Ship Hull Inspection: A Survey★

Bosen Lin[a], Xinghui Dong[a,*]

[a]*School of Computer Science and Technology, Ocean University of China, No.238 Songling Road, Qingdao, 266100, Shangdong, China*

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ABSTRACT

To ensure the safety of ship navigation, a regular hull inspection is essential, which can identify affected structures and guide the appropriate maintenance. Traditional hull inspections severely rely on inspectors who tour the entire hull and perform close inspections, which are tedious, subjective, dangerous and expensive. The applications of computer algorithms and robots to data processing and data collection respectively have been receiving increasing attention, to facilitate hull inspections and reduce costs. In this paper, we first review the background knowledge of hull inspection. Then we categorize different inspection approaches into three classes: in-dock, underwater and health monitoring based inspections and conduct an extensive, deep survey. In addition to manual inspection approaches, we survey both the automatic data processing methods and automated platforms used to improve the efficiency and effectiveness of hull inspection. Different approaches are reviewed based on the type of Non-destructive Testing (NDT) techniques, data processing methods and automated platforms. Discussions are further made regarding the existing work. To our knowledge, this study is the first survey performed in such an extensive manner, which can help both the research and industry colleagues build up an overall understanding of hull inspection and identify potential directions for future development.

1. Introduction

Seaborne transport can be regarded as a crucial part of the global supply chain due to its ability to transport large volumes of goods over a long distance and the positive trade-off between speed and cost (Michail, 2020) (Bonnin-Pascual and Ortiz, 2019). According to the Review of Maritime Transport 2022 published by the United Nations Conference on Trade and Development (UNCTAD) (Sirimanne, Hoffman, Juan, Asariotis, Assaf et al., 2022), over 80% of world trade by value has been carried out by ship. This statistic shows the indispensable importance of shipping to world trade.

However, the growth of the shipping industry increases the probability of maritime accidents, which pose a threat to human lives, economic property and marine pollution. One of the major causes of serious maritime accidents is structural failure (Dong, Garbatov and Guedes, 2022) (see Figure 1 for two examples), typically resulting from the effects of time-dependent (gradual) deterioration mechanisms, such as structural overloading, errors in ship design, the utilization of low-quality materials, inferior alignments or welding, coating breakdown and vibrations induced by hydrodynamic loads or the machinery.

To avoid (or at least reduce) the occurrences of these factors, ships are built in accordance with stringent standards of safety and pollution prevention. In addition, ships have to undergo detailed inspections during both the building and service periods (Nair, Sivaprasad and Nandakumar, 2017).

Figure 1: Two disastrous maritime accidents caused by structural failure: (a) the MOL Comfort accident occurred in 2013, Yemen (Jo, 2020) and (b) the Prestige sinking occurred in 2002, Galicia, Spain (Muc et al., 2018).

In this case, timely ship maintenance and repairs can be arranged based on the identified defects and faults. As a result, hull structures can be kept in a satisfactory condition and the risk of the occurrence of structural failure is reduced (Davies, Truong-Ba, Cholette and Will, 2021).

At present, hull inspection is performed as part of class surveys, conducted by classification societies in accordance with a set of strict rules. As stated in the rules published by the International Association of Classification Societies (IACS), ship hull inspection should be performed in both the building and service periods. The in-building hull inspection, namely, hull inspection for new construction (IACS, 2020a), is normally used to inspect the raw materials, welding and assembly employed in the ship-building stage and to certify that a ship has been built according to the rules and regulations. On the other hand, the in-service hull inspection is of prime importance in evaluating the structural condition of the hull. These inspection operations are carried out on a regular basis, including Special Surveys conducted every five years and Intermediate Surveys performed in between Special Surveys (IACS, 2020b). The ship owners or operators may also perform Condition Surveys which are less

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*Corresponding author
linbosen@stu.ouc.edu.cn (B. Lin); xinghui.dong@ouc.edu.cn (X. Dong)
ORCID(s): 0000-0003-1047-427X (X. Dong)
1

Abbreviations

μT	Microwave Testing	LBL	Long Baseline
ACFM	Alternating Current Field Measurement	MARC	Magnetic Autonomous Robotic Crawler
ACUT	Air-Coupled Ultrasonic Testing	MPI	Magnetic Particle Inspection
AE	Acoustic Emission	NDT	Non-destructive Testing
AIT	Automatic Inspection Technologies	PAUT	Phased Array Ultrasonic Testing
AUV	Automated Underwater Vehicle	PEUT	Pulse-Echo Ultrasonic Testing
CNN	Convolutional Neural Network	PT	Penetrant Testing
CSRT	Channel and Spatial Reliability Tracker	RIT	Remote Inspection Technologies
CT	Computed Tomography	ROV	Remotely Operate Vehicle
DIDSON	Dual-Frequency Identification Sonar	RT	Radiographic Testing
DVL	Doppler Velocity Log	RVI	Remote Visual Inspection
DWT	Discrete Wavelet Transform	SHM	Structural Health Monitoring
ECT	Eddy current testing	SLAM	Simultaneous Localization And Mapping
ET	Electromagnetic Testing	SVM	Support Vector Machine
FPSO	Floating Production Storage Offloading	THz	Terahertz
GFRP	Glass Fiber Reinforced Polymer	TOFD	Time-of-Flight Diffraction
GLCM	Gray-Level Co-occurrence Matrix	UAV	Unmanned Aerial Vehicle
GWUT	Guided Wave Ultrasonic Testing	UT	Ultrasonic Testing
IACS	International Association of Classification Societies	UTM	Ultrasonic Thickness Measurement
IoT	Internet of Things	UWILD	Underwater Inspection in Lieu of Dry-Docking
IRT	Infrared Thermography	VT	Visual Testing

formal than both Special and Intermediate Surveys (Bonnin-Pascual and Ortiz, 2019). Moreover, different methods of hull inspection and the areas of concern may be required when the type of vessels varies (IACS, 2018) (IACS, 2007) (IACS, 2017b) (IACS, 2019a).

These differences resulted from the discrepancies in hull construction, vessel use and manufacturing materials. Although the independent classification societies that operate under the IACS typically adhere to a common set of standards and specifications in order to maintain consistency in hull inspections, independent classification societies may also follow distinct regulations in accordance with their respective national regulatory mandates and operating conditions. In addition, these classification societies may issue their own guidelines or interpretations, which can support the implementation of innovative ship surveying and shipbuilding techniques.

Inspection operations can produce valuable information regarding the defects and structural condition of the hull. This information benefits the damage evaluation. This again further facilitates ship maintenance and repairs. In this context, the accurate measurement of both the location and extent of defects are essential. To achieve these goals, various Non-destructive Testing (NDT) techniques, for example, visual inspection, ultrasonic testing and electromagnetic testing play important roles.

Traditionally, hull inspection is carried out by human inspectors in a dockyard. To fulfill this task, inspectors have to reach and inspect each part of the hull. These parts include some dangerous and potentially lethal areas, which either contain flammable and toxic gases or have significant heights. Therefore, hull inspection requires a set of preventive operations, including cleaning, lighting, ventilating, temporary set-up of cherry pickers or ladders, in order to ensure that the inspectors can access those areas and reach inaccessible zones safely (Poggi, Gaggero, Gaiotti, Ravina and Rizzo, 2020). However, these operations increase the cost of a single hull inspection. Besides, decreasing the time required for these operations can further reduce the time cost of hull inspections. As a result, shipowners will benefit from the extended ship availability. In this situation, the development of ship inspection aims to decrease the cost by accelerating the inspection and improving inspection accuracy by applying automated NDT approaches.

With recent developments in digitalization and robotic technologies, additional alternative methods, such as remote inspection technologies and automatic inspection technologies, are being evaluated and are gaining acceptance by the Class and Statutory bodies (Wen, Pray, McSweeney and Gu, 2019). Compared with the manual inspection performed by humans, remote inspection technologies can be conducted using mobile digital devices in conjunction with the collaborative software platform, without the physical attendance of an inspector on board the vessel. Automatic inspection technologies go a step further and use robots to inspect the hull without relying on human intervention. To be specific, this job is fulfilled using some onboard NDT devices to collect data and by applying automatic data processing algorithms. Using these technologies, it allows the inspector to evaluate the structural condition at a safe and stationary location, reduces operational intrusiveness and minimizes downtime for ship owners whilst also providing flexibility during survey activities (Wen et al., 2019). However, the implementation of these technologies raises some new challenges.

We divide these challenges into three types: (1) *Collection*: It is a challenge for robots to collect the comprehensive data without missing a part of the hull structure; (2) *Identification*: It is struggling to promptly identify defects from a large quantity of data collected, without missing fatal defects. It is also faced with time pressure and generally requires real-time detection in edge systems with limited computational power; and (3) *Assessment*: It is challenging to conduct structural condition assessment using the defect information for decision-making. The possible solutions to those challenges include applying automated platforms and data processing techniques to data acquisition and processing and fusing the data acquired using multiple sensors for comprehensive assessment of hull condition. As a result, critical areas with defects can be identified for further inspection and assessment by inspectors.

Although many surveys have been performed in the field of hull inspection (Bonnin-Pascual and Ortiz, 2019) (Caldwell, 2017) (Poggi et al., 2020), an extensive and deep survey, which distinguishes between different NDT techniques, automatic data processing methods and automated platforms, is demanded, in order to help readers build up a comprehensive understanding of this field. To this end, we first review the background knowledge of hull inspection, which provides readers with a wide knowledge base. Then, we investigate the related techniques to the in-dock, underwater and health monitoring-based hull inspections, including manual inspection techniques and automatic approaches. In particular, the techniques are classified and reviewed in terms of different NDT techniques, automatic data processing methods and automated platforms.

To the authors' knowledge, this work is the first attempt to conduct such an extensive and deep survey in the field of hull inspection, which is potentially helpful for colleagues in both academia and industry to understand this field and identify potential directions for further research. It is worth noting that we focus on surveying the hull inspection techniques used for in-service ships rather than in-building ships, and do not pay attention to the management, planning and scheduling methods associated with hull inspections.

The rest of the paper is organized as follows. In Section 2, the background knowledge, which comprises the types of hull defects, the techniques and automatic robots used for hull inspection, is first presented. Then, an extensive, deep survey is conducted in the three following sections in terms of three different classes of inspection techniques: in-dock, underwater and health monitoring-based methods respectively. Discussion is made with regard to the studies reviewed here in Section 6. Finally, our conclusion is drawn in Section 7.

2. Background Knowledge of Ship Hull Inspection

In this section, we will briefly review the background knowledge involved in hull inspection, including different hull defects, NDT techniques and automated robots.

2.1. Ship Hull Defects

Different types of defects normally occur on the surface of ship hulls, for example, corrosion, cracks, coating breakdown and biofouling. In this subsection, we will introduce four types of ship hull defects and the circumstances that result in these defects.

2.1.1. Corrosion

In essence, corrosion can be treated as a chemical process, which describes the physical and chemical changes of the body of materials, resulting from the interaction with the surrounding environment (Bru Roncallo, 2017). Corrosion inevitably accompanies the deterioration of a ship. This process leads to a reduction in the thickness of the affected areas, until hull perforations are created. It also reduces the bending resistance of the hull. As a result, the ship may ultimately be subject to a loss of its designed structural functionality. Different factors can affect the occurrence and evolution of corrosion, e.g., biofouling, dissolved oxygen content, pH, salinity, sulphide pollution, water temperature and water velocity. Five different types of ship hull corrosion are introduced in detail as follows.

• General (uniform) corrosion, manifested as the non-protective friable rust usually occurs on the uncoated surface uniformly. Due to general corrosion, a uniform layer of corrosive material is usually generated on the metal surface, which ultimately leads to a reduction in the overall thickness. This thinning process compromises the strength and durability of the hull structure. As a result, structural damage under stressful conditions may occur. Given an unprotected ballast tank, the reduction in the bulkhead thickness caused by general corrosion is normally by 0.2 - 0.4 mm per year (Caridis, 2001). Figure 2(a) displays an example image of general corrosion.

• Pitting (local) corrosion, which is a localized corrosive phenomenon, generates relatively small but deep pits. Hull penetration may occur at the isolated locations resulting from these pits. Pitting corrosion is normally initiated because of the local breakdown of coating. The notch effect of corrosion pits can further lead to stress corrosion cracking, which causes cracks or structural failure when the hull is subjected to a certain level of stress. Figure 2(b) presents an example image of pitting corrosion.

• Weld metal corrosion is usually caused by the corrosion of weld deposits. These deposits are produced by the electrochemical action on the base metal during the welding operation. In contrast to the irregularities and insufficient surface control associated with manual welding, mechanical welding methods normally achieve superior quality, which alleviates the risk of weld metal corrosion. Figure 2(c) shows an example image of weld metal corrosion.

• Grooving corrosion is a special type of pitting corrosion that is characterized by the linear-shaped corrosion caused by a set of connected pits. This type of corrosion often occurs at the intersection of different structures where an incline causes water to collect and flow (Jakubowski, 2013). An image of grooving corrosion is displayed in Figure 2(d).

• Corrosion fatigue is a synergistic effect of corrosion and fatigue. This type of fatigue is caused by the simultaneous actions of corrosive environment and cyclic stress loading. Cracks resulting from corrosion fatigue may rapidly expand under cyclic stress.

For the corrosion that occurs on the hull surface, the most commonly used technique is visual inspection, including both traditional visual testing and remote visual inspection methods. Using these methods, the size and distribution of the surface corrosion can be directly observed and recorded. However, visual inspection has its limitations, which may not accurately determine the extent of corrosion. Considering that corrosion can have a significant impact on the hull's structural thickness, ultrasonic thickness measurement is often applied. In contrast to visual inspection, this acoustic testing method provides more accurate information on the extent of corrosion. Electromagnetic and imaging-based testing approaches, such as eddy current testing and X-ray testing, can also be used to determine the size and location of corrosion, particularly, in the case of weld metal corrosion. These approaches are able to provide a more comprehensive analysis of the impact of corrosion on the hull structure.

