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Recent developments in remote inspections of ship structures

Laura Poggi, Tomaso Gaggero, Marco Gaiotti*, Enrico Ravina, Cesare Mario Rizzo

DITEN, University of Genova, Via Montallegro 1, 16145, Genova, Italy

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A B S T R A C T

In recent years robotics has become an important resource in engineering. Adoption of Robotics and Autonomous Systems (RAS) in activities related to ship inspections has obvious potential advantages, but also arises particular challenges, both from technical 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 inspections approach and available robotic technology, both from technological and regulatory point of view.

Main goal of the present work is to highlight how ship inspections are currently carried out by humans, how they could be improved using RAS, even if not completely autonomous for the time being, at least in selected operational scenarios and how the performances of RAS platforms can be tested to assess their effectiveness in carrying out surveys onboard. In such a framework, a testing facility aimed at assessing RAS' capabilities as well as providing suitable environment for their development has been built and it is still under development along with dedicated testing protocols, able to assess the equivalence between human and RAS inspection of ship and marine structures.

The features of a testing facility where RAS can be tested and the testing protocols are presented, showing how technological and regulatory gaps are filled.

1. Introduction

Surveys on board ships are generally carried out by a number of bodies such as flag states, port state authorities, classification societies, P&I clubs, insurance companies and cargo owners. On average, the frequency of inspection can be estimated to be 6 inspections per year for dry bulk carriers, 11 for tankers and even more for passenger ships with at least 50 h per year spent aboard to carry out inspections, (Knapp and Franses, 2006). Coming to costs, it was estimated, and confirmed by recent private communications of authors with a few shipping stakeholders, that for bulk carriers costs are around 25 k$ per year and around 50 k$ per year for tankers, (Knapp and Franses, 2006). Nowadays, apart from rare cases, inspections are carried out by human surveyors. In general, surveyors reach and inspect every part of the ship, also including very dangerous and potentially lethal areas. For this reason, the International Association of Classification Societies (IACS), that gathers the twelve largest ship classification societies worldwide covering more than 90% of the world's cargo carrying tonnage, issued a series of documents containing recommendations and guidelines aimed at minimising risks for surveyors and at complying with minimum safety requirements. Recommendations range from the provisions to safely enter into confined spaces, (Procedural Requirem, 2013), (No, 2017), to the safe use of rafts and boats to navigate in tanks (No, 2009), to the safe use of portable ladders to reach high locations, (No, 2002), (No), to guidelines for working in height, to boat transfer safe practice, (No, 2014), to recommendations for safe precautions to survey pressurised systems, (No, 2015a), to generic recommendations to assess the safety of the workplace (No, 2015b). All the above cited documents highlight the complexity of on board surveys suggesting that each survey must be anticipated by a series of preventive operations such as cleaning, ventilating, lighting, temporary set-up of structures, such as ladders and cherry pickers, to allow the surveyor safely entering spaces and reaching significant heights and inaccessible zones (see e.g. Fig. 1). This reflects into an increase in risks, time and costs of inspection.

In order to reduce time, costs and risks related to on board

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* Corresponding author.

E-mail addresses: laura.poggi@edu.unige.it (L. Poggi), tomaso.gaggero@unige.it (T. Gaggero), marco.gaiotti@unige.it (M. Gaiotti), enrico.ravina@unige.it (E. Ravina), cesare.rizzo@unige.it (C.M. Rizzo).

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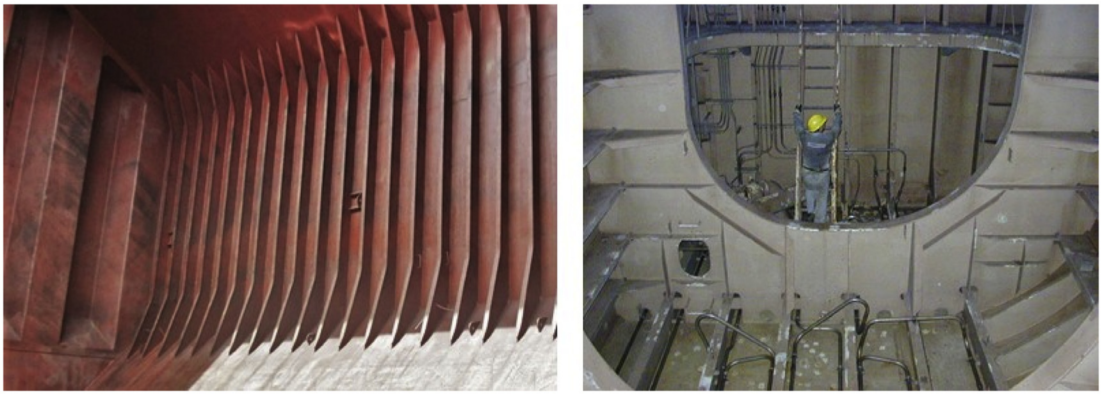

Fig. 1. Typical structure of a bulk carrier cargo hold and of an oil tanker cargo tank, being inspected by human surveyors using various means of access.

inspections, most of classification societies are exploring the possibility of using Robotics and Autonomous Systems (RAS) to carry out remote inspections, (Caldwell, 2017), (Huang et al., 2017), (Rizzo et al., 2007). IACS has recently published an updated version of its Recommendation 42, (Rec 42 Guidelines f, 2016), where the conditions and procedures for the use of remote techniques for inspection of ships are addressed, and a non-exhaustive list of possible techniques that can be used to the purpose is given. RAS suitable for ship surveys can range from aerial drones for visual inspections to crawlers in direct contact with the structure, intended to carry out thickness gauging and non-destructive testing. Another possible grouping of RAS can be based on the ability of carrying flight operations in enclosed spaces, where impacts with structures are highly probable, such as ballast tanks, versus the ability of covering wide open areas such as cargo holds. RAS can either be used as autonomous information collectors without the presence of the surveyor, that is supposed to examine the data offline, or as a support to the surveyor who is generally looking at live images and streaming videos transmitted by the RAS, in order to instruct the pilot to approach zones requiring a closer inspection, according to the surveyor experience.

The American Bureau of Shipping (ABS) e.g. has been conducting field tests with Unmanned Aerial Vehicles (UAV) for the survey of marine and offshore structures since 2015. The main outcomes of such experimental campaign were published in (Wen et al., 2018). Moreover, ABS has recently published some guidance notes on the use of unmanned aerial vehicles for structural surveys, (ABS, March 2018).

In general, the use of RAS is considered as an assistance, and acceptance of the inspection results will be to the satisfaction of the attending Surveyor. If the Surveyor is not satisfied with the inspection results provided by RAS, alternative or traditional survey techniques may be required. This means that the final decision about the applicability of remote techniques is demanded to the surveyor, on a case by case basis, according to his/her own experience.

