Autonomous Robotic Inspection and Maintenance on Ship Hulls and Storage Tanks

Deliverable report – D1.1

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ABBREVIATIONS

DoA	*Description of Action*
GNSS	*Global Navigation Satellite System*
ATEX	*ATmospheres EXplosible*
WiFi	*Wireless Fidelity*
SDK	*software development kit*
RGB-D	*Red, green, blue, and depth*
GPS	*Global Positioning System*
ABS	*American Bureau of Shipping*
UR	*Unified Requirements*
SOLAS	*Safety of Life at Sea*
MAV	*Micro Aerial Vehicle*
IMU	*Inertial Measurement Unit*
SLAM	*Simultaneous Localisation and Mapping*

HISTORY OF CHANGES

Date	Written by	Description of change	Approver	Version No.
09/04/2020	Prof. Panagiotis-Antonios Varelas (DANAOS)	Final version for review	CNRS	0.4
04/05/2020	Laura Monnier (CNRS) Cédric Pradalier (CNRS)	Review Validation	CNRS	0.5

REFERENCED DOCUMENTS

1. BugWright2 Description of Action (DoA)

This document will be stored on the file sharing site hosted by CNRS.

1. Abstract

Deliverable 1.1, as defined in the DoA, is an open-to-public report discussing use case analysis and requirements for the successful development and implementation of BugWright2's adaptable autonomous robotic solution for servicing ship outer hull.

It is noted that two releases of Deliverable D1.1 are scheduled to be submitted. In this first version, an initial definition of user requirements, system functional set-up and identification of key performance indicators is given, on the basis of related information provided by the consortium members. Use cases layout is also sketched out to deliver input to WP9 for pilot integration and testing.

A second and more consolidated version will be delivered at M18, taking into consideration the progress and results of the technical development, as well as feedback retrieved from a workshop that will be organized to establish a more detailed use case definition and system requirements identification. External stakeholders and potential users of the BugWright2 system will participate in this workshop.

2. Introduction

Vessels are extremely complicated and comparatively high-cost assets operating in diverse and harsh conditions resulting to various types of hull deficiencies. Typically observed hull deficiencies can be caused by one (or a combination) of the following reasons:

- metal corrosion,
- metal erosion,
- wear and tear,
- design faults,
- material defects and/or poor workmanship,
- loading and unloading (cargo) operations,
- contact (e.g., with quay side, ice, touching underwater objects, etc.), and
- accidents (e.g., collisions, groundings, fire, explosions).

The metal corrosion, which may be considered as the dominant reason, appears as a non-protective, friable rust. The rust scale continually breaks off, exposing fresh metal to corrosive attack. Thickness loss cannot usually be judged visually until excessive loss has occurred. Failure to remove mill scale during construction of the ship can accelerate the corrosion that takes place, while in service. Severe general corrosion in all types of ships, usually characterized by heavy scale accumulation, can lead to the need for extensive steel renewals.

The hull deficiencies caused by the aforementioned reasons are manifested in the following forms:

- material wastage,
- fractures,
- deformations, and
- catastrophic failures.

Currently, hull inspection for all sea going vessels is moderated via surveys carried out by Classification Societies on scheduled intervals. Inspections could be also ordered by ship owners or requested by the charterer of the ship. Nowadays, visual inspection in full with accredited personnel is carried out on dry dock or performed by divers while ship is afloat. Class surveys generally consists in:

- An overall survey (visual inspection) of the hull in accordance with rules requirements; it is intended to capture the overall condition of the hull structure and determine the extent of additional close-up survey. The latter focuses on details of structural components, which are within the close visual inspection range of the surveyor, i.e. normally within reach of hand.

- Hull steel plate condition assessment by mean of thickness measurements. Thickness measurements may be required on predetermined structural elements, as described by Class regulations, with special focus on suspected areas of defects and areas of substantial corrosion.

The employed class surveyor uses previous knowledge in collaboration with an 'immersive' / real experience of the hull condition and surrounding environment to form an accumulative impression of the vessel condition. Additionally, the surveyor can use tools to test more thoroughly critical points of interest, e.g. by hammering, or manually removing rust scales or superficial coating.

The objective of BugWright2 is to bridge the gap between the current and desired capabilities of ship inspection and service robots by developing and demonstrating an adaptable autonomous robotic solution for servicing ship outer hulls. The considered ship outer hull services include: visual inspection, steel structure thickness measurements and hull cleaning.

BugWright2 aims to capitalize on the state of the art in robotic remote inspection, tailor and improve functionalities and deliver a holistic ecosystem from heterogeneous devices that will be able to detect and evaluate defects, cover all areas of interest across the outer hull, feed users with full-fledged data on hull condition and navigate with the least of human intervention.

In a nutshell, the consortium's principal concept is to deliver an advanced autonomous robotic technology that will execute a qualitative inspection and cleaning service in the least possible operational time. Furthermore, the project will investigate the applicability and adaptability of the BugWright2 technologies to different structures assembled out of metal plates and in particular to storage tanks as secondary application domain.

Taking into consideration the aforementioned hull inspection and cleaning services framework, this deliverable constitutes a first attempt at defining the end-users needs that will be translated in functional requirements for the BugWright2 system.

The current state of the art in remote robotic inspection and hull cleaning is described in Section 3. The technology gaps to be filled in order to enhance and adapt existing robotic systems capabilities to match end-user requirements, are discussed in Section 4. In BugWright2, a complete value-chain validation – robot providers, inspection service providers, certification agencies, shipyards, harbours and ship-owners – will be involved in the specification and evaluation of the system. Under this scope, the requirements definition will consider a multi-stakeholder approach taking into consideration the point of view of the owners, the service providers and the classification societies. These requirements are given in a consolidated table in Section 5 for common reference. The same overall user perspective will be followed for the classification and measurement of key performance indicators assigned to the evaluation of the system as discussed in Section 6.

Concluding, a mission scenario is drafted to deliver an initial layout of use cases that will establish the validation framework for BugWright2 technologies against different stages of system maturity as it gradually evolves throughout project timeline, from basic to more advanced standards.

3. State of the Art in Hull Inspection and Cleaning-Technology

Robotics and Autonomous Systems (RAS) is an emerging technology that received a considerable attention in the last years from a wide range of business sectors including the maritime industry. The IEEE Robotics and Society (RAS) Marine Robotics Technical Committee (MRTC) was first established in 2008 following the dismissal of the Underwater Robotics Technical Committee in spring 2008. The goal of the MRTC is to foster research on robots and intelligent systems that extend the human capabilities in marine environments and to promote maritime robotic applications important to science, industry, and defence.

Inspection and mapping using robotic platforms has begun to be adopted in the industry over the past few years. Application scenarios such as agricultural fields and quarries have been among the first areas where e.g. airborne platforms have been deployed to implement for both tasks (see

Figure 1). Such environments are generally well textured having limited complexity in their structure and therefore, are suitable for 2D and 3D reconstruction methods through vision and other sensor modalities.

Siemens SIEAERO power line inspection | **SenseFly quarry mapping** | **Airbus airplane inspection**

Figure 1: Examples for airborne inspection and mapping applications already used in industry

With respect to the inspection and condition monitoring of industrial facilities and assets, the research community is mainly focused up to now in the development and utilization of helicopter-type Micro-Aerial Vehicles (MAVs) for data collection at large-scale, remote, hard-to-reach and/or safety-compromised areas. Nevertheless, applications of remotely operated vehicles (ROV) underwater or on the surface of the inspected structures have also been deployed.

In the following sections, a brief overview of the state of the art according to the different platforms and applications has been aggregated.

3.1. Aerial Visual Inspections

Application examples of Micro-Aerial Vehicles, sorted by year of publication, are summarized in the Table 1. As can be observed, there are very few solutions connected with vessel inspection, and, those that have been designed to operate within this scenario, mostly focus on the inner hull structure.

Table 1: Representative approaches for infrastructure inspection using aerial platforms.