2.1.2. Cracks

Steel ship hulls tend to develop cracks due to their completely welded construction, corrosion, fatigue, loading conditions and material imperfections. A large number of cracks may be found during a routine inspection of the ship hull. Structural failures may be caused by these cracks (Blagojević, Domazet and Žiha, 2002). Since cracks lessen the local strength of the hull, they have a harmful effect on the safety of ships. This effect compromises the structural reliability of the hull by increasing the global stress. In the case that a sudden impact force is pushed on a ship, which normally results from an allision, collision or grounding accident, cracks may rapidly propagate, which could possibly cause a sudden fracture and eventually lead to a structural failure (Nair et al., 2017). An example image of ship hull cracks is shown in Figure 2(e). We will introduce five different types of fatigue cracks below.

• Fatigue cracks typically originate at locations where stress concentrations occur or as a result of repeated stress factors, including cyclic loading and vibrations that took place during the operational cycle of a vessel. These cracks are normally small in the initial stages. However, they have the potential to gradually propagate over time.

• Welding cracks are caused by improper welds or the presence of weld impurities, such as slag, porosities and contaminants.

• Impact cracks are the dents and deformations that occur in the ship structure because of dropped objects or violent contact such as slamming and pounding.

• Cracks resulting from fabrication are produced due to the presence of notches, geometrical misalignment and structural discontinuities. These abnormalities are usually associated with assembly and welding issues during the manufacturing process.

• Cracks resulting from the material are generated when a defective or non-homogeneous material is used.

Regarding cracks appearing on the hull surface, visual inspection is the most widely used technique. Penetrant testing and magnetic particle inspection are also employed, particularly for detecting cracks on welds. To examine the cracks which occur on the fabrication and material of the hull structure, the acoustic-based testing and electromagnetic testing methods are more effective in determining the size and location of these. On the other hand, the electromagnetic testing approach has the advantage of detecting those cracks without removing the coatings or attachments on the hull surface. Given the cracks resulting from welding, both the acoustic-based and imaging-based testing methods enable detection of internal discontinuities, due to the intricate structure of welds.

2.1.3. Deformations

The deformation of ship hulls can be categorized as local deformation which occurs on the hull surface, panel or stiffener, and global deformation which occurs in the beam, frame, girder or floor (IACS, 2007). Deformation is often caused by contact damage, such as bottom slamming and wave impact forces. There are two types of ship deformations, i.e., permanent (or plastic) buckling and elastic buckling. Overloading and excessive corrosion are the main causes of permanent buckling, especially when there is a reduction in the structural thickness of the hull. Elastic buckling occurs more subtly, but can be detected based on the coating damage, stress lines or shedding of scales (IACS, 2007). An example image of ship hull deformations is displayed in Figure 2(f).

Visual inspection can be considered a reliable method for detecting deformation on the hull surface. To fully understand the impact of deformation on the internal structure, additional inspection approaches, such as ultrasonic testing and electromagnetic testing, may be required. These approaches normally provide more comprehensive insights into the extent of damages caused by deformation.

2.1.4. Coating Breakdown

To mitigate the risks which result from corrosion, hull surfaces are typically coated with a layer of protective paint. However, the coating will gradually degenerate due to the influence of different mechanisms. The initiation of corrosion can be eventually brought about due to the failure of the coating, which is the principal reason for structural risks for the ship (Davies et al., 2021). Therefore, a maintenance strategy is required in order to rapidly find coating defects and perform a repair operation before serious corrosion and structural damages are produced. Figure 2(g) presents an example image of the hull coating breakdown.

Most of the coating breakdown can be detected using visual inspection. Ultrasonic thickness measurement can also be used as a supplementary method in evaluating the thickness of coating on the hull structure. A more comprehensive understanding of the condition of the coating can be obtained by combining both methods.

2.1.5. Biofouling

During the lifetime of a ship, microorganisms, plants, algae and shellfish will gradually gather on the surface of its hull. This process is referred to as "bio-fouling". These organisms can impair the operation of the ship and decrease the fuel efficiency. An example image of the ship hull biofouling is shown in Figure 2(h). In terms of the types of organisms that cause biofouling (Guo, Chin, Clare and Ma, 2016), they can be divided into micro-fouling and macro-fouling. Micro-fouling is caused by some microorganisms, for example, bacteria and diatoms, which produce a slime layer on the hull. Macro-fouling is produced by larger organisms, namely, macro-organisms, which are visible to human eyes, such as barnacles, tubeworms and fronds of algae.

Since biofouling normally occurs on the surface of ship hulls, it can be detected using visual inspection in both the in-dock and underwater environments. The use of a high-resolution imaging sonar is also an effective method for detecting the biofouling below the water surface.

2.1.6. Other Defects on Composite Hulls

Composite ship hulls are constructed from different materials, in order to achieve both the lighter weight and the greater strength. Unlike traditional metal materials, composite materials have different response characteristics when they are exposed to external stimuli. Laminated composites, such as Carbon Fiber Reinforced Polymer and Glass Fiber Reinforced Polymer (GFRP), hardly alter the surface appearance and dimensions during the aging process, while they may still develop internal defects. Composite hull defects, which require inspection during the service period, include debonding, delamination and structural failure (Greene, 2014).

• A void or bubble refers to the air entrapped within or between the plies of the composite material. A single or isolated large air bubble is referred to as a void. Such a defect is produced due to poor volatile resin curing or air control during the manufacturing process.

• Debonding refers to the de-cohesion between two different materials, particularly when the skin of the composite sandwich structure separates from the core. This defect may occur as a result of poor material adhesion, in-service loading and impact damage.

• Delamination refers to the separation of materials at the interface between the layers in the laminate, which breaks the laminate and reduces the effective stiffness and the ultimate strength of structural assemblies (Greene, 2014). Delamination may develop from debonding or occur due to matrix cracks and stress concentrations.

• Structural failure occurs at different parts of the composite material. Crushing and shear failure may occur in the core material. The former is normally caused by the local impact or excessive through-thickness loading, while the latter may result from the shear load. In fiber structures, a fiber failure occurs because of external forces.

It was observed that ultrasonic and imaging-based techniques had been widely applied to the inspection of composite hulls (Verma and Goh, 2019). In practice, both conventional (Lee, Oh and Woo, 2021b) and advanced (Quattrocchi, Freni and Montanini, 2020) ultrasonic testing methods were employed for inspection of composite hulls. When hulls built from the fiber-reinforced polymer materials were inspected using ultrasonic testing, which are categorized as high-attenuation materials for ultrasonic waves, however, significant errors were usually encountered (Battley, Skeates, Simpkin and Holmqvist, 2002). Imaging-based methods, such as infrared thermography (Suratkar, Sajjadi and Mitra, 2013), Terahertz testing (Ibrahim, Headland, Withayachumnankul and Wang, 2021), radiography testing (Ibrahim, 2016) and laser shearography testing (Tao, Anisimov, Elenbaas and Groves, 2022), were also employed for inspection and assessment of the subsurface of composite hulls.

On the other hand, the electrically conductive composite material, e.g., carbon-fiber, can also be inspected using electromagnetic-based techniques, such as eddy-current testing (Łukaszuk and Chady, 2023). These techniques can also be used to detect the presence of moisture in composite hulls (Ibrahim, 2016). Due to the diverse compositions and varied properties of composite materials, it should be noted that an individual technique may be not competent at identifying all defects which occur on the composite hull (Battley et al., 2002). In this situation, the joint use of multiple NDT techniques should be given more attention.

2.2. NDT Techniques Used for Ship Hull Inspection

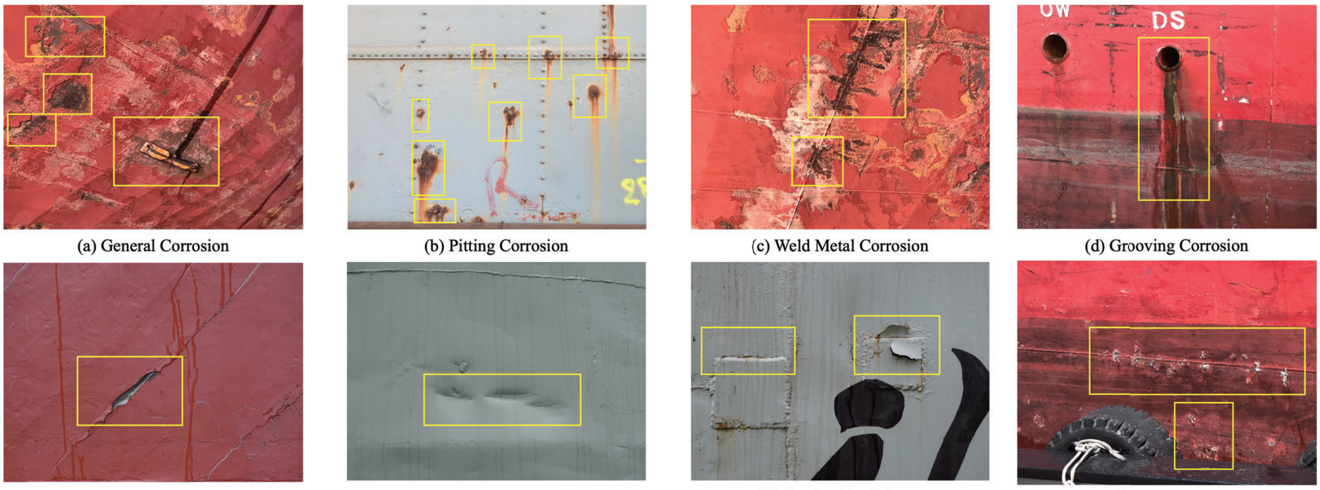
In this subsection, we will review four sets of NDT techniques used for ship hull inspection, including visual inspection, acoustic-based testing, electromagnetic testing and imaging-based testing, respectively. The comparison of these techniques is shown in Table 1.

2.2.1. Visual Inspection

Traditionally, the most straightforward inspection operation, namely, visual inspection, can be conducted by observing the surface of a ship hull directly, or using optical instruments. Besides, the surface may have been processed using a penetrant before testing is performed in order to enhance the inspection accuracy.

Visual Testing

Typically, Visual Testing (VT) is performed by skilled inspectors in order to detect discontinuities on the hull surface. Inspectors survey the details of the hull structure at a close distance preferably of less than 300mm (Zawawi, Liew, Alaloul, Shawn, Imran and Toloue, 2019). Thus, VT is also known as close-up surveys (IACS, 2020b). The defects which have been detected can be recorded manually, or stored in the form of photographs or videos. Considering its cost-effectiveness and ease of application, VT is always the first step of an inspection before other NDT methods are utilized (Zawawi et al., 2019). However, this technique still has some limitations which result from the level of experience and knowledge of inspectors, the accessibility problem due to the hull coating and biofouling, lighting levels and viewing distance.



(a) General Corrosion (b) Pitting Corrosion (c) Weld Metal Corrosion (d) Grooving Corrosion
(e) Cracks (f) Deformation (g) Coating Breakdown (h) Biofouling

Figure 2: Eight types of hull defects which occur on the surface of the ship hull, including (a) general corrosion, (b) pitting corrosion, (c) weld metal corrosion, (d) grooving corrosion, (e) cracks, (f) deformation, (g) coating breakdown and (h) bio-fouling. Note that images (a-d) and (h) were published in the MaVeCoDD data set (Chliveros et al., 2021).

Remote Visual Inspection

Basic visual testing normally requires an observation distance within hand reach. This distance is often inapplicable inside the hull because it is difficult for observers to access the tight spaces. Alternatively, Remote Visual Inspection (RVI) allows an inspector to visually inspect an area, that does not have direct visual access or is dangerous to enter, using a viewing device, e.g., a camera, video borescope, robots and autonomous systems (Poggi et al., 2020). The visual data can be recorded and online or offline inspected in order to identify potential abnormal areas. To improve detection accuracy, additional imaging techniques and automatic data processing methods can be further applied to the visual data before inspection is performed. If RVI reveals the damage or deterioration that requires attention, a detailed close-up inspection needs to be undertaken (IACS, 2016).

Penetrant Testing

Penetrant Testing (PT), also referred to as liquid penetrant testing or dye penetrant testing, can be used for detecting the surface-breaking defects produced during the welding, casting and forging process (Youshaw and Criscuolo, 1974). Due to its low-cost advantage, PT has been widely used to inspect the steel welds of the ship hull (IACS, 2017). To be specific, the penetrant is first applied to the surface of the material. Then, the surplus penetrant is eliminated from the surface by washing or other procedures and the developer is applied to it. Finally, the inspector analyzes the position and size of defects by observing the characteristics of the penetrant bleed-out on the surface.

2.2.2. Acoustic-Based Testing

As a representative technique of acoustic-based testing, Ultrasonic Testing (UT) is one of the most favored NDT methods utilized for the inspection of ship hulls. An ultrasonic device normally comprises two parts: a couplet that emits ultrasonic waves and a pulser/receiver that receives the reflected waves after they have been propagated into a structure. The propagation characteristics of the ultrasound can be used to analyze the thickness of the structure or to detect damage in the structure.

Ultrasonic Thickness Measurement

Ultrasonic Thickness Measurement (UTM) performs non-destructive measurement of the local thickness of a structure. This technique is designed on top of the difference between the arrival times of the direct and reflected waves, namely passage period (Ivošević and Bauk, 2018). Typically, waves are emitted by an ultrasonic sensor placed at the outside of the hull surface and the same sensor is used to record the waves reflected on the boundary of the hull.

However, UTM has to be performed with the ultrasonic sensors which directly contact the structure. The hull surface needs to be treated to remove coatings, corrosion and biofouling. Hence, it encounters the challenge of a large quantity of locations to be inspected. In practice, the final area and location required for thickness measurements can be decided given that a comprehensive survey of typical positions has been completed (IACS, 2017a). The locations chosen for measurement should be representative of the average level of the hull structure.

Pulse-Echo Ultrasonic Testing

Pulse-Echo Ultrasonic Testing (PEUT) can be used to analyze the internal defects of a structure. The pulse-echo UT technique employs a one-sender-one-receiver system, which generates and receives ultrasonic waves. Using the maximal amplitude and velocity of ultrasonic echoes reflected by defects, the size, location and nature of defects can be analyzed (Gholizadeh, 2016). The inspections of hull

Table 1
Comparison of the NDT techniques used for ship hull inspection.