DNV GL, the society born as the merging of the former Det Norske Veritas and Germanischer Lloyd, announced that they performed their first production survey using UAVs in 2016 and their first offshore survey in 2017. Bureau Veritas, among other research projects, has joined RECOMMS, a joint investment project (JIP), to develop drones with the capability to inspect steel structures in enclosed spaces. Lloyd's Register (LR) has moved a little step forward by issuing an assessment standard for Remote Inspection Technique Systems (RITS), (Remote Inspection Tec, 2018), in which indications for the performance requirements, performance test and certification of RITS are present.

Recently, also Registro Italiano Navale (RINA) embedded in their rules for the classification of ships a former guideline about RITS previously issued in 2017, (RINA, March 2018).

Worth to be mentioned are also pioneering EU funded collaborative research project such as INCASS (Inspection Capabilities for Enhanced Ship Safety) and MINOAS (Marine INspection rObotic Assistant System), involving several shipping stakeholders including classification societies, shipowners and service suppliers, beside robotic systems developers.

The above overview highlights that the market is hardly pushing to introduce RAS-aided inspections in the inspection procedures, and that most of interested parties are actively operating in this direction, following different approaches. All of them agreed on the fact that technology is ready and promising but, to be successfully applicable in the shipping field, the information gained by machines should be at least at the same quality level as that normally obtained by a human surveyor and the assessment and certification of the achievement of such result is eventually demanded to the surveyor itself.

There is therefore the need to ascertain that RAS-aided inspections are at least as effective as human ones and such equivalency needs to be appropriately verified, possibly in a controlled environment where well defined and repeatable tests can be performed collecting all necessary information. To this aim, in 2018, the ROBINS project (ROBotics technology for INspection of Ships, www.robins-project.eu), a three-year EU collaborative project cofunded within the Horizon 2020 EU Research and Innovation program was launched. Final goal of the ROBINS project is to fill the gap, both from a technological and regulatory point of view, between current ship inspections and available robotic technology. In the present paper, in particular, the philosophy followed within the first period of the project to set up testing protocols and to conceive a testing facility for assessing RAS performances is presented. Outcomes of the trials carried out up to now are summarized as well.

2. Brief overview of current (human) survey practice

Considering the relatively good safety records of shipping, any approach to the definition of tests for the assessment and certification of RAS platforms performances in ship surveys should start from a comparison with current inspection practice by human surveys (Rec 76 Guidelines f, 2007). To this aim, it is important to analyse the scope of surveys. An approach to do this is to apply the "Four Ws and How" method, as presented in (Rizzo et al., 2008) and (Rizzo, 2011) by answering to five basic questions:

Who?

For the time being, human surveyors but in some cases RAS have already been used in collaboration with surveyors.

Why?

This question relates either to:

- For whom is actually carried out an inspection, i.e. implicitly setting the inspection aims, but also whether there are specific reasons for such an inspection.

- For which reasons inspection is carried out, e.g. whether it is a periodic scheduled inspection, or it is due after an accident or an imposed condition of class, or there are suspect areas where more frequent inspections are necessary.

What?

It refers to the specific items to be checked on board. Since it is usually not possible to carry out an inspection of the entire structure of the ship or its machinery, there are rules and guidelines based on empirical experience indicating which parts/components are targeted for inspection depending on type and age of the ship. For these reasons, surveyors use check-lists listing the items to be surveyed for any given survey type, ship type and ship age. Instruction to surveyors are generally provided by inspection bodies and such documentation is considered confidential in commerce and not shared even among IACS members.

Where?

It indicates the location of the ship in which the inspection has to be carried out. It depends on the ship type, on its maintenance status and if it is in service or at dock. Actually, also the location of the ship during the survey event is significant as e.g. environmental conditions and shore support may largely influence the inspection performances.

How?

An inspection can be performed visually or by investigating selected areas using a method of non-destructive evaluation. Moreover, in order to classify the visual inspection level, ship surveys are generally categorized as follows:

- An **Overall Survey** is intended to report on the overall condition of the hull structure. Surveyors visually inspect the hull structure at a certain distance in order to determine the location of the problem areas and the planning of additional close-up surveys. Normally, no detailed data on defects is expected to be gathered.

- A **Close-Up Survey** is a survey where the details of structural components are within the close visual inspection range of the surveyor i.e. normally within reach of hand. Data on cracks, thickness gauges and other localized defects are expected to be measured and recorded. Rules require close-up surveys of critical areas depending on the ship's age and type.

When?

It takes into consideration both the frequency with which the inspections are carried out, as well as the timing of the inspection. They can be briefly described as follows:

- **Annual Surveys**, mainly visual inspections, lasting approximately one or two days. They are carried out annually to ensure that the hull structure, equipment and machinery are kept in satisfactory condition;

- **Intermediate Surveys** carried out in the middle of each five-year cycle, lasting 3–4 days. They are similar to the annual surveys with additional detailed examination of one or few selected parts, e.g. ballast and cargo tanks. It is noted that the ship's bottom is examined during this survey. This can take place in water either by remotely instructed/operated human divers and/or vehicles or in a dry-dock;

- **Special Surveys** carried out every five years, lasting one or two weeks. They consist in a thorough analysis of each compartment in order to provide a complete picture of the condition of the ship's structure, facilities and machinery.

Twenty years ago, the survey schedules have been partially harmonized and regulated by the International Maritime Organization (IMO) under the harmonized system of survey and certification (HSSC) with the aim at providing a list of details to be checked during the dry-docking surveys of the ship in a five years scheme. The IMO Enhanced Survey Programme (ESP) had been earlier introduced to face the lack of safe handling practices of bulk carriers and tankers by IMO resolution A 744 (18). However, the survey scope and approach have basically been unchanged for decades, despite the tremendous advancements of technologies in several fields.

The above definition of close-up survey was however clearly inadequate considering nowadays-available technological resources and it has been recently updated by IACS considering the possibility to use RAS for remote inspection, (Z10.1 Hull surve, 2010), (Z10.2 Hull surve, 2015), (Z7 Hull classific, 2011). The surveyor would not be within reach of hand, but he/she may have a similar sensorial experience through new technologies. Such a minor modification would be probably followed in the next years by more substantial improvements of the ship inspection regulatory regime to account for the tremendous advancements in digital technologies. Starting from the above detailed analysis of surveys, the needs for creating RAS testing protocols and scenarios is derived.