Reference	Use Case	Type	Sensors/technology	Output
Campoy et al. (2001)	Power line	Helicopter	Stereo	Image
Jones (2005)	Power line	Ducted-fan	Camera	Image
Serrano (2011)	Culvert	Quadcopter	EKF: LiDAR + GPS + IMU	Image
Eschmann et al. (2012)	Building facade	Octocopter	—	Image + mosaic + cracks
Michael et al. (2012)	Building	Quadcopter	SLAM: LiDAR + RGB-D + IMU	3D map
Bonnin-Pascual et al. (2012)	Vessel str.	Quadcopter	SLAM: LiDAR + IMU	Image + cracks + corrosion
Burri et al. (2012)	Boiler system	Quadcopter	EKF: stereo + IMU	Image
Lippiello and Siciliano (2012)	Wall	Simulation	Optical flow: stereo + IMU	Image
Marconi et al. (2012)	Contact	Ducted-fan/ Coaxial rotor	IMU, contact	Physical interaction
Wu et al. (2012)	Power tower	Simulation	—	Image
Nikolic et al. (2013)	Boiler system	Quadcopter	EKF: stereo + IMU	Image
Sampedro et al. (2014)	Power tower	—	—	Image + tower
Martinez et al. (2014)	Power tower	—	—	Image + tower
Quater et al. (2014)	Photovoltaic plant	Hybrid/ Hexacopter	—	Image + thermal image
Hallermann and Morgenthal (2014)	Bridge	Octocopter	—	Image
Satler et al. (2014)	General	Quadcopter	SLAM: LiDAR + IMU, 2 US	Image
Omari et al. (2014)	General	Hexacopter	EKF: stereo + IMU	3D reconstruction
Gohl et al. (2014)	Mine	Hexacopter	EKF: stereo + IMU, 2 cameras, LiDAR	3D reconstruction
Høglund (2014)	Wind turbine /Building	Hexacopter/ Simulation	Optical flow: camera + IMU + 2 US	Image
Santamaria and Andrade (2014)	General	Quadcopter/ Simulation	—	Image
Ortiz et al. (2014)	Vessel str.	Quadcopter	SLAM: LiDAR + IMU/visual odometry	Image
Choi and Kim (2015)	Building	Hexacopter	—	Image + cracks
Sa et al. (2015)	Pole-like str.	Hexacopter	IBVS/PBVS: camera + IMU	Image
Máthé and Buşoniu (2015)	Railway	Quadcopter	Camera	Image + track
Jimenez-Cano et al. (2015)	Bridges, etc.	Octoquad	—	Physical interaction
Cacace et al. (2015)	Contact	Ducted-fan/ Quadcopter	Camera/stereo + IMU	Physical interaction/image
Ozaslan et al. (2015)	Tunnel-like env.	Quadcopter	Particle filter: LiDAR + IMU	Image
Bonnin-Pascual et al. (2015) Ortiz et al. (2015)	Vessel str.	Quadcopter/ Hexacopter	Optical flow	Image + corrosion
Roberts (2016)	Metallic str.	Quadcopter	—	Image + corrosion

Ellenberg et al. (2016)	Bridge	Quadcopter	—	Image
Campo et al. (2016)	Open env.	Quadcopter	EKF: GPS + IMU	Image
McAree et al. (2016)	Wall	Octocopter	LiDAR	Image
Alexis et al. (2016)	Contact	Quadcopter	Motion tracking	Physical interaction
Bonnin-Pascual and Ortiz (2016) Bonnin-Pascual et al. (2019)	Vessel str.	Quadcopter/ Hexacopter	KF: optical flow + LiDAR + IMU	Image + defects
Fang et al. (2017)	Shipboard environment	Quadcopter	Particle filter: RGB-D visual odometry + IMU	Thermal image + fire

The fast adoption of MAVs for, in particular, inspections can be attributed to the reduction in size of computation boards and sensors which enabled system makers to offer small-size platforms. Additionally, multi-rotor MAVs are preferred because of their mechanical simplicity, their stationary ability at low-speed flights, and the fact that each rotor individually stores less kinetic energy (Castillo et al. 2005). Among the different type of configurations, quadcopters and hexacopters are the most used.

While the methods and platforms from Table 1 can already be found in certain industry sectors for well-textured environments, the handling of mostly homogeneous hulls and low-texture surfaces is still a challenging task whose complexity is amplified in GNSS-poor areas. Among other solutions, the industry has mitigated this technology gap by only providing 2D images patched to an existing 3D model for further human interpretation (see

Figure 1, right).

3.2. Above-water plate thickness measurements for ship hull and storage tanks

Plate thickness measurement, as discussed in this report, is an important part of the inspection process for ships and storage tanks. This is typically performed using ultrasonic transducers that sends a high-frequency pulse (e.g. 5MHz) inside the structure and wait for the echo from the plate other side.

Outside the ship hull, these wall thickness measures are performed by one or two controllers from a cherry picker. For the storage tanks, they can be collected by two controllers with rope access.

Figure 2: Ship outer hull and storage tank thickness measurements (Credits: P.L Tzaneas & Partners, ROBOPLANET)

The localization of the measures on the inspected structure is approximated from external reference points such as welds or hull fittings, which can be difficult to match with the internal area in the ship.

Measures are mainly punctual with a footprint of 1 cm^2, which results in a small probability of detection of small thickness losses and a limited coverage of the structure.

Since 2005, storage tanks have been controlled with magnetic crawlers introduced by a number of companies around the world, among which RoboPlanet in the consortium. Those are remotely driven by a controller from the ground. On storage tanks, the normal process is to drive the crawlers so as to acquire ultrasonic samples automatically on 1cm vertical tracks regularly spaced on the tank circumference.

Because these systems are manually operated, the acquisition requires time, which results in a reduced coverage of the surface by the equipment in order to be commercially viable. Additionally, the continuous acquisitions on 1cm-wide tracks may miss localized corrosion.

Figure 3: Crawler for hull thickness measurements (Credits: ROBOPLANET)

Within BugWright2, it is expected that most of these issues will be addressed. Introducing autonomous driving capabilities will not only reduce the demand of pilot time but will also allow deploying multiple rover simultaneously, with the potential to achieve a higher surface coverage within the same amount of time.

3.3. Underwater visual inspections

Underwater Remotely Operated Vehicles (ROV) have been used more and more for ship inspection in recent years. These platforms have a great potential for saving costs by replacing or helping divers or avoiding getting the boat in a dry dock. The current usage is focused on visual inspections and can have various objectives among the following:

- Inspection of the hull for detecting fouling and corrosion
- Propeller and thrusters
- Sea chest
- Anodes
- Rudder
- Damage survey
- In water class survey
- Supervising diver work
- Preparation for dry dock operations

Besides the usefulness of such vehicles, there are some limitations that must be taken into consideration. Inspection of big vessels have different challenges that BugWright2 is trying to tackle and minimize. Such limitations include:

- Navigation and positioning. Large ships are hard to navigate for the remote operator due to usually lack of positioning tools and poor visibility.
- Lack of scale. It is hard to interpret the size of objects without a reference using a video stream.
- Low visibility, current and waves. These are the main disturbances for such vehicles that make their task more challenging. Current and waves affect their performance and manoeuvrability and low visibility affects navigation and its assessment during the inspection
- Ability to touch/interpret thickness of hull steel plate or fouling.
- Tangling tether. The tether has always a high risk of getting tangled around the boat structures, especially propellers.
- EX/ATEX limitations. Explosive atmospheres require of stricter certifications.

All those limitations (except the EX/ATEX one) will be addressed during the project by converting the available technology of ROV-inspection into a robust autonomous inspection system.

In the context of the project, we start from the Blueye Pioneer, an underwater drone that is currently used on different business ranging from Aquaculture to Shipping. It is provided with four thrusters to manoeuvre underwater with ease. Two Horizontal thruster to go forwards/backwards, a vertical thruster for depth control and a lateral thruster to sweep along walls, nets, ship hulls etc.

The drone has active heading and depth controls to increase its stability during operation. Pitch and roll are passively controlled with its mechanical design, damping those motions and enhancing video quality during inspections. The communication and video streaming is done via an umbilical (twisted pair) connected to a Blueye Surface Unit. This device acts as a router and allows smartphones to connect to it through WiFi.

The video streaming can be recorded and stored in the drone during the operation. Once the dive is completed the user can download the videos (.mp4) into a smartphone and/or computer. Pictures can also be taken during operation in JPG format and stored both on the drone and smartphone device. In addition, overlay with navigation data can be embedded in the videos and pictures to help operators to visualize data.

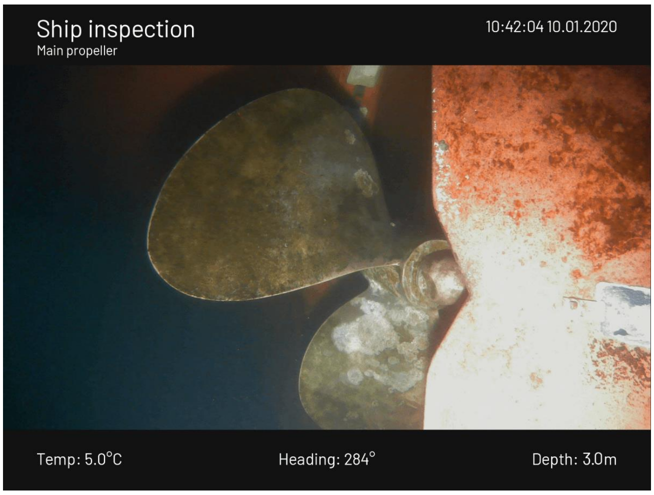

Figure 4: ***Picture X Ship inspection overlay example***

This data can also be used to create 3D models out of the video streaming for better visualization. Blueye has an account at Sketchfab where many 3D models are shared as examples.