Category	Technique	Defect Location	Structure Type	Usage frequency & Industry Representation	Advantages	Disadvantages
Visual Inspection	VT	Surface	Any kind	Most-popular	Cost-effectiveness; Ease of application;	Easily influenced by surveyors; Accessibility problem due to external environment;
	RVI	Surface	Any kind	Alternatives to VT	Avoiding accessibility problem; Automated collection and processing of data	Requirement of equipment i.e. UAV, climbing robot;
	PT	Surface	Any kind	Commonly used with hull welds	High sensitivity for small defects; High economy; Easy to use	Requirement surface treatment; Time consuming;
Acoustic-Based Testing	UTM	Overall	Metal	Most-popular	High-precision thickness measurement	High surface preparation requirements; Measurement Quantity Challenge;
	PEUT	Internal	Metal, composite material	Popular	High-resolution inspection of small internal defects	High surface preparation requirements; Not applicable to complex structures;
	PAUT	Internal	Metal, composite material	First choice for complex structures and deep defects	High-resolution inspection for defects in complex structures; Controllable ultrasonic elements for large inspection area;	High inspection costs; Complex data analysis
	GWUT	Internal	Metal	Special solutions to long-range structures	Suitable for inspecting large hull structures; Efficiently covering a large areal; Reducing accessibility problem;	Low inspection resolution; Not suitable for complex structures; High dependence on surveyors;
	TOFD	Internal	Metal	Special solutions to high-accuracy inspection	High-resolution inspection for small defects in complex structures and welding; Accurate defect size assessment;	High dependence on surveyors; Complex data analysis;
	ACUT	Internal	Metal, composite material	Enhanced application potential	Non-Contact inspection; Avoiding acoustic coupling medium contamination;	Low depth of defect inspection; Complexity of equipment;
	Sonar	Surface	Any kind	Popular usage for underwater inspection	High resolution underwater inspection;	Dependent on water quality conditions; Complexity of equipment;
Electromagnetic Testing	MPI	Surface	Metal	Limited application for metal part integrity	Intuitive visibility; Rapid inspection;	Surface treatment requirements; Surface inspection of ferromagnetic material;
	ECT	Sub-surface	Metal	Application for metal part integrity	High-resolution inspection for small defects	Surface treatment requirements; Limited defect detection depth;
	ACFM	Sub-surface	Metal	Limited application for high conductive material	High sensitivity for small defects;	High requirements for material conductivity; Limited defect detection depth;
Imaging-Based Testing	IRT	Sub-surface	Composite material	Commonly used for composite materials	Rapid inspection; High visibility;	Limited detection depth; Vulnerable to external environment; Unable to determine the nature of the defect;
	μT	Sub-surface	Any kind	Limited application	High-resolution inspection for small defects; Suitable for various materials	Complexity of equipment; Vulnerable to external environment; Limited detection depth;
	THz	Sub-surface	Any kind	Under-representative	High-resolution inspection for small defects; Suitable for various materials	Complex and expensive equipment; Vulnerable to external environment; Limited detection depth;
	RT	Internal	Any kind	Popular	High-resolution inspection for small defects; Intuitive visibility;	Complex and expensive equipment; Vulnerable to external environment; Radiation risk;
	Shearography	Surface	Any kind	Enhanced application potential	Rapid inspection; Complete surface inspection;	Complex and expensive equipment; Vulnerable to external environment;

welds or constituent materials and the thickness measurement are two common scenarios of the PEUT (Mabuza and Shavhani, 2018). The principle of the PEUT of ship hull cracks is demonstrated in Figure 3(a).

Phased Array Ultrasonic Testing

In the case of complex structures, the use of PEUT can be challenging because it necessitates precise positioning and angling of the transducer to acquire accurate data. In contrast, Phased Array Ultrasonic Testing (PAUT) utilizes a set of arrays of ultrasonic elements to focus and scan the area of interest by controlling each ultrasonic element in the array, without moving the probe. The control of the elements' concentration is able to bend, deflect and focus the energy of the wavefront and produce the cross-sectional images of defects (Jung, Park, Bae and Shin, 2018). Figure 3(b) illustrates the principle of applying the PAUT to ship hull cracks.

Guided Wave Ultrasonic Testing

Given the PEUT technique, an ultrasonic probe must physically scan throughout the area of interest in order to test or interrogate a large volume of structure. To realize the application of UT methods to long plate-like structures for the detection and localization of defects, Guided Wave Ultrasonic Testing (GWUT) was developed. Using a guided

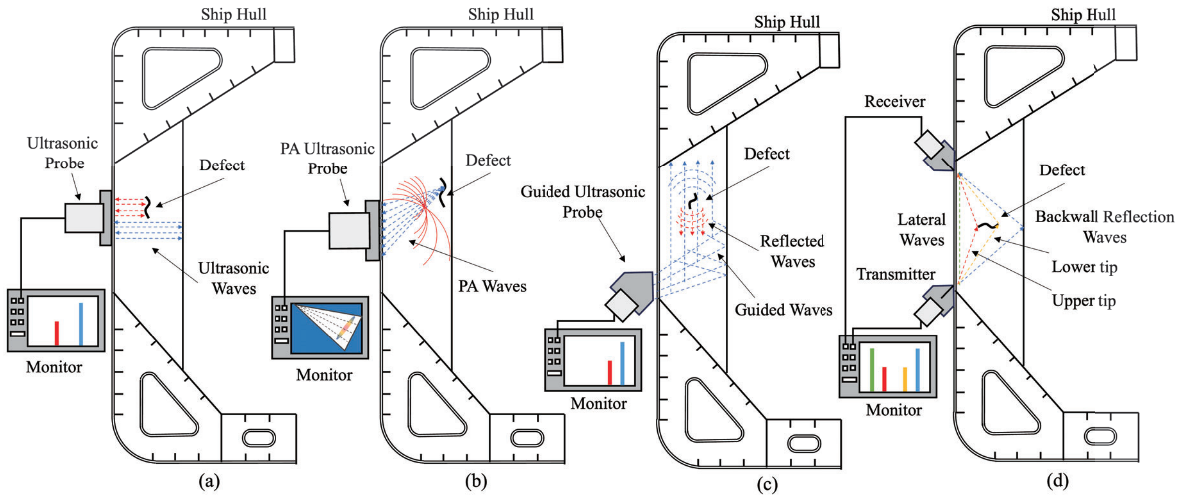


Figure 3: The principles of applying three different ultrasonic testing techniques to a ship hull structure, including (a) Pulse-echo Ultrasonic Testing, (b) Phased Array Ultrasonic Testing and (c) Guided Wave Ultrasonic Testing. (d) Time-of-flight diffraction Ultrasonic Testing

ultrasound wave array, such as Lamb waves, defects at the remote location can be detected using this technique because the transmission of a sound wave is fulfilled through the thin-wall structure (Wilcox, Lowe and Cawley, 2005). Since guided waves are able to confine themselves inside the constant cross-section thin-wall structures, they can propagate over significant distances with minimal attenuation and loss of energy (Abbas and Shafiee, 2018). It should be noted that, however, the GWUT may not be applicable to curved structures or structures with varying geometries. The principle of applying the GWUT to ship hull cracks is shown in Figure 3(c).

Time-of-flight diffraction Ultrasonic Testing

Time-of-flight diffraction (TOFD) ultrasonic testing makes use of the time of flight of an ultrasonic pulse rather than the amplitude of the reflected signal, to determine the position and size of defects (Mondal, Sattar and Bridge, 2002). TOFD testing is performed using a pair of ultrasonic probes. The transmitter probe emits an ultrasonic pulse that is picked up by the receiver probe. In undamaged structures, only two waves are received: one wave travels along the surface and the other wave reflects off the back wall. If a crack occurs, ultrasonic waves are diffracted from the crack tip. The size of the crack can be calculated using the time of flight of the diffracted waves. The principle of applying the TOFD to ship hull cracks is shown in Figure 3(d).

Air-Coupled Ultrasonic Testing

To ensure the ultrasonic wave can be transmitted with sufficient energy through the testing sample, a liquid couplant (e.g., water) or some type of gel or oil is necessary for traditional contact mode ultrasonic testing (Chimenti, 2014). This operation is time-consuming and inconvenient, which limits the online implementation of contact ultrasonic testing. The development of non-contact Air-Coupled Ultrasonic Testing (ACUT) makes ultrasonic methods more feasible in health monitoring and NDT. This testing technique uses air as the coupling medium to eliminate the inherent defects of contact ultrasonic inspection and provides efficient inspection resolutions. As a result, ACUT is more suitable for inspection of large-scale hulls which are made of metal or composite materials.

Imaging Sonar Testing

Imaging sonars are able to create an image of an underwater object based on different acoustic techniques. They have been widely used in the tasks of subsea port security (Christ and SRL, 2013), marine fish identification (Jones, Griffin and Unsworth, 2021) and real-time underwater navigation (Johannsson, Kaess, Englot, Hover and Leonard, 2010). High-frequency imaging sonars, which can capture high-resolution images of small targets in the nominal range under low and even zero visibility conditions, have been miniaturized in order to equip on underwater robotics. Some widely-used imaging sonars, including Dual-Frequency Identification Sonar (DIDSON) (Belcher, Hanot and Burch, 2002), Teledyne BlueView Sonar (Guerneve and Petillot, 2015) and adaptive resolution imaging sonar (Shahrestani, Bi, Lyubchich and Boswell, 2017), can provide fine control over the sampling range. Therefore, they are particularly suitable for the detailed inspection of the areas of interest of the hull. Imaging sonars are also used for the identification of foreign objects on the hull (Teixeira, Kaess, Hover and Leonard, 2016).

2.2.3. *Electromagnetic Testing*

Electromagnetic Testing (ET) is normally fulfilled based on inducing electric currents or magnetic fields inside the

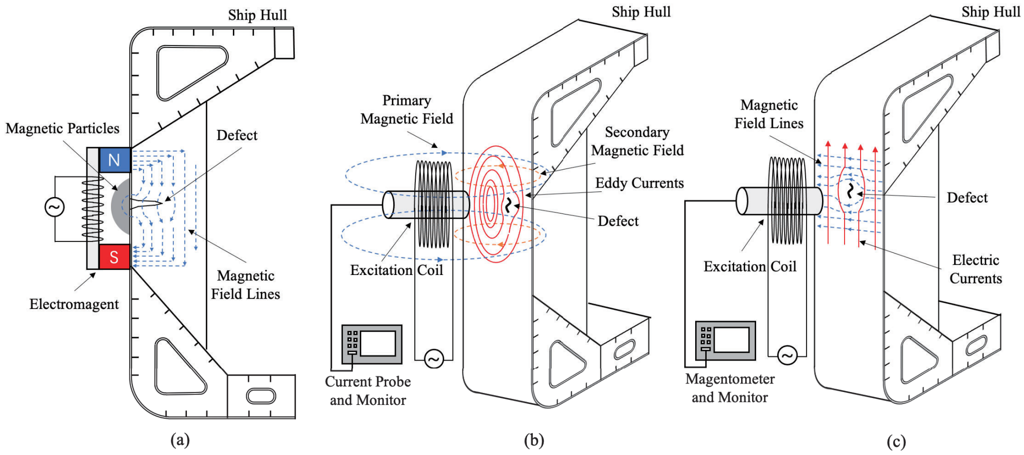


Figure 4: The principles of applying three different types of electromagnetic testing techniques to a ship hull structure, including (a) Magnetic Particle Inspection, (b) Eddy Current Testing and (c) Alternating Current Field Measurement.

ship hull structure and observing the electromagnetic response. The defect inside the structure may generate a measurable response that can be recorded and analyzed. It is noteworthy that military ships often have demagnetization requirements and are therefore not suitable for performing electromagnetic testing.

Magnetic Particle Inspection

Magnetic Particle Inspection (MPI) can be employed for detecting surface and shallow subsurface discontinuities in ferromagnetic materials (Youshaw and Criscuolo, 1974). This technique first puts a magnetic field into the inspection part. If there are cracks in the structure, the discontinuity in the material will cause the magnetic flux to leak. Then, ferrous particles are applied to the outside of the structure and are attracted to the areas of magnetic flux leakage in order to indicate the position and size of defects. The principle of applying MPI to a ship hull surface crack is shown in Figure 4(a).

Basically, two different magnetization methods (Lovejoy, 1993), i.e., direct magnetization and indirect magnetization, can be used. Regarding direct magnetization, a magnetic field is formed in the material when the electric current is passed through the ferromagnetic material. In the case that the indirect magnetization method is used, a magnetic field is built using an outside source.

MPI can even be carried out in an underwater environment. Assuming that marine growth has been cleaned off the hull surface, magnetic particles held in a squeezable container in the form of slurry can be used to complete the inspection (Youshaw and Dyer, 1979).

Eddy Current Testing

Eddy current testing (ECT) is usually employed for conducting surface crack detection on the electrically conductive material. The material can be ferromagnetic or non-ferromagnetic (García-Martín, Gómez-Gil and Vázquez-Sánchez, 2011). The ECT technique is developed based on an electromagnetic induction phenomenon in order to characterize and detect sub-surface and surface defects in conductive materials (Hendroprasetyo and Andrian, 2022). Figure 4(b) illustrates the principle of applying ECT to a ship hull surface crack.

In the most fundamental case, a coil of conductive wire is excited with an alternating electrical current. The excitation coil produces an alternating magnetic field around itself which is referred to as the primary magnetic field. When the probe approaches around an electrically conductive material (e.g., the steel ship hull), a secondary magnetic field will be generated along with a circular eddy current. Given that a crack is located on the material, the variation of the eddy current path will cause an alteration in the probe impedance (Hendroprasetyo and Andrian, 2022).

It should be noted that, however, ECT methods have to be performed together with the metallic materials or the non-metallic materials that are able to generate eddy currents. Since these methods have a limited depth of penetration, they are only suitable for inspecting surface and near-surface defects rather than internal defects. Besides, the eddy current effect is influenced by many factors and those methods are therefore struggling with characterizing and quantifying the defects detected.

Alternating Current Field Measurement

The Alternating Current Field Measurement (ACFM) approach was introduced for detecting fatigue cracks in the underwater oil structure (Lugg and Mill, 2008). This sort of technique has been extensively used to detect and size the surface-breaking defects in highly conductive materials, for example, aluminum and copper. The principle of applying ACFM to a ship hull crack is demonstrated in Figure 4(c).