Rules, standards, training and experience of inspection practice, developed for decades, brought the influence of human factor at such an acceptable level that, at present, the aim of using RAS is not to obtain more accurate and reliable results than those available from human surveyors. Robotic means must achieve at least the same information quality a human can collect for structural assessments and possibly in a format easy to elaborate either automatically or by engineering judgment.

In the light of this, it is clear that every effort in trying to identify procedures, metrics and scenarios to objectively assess RAS performances cannot leave aside, at least at this stage, a certain level of human evaluation. In the following, a possible approach, as followed in the framework of the ROBINS project to carry out the assessment of RAS-aided inspections, is presented.

3. Overview of RAS' capabilities

3.1. General overview

In order to assess equivalency between current (human) survey practice and RAS assisted one, it is necessary to evaluate the RAS abilities in a ship environment by studying the challenges to be faced in this operational context. While the "Who?", "Why?" and "What" questions can be considered, for the time being, somehow trivially dealt with only considering minor differences between current and RAS-assisted inspections, this is not the case for "Where?" and "How?" ones.

It is in fact common to find wide open spaces on board of a cargo ship, as well as narrow areas and dark passages. To inspect these zones, RAS platforms must be able to move in large areas, by reaching significant heights in suitable time, analogous or shorter that of a typical human inspection event, but also to go through narrow spaces and this limits the size of the RAS. Moreover, it is often required to check the status of a specific area, machinery or hull fittings and equipment as well, despite the ROBINS project and the involved RAS are intended for ship structures. To this purpose, it is essential for the RAS to have localization systems to avoid obstacles and define precise paths to reach pre-established points, i.e. orienteering capabilities. Regarding the question "*How?*", the autonomous systems have to carry out overall surveys by means of visual inspections and close-up surveys also measuring the thickness of the structural components, as a human surveyor would do.

This calls for rather differentiated RAS features and capabilities.

Currently, the available technology does not allow to have a universal RAS able to satisfy all requests. However, research projects developed in recent years have identified different suitable RAS tools for this aim. Below a non-exhaustive list of possible different sensing devices currently available is exemplarily reported to offer an overview of the potential of RAS technologies, if various RAS types are used:

- 2D and 3D laser scanners allow obtaining a geometrical model of the inspected area without resorting multi-level mapping approaches. This technology is widely used for its accuracy and speed; however, it requires rather large platforms due to the weight and volume occupied by the main navigation sensor.
- Vision-based navigation has become quite popular lately, thanks to the richness of the sensor data supplied, combined with low weight, low power designs and a relatively low price.
- Depth and RGB-D cameras are the last type of sensor that has been incorporated to implement autonomous navigation. RGB-D cameras give reasonably accurate mid-resolution depth and appearance information at high data rates, computing the alignment between frames by jointly optimizing through both appearance and shape matching. These systems can accurately align and map large indoor environments, as well as featureless corridors and poorly lit rooms in near-real time.
- Wireless-based localization has been recently developed as an alternative of GPS in poor signal reception areas like ship cargo holds. Ultra-Wide Band (UWB) systems have emerged as one of the leading positioning technologies because the UWB ultra-short pulses are resilient to frequency-dependent absorption, thanks to their large bandwidth, and because ultimate accuracy can range from 2 cm (ideal conditions) to 50 cm (non-line of sight scenario).

Pursuing this line, aerial vehicles have often been chosen as suitable means to carry out visual evaluations (Overall inspection), while climbing robots, which are in contact with the structure, are selected to perform thickness gauging and non-destructive testing (Close-up survey). Robots based on the motion features of animals (like insects, snakes, lizards, geckos, snails, etc.) belongs to this latter category. Many options have already been studied at the University of Genoa, proposing simulations and prototypes attempting to mimic animals' performances (see Fig. 3).

3.2. Specific examples

The RAS platforms involved in the ROBINS project were selected to cover the whole range of ship inspection needs (except for underwater vehicles, already in use since some time for underwater inspections): two different types of aerial drones and a magnetic crawler exploit the capabilities of different robotic solutions for different needs. Moreover, open trials are planned for other robotics platforms in the future. These RAS, respectively developed by the Universitat de les Illes Balears (UIB), Flyability Sa (FLY) and Ge Inspection Robotics (GEIR), are presented in Fig. 2.

The aerial drones differ in size and abilities. The former is designed to fly in wide open spaces independently, for data collection at safety-compromised areas, difficult to reach by humans and ground vehicles, and with large spaces to be covered as fast as possible, as in the case of cargo holds inspection. The latter is especially dedicated to carry out inspections in narrow spaces being collision tolerant. The indoor inspection of cluttered spaces faces a different type of challenge than in large open areas. Typically, ballast tanks involve flying through manholes in confined spaces where only a few centimetres are available on each side of the robot, typically with a high density of obstacles because of the stiffening system of ship structures. For this reason, fixed protections are added to drones in order to mitigate collision damages.

The third RAS represented in Fig. 2 is a crawler platform. Nowadays crawlers are one of the most common solutions for