Figure 5: ***Picture X – Example of a shipwreck mapped with photogrammetry***

In the context of the BugWright2 project, the Blueye Pioneer will be configured to work as an Autonomous Underwater Vehicle (AUV) so we will have the possibility to not use any tether if this is beneficial for the inspection task. For that purpose, Blueye will design a payload system to attach external equipment to the Pioneer. The main payloads to be attached will be for navigation (USBL) and mapping (Side Scan Sonar or a Multibeam sonar). Additional equipment for the scope of the project might involve Thickness Gauge probes to assess the state of hulls in specific areas and external lights.

On the software side, Blueye will assist NTNU and Porto University with preparing the current embedded software and making it suitable for the other contributors to work on. Blueye will work on a bare-bone version of the drone Operating System (OS) without the control system and custom software but with all dependencies. In addition, Blueye will provide the other partners with an SDK where the code can be cross compiled. This way Porto University and NTNU can install their own software and transform the Pioneer into an AUV.

When operating as an AUV there are some limitations when it comes to data transfer. The USBL system for positioning provides bidirectional communication with a limited bandwidth of 10kbps. Only important data might be shared during operation of the autonomous inspection (critical commands to synchronize with the other robots). After the inspection is completed, all relevant data will be downloaded (video recordings, still images, logs etc.) for additional post processing.

3.4. Underwater thickness measurements

In comparison to the plate thickness measurements performed in dry-dock or on storage tanks, underwater thickness measurements (UWTM) are mostly performed during the class inspection. On aged ships, UWTM can be performed by divers on areas inaccessible from the inside, in order to prepare a dry-dock and anticipate the amount of work.

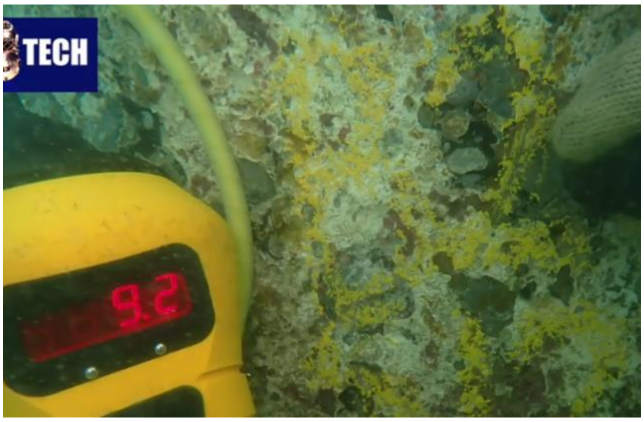

Figure 6: Underwater thickness measurement (Credit: MasterTech Diving Services)

Those underwater inspections generate human risk and require some surface cleaning before being performed. They are also subjected to weather conditions, legal rules. Among the challenges that BugWright2 intend to address, the localization of the measurements is the most important one.

3.5. Underwater hull cleaning

Underwater hull cleaning is currently performed by divers. They use some motorized underwater carts. Those carts are equipped with brushes for cleaning for detaching the fouling (mostly micro and macro organisms) from the hull. The fouling is released in the harbour, typically with particles from the antifouling paint.

This solution generates a high risk for the commercial divers. In the world, more than 10 divers lose their live in this operation yearly. This also increase pollution and invasive species proliferation, because of the lack of waste collection & filtering. Finally, the brushes impact the coating, and reduce its efficiency as a biofouling.

Figure 7: Driver operated kart for cleaning

In the last years, some companies started to operate remote-operated cleaning devices. Those adhere to the hull with venturi or magnetic. They are propelled by hydraulic thrusters or motorized wheels. Some of these systems integrate coating-care cleaning devices such as high pressure cleaning. At the time of this writing, only a few are connected to a water filtering & treatment unit at the surface.

These new systems reduce significantly the risks for the operators, protect the environment and preserve the antifouling thickness. They face several challenges that impede their expansion, in particular their size, manual operation, unique cleaning device for each operation, lack of resilience in case of maintenance.

3.6. Navigation systems

A review of state of the art of navigation systems for robotic platforms is given in this Section. Because the applicable technologies above and below water are quite different, they are considered separately here. However, the above water technologies apply similarly to the RoboPlanet crawlers on the hull or the MAVs around the hull. In a similar way, the underwater technologies will be similar for the Blueye Pioneers or the RoboPlanet crawlers whether they are inspecting or cleaning the surface.

Above water, most existing commercial products use GNSS (Global Satellite Navigation System) to acquire images for offline post processing (see

Figure 1, middle). Nevertheless, infrastructure inspections are often carried out in environments where GNSS signals can be poor (e.g. due to multipath effects) and besides motion-tracking systems cannot be installed, so that the aerial platforms have to estimate their state for stabilization and localization using on-board sensing and processing. Solutions published so far mainly differ in the sensor(s) used and the assumptions made about the environment (Bonnin-Pascual and Ortiz, 2019).

As a result, many of the approaches in Application examples of Micro-Aerial Vehicles, sorted by year of publication, are summarized in the
Table 1. As can be observed, there are very few solutions connected with vessel inspection, and, those that have been designed to operate within this scenario, mostly focus on the inner hull structure.

Table 1 make use of vision systems for state estimation using either different variants of Bayesian Filters or full SLAM (Simultaneous Localisation and Mapping) solutions for computing the platform state. Such vision systems mainly comprise monocular camera configurations, stereo rigs, RGB-D cameras and/or optical flow sensors.

The laser scanner is another sensor which has been highly used in aerial robotics for inspection. It is useful in dark or poorly-illuminated environments where vision systems may fail, even though it typically requires a higher payload capability from the MAV. Finally, the proposed approaches combine, every time more and more, the motion data provided by the selected main sensor (RGB or RGB-D camera, stereo rig or laser scanner) with the 3-axis motion data supplied by Inertial Measurement Units (IMU, supplying linear accelerations, angular velocities and orientation) to improve or complement the platform state estimation (see, among others, Weiss et al. 2013).

Regarding the autonomy of the MAV at the functional level, some inspection solutions focus on fully autonomous systems, what requires from the platform self-localization, obstacle perception and trajectory planning capabilities, while others adopt shared or supervised autonomy approaches. This last control paradigm allows the operator to interactively command the platform. This fits the system with added flexibility for operating in general environments which facilitates integrating them into existing inspection procedures (Bonnin-Pascual et al, 2019).

In BugWright2, the systems operating above water are expected to use a combination of visual-inertial sensing with ultra-wide band beacons as an alternative to GNSS.

In the underwater domain, GNSS systems are only available at surface. Once underwater, inertial and acoustic based navigations come to aid. An Inertial Navigation System (INS) uses accelerometers to measure motion and gyroscopes to measure rotation. This enables the calculation of a dead reckoning position, as orientation and speed can be inferred (relative to a previous position in time) without external aid. Dead reckoning will accumulate errors over time if used alone though. To reduce this effect and improve the overall navigation solution, additional sensors are usually used to measure other variables such as, e.g., speed over ground (with a DVL - Doppler Velocity Loggers), pressure, and external references query by acoustics. Logically, a more accurate INS system will provide a better dead reckoning solution, but the more accurate an INS system is, the more complex and thus expensive they are. Recent developments in microelectromechanical systems (MEMS) are making available small and light INSs which are getting better and less expensive.

To integrate all the information collected from the different sensors and thus produce a better estimated position, sensor data fusion methods are commonly used (such as Kalman filters or other similar algorithms). The typical navigation solution nowadays for a robotic system is to have both dead-reckoning and absolute sensors with a sensor fusion implementation - whether it is a low-cost system with only standard GPS, compass and a "cheap" IMU or a more sophisticated setup with several high-accuracy dead-reckoning sensors and redundant absolute positioning systems.

In what concerns absolute positioning systems underwater, acoustics is the available mean. By using acoustics, external reference sources can be used to periodically reduce the errors that come from the numerical integration of the dead-reckoning sensors. There are several topologies for these acoustic positioning systems, but all make use of measuring the time-of-flight of the acoustic sound on the water, and estimating ranges. One such topology is the LBL (long baseline). LBL requires fix position transponders in a number bigger than one and separated by large distances (from 100m to kilometres). The main advantage of the LBL is its accuracy independent of water depth, but the setup is complex for deployment and requires some knowledge. SBL (short baseline) can be assemble on a ship hull or a dock structure and is less complex than LBL to setup. The distance between transponders (10 to 50m) influence the accuracy. The disadvantages are the need for a careful calibration, the use of additional sensors such as gyroscopes and vertical reference, and the need for more than three transponders. USBL (ultrashort baseline) is the less complex one because it only needs a pair of transponder/transceiver, one on the surface and other on the target object. The difference is that the USBL transceiver as an array of transducers only a few centimetres apart from each other, which allows it to calculate the range and bearing (using phase-differencing) to the target transponder. This lowers the complexity of the solution significantly, but its accuracy is lower when compared to LBL/SBL solutions, especially as distance increases (accuracy is better within short ranges). Its main advantage is not needing deployment of transponders and which makes it a viable ship based system.