When the ACFM approach is applied, an alternating, locally uniform current will be generated, which flows in the structure under test. The electrical current will be undisturbed when there does not exist a defect. When a surface-breaking crack shows up, however, the current will become nonuniform. As a result, the current will flow around and

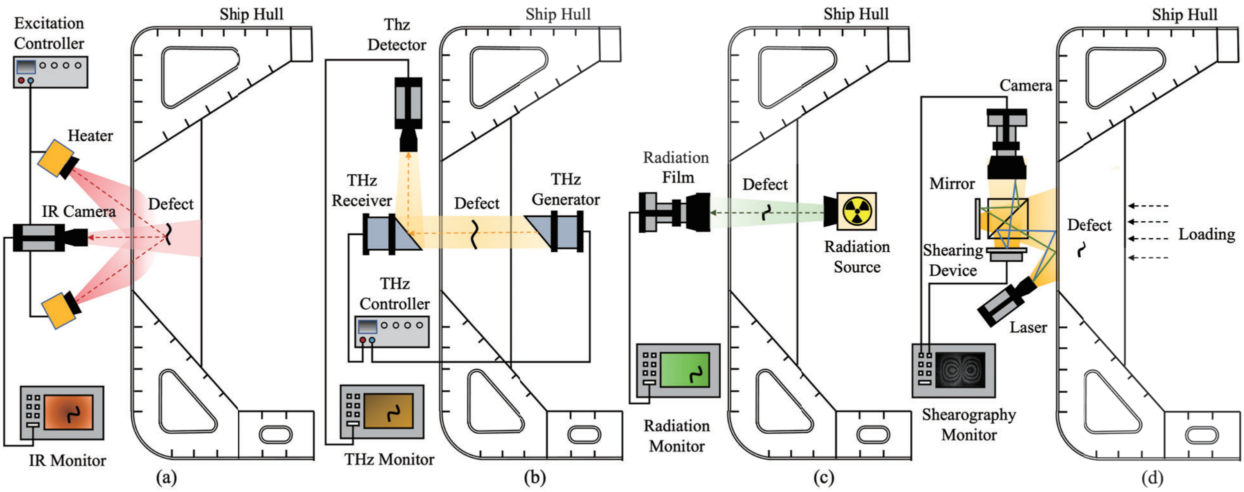


Figure 5: The principles of four sorts of imaging-based testing techniques applied to a ship hull structure, including (a) Infrared Thermography Testing, (b) Terahertz Imaging Inspection, (c) Radiographic Inspection and (d) Laser Shearography Testing.

under the crack. In this situation, the magnetic field over the surface associated with the current flowing in the structure will also be disturbed (Lugg, 2011). Hence, the detection of those defects can be achieved by evaluating field disturbances. Both the size and depth of defects can be further analyzed by evaluating the components of the field. Besides, the ACFM approach can be applied to the detection of cracks contained in the weld.

2.2.4. Imaging-Based Testing

In addition to visual testing techniques, various imaging techniques can be used for inspection of hull defects. For imaging-based testing, inspectors normally observe the images acquired using different imaging techniques, e.g., infrared thermography, microwave imaging, terahertz imaging and radiographic imaging, in order to detect, locate and assess the discontinuities or defects that appear on the hull structure.

Infrared Thermography Testing

Infrared Thermography (IRT) is an approach used to detect and process infrared radiation emissions from an object by measuring and mapping thermal distributions (Wang, Zhong, Lee, Fancey and Mi, 2020). The intensity of infrared radiation mainly depends on the temperature of an object. IRT is widely used for inspecting cracks, debonding, delaminations, humidity and inclusions in the composite materials and structures.

IRT systems can be categorized into two classes: passive thermography and active thermography (Usamentiaga, Venegas, Gueredíaga, Vega, Molleda and Bulnes, 2014). When a passive thermography system is applied, thermal radiation is directly emitted from the test structure under natural conditions and is monitored using an infrared radiometer. On the other hand, the test structure is first heated or cooled using an excitation device in the case that the active thermography system is used. Then the thermal response of the structure is detected and recorded by an IR camera in order to reveal internal structures. Active thermography systems are now rapidly developing and being used for inspection of composite materials. These methods normally inspect the integrity of the material and system using both an exterior energy source and an infrared detector (Ibarra-Castanedo, Genest, Piau, Guibert, Bendada and Maldague, 2007). The principle of applying an active thermography system to inspection of a ship hull crack is shown in Figure 5(a).

Microwave Testing

Microwave Testing (μT), also referred to as Microwave Non-destructive Testing, is developed based on the microwave imaging technique. It is mainly employed for defect detection with the electrically insulating composites (Kharkovsky and Zoughi, 2007). This method can be operated in the reflection phase from one side of the structure and the transmission phase from both sides of the structure. To characterize the micro-structural reflection of the material, the magnitude or phase of the microwave, which passed through or was reflected from the structure, was mapped in the two- or three-dimensional images (Green, Campbell and Zoughi, 2004).

Terahertz Imaging Inspection

Terahertz (THz) radiation is usually treated as electromagnetic radiation distributed in the frequency range between 0.1 THz and 10 THz, which is located from the microwave portion to the infrared portion within the electromagnetic spectrum (Kilcullen, Shegelski, Na, Purschke, Hegmann and Reid, 2017). Since THz radiation is transparent to dry and non-conductive materials, it can be used for the imaging of the concealed structures (Zhong, 2019). On top of this technique, THz reflection tomography has been utilized in the NDT scenarios. Figure 5(b) illustrates the principle of application of Terahertz imaging inspection to a ship hull crack.

Radiographic Testing

Radiographic Testing (RT) uses ionizing radiation to inspect materials and components that may contain internal defects, for example, inclusions, incomplete penetration, lack of fusion, porosity and shrinks (Abouelatta, Khalifa, Gadelmawla and Elewa, 2014). Radiographic testing instruments used for the underwater inspection tasks have also been developed (Haith, Ewert, Hohendorf, Bellon, Deresch, Huthwaite, Lowe and Zscherpel, 2017) (Husain, Hashim, Zakaria and Mohamed Z, 2018).

Normally, radiographic testing employs either gamma rays produced by the natural radioactivity from the radionuclide source which is sealed in a container, or X-rays generated using an X-ray generator. The inspection can be performed using two-dimensional images (i.e., radiography or fluoroscopy), or three-dimensional images after image reconstruction has been finished (i.e., Computed Tomography or CT). It should be noted that radiographic testing requires that the film and radiation source are located at the opposite sides of the hull (Youshaw and Dyer, 1979). Figure 5(c) demonstrates the principle of applying radiographic testing to a ship hull crack.

Shearography Testing

Shearography testing is particularly used for delamination, debonding, poor adhesion and other defects in composite material hulls. This technique uses a scanning laser system to determine the surface strain fields from the phase difference between the unloaded and loaded structures (Zhao, Dan, Sun, Wang, Wu and Yang, 2018). Specifically, a camera with an image shearing device is used to capture a scattered laser light reflected from the surface of the structure. Separate areas of the surface of the object overlap on the sheared image, which interferes and produces a speckle interferogram. When the surface of a damaged structure deforms due to external loading, the speckle pattern changes. Loading can be achieved by mechanical loading, vacuum loading, heating or internal pressure. Due to the high precision of the laser, the loading does not need to be large. Figure 5(d) demonstrates the principle of applying laser shearography testing to a ship hull crack.

2.2.5. *Discussion on the NDT Techniques*

Visual inspection can be treated as the simplest and most straightforward measure for inspecting the surface of ship hulls. After surface defects have been identified and recorded, more advanced inspection techniques, such as UT and ET, can be further used to evaluate the areas of interest. Visual inspection often encounters several challenges, particularly, when the efficiency of “close-up survey” or comprehensive inspection of large ship hulls is considered. Besides, the accuracy of visual inspection is highly dependent on the environment, for example, the dirt and debris on the hull surface, insufficient lighting, poor underwater visibility and small or obscured damages. Currently, RVI based on deep learning techniques is the focus of development.

To identify internal defects in the hull structure, ultrasonic inspection can be performed. The traditional UTM and PEUT methods require that the probes stay very close to the surface with an acoustic coupling medium. In this context, the inspector has to find a clean region or clean off the fouling before performing the inspection task, which is costly and time-consuming. To address this challenge, ACUT methods with high accuracy and high detection range can be developed. On the other hand, the operation usually results in the reasonably sparse sampling of sensor measurements. As a result, critical sections may be missed because there are often not enough resources for cleaning the entire hull. Advanced ultrasonic inspection methods, such as PAUT, GWUT and TOFD, which are able to produce two-dimensional images of internal defects, can be used to obtain more accurate and reliable results. Nevertheless, the cost of implementing these techniques has to be reduced while the sophistication of data analysis algorithms has to be enhanced, to further improve the effectiveness of the operation.

Imaging sonar testing is normally performed together with underwater robots for the inspection of underwater hulls. However, the size of the imaging sonar has to be further reduced for the limited load capacity of underwater robots.

Electromagnetic testing allows for the detection of defects near the surface of electrically conductive materials. The widespread application of this technique is restricted by the bulky size of the ET equipment, the high cost of the testing process and the prolonged time used for manual analysis. Automated data analysis algorithms may be useful for improving the inspection accuracy of ET methods.

As an effective tool for identifying defects in composite structures and welds, imaging-based testing has been widely used. This technique enables the acquisition and preservation of a digital image of defects, which can be used for further analysis. Due to the complexity of manual analysis, the process of identifying and characterizing defects is time-consuming. In addition, the radioactivity of the imaging equipment limits the wide use of radiographic testing techniques.

To address the above-mentioned issues, multiple sensors can be brought together for the purpose of building a practical system. In (Sheppard, Phillips and Cooper, 2009), defects on the composite hull were visually identified along with the laser shearography or the traditional tapping method. A UT approach was further used to assess the full extent of these defects.

2.3. Robots Used for Ship Hull Inspection

With the development of inspection techniques, unmanned vehicles and robots without a pilot onboard have been extensively used for the inspection of ship hulls. The use of these robots can reduce the risks encountered by

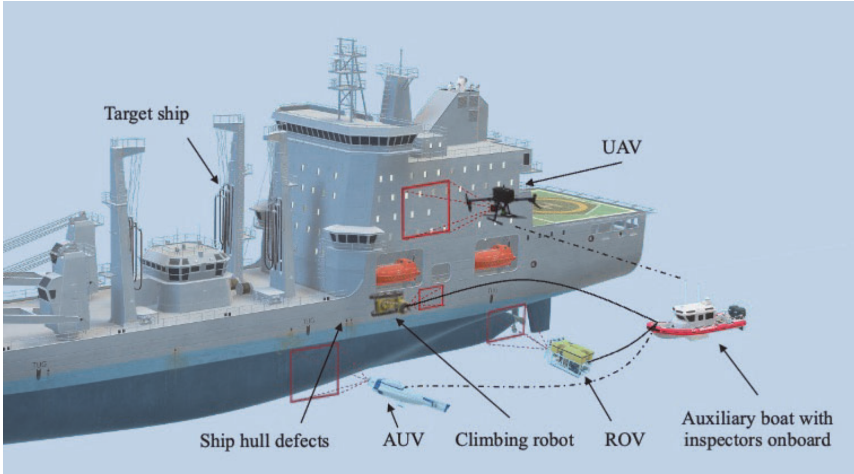


Figure 6: The diagram of the inspection of a ship hull using robots, including the Automated Underwater Vehicle (AUV), Remotely Operate Vehicle (ROV), Unmanned Aerial Vehicle (UAV) and climbing robot.

inspectors by maximally avoiding access to possibly dangerous areas at height or other locations (Wen et al., 2019). We will describe three types of robots in this subsection, including underwater vehicles, Unmanned Aerial Vehicle (UAV) and climbing robots. A schematic diagram of the inspection of a ship hull using these robots is shown in Figure 6.

2.3.1. Underwater Vehicles

Small, free-swimming underwater vehicles have been used in underwater inspection for floating structures/vessels such as ships, floating offshore wind turbines and floating platforms (Zhao, Thies and Johanning, 2022). The usage of underwater vehicles eliminates the safety hazard of diving work and avoids the unreliability caused by human errors. There are mainly two types of underwater vehicles, including Automated Underwater Vehicles (AUV) and Remotely Operate Vehicles (ROV), depending on whether the vehicle is driven by autonomous navigation or remote control.

When performing hull inspection tasks, the underwater vehicles can also be divided into free-swimming vehicles and adherence vehicles, which depend on the mode of movement. For the free-swimming mode, the vehicle uses thrusters. Regarding the adherence (or crawler) mode, the vehicle uses motorized wheels to move on the surface of the hull.

In practice, the application of underwater vehicles benefits both the human-supervised and the human-assisted hull inspection operations (Zugno, Campagnaro and Zorzi, 2020). For example, the vehicle enables the automation of low-level tasks. The benefit allows the inspector to focus on the higher-level vital stages of the operation, for instance, defect recognition and localization. The live video and data transmission can also support the inspector in updating the mission or taking over the operation of vehicles.

In terms of the operation manner of vehicles and the level of automation, the underwater vehicle-based hull inspection can be classified into three categories: the remote control with inspector onboard scenario, single-person vehicle-assisted survey scenario and full-autonomous scan scenario. In the remote control with inspector onboard scenario, underwater vehicles are usually used to replace divers. To find the location of defects, a pilot manually cranks the vehicle under the order of the inspector. Images of the defects are transmitted to the inspector for damage assessment. Although this inspection approach reduces the risks of divers who usually carry out underwater inspections, the problem of defect localization remains unresolved because the navigation of the vehicles is uncertain.

When the single-person vehicle-assisted survey scenario is applied, only a single inspector is used for hull inspection without requiring a pilot. The vehicle automatically scans the entire underwater hull, while the inspector observes live videos and marks defects. The inspector can terminate the movement of the vehicle freely in order to perform a further inspection of the area of interest. In this context, the problem of locating defects is partially solved, as the path of the movement can be saved.