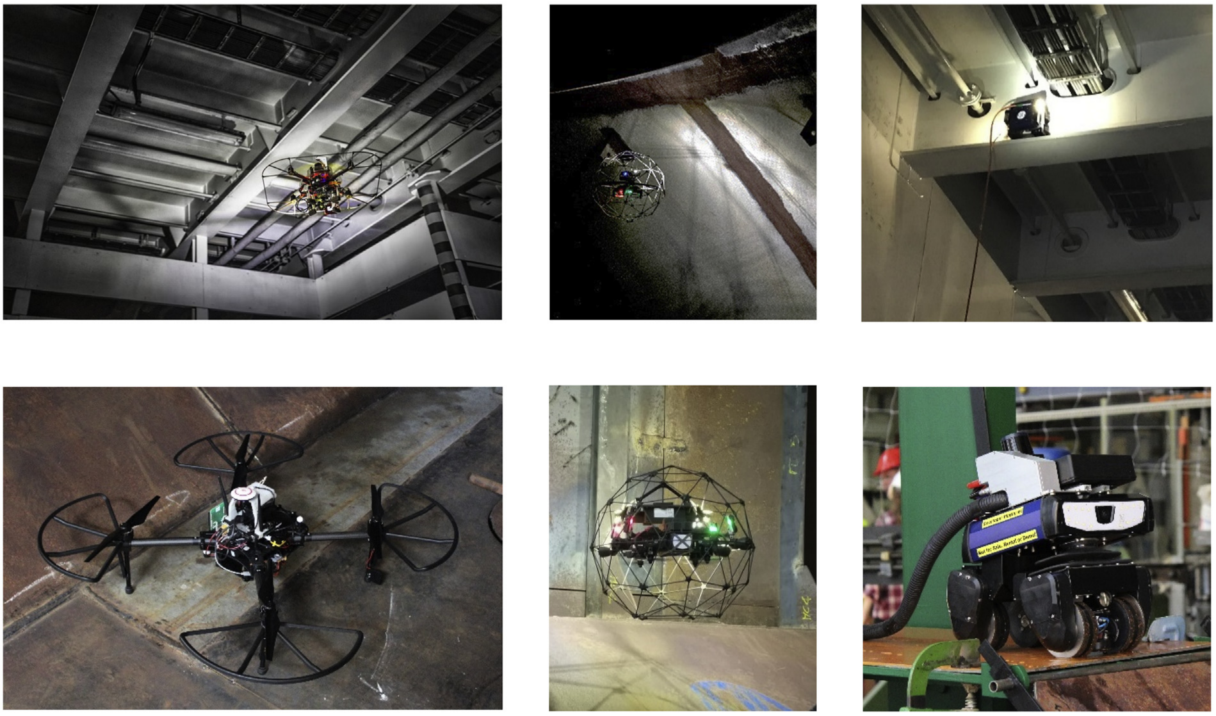

Fig. 2. RAS involved in the ROBINS project: from left UIB drone, FLY drone, GEIR crawler.

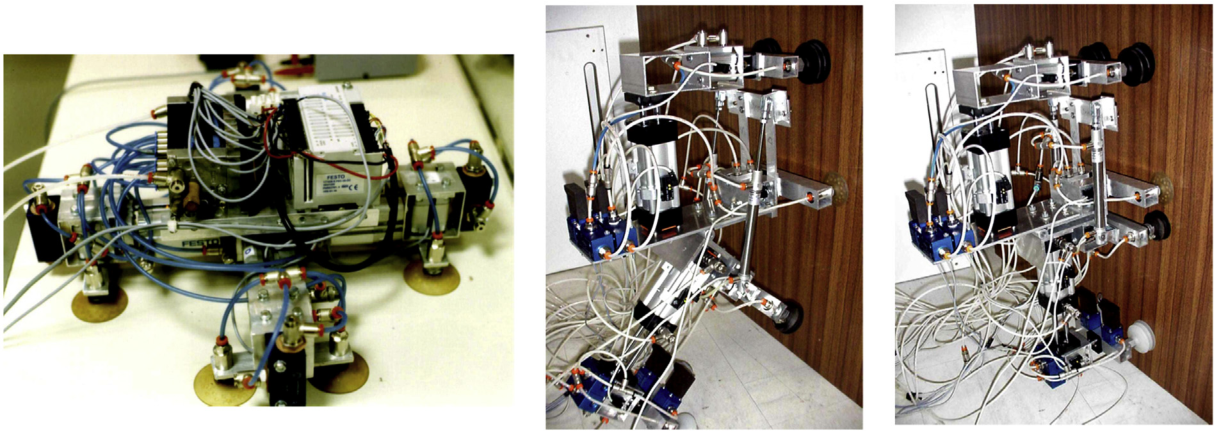

Fig. 3. Prototypes of zoomorphic robot realized in the UNIGE laboratories.

close-up surveys. As the ship structure is made of steel, magnetic adhesion is typically used for generating the contact force required to provide both adhesion and propulsion. To this way, crawlers run on magnetic wheels or tracks, inspecting vertical or even overhanging structures. The wheels can easily deliver magnetic forces 2 to 5 times the weight of the robot, thus providing a reasonable safety margin against detachment even under sub-optimum surface conditions, such as paint and dirt layers or rust.

Nevertheless, these devices still have many limits in their application.

In general, flying in confined spaces involves many challenges for a conventional drone:

- Electromagnetic field disturbances between RAS platforms and onboard electronic systems can be an issue, both for vessel and robots, considering that nowadays ships are more and more digitalized. Furthermore, since the surrounding environment is made of steel, GPS signals for RAS localization cannot be used inside ship hulls. Although, alternatives, such as inertial systems or distance detection for positioning has to be adopted and properly tested.
- Problems related to the obstacles detection or keeping position on a visual reference in environments with poor (or no) lighting such as ballast tanks, where cameras are usually affected by motion blur;
- Environments with no feature (e.g. mostly uniform walls, such as a steel plate in a tank), or with reflective surfaces, such as smooth metallic plates, prevent lasers and cameras to work properly, making hard the detection of distance between obstacles;
- Drone's stability is affected by the air turbulences caused by its own propellers in narrow spaces, where the airflow tends to circle back towards the drone. Moreover, in such confined and dirty spaces the raised dust disturbs cameras providing unclear images. Trials highlighted that dust can also affect performances of electric propulsion motors.
- The flight is often carried out beyond line of sight of the operator, with a take-off location outside the hold or tank to maximize safety or due to accessibility issues. This means that the drone cannot be monitored through a direct visual line of sight.

Similarly, several crawlers have been developed for ship inspection, but due to the limited obstacle handling ability they are not suited to inspect some parts of the ship, such as structured cargo holds, stiffeners or (ballast) tanks. The main issue is represented by limited ability to pass non-flat obstacles (e.g. the transition between two surfaces with different slope that needs large forces to free the wheel from the first surface and then move on) as well as the contamination of the wheels with magnetic particles.

It is worth noting that hull structures do not need special cleaning in general, at least not different from usual cleaning for human inspections. Truth to tell, in some cases, less cleaning is required (e.g. for flying RAS some water residuals on the bottom of a tank are acceptable being removed by propeller flow). For thickness gauging, the RAS are equipped with devices able to locally clean the gauging spot as appropriate.

Another solution for RAS in direct contact with the structures, i.e. able of performing direct measures, are those with adhesion based on suction cups. A team of cooperant climber robots has been designed at UNIGE for autonomous inspections inside ships and offshore platforms consisting of four units pneumatically powered and controlled by Actuator-Sensor-interface technology (Fig. 3). 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. The aim of these RAS is to realize a portable and user-friendly tool able to move itself on horizontal, inclined or vertical surfaces, with the capacity to jump stiffeners, girders or other structural elements, simplifying and speeding up the inspections with an automatic generation of survey reports, (Ravina, 2007), (Ravina, 2010), (Ravina, 2011), (Ravina, 2012), (Ravina, 2015), (Ravina, 2107), (Ravina, 2017).

What above highlights the efforts made by Universities and private companies to design RAS platforms able of performing inspections on board. Furthermore, it gives a picture of the large variety of possible solutions already available.

In general, the reliability of such technologies in terms of safety and in case of failure has to be developed and assessed. For the time being, fail-safe systems are mainly related to prevent risks for operators but there are also safety ropes for crawlers and warnings for battery discharge to avoid losing the platform during the survey. However, since recovery operations may be dangerous for humans or even impossible, especially onboard ships in service, often damaged RAS are considered missing in action.

