offshore structures				
What (detection)	*What (sizing)*	*Where*	*How*	*When*
Ship type & dimensions Ship age Ship conditions Ship-owner / crews	Scope of survey Interpretation of outcomes Type of material	Location of ship Size of ship Structure type / area Cleanliness/Environment Means of access Lightening	Skills of surveyor Fatigue & motivation of surveyors Manual or automatic Instrumentation portability Means of recording data Costs	Weather Ship in service or not Time allowed for inspection
Variables related to degradation effects affecting the POD and POS of inspection in ship structures				
What (detection)	*What (sizing)*	*Where*	*How*	*When (class survey)*
			⇩ Current practice ⇩	
Corrosion				
General (uniform)	Thickness decrease (average)	Plate surface in general	Visual, close visual + NDT (UT)	Special + intermediate (or annual if required)
Localized (pitting)	Pits shape, depth and extension on surface	Plate surfaces	Visual, close visual (approx. % of affected area required)	Special + intermediate (or annual if required)
Grooving / necking	Extension and thickness decrease	Stiffeners connection	Visual, close visual+ NDT (UT)	Special
Protection systems (anodes, coating)	Wear & breakdown	=	Visual, close visual	Special
Cracking				
Brittle	Shape and sizes	Structural details	Visual, close visual (+ NDT)	Special
Fatigue	Shape and sizes	Structural details	Visual, close visual (+ NDT)	Special
Mechanical damage				
Dent (collision, impact)	Shape, depth, length, width	Shell	Visual, close visual	Special + intermediate + annual
Distortion	Misalignment	Stiffeners	Visual, close visual	Special + intermediate + annual

Table 2 – Current access methods for ship and offshore structures inspection (adapted from [13] and [2])

Method	**Advantages**	**Disadvantages**
Walking through	Inexpensive	Poor accessibility, only line of sight view
Permanent means installed as built (ladders, bulwarks, etc.)	Safety increased, good accessibility	Cost, weight, maintenance, unwanted structural details
Climbing w/o safety devices	Increased accessibility, inexpensive	Unsafe and out of rules, impossible to climb some areas
Climbing with fall safety device	Increased accessibility, inexpensive	Initial rigging difficult, physically demanding
Wire lift platform	Increased accessibility, inexpensive	Initial rigging difficult, training required
Fixed staging	Access available to all members in party, repairs possible	Expensive and labor intensive, time consuming
Portable staging	Relatively safe, light repairs possible	Expensive, difficult initial rigging
Cherry picker	Increased accessibility	Expensive
Rafting	Applicable during service, inexpensive	Expensive, time consuming, unsafe
Binocular and other optical devices	Applicable during service,	Hands on inspection not possible, only line of sight view
Divers	Applicable during service, relatively expensive and time consuming for large areas	Expensive, time consuming, unsafe, need divers experienced in ship inspections, only for outside shell
Remote Operated Vehicles	Applicable during service, gas freeing not required (if equipment of intrinsically safe)	Expensive, easy to be disoriented, skilled operators required

Table 3 - comparison of methods for detecting and measuring structural deterioration (adapted from [13] and [2])

Technique	Degradation mechanism			Rank (1 to 5)			Remarks and notes
	Wear / Corrosion	Fracture / Cracks	Mechanical damage	Skill needs	Results accuracy	Costs	
Visual inspection	X	X	X	5	4	2	Small equipments as hammer, flash, caliper, measuring tape, weld-sizer, notebook, etc. are included. Surface defects only, no permanent records, applicable while work in progress with indication of incorrect procedures
Close up inspection	X	X	X	4	4	3	Small equipments as hammer, flash, caliper, measuring tape, weld-sizer, notebook, etc. are included. Surface defects only, no permanent records, applicable while work in progress with indication of incorrect procedures
Digital imaging / endoscopy	X	X	X	3	2	2	Recently developed, need of regulations and automatic processing
Leak / pressure testing	X	X		1	5	4	Leaks of gases and liquid in tanks, pits and cracks detection
Dye penetrants, chemical sensors		X		2	3	2	Affected by environmental factors (cleanliness and surface conditions), excellent in locating leaks in weldments, easy to use and low cost
Ultrasonic tests	X	X		5	3	4	Highly depending on operator's skill for interpreting pulse echo patterns of defects (influence on time and costs), no permanent record (except for thickness gaugings UT equipment)
Strain gauges	X	X		4	3	4	Reduction of stiffness, corrosion
Electro-magnetic field techniques [1]		X		5	4	5	Surface and subsurface cracks and seams, heat-treatment variations, wall thickness, coating thickness, crack depth
Magnetic particle		X		2	2	2	Only magnetic materials (sub)surface discontinuities, relatively low cost, difficult to use on rough surfaces.
Radiometry (X-ray)		X		4	4	5	Danger of radiations, only by specialized firms. For interior large flaws but non suitable for fillet welds, costly. Permanent records.
Acoustic based techniques	X	X		5	4	5	Different techniques (Acoustic emission, natural frequencies, noise, vibrations). Need of preliminary structural assessments (at commissioning) for measurements interpretation
Thermal imaging	X			5	4	5	Limited to specific materials / situations
Replica		X		1	2	2	Simple and cost effective, records surface defects
Test coupons	X			2	3	3	Need preliminary calibration
Fiber optic		X		4	4	5	Emerging technique, safe even in oil tanker (no electric power)

[1] Alternating current field measurement (ACFM), alternating current potential drop (ACPD), eddy current, etc.