Fully automated ship hull inspection solutions are still being developed. The most common setup for a ROV for hull inspection is using an IMU, a depth sensor and a DVL (measuring distances to the ship hull) - this allows the navigation solution to know where the ROV is in relation to the ship. Using also an acoustic position system enables the knowledge of an absolute position. There are other approaches to hull-relative navigation using mosaic-based methods using cameras or feature-based SLAM with imaging sonars.

For the BugWright2 project, the approach being currently considered is using the IMU and depth sensor already onboard Blueye ROVs, add an USBL system and an imaging sonar to allow a hull-relative navigation.

4. End-Users requirements

4.1. Ship Owner expectations

Hull integrity is of outmost importance for vessels' seaworthiness. The hull is the most notable structural entity of the ship having significant effect on ship operational performance in terms of safety, protection of the environment, energy efficiency and overall structural health of the asset. Hull inspection either in dry dock or at quay (afloat) is performed to evaluate the state of hull structural components against corrosion, cracks or deformations and excessive biofouling. According to the International Maritime Organization (IMO), if the entire world fleet were kept clean of fouling assuming well-coated, smooth hulls without any defects, the savings in fuel per annum would be 66 million tonnes - €31.2 billion (HYDREX, 2010). As every tonne of fuel produces 2.25 tonnes of CO_2, that could be translated in 148,500,000 tonnes of CO_2/year saved.

Currently, hull operational reliability and safety for all sea going vessels is assessed via scheduled surveys carried out by Classification Societies on a periodic basis, i.e., every 1, 21/2 and 5 years (Annual, Intermediate, Class renewal/special survey). Classification Societies' verification process is based on the application of their own rules which comply with international and/or national statutory regulations of Flag Administrations. Hull surveys may be also ordered ad-hoc by owners in their own discretion following company's defined measures for continuous improvement in Ship Energy Efficiency Management Plan (SEEMP). Additionally, it may be the charterer that requests inspection in predefined intervals (e.g. annually) following charter party terms, especially when fuel cost is of charterer responsibility given the direct association of fuel consumption with hull integrity. It may even be ordered for the purpose of vetting inspection.

From the ship owner / manager perspective, the expectations, for the holistic and adaptive robotic ecosystem that BugWright2 intend to deliver for hull inspection and cleaning, should satisfy three basic criteria: 1. Improving the quality of the inspection 2. Reducing maintenance time 3. Exploiting captured data. Quality in inspection is defined by hull survey coverage, precision and detection accuracy whereas any potential hull integrity problems should be spotted early on to minimize operational downtime. The objective of such a robotic ecosystem is to enhance the capabilities of a generic man-based visual survey by detecting, assessing and recording defects with the least human intervention consuming significantly less time in maintenance operation (in typical dry dock, a full hull survey covers one working day but, if we include thickness measurement in close-up surveys, then this time is escalated to 5-8 working days).

Special attention should be paid to underwater survey, when the ship is afloat, necessary for estimation of the general and detailed technical state of the ship's hull underwater parts. The detection of a fault on a ship afloat by the BugWright2 robotic system, without necessity of docking, should be made equivalent to carrying out a qualitative examination of the hull shell plating. In particular, this would require to check the ship anode and cathodic protections and fasteners, the state of the plates in the shell plating, to detect the occurrence and localization of dents, cracks or fractures, to inspect the sea valve gratings, to inspect the propulsion/steering unit by measuring the bearings sag of the rudder blade stock and stern gear. Besides thorough examination of hull parts, the underwater BugWrigh2 robotic system should be able to navigate on or around the hull to capture its condition and record defects as long as the vessel stays in port**.** Port stays are ranged from 8 hours to 48 hours or more and it is determined by the cargo volume, the stevedoring capacity or the cargo loading/discharging performance of the terminal. BugWright2 should deliver a qualitative underwater survey in less time than the ship's port stay.

Inspection afloat makes it easier to identify the possible risks and to better define the list of the forthcoming repair works. Most important is for the BugWrigth2 ecosystem to ensure reliable data streams and full information coverage. The robotic ecosystem should not only record and capture data but effectively handle and classify information to define a well-structured ordering of the estimated work that should be performed on the vessel in its next dry-docking period. Under this scope, an integration with vessel maintenance software (PMS) should be expected to support the decisions regarding the list of tasks that should be performed against detected defects.

Above all, BugWright2 should not only be able to detect and visualize a defect but to either assess their severity automatically or provide enough information to assist the surveyor or the owner in the decision for an on spot cleaning or repair while the ship is afloat. In this context, the BugWright2 system will integrate expert input to define the impact of a detected hull defect and correlate risk factors against vessel operational profile as well as ship maintenance scheduling, supporting therefore the decision making on how and when should the defect be tackled (on spot repair or waiting for schedule preventive maintenance in a dry dock period). In cases where the hull needs to be cleaned from excessive biofouling, when the ship is either at quay or at the anchorage, the BugWright2 underwater system should take into account the restrictions imposed by the port authorities and comply with the harbour water quality regulations by ensuring, in particular, that an effective filtering is in place for the removed fouling.

With regard to data exploitation, BugWright2 could assist the ship owners in their continuous monitoring of hull performances. In this respect, it would be an option to equip the BugWright2 robotic system with the ability to measure the hull roughness**.** Systematic underwater measurement of coating thickness would facilitate hull cleaning scheduling in advance. At the same time, this would allow identifying recurring patterns between ship operation profiles (vessel active days, voyage weather conditions, routing plan, and maintenance and repair history) and hull performances, assessing the impact of antifouling on vessel energy efficiency. Therefore, BugWright2 would support the operators in maximizing their hull performances and thereby reduce fuel costs and control emissions.

In summary, the point of view of the ship owners / managers is that the BugWright2 ecosystem of heterogeneous autonomous technologies will lead to an increased use of advanced robotic application in hull inspection. This is expected to support them to secure the hull structural integrity and improve the hull performance, leading to a reduction of unscheduled ship repairs and structural failures as well as a reduction in operational downtime and off-hire days. As a result, the ship operators will be able to increase the fleet utilization rates and achieve savings both in maintenance and operational costs (fuel savings).

4.2. Service provider requirements

Current hull inspection practices are mainly based on the employment of class surveyors in collaboration with experienced service engineers to assess hull condition.

The utilization of robotic technologies for hull inspection purposes must ensure that at least an equivalent amount and quality of information is provided so that their application will not result to any loss of reliability in the condition assessment.

In this respect, robotic platforms utilized for hull inspections, e.g. drones, crawlers and ROV, must be able to

- **Operate at least in the same environmental conditions as those assumed for the inspection of a human surveyor in person.** Platform design and applied construction materials should be compatible with, and not hazardous for, the environment in which inspections will be carried out. In addition, critical parts of the platform and ancillary components have to be designed in such way that associated risk with most probable failure is minimized.

- **Follow a planned path in the presence of unknown obstacles.** The platforms should be also able to keep a given position for a given length of time (assuming a predefined error margin and magnitude of disturbance). Typical sources of disturbance for aerial platforms can be varying air flows, turbulence induced by vicinity to surfaces, environmental conditions generating uncertainty in sensor measurements (e.g. sunlight or lighting conditions in general). For magnetic crawlers, they are intrinsically stable and attached to the inspected surface but their closeness to the surface makes them potentially very sensitive to the tether entanglement (e.g. anodes, structure cleanliness, hard scale, corroded surface, etc.). In the case of underwater platforms, waves and currents will be the main source of disturbance but the tether may also create constraints and disturbances (e.g. hull cleanliness, sea-growth, etc.). In addition to the above, a requirement of critical importance for robotic platforms aimed to be used for thickness measurements is their ability to reach points of interest at a distance suitable for taking thickness measurements.

- **Provide visual information with level of detail, colour, contrast, brightness etc. sufficient for detecting and ranking defects in a way that is comparable to the information available to the surveyor when operating in person.** The visual information, still images and/or video, provided in early stages of hull inspection mainly by aerial platforms but also by ROV shall be able to enable a first level identification of hull defects (e.g. hull corrosion, sea-growth) and their extend. The photographic sequence of Figure 8 shows an example of intense hull corrosion. Corrosion may appear in different forms including localized corrosion in the form of pitting, cavities (shallow, wide, or elliptical) and “holes”, barnacle depositions, residue of the antifouling paint (for the inhibition of living organism growth on the surface), loose flakes of plates, and crevices.