Actually, stop functioning/malfunction may occur especially for newly developed RAS and/or pilots under training. Adequate RAS testing, pilot training and team working assessment is essential for the successful implementation of RAS assisted inspections. Such a technological readiness highlights again the need of common protocols and a controlled testing environment to demonstrate their abilities before going onboard ships.

4. RAS vs. human benchmark

It is worth again noting that the current inspection regime originates from a long lasting and sometime painful history and it is nowadays widely accepted by the stakeholders of the shipping community as a good compromise between safety and operational needs.

Remote Inspection Techniques (RIT) may be used to facilitate the required external and internal examinations, including close-up surveys and gauging. Hence, overcoming the need for human inspections, routine maintenance can be remotely monitored in real-time by surveyors and the process of selecting representative spaces could be improved. This is possible, especially for new ships where digitalization is becoming more and more available and user-friendly, as long as realistic virtual representations of on-board spaces are available beforehand, as a result of previous overall inspections and scans, reconstruction of 3D models, advanced processing of images, point clouds and thickness measurements. This, in turn, reduces costs, increases efficiency and significantly reduces the risks for human surveyors. Older ships, on the other hand, may involve higher costs for the remote survey planning to make the 3D models/representations available, but certainly their updating and accessibility is much easier than paper drawings and reports filed in the offices of various stakeholders.

Because of significant implications on safety as well as on commercial activities, the survey practices of ship and marine structures, their effectiveness and quality level are crucial. As a matter of fact, while the technologies are in principle available, it is necessary to assess and possibly to adapt them to the rather special features of ship and offshore structures, and of the shipping community in general in order to be widely accepted and effectively applied.

These motivations have led to the development of projects aimed at the assessment and certification of systems for remote inspections, even if it is not currently possible to implement a single device which is able to perform all the actions carried out by a human surveyor during an inspection (e.g., look with two eyes, climb over obstacles, smell, touch, hammering, etc …). For this reason, human evaluation still remains the absolute criterion for ship hull surveys and, up to now, comparison between human and RAS performances is the only agreed assessment pathway.

There is therefore the need to ascertain that RAS inspections are at least as effective as human ones and such equivalency needs to be appropriately verified by a third party, possibly in a controlled environment where well defined tests can be performed collecting all necessary information.

It is believed that RAS technology are mature enough to think that some tasks of the surveyor can be accomplished by their use. The real challenge is represented by the assessment of their accuracy and, more in detail, the assessment of the difference between human and RAS survey output.

For example, a thickness gauging taken by the robot must be equivalent to that measured by the human surveyor in the same environmental conditions (light, humidity, air currents) or surface conditions (dirty, wet, clean, reflective, tilted, etc.), taken within a reasonable time and with pre-established tolerances. For the time being, thickness measurements are generally carried out employing same sensors used by human surveyors and therefore measured data have similar uncertainties. Of course, human and RAS-assisted surveys adopt different handling and practical management in thickness gauging. Hence, equivalency is to be assessed as well in terms of sampling frequency, readings per unit area, averaging approach, etc.

To this purpose, testing protocols have been conceived to evaluate the efficiency of RAS in performing selected tasks, including thickness measurements, and testing facility layouts were developed within the ROBINS project looking forward to become the basis for a proposal of international standards, recognized and accepted by stakeholders and authorities. Standards are a precondition to stimulate the robotics industry and unleash the economic potential of new markets.

5. Testing facility and testing protocols description

5.1. Testing facility for general purpose trials

As above mentioned, performing tests of RAS on-board is a challenging task due to limited time and space availability of ships. Indeed, during annual and intermediate surveys, the ship is generally in service and on-board tests on hull structures are very limited if not impossible, while during dry-docks at special surveys repair works often prevent the free use of ship compartments and spaces. Moreover, logistical issues also arise when taking into account an operating shipyard.

For this reason, the construction of a testing facility for remote inspections on-board ships has been proposed and started at the University of Genova in the framework of the ROBINS project; moreover, testing protocols aimed at assessing RAS inspection abilities were developed.

Currently, no dedicated testing facility 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 not specifically designed for inspection of ship structures.

The aim of the ROBINS project is to focus on inspections of bulk carriers, as reference ships, which present many aspects of interest also for other types of vessels, in order to reproduce, as much as possible, the various scenarios that can be found on board during structural inspections. According to that, the main module of the testing facility aims at recreating an environment with typical elements of a bulk carrier ship to enable RAS platforms and to assess for their abilities in ship inspections as a general-purpose testing scenario where an inspection event can be suitably simulated.

The RAS should be able to inspect both enclosed narrow spaces full of obstacles, typical of the double bottom and double side structures (ballast tanks), as well as wide volumes with significant heights like bulk carrier cargo holds (see Fig. 4 showing the main module of the testing facility recently established in Genova).

Fig. 4. Photo of the main module of the testing facility (main dimensions LxWxH 7000x4000 × 4000 mm).

Fig. 5. From the left: example of crack, corrosion and pitting occurring in the testing facility structures.

The testing facility 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. lightening, humidity, dirt, etc.). It is also composed by an enclosed large volume, with metallic boundaries that simulate a cargo hold, to assess for localization and orienteering abilities, path planning and area coverage capabilities of the platforms.

Besides, one of the main features is represented by 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, etc. as overviewed e.g. in (Rizzo et al., 2007) and (Rizzo et al., 2008). Fig. 5 shows an example of such typical structural defects and surface condition in specific locations.

The trials sessions carried out up to now in the testing facility were aimed at a general RAS-human comparison of capabilities in orienteering, localization and identification of structural defects. To this aim the testing protocol is a relatively simple one: selected paths were defined along which either real defects and markers were placed as key-points, similarly to current surveyors' inspection practice.

The assessment was carried out in terms of time of inspection and ability to find and locate the key-points (see Fig. 6). Noticeably, it was found that a class (human) surveyor and a team composed by a RAS, its pilot and a ship superintendent completed the test protocol with very similar results (only one key-point with defect missed) and in approximately the same time. However, it was noted that communication and cooperation between pilot and superintendent represent a key point. As a matter of fact, in many cases, drone pilots are not familiar with a ship environment often missing the terminology about the different structural elements. On the other side the human surveyor may lose orientation by looking only at the screen.