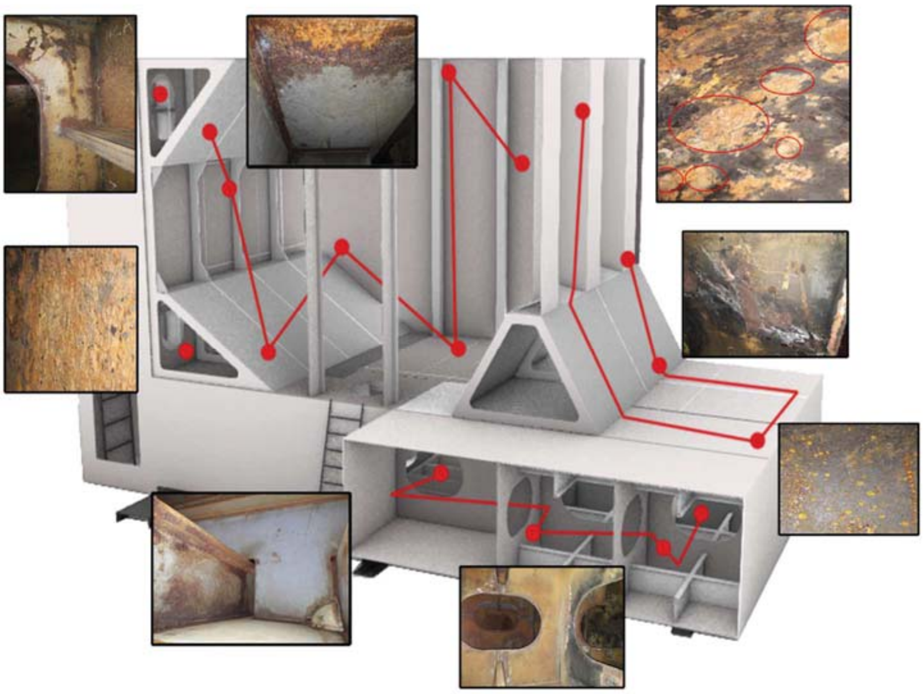

Fig. 2. Path planning test in Section A of the Testing Facility. RAS should be able to follow a fixed path and to reach control points in a given sequence (structural defects of the testing facility are also shown)

IV. 5 TESTING FACILITY AND TRIALS

Performing experiments on-board, aimed at testing RAS features, is a challenging task due to the very little time spent at berth by an actual ship, also considering that during these operations only limited areas of the ship are typically available to perform experimental tests. For this reason, a Testing Facility (TF) is under construction in the University of Genova MArine Structures Testing Lab (MASTEL) and Drives and Experimental Automation for Marine Systems Lab (DREAMS), also developing specifications for the testing protocols for remote inspections on-board ships. Currently, no dedicated TF for RAS platforms exists to the best of the authors' knowledge. In general, each RAS manufacturer has its own testing protocols, but they are not public and moreover not specifically designed for ship inspections.

The TF is a modular construction with the possibility of changing the environment characteristics in order to simulate the conditions in which real inspections take place (i.e. darkness, humidity, dirt, shielded). It is also composed by an enclosed large volume, with metallic boundaries that simulate a cargo hold, to assess for localization abilities, path planning and area coverage capabilities of the platforms. Besides, one of the main features of the TF is the use of wasted material coming from existing ships that operated at sea for a certain time, in order to have a good variety of actual defects that can be found onboard in terms of coating conditions, pitting, rust, cracks, notches, distortions, mechanical damages. The philosophy is to design a complex experimental set-up, simulating as much as possible reality with particular lighting environment, air currents, humidity and different conditions of the structure surface to be inspected.

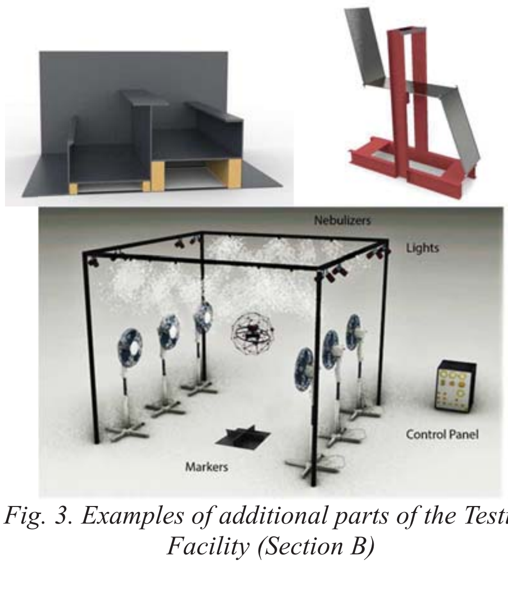

Fig. 3. Examples of additional parts of the Testing Facility (Section B)

V. CONCLUSIONS

Inspections are fundamental tasks required in the management of ships. Nowadays, a survey is performed manually by human surveyors, using sensors like cameras, ultrasonic transducers for testing of metallic walls, welding or, more in general, non-destructive testing.

The intention is to create, around the Testing Facility, a competence center where trials environment and test protocols specific for RAS intended to be used in the inspection of ship and offshore structures are continuously developed along with the RAS improvements.

At the same time, the Testing Facility is aimed at becoming the training and certification environment for the surveyors and the service suppliers working within the shipping community.

VI. ACKNOWLEDGEMENTS

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