In the full-autonomous scan scenario, the vehicle automatically scans the entire hull, detects defects and records the location of defects. Automated methods, such as Simultaneous Localization And Mapping (SLAM), are normally used for vehicle navigation. In addition, the image stitching method and other computer vision algorithms can be utilized in order to boost the performance of defect detection, localization and display.

2.3.2. Unmanned Aerial Vehicles

Flying systems, such as UAVs, are small-sized and flexible and are able to move freely in tight spaces, can be used for investigating the inner structure of hulls quickly (Ortiz, Bonnin-Pascual and Garcia-Fidalgo, 2011). In general, UAVs are able to cover a large area of the inner hull (Wen, Wolling, McSweeney and Gu, 2018). As a result, they can obtain an overall description of the status of the ship structure and can be used for detecting defects, e.g., corrosion, coating breakdown and cracks. As long as the ship cabin is empty, the UAV can perform remote or autonomous hull inspection regardless of the oxygen or toxic gas content. The images collected using UAVs have to be recorded together with the position data because potential defective areas normally require further inspection. Given regulatory considerations, drone-based inspections are often conducted during the special inspection, for the purpose of increasing the efficiency of the operation.

Basically, UAVs are assumed to fly in the low-speed, stationary and vertical manner when they fly in the indoor environment. This often requires sophisticated manual handling skills or automated navigation techniques. According to the level of pilot involvement and the level of automation of the UAV, the UAV-based inspection can be divided into four categories: the partial scan with inspector in-structure scenario, partial scan with inspector onboard scenario, single-person drone-assisted survey scenario and full-autonomous scan scenario (Stensrud, Skramstad, Cabos, Hamre, Klausen, Raeissi, Xie and Ødegardstuen, 2019).

In the partial scan with inspector in-structure scenario, the inspection is performed by an inspector and a dedicated drone pilot who operates the drone using a remote control. However, the inspector still has to enter the hull structure and keep the drone within sight. The inspector will monitor the video captured by the drone camera and decide where the drone needs to position while the pilot will manually control the drone accordingly. This method not only reduces the requirement for the inspector to approach the hull closely but also increases the efficiency of hull inspection.

With regard to the partial scan with the inspector onboard scenario, both the inspector and the pilot only need to get aboard the ship rather than enter the ship structure. To scan the structure and transmit the video stream to the inspector, the drone will enter the ship structure individually. In this case, the sensing and anti-collision functionalities of the drone have to be improved. Since the personnel do not enter the ship structure, the toxic gas or oxygen content inside the structure can be left unvented.

Given that the single-person drone-assisted survey scenario is used, an individual inspector is able to conduct hull inspection without being accompanied by a dedicated drone pilot. This improvement can be fulfilled using high-level navigation commands instead of direct steering with a joystick.

In recent years, UAVs have been developed for performing full-autonomous scans of ship hull structures. This task requires that the UAV has full indoor navigational capability in one of the following two manners. First, the UAV can generate a flight path on top of an existing 3D structure model of the ship. Navigation is conducted based on the self-identification of the structure using the 3D point cloud information. Second, both navigation and flight path generation are realized "on the fly" using SLAM techniques (see (Fang, Yang, Jain, Dubey, Roth, Maeta, Nuske, Zhang and Scherer, 2016) for a successful case). Hence, the 3D model is not required before flight. The inspection results are mapped onto the existing model or the generated 3D model derived from the flight. No matter which manner is realized, the inspector is able to perform the inspection operation without getting aboard the ship.

2.3.3. Climbing Robots

For the dry inspection of cargo holds and other plate structures, climbing robots (also known as robotic crawlers) are particularly suitable for detailed observation of defective areas. To perform close-up inspections, mark defective areas, or perform thickness measurements, these robots are able to transport the corresponding sensors near the inspected area. For this purpose, they have to be able to move on the vertical, sloped and horizontal ferromagnetic surfaces (Eich, Bonnin-Pascual, Garcia-Fidalgo, Ortiz, Bruzzone, Koveos and Kirchner, 2014), such as climbing up bulkheads and moving along the large flat hull. Generally speaking, there are two types of climbing robots: lightweight magnetic crawlers and heavyweight magnetic robots.

The lightweight crawler usually carries cameras for the sake of performing a steady and very close inspection. In this case, high-resolution, high-quality images of the areas of interest can be derived. These images are useful for characterizing the extent of the damage because they provide careful observation of the defective surface. The robots need to tag the images with the location information in order to mark defects. Considering that they have to maneuver between ship shell frames, the size of robots needs to be constrained.

In contrast, the heavyweight magnetic robot requires a higher load capacity in order to carry heavy devices and corresponding manipulator arms used for some inspection tasks, such as ultrasonic thickness measurement or electromagnetic measurement. Regarding this type of robot, the locomotion speed is not important but precise positioning is necessary for detailed defect observation.

Climbing robots can also be used together with remote and automation controls. The application of automated navigation techniques to precise defect localization has become the focus of current research.

2.3.4. Discussion on the Hull Inspection Robots

Generally speaking, the application of robots to hull inspection improves the efficiency of the operation, which is achieved by enhancing the accessibility to complex operating environments and increasing the accuracy of locating defects.

However, there are also some challenges to the robot-based inspection operation. First, the low reliability of inspection results is normally caused by the instability of a robotic system. To address this challenge, improvements can be applied to the sensitivity of the onboard sensors and the positioning capability of the robot. Second, manual operations are still required occasionally due to the low level of automation in the current robotic systems. This dilemma can be alleviated by developing more effective navigation and planning algorithms. Third, the limited load capacity of the robot constrains the size of the sensors deployed. The use of smaller sensors may hinder the detection of complex defects and hence results in low accuracy. To solve this issue, further developments in the sensor design and automatic data processing techniques are required. Besides, the operational interface of the robot can be optimized in order to reduce the deployment difficulty.

3. In-dock Ship Hull Inspection

In-dock ship hull inspection aims to ensure the structural condition of a ship meets the requirements of seaworthiness. Special survey and bottom survey are two forms of in-dock ship inspection methods defined by the IACS. They are normally carried out every five years in dock (IACS, 2007). To be specific, the special survey is normally used to perform a close-up assessment associated with thickness measurement and can be used to detect bucking, corrosion, fractures and other structural degeneration; while the bottom survey is aimed at assessing the surface of the underwater hull structure and associated components. Typically, in-dock ship hull inspection is performed using NDT approaches, including visual inspection, electromagnetic testing and ultrasonic testing. In this section, we will conduct a review of the scenario of in-dock ship hull inspection with regard to manual inspection approaches and both the automatic data processing methods and automated platforms used for automated inspection.

3.1. Manual In-dock Inspection

In practice, hull inspections are generally carried out by the inspector manually, who stays inside the hull structure, or stays out of the hull located in a dry dock. The structure of adjacent tanks and cargo holds are also the focus of manual inspections. The inspector first carries out an Overall Survey to obtain the comprehensive state of the ship hull. To decide the position of defective regions and make a schedule for further close-up surveys, the ship hull is assessed with a certain gap. Then, a Close-Up Survey is performed in which the inspector is physically close to the inspection area at arm's length while recording and locating the structural defects for further assessment and repair (Wilken, Cabos, Baumbach, Buder, Choinowski, Grießbach and Zuev, 2015). As a result, the size of thickness gauges, cracks and other defects are measured and logged (Poggi et al., 2020). In the rest of this subsection, we will review a series of manual in-dock inspection methods.

3.1.1. Visual Inspection

As the fundamental operation of hull inspection, visual inspection is often carried out before other NDT methods are performed. This method is normally used to decide the overall status of the hull and identify the position and grade of surface defects. In dry docking, visual inspection is typically conducted by inspectors who stand on the hull surface or crawl through the ballast areas and other locations in the hull.

Frantsev (2013) described a visual inspection method for composite hulls. Visual examination was the primary stage before the instrumental nondestructive testing was conducted. The method is used to not only determine the location of the waterline but also find the external defects on the surface, damages to the individual components of the structure and signs of the osmotic variation on the surface.

3.1.2. Acoustic-Based Testing

The ultrasonic-based method is widely used for measuring the thickness of the hull structure and detecting internal hull defects for in-dock inspection. To visibly detect the reduction in thickness caused by corrosion, Chatzifotis (2014) conducted ultrasonic measurements of the thickness of the ship weld plate. Ivošević and Bauk (2018) developed a corrosion damage monitoring device based on the measurement of hull thickness using UTM. The data collected at regular intervals was transmitted to the computer for the long-term utilization and maintenance of the vessel. Kudryavtsev, Kleiman and Polezhayeva (2011) proposed a method for modeling the residual stress distribution and relaxation in the large welding panels of a ship. The residual stresses were detected using ultrasonic measurement devices during the fatigue loading of the hull welds. Suratkar, Sajjadi and Mitra (2011) made use of nonlinear wave modulation spectroscopy in ship micro-damage detection. This technology used the waves of two separate frequencies to excite the object. The harmonic of the two waves was analyzed and the resonance frequency was used to decide the location and size of damages.

For the purpose of increasing the effectiveness of in-dock ship hull inspection, PAUT can be performed. Bulavinov, Pinchuk, Pudovikov and Boller (2011) investigated the effect of PAUT on the weld joints in the construction stage of the ship structure compared to X-ray testing. Tang and Yu (2020) compared three different flaw detectors implemented using PAUT, PEUT and X-ray testing, respectively, for inspection of the butt welds on the ship deck. The results demonstrated that the PAUT was comparable to its two counterparts. To inspect the submarine pressure hull, Jung et al. (2018) utilized PAUT to detect defects and measure their size. Particularly, the quantity of the piezoelectric elements in the PAUT device was set to 64 in order that the accuracy for detecting both porosity and cracks can be verified.

In (Mondal et al., 2002), TOFD ultrasonic testing is used for the inspection of long welds on the hull of a container ship. Defects including porosity, lack of root penetration, and internal cracks in V groove butt welds can be detected. In (Alkhateeb, Riccioli, Morales and Pahlavan, 2023), non-contact acoustic emission sensors were used to detect the hull corrosion under biofouling. Although the amplitude of ultrasonic waves that passed through the marine life decreased, the corrosion could still be located.

In addition to the aforementioned studies, ultrasonic techniques have also been used for defect inspection of composite hulls. Frantsev (2013) introduced a hybrid acoustic approach which aimed at detecting lamination-type defects in the multi-layer composite hulls. A combination of two different acoustic methods, i.e., the local free-vibration method and the impedance method, was proposed. The impedance method localized the position of inner defects and obtained images of these defects. In contrast, the local free-vibration method was used to quickly evaluate the components of the hull at the resolution of a measurement/cm^2. Wijerathna (2016) uses PEUT to inspect the flexural strength of the GFRP ship hull, and establishes a correlation analysis between the percent echo height and flexural strength. Mabuza and Shavhani (2018) applied PAUT to defect detection in the flat composite panels of the boat hull.

Quattrocchi et al. (2020) discussed the ability of the ACUT method to evaluate the hull of the GFRP material. The results showed that ACUT was able to recover the shape of defects with a thickness of more than 15mm. Han, Jang, Lee, Lee and Oh (2021) investigated the UTM errors that occurred on the GFRP ship structures. It was found that strong ultrasonic interference often happens between hull plates due to thickness variations, which may result in an increased error. Lee et al. (2021b) made use of PEUT to explore the impact of the production quality and thickness of the GFRP material of the hull on the accuracy of ultrasonic inspection.

3.1.3. *Electromagnetic Testing*

For the sake of detecting structural defects on the hull in the dock, particularly, weld defects, many electromagnetic testing methods have been used. Hendroprasetyo and Andrian (2022) detected ship structure cracks, which were located beneath the protective coating, using an ECT method. Li, Yuan, Chen, Ge, Yin and Li (2016) developed a Rotating ACFM approach in order to address the directional detection issue encountered by conventional ACFM methods. The arbitrary-angle underwater cracks in the offshore oil and gas exploitation systems can be detected using this approach. To detect the tiny surface cracks in the bumpy welds of ship hull structures, Yuan, Li, Yin, Chen, Zhao, Jiang and Ge (2020) presented an ACFM-based method. A signal gradient algorithm was presented, which was able to increase the signal-to-noise ratio and benefit the manual identification of tiny surface cracks. Bardanachvili, Pope, Goulart, Adelson, Alves and Pereira (2008) made use of ACFM to measure the depth of cracks found by visual inspection. This technique was applied to fatigue assessment in the very large crude oil carriers and the ultra-large crude oil carriers.

3.1.4. *Imaging-Based Testing*

A microwave imaging NDT method was introduced by Green et al. (2004) for inspection of the GFRP material of the ship hull. Specifically, this method was used to detect skin/core debonding, core cracking and impact damages. The ability to detect the corrosion and surface breaking defects contained in the metallic components using microwave imaging was also investigated, without removing the non-conducting lagging covering on the structure.

Kilcullen et al. (2017) made use of a THz time-domain waveform imaging system to detect hidden water-filled voids contained in a rubber tile sample. This study simulated a hull inspection application for submarines. The THz imaging system was also applied by Tu, Zhong, Shen and Incecik (2016) to inspection of marine protective coatings. This system used the finite difference time domain approach to compute the reflection of THz radiation. Both the occurrence of the defects beneath the coating and the thickness of the coating were studied based on the reflected Terahertz waves.

In (Zhang, Loader, Schilling, Hernandez, McSweeney and Gu, 2021b), the 3D laser scanning technique was compared with the manual ultrasonic testing method for thickness measurement of the hull structure. Given the uncoated and corroded plates, the difference between the two thickness measurements derived using both methods respectively, was within 3%. This difference was acceptable according to the acceptance criteria. In (Tao et al., 2022), a shearography testing method was used for the inspection of the large-scale composite ship structure. The comparison between the thermal loading and mechanical loading in thick composite inspection with shearpgraphy was conducted.

3.2. Automatic Data Processing for In-dock Inspection

It is known that manual hull inspection requires skilled inspectors who have a wide knowledge of the hull structure. However, both the expertise and experience of the operator may affect the accuracy of hull inspection. Also, manual inspection is time-consuming. In contrast, automated hull inspection is robust and efficient. Given that this type of technique can be applied, not only the inspection efficiency will be increased but also the demand on the inspector will be reduced. Therefore, many automatic data processing methods were proposed for automated hull inspection.