A controlled and easily accessible environment, where repeatable test protocols can be implemented, significantly increases development opportunities for new platforms and reduces costs and risks. The data obtained from laboratory tests could be compared with those collected during on-board trials. Any gap found may be used as feedback to review the testing protocols, thus creating an iterative refining process leading to the reasonable replacement of on-board trials with equivalent tests in a controlled environment, with the purpose of developing the RAS platforms as well as assessing the RAS capabilities according to standardized procedures.

5.2. Navigational skills and rule requirements

Localization, path planning and area coverage capabilities are key features in remote inspections, so they should be adequately assessed. Hence, developing and testing navigation skills of RAS is of paramount importance along with the abilities aimed at detecting and characterize structural defects in ship structures.

As a matter of fact, human surveyors localize themselves and then use their own sensorial experience to detect and characterize structural defects they deem useful for subsequent structural assessments according to rule requirements. Contrarily, to localize the robots in GPS-denied environments, RAS have to develop alternative ego-motion features, such as visual or odometry systems, which are able to continuously update their position not depending on external infrastructures. In other words, the drone must be able to localize itself by elaborating data (e.g. pictures or distance measures) locally collected and processed onboard without communication with an external infrastructure (e.g. GPS satellites). As above mentioned, the electromagnetic compatibility of such systems need also to be checked in the testing facility.

In the previously described test protocols, the RAS must reach key-points in a given sequence and follow specific paths facing different challenges, obstacles and disturbances. While moving from one point to another the RAS, analogously to human surveyors, collect data useful for structural assessment: i.e. when a specific point is reached, RAS (or surveyor) has to accomplish the tasks related to detect and characterize structural defects in that specific point. Generally, narrative reports produced by humans contain a limited amount of already pre-processed data, if compared to what can be acquired by a digital system, which instead is a massive amount of raw information to be further elaborated.

Points were placed inside the testing facility at significant locations depending on current rule requirements and according to usual inspection practice (e.g. critical areas inside a bulk carrier's Cargo Hold as defined in IACS Unified Requirements for inspections such as Z10.1 and Z10.2, (Rizzo, 2011), (Z10.1 Hull surve, 2010), (Z10.2 Hull surve, 2015)). I.e. for the time being the testing protocols simulate the human approach to inspection.

In order to address the need of standardized test protocols, each point is identified by a marker symbol placed onto the structure (see Fig. 7). The control points were divided in families, categorized on the basis of the location (cargo hold or ballast tank), the position (e.g. on a plate or on stiffeners, beside their actual location in the main module of the testing facility) and on the basis of the difficulty

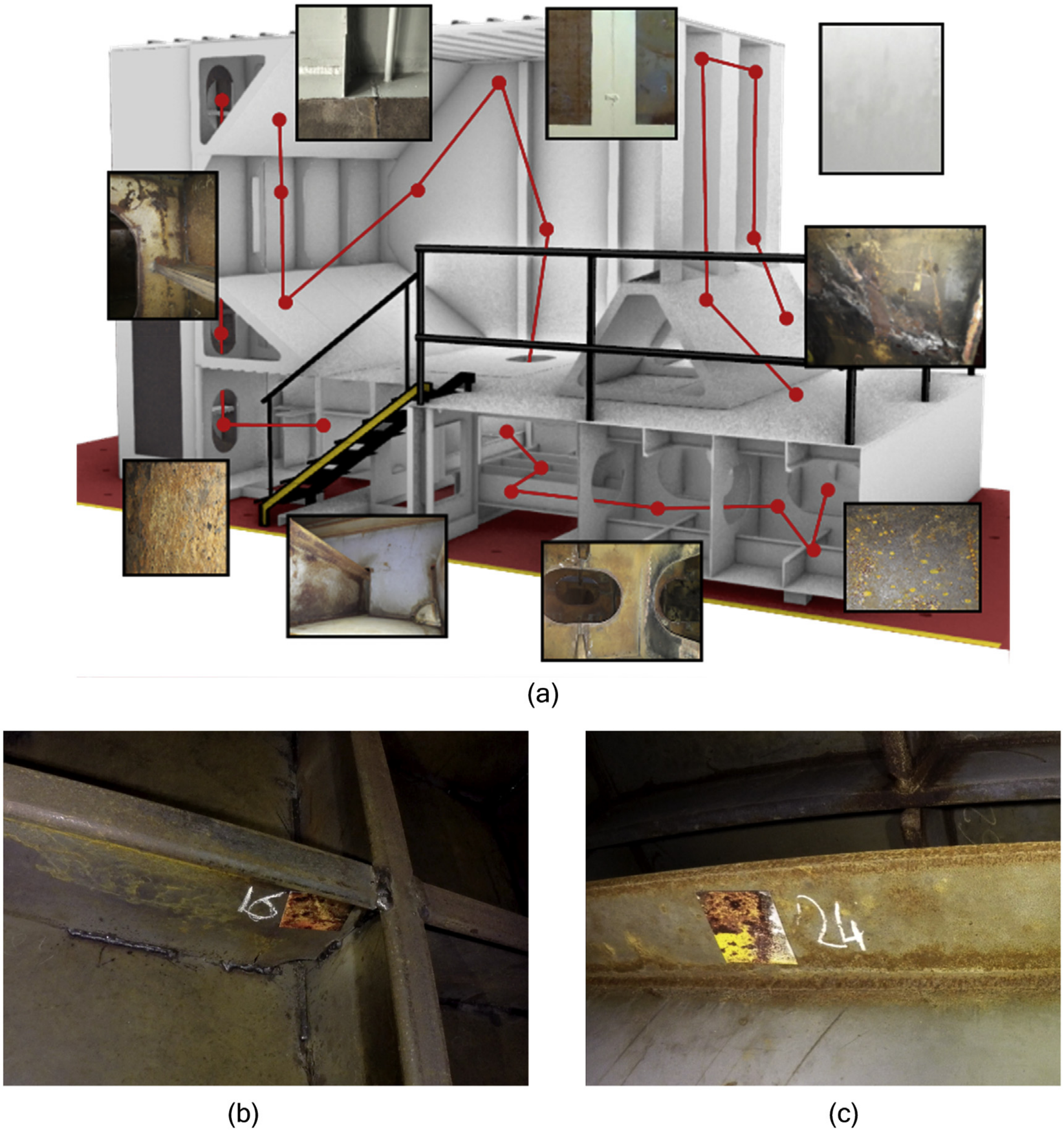

Fig. 6. Path planning test (a). RAS should be able to follow a fixed path to reach control key-points e.g. (b) and (c) in a given sequence.