Figure 8: Photographic sequence of hull corrosion

Pitting corrosion is defined as scattered corrosion spots/areas with local material reductions and is generally considered to be more dangerous than uniform corrosion damage because it is more difficult to detect, predict, and design against. Generally, the quantization of pitting corrosion is based on a visual comparison of the area under examination with charts like the ones shown below. In this respect, the employed robotic platforms and utilized image processing software shall be able to identify and detect with high reliability pitting and other types of corrosion at an early stage of development.

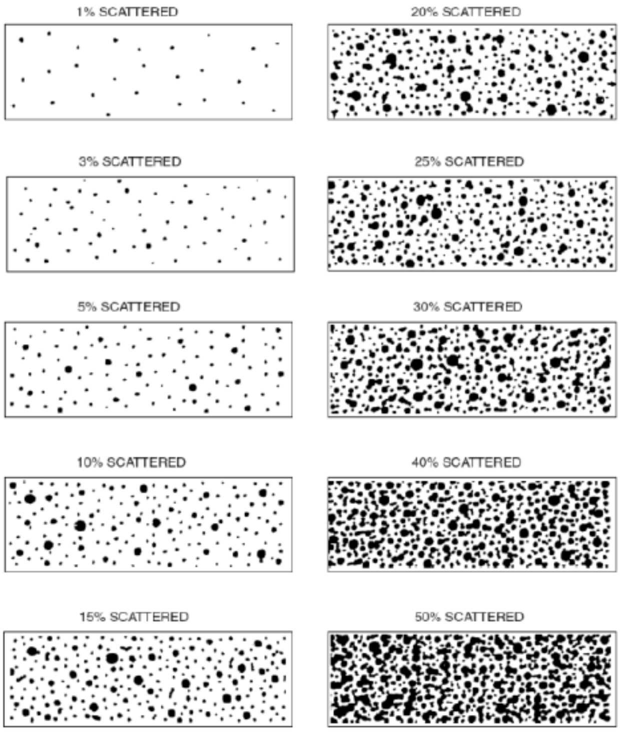

Figure 9: Pitting intensity diagrams

The visual information provided by ROVs shall be able to enable the detection of developed sea-growth in the ship hull. The accumulation of sea-growth in the hull, the marine fouling, has a huge impact in vessel performance and thus on the economics of the ship because it increases vessel drag and therefore fuel consumption. The use of ROV-based visual inspection at regular time intervals will provide valuable information about marine fouling evolution and assist in an effective planning of required maintenance actions (hull cleaning).

Figure 10: Examples of sea-growth organisms

In addition to the above, the importance of post-processing collected visual data has to be emphasized. The post-processing of collected 2D images by 3D reconstruction algorithms will enable the establishment of 3D hull models which can be later used in a number of cases as for example for remote inspections when the physical presence of surveyor is not possible.

- **Provide measurement data, e.g. steel plate thickness, at least with the same accuracy and for the same locations as in traditional surveys, as described in the relevant rules and guidelines.** Thickness data should be sufficient to allow reliable estimation of the actual thickness following provisions stated by rule requirements as well as to enable the detection and localization of corrosion patches.

  In addition to the 'traditional' thickness measurements, the need of collecting hull coating thickness measurements when the vessel is at quay or at anchorage, is strongly highlighted. Hull coating is a technique applicable for all vessel types and ages aiming to reduce surface roughness and therefore, induced drag and fuel consumption. Practically, as the hull coating thickness is reduced the surface roughness is increased. Ships are regularly delivered with a very low surface roughness at around 75μm. The hull roughness increases during vessel life cycle; each additional 10μm to 20μm of 'roughness', according to ABS estimates, can increase the total hull resistance by 1% for tankers and carriers. A vessel could enter a dry dock with a roughness of 250μm resulting to an increased resistance of up to 17% and fuel consumption of 3 to 4% compared to when it first went into operation. The benefits of easy inspection of hull coating thickness or hull surface roughness during vessel operation are evident since it will give vessel operators critical information to plan future maintenance actions.

Additionally, **the time required for a complete scan** of the space to be inspected should be compatible with the time constraints of a typical class survey. **The power source** should be such to allow effective performance of assigned tasks.

In respect to the requirements on BugWright2 hull cleaning functionalities, it shall be mentioned that, up to now, there is no relevant regulatory framework and therefore, provided services are mainly commercially driven, aiming to minimize performance loss and consequently, fuel consumption increase. It must be noted that, in assistance to this task, the International Organization for Standardization has released the ISO 19030 'Measurement of changes in hull and propeller performance' as a global standard for measuring hull and propeller performance. ISO 19030 was finalized in 2016 following three years of development by a wide range of industry stakeholders, including coating and propeller manufacturers, academics, ship-owners and data analysts. It became effective in March 2017. The ISO 19030 outlines general principles for measuring changes in hull and propeller performance. It also defines a set of performance indicators for hull and propeller maintenance, repair and retrofit activities

The hull cleaning procedure typically followed consists of the following steps:

- The propeller and hull condition as well as the type and extent of accumulated sea growth is inspected by experienced divers when the vessel is at quay or at anchorage.
- The decision on the maintenance actions to be taken, propeller polishing and/or hull cleaning, is typically based on the extent of the sea-growth and previous experience.

- Underwater cleaning is performed either by a diver with brushers or by a remotely operated vehicle (ROV). The applied cleaning method depends on the antifouling coating & marine fouling type and degree.

The BugWright2 platforms (ROV, crawlers), taking under consideration the aforementioned procedure, shall meet the requirements listed below. In particular, they should:

- follow a planned path in the presence of unknown obstacles and various weather conditions
- provide visual information with a level of details sufficient for detecting the type, location and extent of marine growth
- utilize different types of cleaning methods depending on hull coating type and condition as well as on the marine fouling type and degree
- provide, if possible, measurements of hull coating thickness or hull surface roughness (optional).

Finally, with regards to the decision support for maintenance functionalities of the BugWright2 platform, it shall be mentioned that provisions have to be made so that the information listed below, in addition to the visual data and measurements acquired by the utilized robotic platforms, is included in the system database and used in the condition assessment procedure:

- vessel particulars
- historical data of sister vessels (if available)
- statistics of similar type of vessels regarding probability and evolution of defects, for instance the type and rate of corrosion, the type and rate of coating breakdown, steel structure thickness measurements, etc. Information of this type is generally available in Class Societies.

The decision-making procedure shall evaluate and utilize appropriately defined metrics, the Key Maintenance Indicators (KMI), parameters defined and introduced by Glafcos Marine in in-house procedures and tools, which are representative of the type and magnitude of different types of defects. As an example, a parameter represents the percentage of hull coverage from sea-growth, the steel structure thickness decrease and so on. A Key Maintenance Indicator giving an overall picture of hull condition can be derived by the following formula

$$KMI_v = \sqrt{\sum s_i * {KMI_i}^2} \quad i = 1 \dots N$$

where

KMI_v : Vessel overall Key Maintenance Indicator

S_i : Severity factor of each KMI

KMI_i : Key Maintenance Indicator of specific defects.

N : Number of considered defects

As a final comment, it is worth mentioning that in all cases the presence of an experienced surveyor and / or service provider engineer will be required to ensure the successful completeness of the inspection surveys and the reliability of the condition assessment.

4.3. Hull Survey Standardization, legal framework, and reporting requirements

The shipping industry and international regulatory bodies have started considering the possibility of drone-assisted, class-related and statutory surveys of ship hull a few years ago.

The International Association of Class Societies (IACS), a not for profit membership organization of classification societies that establishes minimum technical standards and requirements addressing maritime safety and environmental protection and ensures their consistent application, has outlined the basic principles of the so-called Remote Inspection Techniques (RIT) in its Recommendation 42 Rev.2 “Guidelines for Use of Remote Inspection Techniques for Surveys” published in June 2016, as follows:

- RIT may be used to facilitate external and internal examination, including close-up surveys and gauging
- RIT are to provide the survey results normally obtained by the Surveyor
- The results obtained by RIT are to be acceptable to the attending Surveyor
- Inspections should be carried out in the presence of the Surveyor

IACS 2016 Rec.42 Clause 1.2

According to Rec.42, the use of RIT in ship hull inspection is however subject to some restrictions. The use of RIT may be restricted or limited where there is a record or indication of abnormal deterioration or damage, and it may be inapplicable if there are recommendations for repairs or if conditions affecting the class of the vessel are found during the inspection (IACS 2016 Rec.42 Clause 2.1).

Inspection using RIT should be carried out by a qualified technician with adequate knowledge of the items to be inspected (IACS 2016 Rec.42 Clause 3.1). Prior to commencement of surveys, a pre-meeting should be held between the Technician, an Owner’s representative and the attending Surveyor, to ascertain that all the arrangements are in place to ensure a safe and efficient conduct of the inspection (IACS 2016 Rec.42 Clause 3.1).