3.2.1. *Visual Inspection*

Automated visual inspection methods have been widely studied for ship hulls. These methods were normally designed on top of computer vision techniques. It has been shown that those methods are promising in distinguishing between the defect-free and defective regions on a surface (Xie, 2008). In this subsubsection, we will review the automatic data processing methods used for automated visual inspection of in-dock hulls. The details of these methods are shown in Table 2.

Handcrafted Feature Based Visual Inspection

Traditionally, handcrafted features, including color, texture, edge and morphological features, can be used for automated visual inspection of hulls. In general, the corroded areas of a ship hull significantly differ from the uncorroded areas in color. As a result, color features have been used for hull corrosion detection. Bonnin-Pascual and Ortiz (2010) proposed a codeword dictionary-based ship hull corrosion detector. This detector was trained according to the distribution of colors. The roughness of the corrosion area was used to improve detection accuracy. Using both the entropy data

Table 2
Summary of the automatic data processing methods used for automated visual inspection of in-dock ship hulls.

Feature	Classifier	Defect	Target Structure	Computational Cost	Practical Application	Reference
GLCM + RGB histogram	Cluster codewords dictionary + weak-classifier	Corrosion	Internal structure of metal hull	Small	No	(Bonnin-Pascual and Ortiz, 2010)
Hue histogram and entropy data	Gaussian mixture model classifier	Corrosion	Outer surface of metal hull	Small	No	(Jalalian, Lu, Wong, Ahmed and Chew, 2018)
Histogram range for background determination	Unsupervised threshold method	Corrosion	Outer surface of metal hull	Small	Yes	(Navarro, Iborra, Fernández, Sánchez and Suardíaz, 2010)
Color moments	SVM, Bayesian and Random Forest classifier	Corrosion	Outer surface of metal hull	Medium	Yes	(Maglietta, Milella, Caccia and Bruzzone, 2018)
Hue and Saturation histogram + GLCM	AdaBoost classifier	Corrosion	Internal structure of metal hull	Small	No	(Bonnin-Pascual and Ortiz, 2014a)
Greyscale based edge features	Threshold method	Welding defects	LGNC tank	Small	Yes	(Lee, Yuk, Kim, Park, Kim and Cho, 2004)
Shannon entropy based wavelet transform texture features	Threshold method	Corrosion	Outer surface of metal hull	Small	Yes	(Fernández-Isla, Navarro and Alcover, 2013)
Greyscale level features	Threshold method + regional growth algorithm	Crack	Internal structure of metal hull	Small	Yes	(Bonnin-Pascual, 2017)
Saliency of contrast and symmetry	Probability density functions	Corrosion, crack, coating breakdown	Internal structure of metal hull	Small	No	(Bonnin-Pascual and Ortiz, 2014b), (Bonnin-Pascual and Ortiz, 2017b), (Bonnin-Pascual and Ortiz, 2017a)
Faster R-CNN object detector + VGG-VD-19 object classifierleft		Corrosion and coating breakdown	Internal structure of metal hull	Large	Yes	(Liu, Tan, Zhen, Yin and Cai, 2018c), (Liu, Tan, Cai, Zhen and Yin, 2018b), (Liu, Tan, Cai, Yin and Zhen, 2018a)
Xception object classifier + Fully convolutional segmentation networkleft		Corrosion and crack	Internal structure of metal hull	Large	Yes	(Jing, Geir, Erik and Bahman, 2018), (Stensrud et al., 2019)
AlexNet object classifier		Corrosion	Outer surface of metal hull	Large	No	(Yao, Yang, Wang and Zhao, 2019)
DWT features	CNN classifier	Biofouling	Outer surface	Medium	No	(Sundar, Madhavi, Veerakumar and Suresh, 2021)
RetinaNet object detector + U-Net segmentation network		Cracks	Internal structure of metal hull	Large	Yes	(Stensrud, Torstensen, Lillestøl and Klausen, 2021)
RetinaNet object detector + CSRT		Cracks	Internal structure of metal hull	Large	N	(Xie, Stensrud and Skramstad, 2021)
Centroids Attention U-Net segmentation network		Corrosion	Internal structure of metal hull	Large	No	(Kai, Ortiz and Bonnin-Pascual, 2021)
Spatial Gray Level Difference Matrix	Self-organizing map neural network classifier	Biofouling	Outer surface	Medium	No	(Wang, Lieberman and Ho, 2006)
Color channel feature values	Shallow neural network and feed-forward neural network classifier	Corrosion and coating breakdown	Internal structure of metal hull	Large	No	(Ortiz, Bonnin-Pascual and Garcia-Fidalgo, 2015), (Ortiz, Bonnin-Pascual, Garcia-Fidalgo and Company-Corcoles, 2016)
Improved YOLOv5 Detector		Cracks and Corrosion	Internal structure of metal hull	Large	No	(Zhou, Li, Fang, Zhang and Pan, 2022)

and the histogram of the hue, Jalalian et al. (2018) introduced a ship hull corrosion detection method. A wrapped Gaussian mixture model was employed in order to distinguish the defects together with the circular hue histograms. The entropy data of the hue was further fitted using the Gaussian model for segmenting defective regions.

Navarro et al. (2010) designed a real-time ship hull rust detection system. This system was designed on top of the thresholding operation using an unsupervised background estimation method in non-uniform and variable lighting conditions. The histogram range for background determination was first calculated using the gray-level histogram of an image. Then the image was scanned using the determination in order to segment the corrosion damage.

Classical machine learning methods have also been used for defect recognition along with color features. Maglietta et al. (2018) introduced a ship hull corrosion detection approach based on the combination of the Bayesian, random forest and Support Vector Machine (SVM) classifiers. A set of color moments, including mean, variance, skewness and kurtosis, computed in the HSV color space were used as features. It was shown that the non-symmetrical and non-pairwise metrics of diversity for building ensembles lead to better classification accuracy.

A ship hull corrosion detector was developed using a shallow neural network, together with the texture and color information (Ortiz et al., 2015). Two different color descriptors were evaluated, while the uniform local binary pattern features with the signed surround differences were used as the texture descriptors. In (Ortiz et al., 2016), both the color descriptors computed according to the dominant colors within a square region and the texture descriptors calculated using statistical measures for each single color channel were used for coating breakdown or corrosion detection.

The corroded areas of the ship hull structure may also be represented using different texture features. Bonnin-Pascual and Ortiz (2010) developed a corrosion detection method using the color information. For the purpose of increasing the detection accuracy, Gray-Level Co-occurrence Matrix (GLCM) features were utilized to describe the roughness of the corroded area. A weak classifier was proposed based on the cascade of the color and roughness detectors. Bonnin-Pascual and Ortiz (2014a) further improved the above method by using the adaptive boosting paradigm for texture feature learning and texture classification.

Fernández-Isla et al. (2013) introduced an image reconstruction approach based on the wavelet transform for detecting texture defects on the ship hull surface. A Shannon entropy-based method was developed for the automatic selection of the wavelet decomposition level. It was found that the reconstructed image boosted the segmentation operation used for hull defect detection. For the sake of classifying ship hull fouling conditions, Wang et al. (2006) proposed a self-organizing map neural network classifier, which was utilized together with the spatial gray level difference matrix texture features.

Since weld seams generally have neat edges, edge features can be used to detect hull weld defects. In (Lee et al., 2004), a visual inspection method was developed for the sake of monitoring weld quality during the shipbuilding period. Four types of detection were concerned, including arc strike, bead pitch abnormality, bead shape abnormality and scratch. The features extracted on top of the edges were used to determine the presence of defects in the weld regions.

Morphological operations are able to connect a large area with a similar appearance. These operations provide an effective solution for area assessment of hull defects. In (Bonnin-Pascual and Ortiz, 2010), a hull crack detector was implemented on top of a percolation process. Normally, the steel surface cracks show a dark, narrow and elongated appearance. Considering these morphological characteristics, the detector took into account the gray level of the pixels around the seed pixel and used this information to expand the candidate crack area. Bonnin-Pascual (2017) further improved this detector by incorporating an additional step that merges different candidate areas into a single region.

Saliency-Based Inspection

Visual saliency approaches are normally designed based on the human visual perceptual mechanism. They aim to identify the areas which present significant characteristics in an image. Those approaches can be applied to damage and corrosion detection for ship hulls.

To inspect ship hull coating breakdown, corrosion and crack, Bonnin-Pascual and Ortiz (2014b) proposed a saliency-based inspection approach. This approach used a Bayesian algorithm to compute the saliency data on top of a set of natural characteristics, which combined the symmetry and contrast data. A training operation was first conducted, which estimated the basic probability density functions. Then, the algorithm utilized both the top-down and bottom-up saliency data for defect inspection. The above-mentioned approach was further improved by combining different visual features and introducing a multi-stage generic framework (Bonnin-Pascual and Ortiz, 2017a) (Bonnin-Pascual and Ortiz, 2017b).

Deep Learning Based Inspection

Deep learning-based computer vision methods, including image classification, image segmentation and object detection, have been widely applied to the field of ship hull inspection. Due to the use of these techniques, the accuracy of defect detection has been greatly enhanced.

As one of the most common computer vision topics, image classification has been extensively used for different tasks. In the scenario of hull inspection, local image patches will be sent to the classifier in order to discriminate the defected and undetected regions on the ship hull or identify the type of defects. Jing et al. (2018) made use of the pre-trained Xception (Chollet, 2017) network as a crack classifier. To perform dichotomous classification of cracks, the high layers of the network were fine-tuned. Stensrud et al. (2019) further improved the classification accuracy by adding more training data. A corrosion inspection approach was introduced by Yao et al. (2019) on top of an AlexNet classifier (Krizhevsky, Sutskever and Hinton, 2012) for hull structural plates. The classifier was first trained using a large set of annotated corrosion images. Then it was used to scan an unknown hull structural plate image in order to identify and locate the corrosion damage.

Image segmentation methods are able to indicate whether or not each pixel in an image is damaged. This is particularly important to the hull corrosion and crack detection tasks, as the area of defects needs to be estimated for further analysis. In (Jing et al., 2018), a fully convolutional network based on the dilated convolution was developed for real-time crack segmentation. Considering the impact of low-resolution images, the incorrect predictions in these images were assigned with the higher loss function weights.

Stensrud et al. (2021) used a U-Net-like (Ronneberger, Fischer and Brox, 2015) semantic segmentation network on top of the pre-trained ResNet50 (He, Zhang, Ren and Sun, 2015) model to segment the cracks in ship tanks. The results showed that the network can learn the difference between cracks and similar structures, for instance, sharp edges and shadows. For inspection of vessel corrosion, Kai et al. (2021) proposed a semantic segmentation solution using Attention U-Net (Oktay, Schlemper, Folgoc, Lee, Heinrich, Misawa,

Table 3
Summary of the automatic data processing methods used for automated acoustic-based inspection of both in-dock and underwater ship hulls.

Tech/Sensor	Method	Defect	Practical Application	Reference
GWUT	Automatic generation of approximate image of damage	Cracks (in-dock)	No	(Song, Rose and Whitesel, 2002)
GWUT	Signal pattern matching of simulation results	Cracks (in-dock)	Yes	(Yeo and Fromme, 2006)
GWUT	Excitation parametric method based on dynamic wavelet fingerprint technique	Limpet mines (underwater)	Yes	(Bingham, Hinders and Friedman, 2009)

Mori, McDonagh, Hammerla, Kainz, Glocker and Rueckert, 2018). Weakly supervised annotations of the ground-truth data were utilized in order to reduce the preparation time of the training data. A novel loss function, which comprised a set of partial cross-entropy loss terms, was used to neutralize the effect of the weak annotations.

Compared to image classification, object detection methods are able to obtain the position of defects in addition to classifying defects into different types. In (Liu et al., 2018c) and (Liu et al., 2018b), a coating breakdown and corrosion inspection algorithm was proposed. The algorithm made usage of the Faster R-CNN detector (Ren, He, Girshick and Sun, 2015) to locate coating failures and used the VGG-VD-19 classifier (Simonyan and Zisserman, 2014) to categorize the defects into five types. The algorithm was further developed as a detection system for the purpose of ship condition assessment (Liu et al., 2018a). In (Zhou et al., 2022), an improved YOLOv5 detector (Jocher, Chaurasia, Stoken, Borovec, Kwon, Michael, Fang, Yifu, Wong and Montes, 2022) was used for ship hull defect inspection.

Stensrud et al. (2021) introduced a ship tank crack detection method using the images taken by drones. To perform crack detection, the RetinaNet detector (Lin, Goyal, Girshick, He and Dollár, 2017) was trained using a set of over 1000 images. In (Xie et al., 2021), a tracking method was proposed based on object detection for ship crack inspection. The Channel and Spatial Reliability Tracker (CSRT) was used for continuous crack detection. This tracker operated on the basis of the detection results produced by an object detection network, namely, RetinaNet (Lin et al., 2017).

3.2.2. Acoustic-Based Testing

Given that automatic acoustic-based testing methods are applied, automatic data processing algorithms will use the collected data to decide the position and size of the defects inside the ship hull. The details of the automatic data processing techniques used by these methods are summarized in Table 3. Song et al. (2002) presented a ship hull damage localization and sizing technique based on guided wave ultrasonic testing. The approximate image of the damage was produced on top of the results of guided waves. This image was used to identify and measure the damage in the ship hull. In (Yeo and Fromme, 2006), a corrosion damage inspection method was proposed using guided waves and two-dimensional finite elements. Finite element simulation of the hull structure with corrosion was used to derive the signal distribution pattern of the guided waves, which enabled the automatic detection of defects in the real ship structures.

3.2.3. Electromagnetic Testing

In contrast, automatic electromagnetic testing was relatively rarely studied in the literature. Liu, Lu, Liu, Jiang and Lodewijks (2017) employed the pulsed eddy current thermal imaging technique for crack detection in the welded structure of ship hulls. Both the mathematical morphology and automatic region growing algorithms were used for automatic crack inspection along with the thermal images.