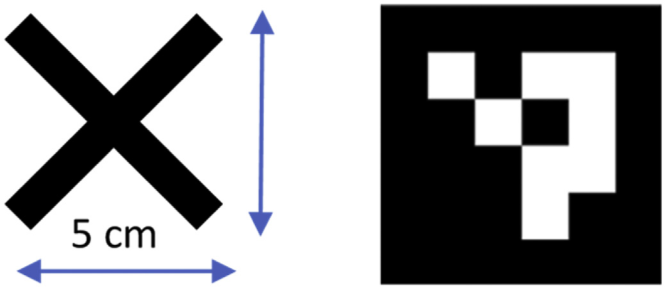

Fig. 7. Example of control point symbol and ArUco marker.

of reaching the point (easy, medium, difficult). The categorization was made with the support of a (human) experienced surveyor, using the same description given for identifying points on board for inspection in narrative reports (e.g. counting frames number from a reference point and locating the height from the deck, etc. As an example, a class surveyor would write in a report: “crack found at bracket toe of the 3rd frame fwd. aft bhd. of hold no. 3, approx. 0.5 m above the top plate of the lower stool”).

To assure the efficiency of the used methodologies, for each configuration, the RAS platform will provide data to be compared with the results obtained by human surveyor, in the same conditions. After the first trials carried out, however, it comes out that there is potential for further development of inspection practice, widening the data acquired and therefore providing more accurate and detailed information for the subsequent structural assessment. Indeed, RAS ego-motion is obtained by well-defined algorithms that can be complemented with databases of detected defects. While human surveyors rely on their skills and experience in order to inspect only a few selected points, likely representing a very small fraction of the actual structural domain to be inspected, RAS are able to scan a much larger part looking for defects. Possibly, this is the way to balance the limited experience in performing RAD-assisted inspections.

As previously stated, RAS are not fully autonomous in the sense that they need some kind of instructions, e.g. a path to follow pre-defined in advance. In principle, no need of piloting is needed for the most advanced RAS during a pre-defined mission, even if a surveyor may require zooming or vision from different viewpoints for the time being in order to reliably assess the structures. Hence, human intervention is somehow necessary.

Protocols would also be required to train the surveyors who will use the images, videos, other results captured by the RAS. This is to ensure that surveyor has a clear understanding of the strengths and limitations of the RAS. Moreover, they should be developed and become specific for the different typologies of robots to ensure the standardization of the tests.

5.3. Specific tests: crawlers' abilities trials

Another part of the test protocols developed in the UNIGE laboratories concerns trials aimed at testing specific RAS abilities to collect information under particularly challenging conditions.

The philosophy of this section of the testing facility is to design a complex experimental set-up, simulating as much as possible a real inspection with particular structural geometries, lighting, environment, ventilation, humidity and different conditions of the structure surface to be inspected, which can compromise the functions of the RAS (e.g. because of presence of corrosion, defects, dust, oil, water, or any other features impairing the proper functioning of the robotic system).

Each conceived trial provides to test one or more abilities of the RAS by changing systematically selected parameters in the test configuration to know to what extent they affect the inspection.

Designed trials shall assess the robustness of the robots to external disturbances in performing specific tasks such as obstacle crossing, adhesion to the surface and recognition of position, quality and accuracy of gathered information, e.g. photos and videos, etc. by evaluating the time taken to carry out each mission as well as the quality of the inspection outcome.

As a typical example, currently the challenges for the crawlers are to climb over obstacles and to move on tilted and dirty panels, since they need a flat steel surface large enough to stand and slide on. It could be hard for this type of RAS to reach and to inspect some reinforced structural parts (e.g. the lower faceplate surface of the stiffeners as shown in Fig. 8).

For this reason, a specific test was developed where, by changing the height of the obstacles, i.e. of three different typical stiffening members of ship and namely bulb profile, "T" shaped, "L" shaped stiffeners, different situations are simulated in which the crawler should inspect and possibly take gauging in selected points of the structure. In this test, the crawler starts from a flat surface, approach the obstacle and attempt to overcome it. The obstacle can be considered crossed if the crawler reaches the flat surface on the other side of the obstacle without external actions with all the wheels or in general the points of contact with the structure (see Fig. 9).

It was noted during trials that, in case the faceplate surface is not offering sufficient space to the RAS, to overcome the obstacle it is needed to select an alternative and likely longer path, obviously increasing inspection time. In some cases, the RAS is even not able to reach the target point. The test results are expressed as Boolean variables (yes/no), beside the duration of inspection, which is considered, as previously mentioned, an appropriate all-purpose quantitative measure of the inspection effectiveness.

Another typical challenge for crawlers and climbing robots in general is to stand still without slipping or moving on tilted surfaces with deposits like salt, dust, paint, rust, flakes of coating or oil. The behaviour of the RAS in the aforementioned surface conditions is tested on a structure designed and built on purpose fitted with two tillable planes and a fixed horizontal one (see Fig. 10). A set of plates characterized by various coating and degradation conditions is available, thus providing a range of simulation scenarios, beside the tilting angle of the surfaces.

Moreover, the crawler should be able to measure the thickness of the surfaces, with or without deposit, even when the slope is changed.

In this case, the RAS assessment is not evaluated in terms of inspection time, rather as ability to face a wider and wider range of different scenarios of increasing complexity. During these trials, it is also worth noting whether the crawler damages or not the surface

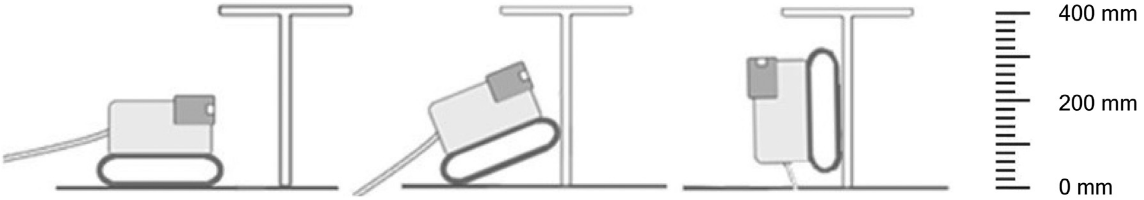

Fig. 8. Sketch of typical crawler movements in way of a T-stiffener welded on a plate.