The extent and procedures for class-related hull surveys are described in IACS Unified Requirement (UR) Z7 “Hull Classification Surveys” and ancillary Z7.X and Z10.X families. In UR Z7 RIT have been taken into account since rev.26 (January 2018). In UR Z7 a definition of RIT is given, clearly referring to the above-mentioned Rec. 42:

“Remote Inspection Technique is a means of survey that enables examination of any part of the structure without the need for direct physical access of the surveyor (refer to Rec.42)”.

(IACS 2018 UR Z7 par. 1.2.15)

This definition of RIT covers both “overall” and “close-up” surveys, where “an Overall Survey is a survey intended to report on the overall conditions of the hull structure and determine the extent of additional

Close-Up Surveys" (IACS 2018 UR Z10.1 par.1.2.3) and "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" (IACS 2018 UR Z10.1 par.1.2.4).

It should be noted, however, that thickness measurements of the ship hull's structural members are required in areas where close-up surveys are required:

"In any kind of survey, […] thickness measurements of structures in areas where close-up surveys are required, shall be carried out simultaneously with close-up surveys".

(IACS 2018 UR Z7 par. 1.4.1)

UR Z7 Rev.26 explains how this can be done using RIT:

"[…] When RIT is used for a close-up survey, temporary means of access for the corresponding thickness measurements is to be provided unless such RIT is also able to carry out the required thickness measurements".

(IACS 2018 UR Z7 par. 1.4.2)

One of the most important criteria remarked in UR Z7 is about the level and quality of information provided when RIT are used, stating that "The RIT is to provide the information normally obtained from a close-up survey" (IACS 2018 UR Z7 par. 1.6.1).

Moreover, it is also clearly stated that the Surveyor is to be satisfied, meaning that he/she is the ultimate decision maker on the evaluation of the health status of the ship. In particular, if the RIT reveals damage or deterioration that requires attention, the Surveyor may require traditional survey to be undertaken without the use of a RIT (IACS 2018 UR Z7 par.1.6.6).

If the survey using RIT is not carried out by the Surveyor himself, it is to be conducted by a firm approved as a service supplier according to IACS UR Z17 and is to be witnessed by an attending surveyor of the Society (IACS 2018 UR Z7 par.1.6.3).

IACS UR Z17 rev.13 (January 2018) describes the certification process and requirements for "Firms engaged in survey using Remote Inspection Techniques (RIT) as an alternative means for Close-up Survey of the structure of ships and mobile offshore units" (Annex 1 Ch.16).

The supplier is responsible for the training and qualification of its operators. The supplier is also to maintain a documented training plan for personnel, including knowledge of Rule requirements for the structure of relevant ships types, recognition of structural deterioration, use of the reporting system and the like (IACS 2019 UR Z17 Annex 1 par.16.4).

Moreover, knowledge is also required of marine and/or offshore nomenclatures, the structural configuration of relevant ships types and Marine Offshore Units (MOUs), including internal structure, the remote inspection equipment and its operation etc. (IACS 2019 UR Z17 Annex 1 par.16.3).

Specific requirements for the equipment also exist. Remotely operated platform with data capture devices should be specifically capable of operation within an enclosed space; means of powering the platforms with sufficient capacity should be available to complete the required inspections, including spare batteries if applicable. Data collection devices which may include cameras should be capable of capturing in high definition both video images and still images. Illumination equipment, high definition display screen with live high-definition feeds from inspection cameras, means of communication, data recording devices, as applicable, equipment for carrying out thickness gauging and/or non-destructive testing, as relevant to the work to be performed (when this is part of the service) should be available (IACS 2019 UR Z17 Annex 1 par.16.7).

Another UR, namely UR Z3, defines the requirements for « Periodical Survey of the Outside of the Ship's Bottom and Related Items », even if compliance with UR Z3 does not absolve the Owner from compliance with the requirements of SOLAS (the IMO convention for safety of life at sea) as amended, especially when shorter intervals between examination of the ship's bottom for certain types of ship are required, or other URs are applicable.

The outside of the ship's hull is to be examined for what concerns the following items (IACS 2018 UR Z3):

> Z3.2.2 The shell plating is to be examined for excessive corrosion, or deterioration due to chafing or contact with the ground and for any undue unfairness or buckling. Special attention is to be paid to the connection between the bilge strakes and the bilge keels. Important plate unfairness or other deteriorations which do not necessitate immediate repairs are to be recorded.
>
> Z3.2.3 Sea chests and their gratings, sea connections and overboard discharge valves and cocks and their fastenings to the hull or sea chests are to be examined. Valves and cocks need not be opened up more than once in a special survey period unless considered necessary by the Surveyor.
>
> Z3.2.4 Visible parts of rudder, rudder pintles, rudder shafts and couplings and stern frame are to be examined. If considered necessary by the Surveyor, the rudder is to be lifted or the inspection plates removed for the examination of pintles. The clearance in the rudder bearings is to be ascertained and recorded. Where applicable, pressure test of the rudder may be required as deemed necessary by the surveyor.
>
> Z3.2.5 Visible parts of propeller and stern bush, are to be examined. The clearance in the stern bush and the efficiency of the oil gland, if fitted, are to be ascertained and recorded. For controllable pitch propellers, the Surveyor is to be satisfied with the fastenings and tightness of hub and blade sealing. Dismantling need not to be carried out unless considered necessary by the Surveyor.
>
> Z3.2.6 Visible parts of side thrusters are to be examined. Other propulsion systems which also have manoeuvring characteristics (such as directional propellers, vertical axis propellers, water jet units) are to be examined externally with focus on the condition of gear housing, propeller blades, bolt locking and other fastening arrangements. Sealing arrangement of propeller blades, propeller shaft and steering column shall be verified.

Usually, the outer shell is examined in dry dock conditions, but inspection may be also carried out in-water, with some caveats, following the general criterion that the in-water survey is to provide the information normally obtained from a docking survey. For example, special consideration shall be given to ascertaining rudder bearing clearances and stern bush clearances of oil stern bearings based on a review of the operating history, on board testing and stern oil sample reports.

The In-water Survey is to be carried out with the ship in sheltered water and preferably with weak tidal streams and currents. The in-water visibility and the cleanliness of the hull below the waterline is to be clear enough to permit a meaningful examination which allows the surveyor and diver from the in-water survey firm to determine the condition of the plating, appendages and the welding. The Classification Society is to be satisfied with the methods of localization of the divers or Remotely Operated Vehicle (ROV) on the plating, which should make use where necessary of permanent markings on the plating at selected points.

If the In-water Survey reveals damage or deterioration that requires early attention, the Surveyor may in any case require that the ship be dry-docked in order that a detailed survey can be undertaken and the necessary repairs carried out. Reporting requirements are also to be complied with in class-related and statutory surveys. Such requirements are precisely described in UR Z10.X family of documents. They describe the tabular format to be adopted for data for each type of ship where the thickness measurement data are taken. As an example, some tables are shown here below for oil tankers. Similar tables are described for other types of ships.

Figure 11: Examples for thickness measurement Reports

Z10.1 TM1-T (cont'd)

Report on THICKNESS MEASUREMENT of ALL DECK PLATING, ALL BOTTOM SHELL PLATING or SIDE SHELL PLATING* (* - delete as appropriate)

Sheet 4

Ship's name......................... Class Identity No. .... Report No. ....

STRAKE POSITION																	
PLATE POSITION	No. or Letter	Org. Thk. mm	Forward Reading						Aft Reading						Mean Diminution %		Maximum Allowable Diminution
			Gauged		Diminution P		Diminution S		Gauged		Diminution P		Diminution S				
			P	S	mm	%	mm	%	P	S	mm	%	mm	%	P	S	mm
12th forward																	
11th																	
10th																	
9th																	
8th																	
7th																	
6th																	
5th																	
4th																	
3rd																	
2nd																	
1st																	
Amidships																	
1st aft																	
2nd																	
3rd																	
4th																	
5th																	
6th																	
7th																	
8th																	
9th																	
10th																	
11th																	
12th																	

Operators Signature... NOTES – See Reverse

Z10.1 TM2-T (i) (cont'd)

Report on THICKNESS MEASUREMENT OF SHELL AND DECK PLATING (one, two or three transverse sections)

Sheet 5

Ship's name......................... Class Identity No. .... Report No. ....