3.2.4. Imaging-Based Testing

In addition to visible light cameras, various imaging techniques have been applied to the automated inspection of different types of hull defects. Lee, Lim, Sohn, Yun and Song (2017) developed an autonomous mobile inspection system for liquefied natural gas cargo tanks using lock-in thermography. Sizes and locations of hidden voids are quantified with a suite of feature-based image processing algorithms. Liu et al. (2018a) made use of active IRT for the detection of the hidden corrosion beneath the coating. After a video was captured, it was sent to the machine learning algorithm in order to fulfill the corrosion detection and evaluation task. Lee, Chung, Ranjit and Kim (2021a) proposed a thresholding-based approach for the detection of circular defects in the stainless-steel plate using the images obtained by the Lock-In IRT. This method is suitable for the inspection operation on the ship-building line.

Defects are normally represented by the change of intensity presented in the radiographic films. The bad contrast, noise, radiogram quality, weak sizes of defects and welding over-thickness often result in the difficulty for the interpretation by humans (Hou, Zhang, Wei, Guo and Zhang, 2020). Thus, the detection of defects in radiography using computer algorithms become the focus of current developments. Yun, Oh and Shin (2022) introduced an image pre-processing method. It was shown that the pre-processing approaches, including concatenation, contrast-L=limited adaptive histogram equalization, image de-noising and thresholding, were effective in highlighting defects.

Stensrud et al. (2021) introduced a ship tank inspection approach using hyperspectral images. Three individual mean spectra were calculated for the humidity rust, paint and salt-spray rust respectively. Both principal components analysis and the Mahalanobis distance were used to categorize the rust.

Table 4
Summary of the automated platforms utilized for in-dock ship hull inspection.

Name	Type	Navigation	Sensor	Reference
-	Magnetic climbing robot	Automatically control	ACFM and PAUT sensors	(Emmanouilidis, Spais, Hrissagis and Sa, 2004)
SIRUS	Magnetic climbing robot	Automatically control	UTM sensor and ECT sensor	(Menegaldo, Santos, Ferreira, Siqueira and Moscato, 2008)
MIRA	Magnetic climbing robot	Remote or semi-autonomous control	RGB video camera	(Eich and Vögele, 2011)
MARC	Magnetic climbing robot	Automatically control	UTM sensor and RGB video camera	(Bibuli, Bruzzone, Bruzzone, Caccia, Giacopelli, Petitti and Spirandelli, 2012), (Koveos, Kolyvas and Drikos, 2012), (Milella, Maglietta, Caccia and Bruzzone, 2017)
X-scan	Magnetic climbing robot	Automatically control	ACFM and PAUT sensors	(Asfis, Carpentier and Panggabean, 2014)
-	Magnetic climbing robot	Remote	Conventional ultrasonic testing sensor	(Huang, Li, Xue, Chen, Liu, Leng and Wei, 2017)
AWI	Magnetic climbing robot	Automatically control	PAUT sensor	(Garrido, Sattar, Corsar, James and Seghier, 2018)
Sparrow	Magnetic climbing robot	Automatically control	UTM sensor	(AR, Veerajagadheswar, LN, Kumaran and Mohan, 2020)
ADRASSO	UAV	Semi-autonomous or full automatically control	RGB video camera, hyperspectral camera and UTM sensor	(Stensrud et al., 2019), (Stensrud et al., 2021)
MUSSOL	UAV	Automatically control	Laser scanner, RGB-D camera and RGB video camera	(Garcia-Fidalgo, Bonnin-Pascual, Company-Corcoles and Ortiz, 2020), (Bonnin-Pascual, Garcia-Fidalgo, Company-Corcoles and Ortiz, 2021)

3.3. Automated Platforms for In-dock Inspection

For manual in-dock inspections, access to the operation locations is dangerous, expensive and time-consuming (Ahmed, Eich and Bernhard, 2015). To address these issues, recent research has been focused on the use of automated platforms to inspect ship hulls in dock. Unmanned aircraft and climbing robots are commonly used. In this subsubsection, we will review the studies which used automated platforms for in-dock hull inspection. Table 4 summarizes the details of these platforms.

3.3.1. Unmanned Aerial Vehicles

With the help of UAVs, inspection of both the outside and inside structures of ship hulls can be inspected, an overview of the hull structure can be obtained and defects can be localized for further analysis.

Stensrud et al. (2019) proposed a ship cargo and ballast tank inspection approach using a semi-autonomous drone. The airborne RGB video camera, hyperspectral camera and ultrasonic sensor were employed. The flight control modes of drones associated with these sensors were also reported. In (Stensrud et al., 2021), authors further improved the drone with the fully automatic mode based on a 3D laser scanner. Since the drone used a tethered power solution instead of a battery, it could be utilized for an extended duration and did not require battery swapping.

In (Garcia-Fidalgo et al., 2020) and (Bonnin-Pascual et al., 2021), a micro-UAV was developed for ship cargo hold inspection. To support the operator with enhanced functionalities and reliable autonomy during flight, the Supervised Autonomy (SA) paradigm was used for behavior-based high-level control, such as obstacle detection and collision prevention. The sensor suite, including a laser scanner, RGB-D cameras, a gimbal camera and ultrasonic sensors, was able to achieve accurate obstacle sensing and useful information for hull inspection. The UAV system was continuously improved by introducing the human in-loop flight control (Bonnin-Pascual, Ortiz, Garcia-Fidalgo and Company, 2015), image processing algorithms (Ortiz et al., 2016) and purely teleoperated experiments (Bonnin-Pascual, Ortiz, Garcia-Fidalgo and Company-Corcoles, 2019) because it had been first developed (Eich et al., 2014).

To further improve the efficiency, the path planning technique has been applied to the UAV-based hull inspection. Grippa, Renzaglia, Rochebois, Schranz and Simonin (2022) compared the efficiency of two path planning algorithms, including Part-TSP and Coop-Frontier, for the UAV-based hull defect detection task. The whole ship hull was covered using a swarm of UAVs at a low resolution in order to detect defects. If the corrosion was detected, high-resolution images were further obtained by approaching the surface of the hull.

3.3.2. Climbing Robots

Climbing robots are usually used for performing the close-up in-dock hull inspection, especially for the detection of defects on the hull surface and at the weld seam.

Different acoustic-based testing techniques have been widely used for climbing robots due to the close inspection range. A Magnetic Autonomous Robotic Crawler (MARC) was developed for the ultrasonic thickness measurement of ship hulls (Bibuli et al., 2012) and (Koveos et al., 2012). In particular, this heavy climbing robot was able to carry the ultrasonic marking and thickness measure devices and displace them over the ship hold wall with a robotic arm. To minimize the probability of crashing and detaching and maximize the contact area with the metal surface, magnetic tracks were more suitable than wheels when a passive adherence system was utilized.

Milella et al. (2017) introduced a MARC which was able to stitch an overhead mosaic image of the ship hull using a set of subsequent input image frames. In (Huang et al., 2017), a wall-climbing robot was developed in order to inspect the vertical structure of a ship during the shipbuilding stage. To climb the ferromagnetic surface, both magnetic caterpillars and magnets were combined into the robot. An ultrasonic probe was used for flaw inspection. Garrido et al. (2018) proposed a robotic system for the sake of conducting PA ultrasonic scans of welds. Magnetic adhesion was used to climb ship hulls and track weld lines autonomously. A magnetic climbing robot named Sparrow was developed in order to perform autonomous hull thickness measurement (AR et al., 2020). Based on autonomous navigation and autonomous thickness measurement, a 2D plot was generated for the purpose of visualizing the evenness of the thickness of ship hull plates.

Optical cameras and electromagnetic sensors have also been used on climbing robots. Considering the large size and high load capacity of these robots, they often carry multiple types of sensors for the sake of improving inspection performance. Menegaldo et al. (2008) described the development status of a magnetic climbing robot, namely, SIRUS, to assess the external surface of Floating Production Storage Offloading (FPSO) vessels and large oil ship hulls. Three different types of sensors, including video cameras, an ultrasonic thickness measurement probe and an eddy current system, were used for hull inspection.

Eich and Vögele (2011) introduced a mobile lightweight magnetic climber, referred to as MIRA, for cargo hold inspection. A dual magnetic wheel was mounted on the climber for the purpose of overcoming the limitation of climbing over sharp obstacles, for example, the sleeve and dresser joints. The video of defects was logged for further analysis, along with the location and time stamp information. In (Ahmed et al., 2015), the robot was adapted to the semi-autonomous control mode. Asfis et al. (2014) developed a laser-guided climbing robot for the inspection of ship hull thin steel gauge welds. ACFM sensors were combined with a PAUT device for detection and sizing of the surface breaking and subsurface flaws. In (Emmanouilidis et al., 2004), a climbing robotic system was introduced for the automated inspection of steel plates. Both ultrasonic and electromagnetic sensors were used to scan the plates in order to detect corrosion and weld defects.

3.4. Comparison of the In-dock NDT Techniques for Different Hull Defects

To guarantee the seaworthiness of a ship, regular in-dock inspections are conducted. These inspections aim to determine the extent of damages by locating and assessing different hull defects. In Figure 7, the histogram presents a statistic of the utilization times of different hull inspection techniques on each of five types of defects, based on the publications reviewed in Section 3. As can be seen, cracks and corrosion have been studied more than the other types of defects in the scenario of in-dock inspections. Normally, corrosion can be detected using both visual testing and remote visual testing. It can also be detected using UTM

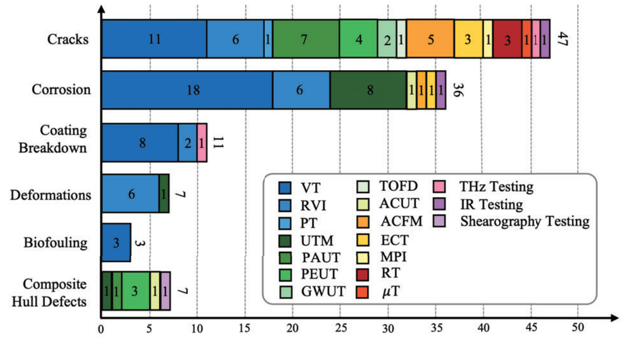


Figure 7: The histogram of five types of hull defects with regard to the frequency of the utilization of each in-dock hull inspection technique.

testing, which is usually used to decide the extent of damage. Although surface cracks can be detected visually, both internal cracks and weld cracks usually require UT and ET techniques. Considering deformations, coating breakdown and biofouling, visual inspection is the favorite method.

4. Underwater Ship Hull Inspection

According to the requirement of IACS, an underwater inspection of the ship bottom can be performed with the ship afloat (IACS, 2019b). This type of ship inspection, referred to as In-Water Survey or Underwater Inspection in Lieu of Dry-Docking (UWILD) Survey, can be used to acquire the data which is usually derived using a docking survey. Compared with in-dock inspection in which the ship has to be taken out of service and enter a dry dock, UWILD can be fulfilled in the case that the ship is moored to the quay or is berthed at the anchorage. As a result, UWLID is more suitable for the inspection of permanently moored offshore structures, such as offshore reservoirs and windmills. Hence, it is not necessary for the ship to quit its current trade route for inspection. Given that underwater inspection reveals damage or deterioration that requires early attention, a detailed inspection will be then performed and the corresponding repairs will be conducted in the case that the ship is dry-docked. Some underwater inspection operations also involved the detection of foreign objects or the items attached to the hull, such as identifying mines affixed to the hulls of warships and detecting smuggled cargo on ocean-going vessels.

In this section, we will investigate existing studies on underwater hull inspection in terms of manual inspection techniques and the automatic data processing approaches and automated platforms employed for automated inspection.

4.1. Manual Underwater Ship Hull Inspection

Traditionally, underwater hull inspection is carried out by divers under the supervision of classification society inspectors. Similar to the in-dock inspection, it also visually inspects the location and condition of hull defects and conducts further defect analysis using NDT methods.

Table 5
Summary of the automatic data processing methods used for automated visual inspection of underwater ship hulls

Feature	Classifier	Defect	Computational Cost	Practical Application	Reference
Graph intensity histogram	Manual analysis	Biofouling	Small	Yes	(Ismail et al., 2013)
Hue histogram	Histogram thresholding	Biofouling	Small	Yes	(Guo et al., 2016)
Inception V3 object detector		Biofouling	Large	No	(Chin, Si, Clare and Ma, 2017)
Haar features	Cascade + Artificial neural network classifier	Biofouling	Medium	No	(Chin, Si, Clare and Ma, 2018)
DWT features	CNN classifier	Biofouling	Medium	No	(Sundar et al., 2021)
CNN features	Probability-based binary classifier	Biofouling	Large	No	(O'Byrne, Ghosh, Schoefs and Pakrashi, 2020)
U-Net segmentation network with MobileNetV2 backbone		Corrosion, crack, biofouling and coating breakdown	Large	Yes	(Waszak, Cardaillac, Elvesæter, Rødølen and Ludvigsen, 2022)
Voting-based object classification method		Biofouling	Large	Yes	(Kim, Kim, Han and Park, 2022)

The underwater visual inspection is normally performed in the following procedures. Divers first dive into the required depth with the equipment of special instruments and video equipment. Then, the real-time video data of the ship hull is transmitted to the inspector onboard. Furthermore, the inspector observes the video data and directs the diver correspondingly. All detected defects are recorded using photography with the position information. For the hull dents detected, further measurements using ultrasonic or electromagnetic instruments will be required. Ismail, Salleh, Yusop and Fakhruradzi (2013) analyzed the growth of the barnacles on the ship hull by applying blob analysis and graph histogram analysis to the underwater images captured.

Typically, underwater acoustic-based testing methods are performed using handheld contact probes. Since these probes have to contact the surface of hulls closely, the operators (such as divers) need to find a clean area or get rid of the fouling before they place the probes on the hull. Considering UT can only inspect a single point at a time, a full inspection of the entire external hull surface is not practical. Therefore, the UT examination is only used to inspect the areas of interest. In (Zhang, Cho, Kim, Ugli Malikov, Kim, Yi and Li, 2021a), an ultrasonic NDT device was employed in order to decide the thickness of the underwater hull coating. The distance between the hull and the optimal water delay line was estimated on top of the reflection coefficient of the vertically incident wave because the energy attenuation and absorption rates of the offshore coating are high. The results of coating thickness measurement were evaluated using the time-of-flight of the reflected echo in the time-domain waveform. A ship hull foreign body detection method based on the imaging sonar was proposed by Teixeira et al. (2016). It was found that the features of a 30cm round metal cylinder together with the submap algorithm were sufficient for the detection task at the scale of a few centimeters.