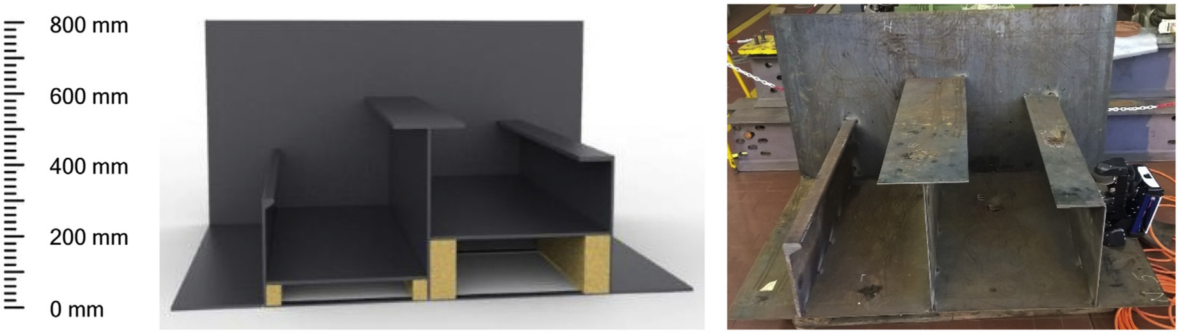

Fig. 9. Obstacle Crossing. Crawlers should cross the beams to inspect selected points of the structure, by simulating different situations changing the height of the obstacles.

Fig. 10. Adhesion Test. Crawlers should stand still without slipping or moving on tilted surfaces with deposits, measuring the thickness of the plates at each step.

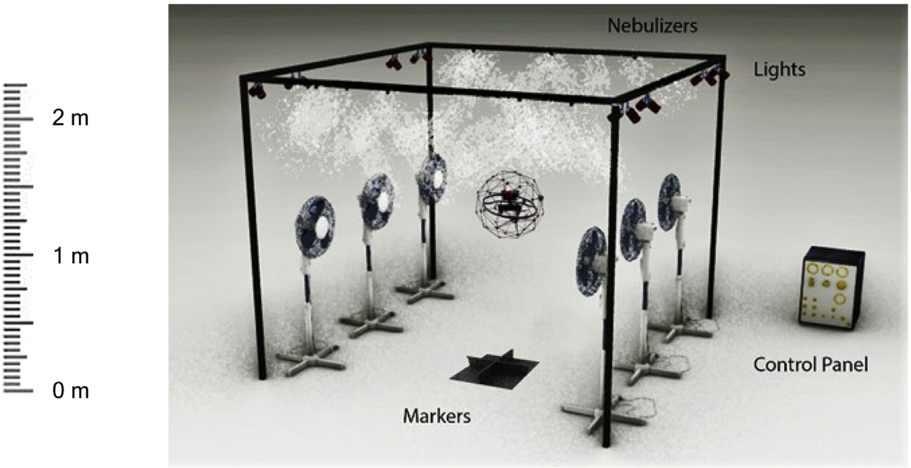

Fig. 11. Flight Robustness. Drones should be able to produce calibrated images of the patterns in unsteady flow conditions, with turbulence wind (maximum gust of 2 m/s) and different configurations of light and nebulization.

coating under inspection, due to the magnetic contact force required to operate on the inclined surfaces.

5.4. Specific tests: aerial drones' abilities trials

Aerial drones, unlike crawlers, are not affected by contact problems. However, since their main task is visual inspection by means of cameras, quality level of collected images need to be assessed. The task could be compromised by external disturbances like humidity, lighting conditions, air turbulence, beside RAS position and path. In this case, the test set-up is made up by several fans surrounding the testing area and a frame where lights and nebulizers are placed (see Fig. 11).

The drones should fly in the testing area, taking pictures of target structural details suitably placed in selected points, avoiding motion blur and other image deficiencies. Especially in this test, RAS pilot skills are crucial: as a matter of facts, the pilot must select the most convenient viewpoint to take the picture taking into account disturbances as well as goals of the mission.

It was noted in the trials that drones' inspection efficiency is generally affected by light painted or varnished surfaces that reflect its own light impairing taken images and by uniform wall surfaces as long as no detection features are present allowing localization of the parts reported in the photos or videos. Assessment of such aspects were carried out also by placing reflective surfaces in the testing areas of the main module of the testing facility.

In this case the inspection duration time is again a measure of the inspection effectiveness along with the quality of image and videos. The pilot ability is more than essential: in one case during trials the pilot decided to land on structural targets and then to take pictures not in flying conditions, which was not foreseen when test protocols were developed. This demonstrates that as for humans, RAS too face the challenges of inspection using different approaches depending on their own specific features and capabilities.

Owing the experience of the first trials carried out, for both aerial drones and crawler, it was suggested to proof RAS abilities to take pictures/gauges of vibrating structures at typical frequencies and motion amplitudes of ship structure, e.g. as those induced by machinery.

6. Conclusions

Inspections are fundamental tasks required in the management of ships. They are currently performed by human surveyors, using rather basic sensors like cameras and ultrasonic thickness gauges and only occasionally other non-destructive testing equipment. It can be affirmed that mostly inspections are currently based on the five human senses, i.e. touch, sight, hearing, smell, and taste, beside surveyor own skills, experience and engineering judgment.

It is usually neither possible nor expected that a survey is extended to the entire structure of the vessel and only the most critical parts or those with higher probability of damage are inspected on the basis of earlier inspection and according to rule requirements derived from decades of ship management history. Consequently, the traditional inspection approach is rather expensive, time consuming and, even if surveyors are trained according to standards (e.g. IACS procedures), based on subjective evaluations, coming from their own experience to a certain extent. This is also due to the intrinsic uncertainties of data collected during human inspections. Rather, during RAS assisted inspections, more quantitative data are gathered, with generally low scatter. Though, needing much more complex post-processing and elaboration, to be properly defined and agreed.

However, as stated in IACS Rec. 42 "The results of the surveys by remote inspection techniques, when being used towards the crediting of surveys, are to be acceptable to the attending Surveyor.", who has in any case the last word and must formulate a repair plan with the shipyard.

The development of latest generation digital technologies, like Robotics and Autonomous Systems, may improve ship inspections widening aims and scope of surveys, provided that inspection approach and procedures are properly updated. Moreover, it may help in making the assessment more objective by acquiring more and more extensive quantitative data, to be automatically elaborated and processed, thus not only identifying the degradation level of the structure but also quantifying it more accurately.

Survey time and preparation costs (e.g. for stagings) can be significantly reduced, still maintaining the quality of the inspection at least equivalent to the traditional ones and improving safety at the same time. But there is potential beyond this first step.

Environments to be inspected and requirements of the surveys are however very different: while many and diversified robotic technologies for automated inspections are being developed, a specific environment to test and assess RAS abilities according to well established standards, specifically devoted to ship and marine structures, is requested.

The testing facility already built and under continuous development in Genoa University has the aim to simulate as much as possible real inspections by proposing structures and typical conditions of an operational ship, stimulating robotics industry towards new potential markets.

The intention is to create, around the testing facility, a competence centre 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. 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, bearing in mind that the first trials already proved that team working including RAS, their pilots and the surveyor is necessary.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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