STRENGTH DECK AND SHEERSTRAKE PLATING																											
	FIRST TRANSVERSE SECTION AT FRAME NUMBER									SECOND TRANSVERSE SECTION AT FRAME NUMBER									THIRD TRANSVERSE SECTION AT FRAME NUMBER								
STRAKE POSITION	No. or Letter	Org. Thk.	Max. Alwb. Dim.	Gauged		Diminution P		Diminution S		No. or Letter	Org. Thk.	Max. Alwb. Dim.	Gauged		Diminution P		Diminution S		No. or Letter	Org. Thk.	Max. Alwb. Dim.	Gauged		Diminution P		Diminution S	
		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%		mm	mm	P	S	mm	%	mm	%
Stringer Plate																											
1st strake inboard																											
2nd																											
3rd																											
4th																											
5th																											
6th																											
7th																											
8th																											
9th																											
10th																											
11th																											
12th																											
13th																											
14th																											
centre strake																											
sheer strake																											
TOPSIDE TOTAL																											

Operators Signature... NOTES – See Reverse

5. Consolidated list (Matrix) of end user requirements

This is an aggregated list of requirements (Table2) from all stakeholder perspective as depicted from Section 4 of this document. Owner of requirement is stated while each user need is separated in mandatory, stressing the necessity to be satisfied, and optional, or in other words a "nice to have" functionality.

Table 2: User Requirements Matrix

#	Description	Owner of requirement	Status (Optional or Mandatory)
1	Spot potential hull integrity problems at an early stage and minimize operational downtime	Ship Owner/Manager	Mandatory
2	Full coverage of critical parts of hull plating and visible parts of propulsion/steering system for inspection and cleaning	Ship Owner/Manager & Class society	Mandatory
3	Able to provide underwater service within ship port stay time limits	Ship Owner/Manager	Mandatory
4	Ensure reliable data streams and full information coverage.	Ship Owner/Manager	Mandatory
5	Potential integration with ship maintenance software (PMS) for recording due maintenance job orders	Ship Owner/Manager	Optional
6	Assess severity and assist owner's surveyor in the decision for an on spot repair or cleaning while ship is afloat	Ship Owner/Manager	Mandatory
7	BugWright2 underwater system should consider restrictions imposed by port authorities and comply with the harbour water quality regulations securing effective filtering of the removed fouling.	Ship Owner/Manager	Mandatory
8	Provide underwater measurement of hull roughness	Ship Owner/Manager & Service Provider	Optional
9	Operate at least in the same environmental conditions as those assumed for the inspection of a human surveyor in person	Service Provider	Mandatory
10	Provide visual information with level of detail, colour, contrast, brightness etc. sufficient for detecting and ranking defects in a way that is comparable to the information available to the surveyor when operating in person. Where Data collection from optical devices is considered, devices should be capable of capturing in high definition both video images and still images	Service Provider & Class society	Mandatory
11	Provide measurement data, e.g. steel plate thickness, at least with the same accuracy and for the same locations as in traditional surveys, as described in the relevant rules and guidelines	Service Provider & Class society	Mandatory

12	The time required for a complete scan of the space to be inspected should be compatible with the time constraints of a typical class survey	Service Provider & Class society	Mandatory
13	The power source should be such to allow effective performance of assigned tasks.	Service Provider & Class society	Mandatory
14	Utilize different types of cleaning methods depending on hull coating type and condition as well as on the marine fouling type and degree	Service Provider	Mandatory
15	Integration with fleet operational database of the ship management company to retrieve information (vessel particulars, historical data of sister, statistics etc.) to be correlated with data captured by BugWright2 system necessary for condition assessment procedure	Service Provider	Mandatory
16	The decision-making procedure shall evaluate and utilize appropriately defined metrics	Service Provider	Optional
17	Should facilitate external and internal examination, including close-up surveys and gauging	Class society	Mandatory
18	Provide the survey results normally obtained by the Surveyor. Results obtained should be acceptable by an attending Surveyor	Class society	Mandatory
19	The use of BUGWRIGTH2 system may be restricted or limited where there is a record or indication of abnormal deterioration or damage	Class society	Mandatory
20	Should be capable of operation within an enclosed space	Class society	Mandatory
21	For in water survey and concerning methods of localization on the plating, System should make use where necessary of permanent markings on the plating at selected points.	Class society	Mandatory
22	BugWright2 data recording and classification should comply with standardized format of reporting	Class society	Mandatory
23	Potential of fill in automatically reports with necessary input avoiding manual data entry	All	Optional

6. Key Performance Indicators (KPIs) for system validation

In the table bellows are listed Key Performance Indicators (KPIs) described in the project proposal, adjusted where needed on the basis of additional knowledge acquired since the initial writing.

Firstly, a list of KPIs is focused on high-level technical requirements and pilot and impact requirements is given in Tables 3 and 4. A corresponding list of KPIs of BugWright2 technologies is provided in Tables 5 to 10.

Table 3: High-Level Technical Requirements KPIs

#	KPI	Metric
1	Autonomous outer hull service: The main objective of the project is to make large structure inspection a mostly autonomous process.	Conduct a complete visual and acoustic inspection or a complete hull cleaning within one port stay, typically at least 8 hours.
2	Precise localisation and navigation on large low-textured structures: The ability to autonomously navigate on a low-texture surface using a combination of vision and other sensors designed for storage tanks or vessel hulls with a surface over $10000m^2$.	Areas/objects of interest can be localised on a hull with a 5cm repeatability.
3	Heterogeneous multi-robot inspection and cleaning: The objective is to enable multiple crawlers assisted by MAVs and AUVs to build a globally consistent picture of the inspected structure and to further reduce the time required to inspect or clean a given structure.	Demonstrator operating with at least 3 MAVs, 3 AUVs, and 4 crawlers on a large ship at quay. Linear performance increase with the number of robots involved in the task.
4	Cross-domain autonomous operation and inspection: Besides the heterogeneous aspect above, the objective is to enable robot operation in different domains. The aim is to avoid dry-dock time by using a team of crawlers or AUVs operating above and below the water surface.	Complete hull inspection of a ship at quay with 4 crawlers, 2 operating above water, 2 underwater. Complete a visual hull inspection with a team of 4 AUVs.
5	Advanced inspection technologies: The objective is to deploy latest advances in inspection technologies based on guided waves to provide a more exhaustive hull status coverage.	Defects bigger than 5cm from a single plate will be detected with measurements from at most 4 positions and localized with a precision better than 10cm.
6	Remote inspection through virtual-reality: The objective is to integrate VR technologies to enable remote inspection capabilities and thus support the system deployment in the field while considering situational awareness and human factors.	6.1. Remote VR interaction is demonstrated to 20 experts. 6.2 The user interface quality is evaluated with a usability rate (SUS) score above 68. 6.3 The rendering performance is above 60 frames per seconds.

Table 4: Pilot Impact KPIs

#	KPI	Metrics
1	Large-scale pilots – from its inception, BugWright2 is designed as a large scale pilot whose performances can be validated through extensive field testing on end-users' sites with the support of inspection service providers offering initial services already within the project phase.	The BugWrigh2 inspection services are offered to at least 20 vessels per year.
2	Complete value-chain validation – robot providers, inspection service providers, certification agencies, shipyards, harbours and ship owners will be involved in the specification and evaluation of the system throughout the project to ensure that integration is focused on practical problems with a clear path to market and realistic market viability.	BugWright2 technology and processes are installed on the site of at least two end-users.
3	Legal insight, human factors and norms – In addition to technologists and industrials, BugWright2 involves partners from the fields of maritime laws and workplace psychology to understand the conditions for its legal and social acceptance in the European workplace. Furthermore, the development of a strategy towards the evolutions of servicing rules will be conducted by WMU through its strong link to the International Maritime Organization.	3.1 Evaluation of distinct success factors for user acceptance, required knowledge and skills. Recommendations for HR managers. 3.2 A strategy for the use of autonomous robots to meet international and European treaty inspection requirements is proposed.
4	Dissemination and Exploitation – in addition to the experimental commercial offering, we aim at a strong dissemination strategy through publications in conferences and journals, presentations in professional fairs as well as a video coverage that explains the project in plain language.	Given the size and strength of the consortium, it should be possible to aim for 30 journal publications within the project lifetime. Through the large-scale pilot, 80 potential customers have been acquainted with the experimental service.

Table 5: Aerial Platforms (MAV) KPIs

#	KPI	Metric
1	Stable flight around the inspected structure	Position keeping accuracy better than 50cm with less than 5kts of wind.
2	Sufficient flight autonomy	Flight autonomy above 10 minutes.
3	Observation of the structure in sufficient detail	Projection of processed pixels on the surface < 2mm (subject to change depending on working distance for optimum 3D reconstruction).
4	Precise localization of the acquired data	Drone pose estimation around 20-25 cm, 3-5 degrees.
5	Safe operation	Safe/successful mission execution close to the hull with autonomous obstacle avoidance.
6	Survey in less time than a port stay	Coverage of at least 600m^2/drone within one battery charge. Coverage of a full hull (aerial part) with a sufficient number of robots (e.g. 2-3).

Table 6: Underwater Platforms (AUV) KPIs

#	KPI	Metric
1	Stable navigation around the hull	Position keeping accuracy better than 50cm with less than 0.25 m/s of current
2	Sufficient operational autonomy	Flight autonomy between one and two hours.
3	Hull observation in sufficient details	Projection of processed pixels on the surface <2mm
4	Precise localization of the acquired data	AUV pose estimation better than <20cm, 1 degree.
5	Safe operation, without tether entanglement	Autonomous obstacle avoidance around the hull and in particular for objects larger than 3cm (cables)
6	Survey in less time than a port stay	Complete coverage of one side of a 200m-hull (underwater part) with sufficient resolution in less than 4 hours with 4 AUVs.

Table 7: Crawler KPIs

#	KPI	Metric
1	Safe operation, without tether entanglement	Proper handling of angle discontinuities up to 5 degrees. Entanglement avoidance for positive obstacles of >7mm shall be avoided by the crawler and >30mm width negative obstacle shall be avoided by the crawler. Positive & negative water flow pit shall be avoided by the crawler.
2	Precise localization of the acquired data	Crawler localisation better than 10cm globally, 5cm with respect to the current plate.
3	Sufficient observation density	100 measurement points per m2, where deemed necessary by the surveyors.
4	Survey in less time than a port stay	Complete coverage of one side of a 200m-hull (aerial part) with sufficient resolution in less than 4 hours with 4 crawlers; may depends on the scanning mesh and the observation technology on board.

Table 8: Inspection technologies KPIs

#	KPI	Metric
1	Precise ultrasonic localisation on a plate	Relative localisation better than 5cm on a plate with less than 5 measurements points, at most 1s per measurement.
2	Damage detection for thickness losses	Detection of thickness loss > 0.1mm, in areas larger than 10x10cm (precision of a standard UT device). Some Influential Parameters such as metallurgical properties, plate roughness, coupling and temperature can impact the global measure exactness. Under the review of CETIM, a +/- 0.15mm global exactness with a 90% confidence may be adequate with the field parameters.

3	Visual detection of damages	Detection of visually detectable damage larger than 1x1cm (e.g. rust patch, pitting), from the air or underwater.
4	Visual detection of fouling	Detection of visual fouling thicker than 5mm over a 10x10cm patch.

Table 9: VR technologies KPIs

#	KPI	Metric
1	Demonstrating remote VR interface	Remote VR interaction is demonstrated to 20 experts.
2	Usability of user interface	The user interface quality is evaluated with a usability rate (SUS) score above 68.
3	Rendering performance	The rendering performance is above 60 frames per seconds.

Table 10: Decision support technologies KPIs

#	KPI	Metric
1	Ensure user acceptance	Evaluation of distinct success factors for user acceptance, required knowledge and skills. Recommendations for HR managers.
2	Database capacity	Database structure and capacity shall be adequate to hold data for a time period of at least 10 years to facilitate time history analysis and prediction.
3	Database performance	Transaction completeness time shall be lower than 2 standard deviations from the average baseline value.
4	Data management system security	System must be ranked in the lower severity range according to the Common Vulnerability Scoring System.
5	Predictive maintenance reliability	The success rate of the decision support system in defect detection and identification shall be higher than 80%.
6	AR performance	AR shall have at least three (3) attributes to support maintenance

7. Mission scenario definition

The main objective of BugWright2 research project is to develop an **adaptable autonomous robotic solution** for servicing ship outer hull and demonstrate its capabilities and benefits against traditional techniques to shipping industry. The core concept of BugWright2 is to combine the survey capabilities of autonomous Micro Air Vehicles, small Autonomous Underwater Vehicles and magnetic-wheeled crawlers directly operating on the hull surface. The detailed information provided by the utilized robotic systems will be integrated into a real-time visualization and decision-support user-interface taking advantage of virtual reality technologies.

The capabilities and benefits of the BugWright2 solution is planned to be demonstrated in the shipping industry by offering experimental commercial services for robotic ship outer hull inspection and cleaning to the community.

The experimental commercial services are foreseen to be offered in three stations:

- Trondheim Harbour (TRH), Norway; robotic maker (BEYE) will offer visual inspection service using current state of the art AUV and MAV as well as their evolutions.
- Arsenal do Alfeite shipyard (ADA), Portugal; BugWright2 technologies will be progressively utilized in offered services as technology demonstrator.
- Piraeus, Greece; a mock-up will be developed by a marine service provider (GLM) member of project consortium to maximize dissemination to end-users.

The experimental services are envisaged to start on the first stages of the project with remotely controlled robots in order to evaluate their operation / performance against functionalities requirements discussed in previous sections. Appropriately selected Use Cases will be defined and used in the frame of this project to achieve the aforementioned goals.

Generally, Use Cases depend mostly on:

- Ship type or ship mock up
- Ship specific space (e.g. dry/wet, cargo hall, ballast tank)
- Operational condition (e.g. sailing, berthed, dry docked)
- Inspection type (e.g. Class Survey, Condition Survey on Ship Owner request for insurance of repair specification purposes)

Table 11: Use cases examples

	Use Case 1	Use Case 2	Use Case 3	Use Case 4
Ship Type	Bulk Carrier	Bulk Carrier	Bulk Carrier	Container
Ship Space	Underwater	Underwater	Underwater	Hull
Operational Condition	Berthed	Anchorage	Berthed	Dry docked
Inspection Type	Condition Survey (Visual Inspection and Hull Coating Thickness Measurements)	Class Survey (Visual Inspection and Thickness Measurements)	Damage Inspection	Class Survey (Visual Inspection, Thickness Measurements, Coating Thickness Measurements)
Robotic System	AUV	AUV	MAV, AUV, Crawler	MAV, Crawler

A preliminary definition of Use Cases that may be evaluated in the frame of the BugWright2 project are listed in Table 3.

It must be noted that once the Use Case is defined **then** the test facilities and the test plan requirements can be derived. On the other hand, the Use Cases selected to be evaluated in the frame of the current project have to consider the capabilities / functionalities of facilities available in project consortium. In the case of the ship mockup, both technologically and financially feasible functionalities have to be considered in the definition of the Use Cases to be evaluated in this facility.

A more detailed definition of Use Cases as well as of the mission scenarios will be established in the course of the project and released, according to work package implementation plan, on M18.

8. Conclusions

BugWright2 is delivering an advanced autonomous robotic technology that will encompass different platforms in one ecosystem executing a full-fledged qualitative inspection and cleaning service in ship's outer hull aiming at minimizing lead operational time and complying with reporting and regulatory schema. In this deliverable, a first approach to identify user needs that BugWright2 technology will be called to satisfy, was made. Needs were captured internally from project partners, but extensive feedback is planned to be retrieved from a workshop that will be organized so to establish a more concrete and robust system requirements identification and use case definition.

Ship operators, service providers, shipyards and classification society represented by members of the consortium have portrayed a list of requirements directed to service coverage, time constraints, reporting specifications, legal terms, data capture and exploitation. Project's robotic components (Micro Air Vehicles, Small Autonomous Underwater Vehicles and Magnetic-wheeled Crawlers) are integrating inspection capabilities from air and while attached to the surface either above or below waterline. All these separated technologies will work together in one autonomous system that BugWright2 delivers facing holistically current challenges and complexities in navigation, positioning, power loads, data localization, acquisition time limits, safe operation and detection precision.

A first elaboration on top of already identified in project's DoA high level key Performance Indicators (KPIs) has been performed so to revise and extend metrics that should be recorded in order to satisfy user requirements. In this respect, KPIs were described and measured, covering all different features and components (inspection, visualization, decision support) as well as individual platforms of the system (MAV, UAV, Crawlers).

Capabilities and benefits of the BugWright2 ecosystem is planned to be demonstrated in three stations (Trondheim Harbour, Arsenal do Alfeite shipyard, Piraeus) following technology readiness and maturity level of the solution as evolved across the project timeline. Experiments and field tests will examine the capacity of the system to satisfy user requirements against the desired performance criteria. Initial framework of the use case scenario was designed in this deliverable for full validation of system applicability in hull remote surveillance and cleaning service as well as system's commercial exploitation. Preliminary design of demonstrators is engaging distinct ship types, vessel space, operational condition, inspection type associating the suitable robotic systems.

Concluding, we should highlight the fact that key validators, stakeholder's requirements and use cases as depicted and described in this deliverable constitutes a first stage approach and should be considered as the reference baseline of a continuous scalable and agile revision that will be applied as BugWright2 technology progresses. A more concrete use case modelling will be delivered in second version of D1.1 in M18. Ongoing registration and revision of user case requirements and key performance indicators will be interrelated with the analysis of system customization, on top of existing functionalities of each component engaged, the multi-robot inspection modelling and the use case mission scenario definition.

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