4.2. Automatic Data Processing for Underwater Inspection

To improve accuracy and efficiency, underwater hull inspection can also be performed using automatic data processing methods. The combination of these methods and automated platforms may enable fully autonomous hull inspection.

4.2.1. Visual Inspection

The underwater environment is different from that in the air. Underwater images often suffer from image degradation, such as image noise, insufficient light and limited visibility, which poses a great challenge to automated underwater visual inspection methods. In this subsubsection, we will investigate automatic data processing approaches used for automated visual inspection of underwater hulls. The details of these approaches are shown in Table 5.

Handcrafted Feature Based Vision Inspection

Guo et al. (2016) analyzed the type and amount of fouling on underwater ship hulls. A threshold was set to the HSV color histogram in order to detect both microfouling and macrofouling. Morphological transformations and the Grabcut algorithm were used to decide the actual fouling area. However, automated inspection methods based on handcrafted features are susceptible to the influence of the quality of underwater images. As a result, inspection accuracy may be impaired.

Deep Learning Based Inspection

Recently, deep learning approaches have attracted much attention from both the industry and the research communities. When a large number of trusted training samples are available, such data-driven approaches are able to directly learn powerful features from these samples. Therefore, they normally achieve better performance than their traditional counterparts.

Chin et al. (2017) proposed a ship hull fouling recognition method which first used the Inception-v3 (Szegedy, Vanhoucke, Ioffe, Shlens and Wojna, 2015) model to classify the type of marine fouling and then employed a color-based segmentation method for measuring the fouling density. The Inception-v3 model was pre-trained using a fouling data set which comprised 1,825 images divided into 10 categories. Considering that the fouling data was not collected in the hull inspection scenario, the direct application of this model to the hull inspection task may encounter the domain shift problem. In (Chin et al., 2018), a ship hull fouling detection method was developed based on a Haar cascade artificial neural network classifier. It was shown that the method could detect barnacles at reasonable accuracy. Sundar et al. (2021) introduced a ship hull surface biofouling detection and identification approach. Features of the biofouling were first extracted using Discrete Wavelet Transform (DWT) and a CNN classifier was then used to differentiate the features at the level of fouling. Kim et al. (2022) designed a voting algorithm for underwater defect classification. Real-time defect detection was achieved by combining the classification results of six different deep networks.

In (Waszak et al., 2022), the performances of different semantic segmentation methods were compared in the scenario of underwater defect segmentation. The results showed that the U-Net (Ronneberger et al., 2015) built on top of the MobileNetV2 (Sandler, Howard, Zhu, Zhmoginov and Chen, 2018) backbone was able to balance the computational efficiency and the accuracy of the task.

It is known that deep learning methods normally utilize a large number of training samples. However, it is usually challenging for underwater inspection tasks to collect such a large data set. To address this issue, image generation methods have been proposed for the sake of increasing the accuracy of the CNN-based underwater inspection approaches. Using the E-on VUE software, O'Byrne et al. (2020) created a virtual scene, which simulated a barnacle-covered ship hull surface. A large and diverse data set was derived, which included different types of barnacles and showed various visibility and lighting conditions and different viewing perspectives. A CNN classifier was trained using the data set. Accurate detection results were achieved by applying this classifier to real ship hull videos.

4.2.2. Acoustic-Based Testing

The automatic data processing methods used for the acoustic-based underwater hull inspection are similar to those utilized in the dock. The reason is that acoustic-based testing techniques are not sensitive to the underwater environment. The details of the automatic data processing methods used for automated acoustic-based testing of underwater hulls are shown in Table 3. Ultrasonic guided waves were employed by Bingham et al. (2009) for identifying the foreign objects or items attached to the surface of hulls, such as underwater limpet mines. For the purpose of rendering the guided wave mode data in 2D binary images, the dynamic wavelet fingerprint technique was utilized. To automatically analyze the presence of mines, an excitation parametric approach was used..

4.2.3. Electromagnetic Testing

Few applications of automated electromagnetic testing methods to underwater hull inspection can be found in the literature. Hedayati, Amidian, Sadr and Razazan (2010) developed an ROV for inspection of the ship hull corrosion and mechanical problems. This ROV was equipped with a searching arm in order to locate electromagnetic flux leakages. The diagnosis was made with regard to the variation of reference alternating circulating current signals using the proposed expert system, which implies that there is a change within the ship hull structure.

4.2.4. Simultaneous Localization and Mapping Based Inspection

A SLAM system builds or updates a map of the unseen environment at the same time it locates the vehicle to which it is attached using multiple sensors. This method can be utilized on underwater vehicles in order to achieve fully autonomous navigation, control and inspection. While the vehicle locates itself relative to the hull, defect inspection is performed via stitching hull images together or building a 3D model of the hull (Ozog and Eustice, 2014).

Underwater SLAM mainly relies on visual implementations, such as image-based sonar (Walter, Hover and Leonard, 2008), stereo-vision and monocular cameras (Hover, Eustice, Kim, Englot, Johannsson, Kaess and Leonard, 2012). In (Kim and Eustice, 2009), a monocular camera system was employed in order to implement a pose-graph SLAM approach. This approach utilized an extended information filter for inference. The 3D points obtained using the SLAM algorithm were fitted in order to generate a smooth ship surface reconstruction for inspection.

Negahdaripour and Firoozfam (2006) proposed an ROV stereo vision system that provided three functionalities in automated inspection of ship hulls: positioning and navigation, 2D mapping using a photomosaic and 3D target structure reconstruction. The performance of the system was demonstrated in an environment where obvious surface texture could not be found. In (Ozog and Eustice, 2015) and (Ozog, Carlevaris-Bianco, Kim and Eustice, 2016), a SLAM system was built on top of a Doppler Velocity Log (DVL) and a stereo camera for ship hull inspection. Given the 3D computer-aided design model of a hull, this system was able to localize the ROV in it. Visually derived 3D shapes could also be labeled based on their deviations in terms of the nominal model mesh. These deviations, which usually result from biofouling, were included in the prior mesh.

4.3. Automated Platforms for Underwater Ship Hull Inspection

To reduce the dependence on divers and also improve the positional accuracy of the information acquired, the use of automated platforms, including ROVs and AUVs, to perform underwater inspection is becoming more and more popular (Zainal, Mokri, Yaakop and Zakaria, 2017). We will survey the automated platforms used for underwater hull inspection in this subsubsection. The details of ROV platforms are presented in Table 6 and the AUV platforms are presented in Table 7.

4.3.1. Remotely Operated Vehicles (ROVs)

In 1983, Nicinski (1983) developed a full-scale demonstration model of a remotely operated Ship Hull Inspection Vehicle (SHIV) for military vessels. This underwater vehicle

Table 6
Summary of ROVs utilized for underwater ship hull inspection

Name	Type	Navigation	Sensor	Reference
SHIV	Hull crawling vehicle	Remote	-	(Nicinski, 1983)
Lamp Ray	Hull crawling vehicle	Remote or waypoints control	UTM sensor, ECT sensor and RGB camera	(Harris and Slate, 1999)
-	Free-swimming vehicle	Remote	Dry film thickness sensor	(Lynn and Bohlander, 1999)
OCTOPUS	Hull crawling vehicle	-	RGB Camera	(Weiss, Andritsos, Schom and Fidani, 2004)
ICARE	Chain climbing vehicle	Remote	RGB Camera	(Weiss et al., 2004)
ROTIS	Free-swimming vehicle	Remote	UTM sensor and RGB Camera	(Weiss et al., 2004)(Andritsos and Maddalena, 2003)
-	Hull crawling vehicle	Remote	Conventional ultrasonic testing sensor	(Carvalho, Sagrilo, Silva, Rebello and Carneval, 2003), (Carvalho, Silva, Rebello, Carneval and Farias, 2005)
-	Free-Swimming vehicle	Stereo-vision based navigation	Stereo-vision camera	(Negahdaripour and Firoozfam, 2006)
AURORA	Hull crawling vehicle	Remote or stereo-vision based navigation	UTM sensor and RGB camera	(Akinfiev, Armada and Fernandez, 2008)
SY-2	Free-swimming vehicle	-	UTM sensor	(Li, Pang, Wan and Zou, 2009)
HISMAR	Hull crawling vehicle	Remote	UTM sensor	(Narewski, 2009)
LBV-5	Hull crawling vehicle	Remote	Imaging sonar	(Newsome and Rodocker, 2009)
SeeByte	Free-swimming vehicle	Remote	Imaging sonar	(Reed, Wood, Vazquez, Mignotte and Privat, 2010)
LBV-150	Free-swimming vehicle	-	RGB camera and stereo-vision camera	(Ishizu, Sakagami, Ishimaru, Shibata, Onishi, Murakami and Kawamura, 2012)
HROV	Free-swimming vehicle with motorized track	-	UTM sensor	(Ferreira, Yuri, Conte, Avila, Pereira, Morais and Ribeiro, 2013)
-	Free-swimming vehicle with motorized track	Remote	RGB camera	(Kostenko, Bykanova and Tolstonogov, 2019)
Étaín	Free-swimming vehicle	Remote	Laser scanner	(FitzGerald, Weir, Duraibabu, Omerdic, Dooly and Toal, 2022)

Table 7
Summary of AUVs utilized for underwater ship hull inspection

Name	Navigation	Sensor	Reference
CetusII	AquaMap long baseline based navigation	Imaging sonar	(Trimble and Belcher, 2002), (Trimble, 2003)
HAUV	Doppler velocimetry based navigation	DIDSON	(Damus, Desset, Morash, Polidoro, Hover, Chryssostomidis, Vaganay and Willcox, 2004), (Vaganay, Elkins, Esposito, O'Halloran, Hover and Kokko, 2006)
REMUS-100	Scanning altimeter based navigation	Imaging sonar	(Packard, Stokey, Christenson, Jaffre, Purcell and Littlefield, 2010)
-	SLAM-based navigation	RGB camera and imaging sonar	(Bin MS, Ismail, Bin Z and Sammut, 2016)
KAIST Mango-2	Stereo-vision based navigation	Stereo-vision camera	(Hong, Chung, Kim, Kim, Kim and Yoon, 2019)
Zeno	Stereo-vision based navigation	Stereo-vision camera	(Tani, Ruscio, Bresciani, Caiti and Costanzi, 2022)

used magnetic wheels to travel over and remained attached to the steel hull. The vehicle was designed to carry different sensors for the sake of performing hull inspection. The Imetrix Lamp Ray (Harris and Slate, 1999) was considered an early commercial hull inspection vehicle. In essence, it was a small ROV, which was used to perform inspection by crawling over the hull surface. Multiple sensors were installed on the ROV, including four channels of ultrasonic thickness gauging utilized for ship hull plate thickness measurement, an eddy current probe used for ship hull coating thickness measurement, a silver chloride probe employed for galvanic potential measurement and video cameras.

Computer vision methods have been commonly used for underwater vehicles. Weiss et al. (2004) introduced a remote robot system, referred to as Instrumentation, Control and Architecture of Advanced Robots, for surface and subsea cleaning and crack inspection of anchor chains, which was able to climb up and down the chain with two claws. Besides, an automated hull crawler, namely, OCTOPUS, was developed, which was equipped with permanent magnets to move on the hull surface and underwater cameras to perform defect inspection. A stereo vision system was proposed by Negahdaripour and Firoozfam (2006) for purposes of navigation, positioning and ship hull inspection based on ROVs. Ship hull inspection was realized by building the instantaneous 3D map of the ship's surface. This technique was used to detect the foreign objects that were attached to the ship structure.

To inspect the ship hull, Newsome and Rodocker (2009) developed the LBV-5 ROV which carried an imaging sonar. It was directly attached to the physical hull of a ship by the negative pressure for performing the inspection task. In (Reed et al., 2010), an ROV solution, namely, SeeByte, was proposed for ship hull inspection. This ROV used a 2D imaging sonar with the image stitching technique to achieve a real-time image display of the hull. A rule-based classification algorithm was employed for the automatic detection of defects in sonar images.

Ishizu et al. (2012) developed an ROV, namely, LBV-150. This ROV had a mechanical contact device that ensured that hull inspection was performed at a constant distance. On top of this device, the ROV was able to obtain close-up and clear images using a stereo vision system and a hand-eye vision system. In their work, Kostenko et al. (2019) also developed an ROV that aimed at facilitating remote monitoring of the hull quality by inspectors. Additionally, the ROV was equipped with underwater laser equipment for automated hull cleaning. In (FitzGerald et al., 2022), an underwater hull defect inspection-repair ROV, namely, Étaín, was developed. This robot could perform not only the cleaning operation but also the laser-based 3D reconstruction task of underwater hull cracks.

On the other hand, UT systems have also been widely deployed on ROVs in order to perform thickness measurement and defect detection tasks for ship hulls. Due to the nature of the UT techniques, the ROV has to be close to the hull. In (Carvalho et al., 2003) and (Carvalho et al., 2005), an automatic underwater inspection system was introduced using the ultrasonic method. This system was designed to inspect the defects resulting from the corrosion on the surface of the hull of the floating units utilized in offshore oil production. In addition, a remote mobile vehicle was introduced, which contained ultrasound pulse-echo equipment and a set of magnetic wheels that secured the vehicle to the hull.

Andritsos and Maddalena (2003) introduced a Remote Operated Tanker Inspection System (ROTIS). A free-floating ROV, which was able to navigate inside the flooded ballast tanks of double-hull vessels, was used to carry out close-up wall thickness measurements based on ultrasonic techniques. In (Akinfiev et al., 2008), an NDT method of ship hulls with the AURORA underwater robot was developed. The sheet thickness of a hull was measured using an ultrasonic probe during the movement of the robot. At the same time, the results were shown on the screen. The robot was attached to the surface of the hull. It was able to position itself using ultrasound and guide its movements by means of visual servos.

The SY-2 ROV developed by Li et al. (2009) was used for ship hull inspection and offshore drilling platform maintenance. To perform ship hull cleaning, Narewski (2009) introduced a remote-controlled underwater crawling robot, namely, HISMAR. This robot fulfilled plate thickness measurement using the UTM device onboard. In (Ferreira et al., 2013), a Hybrid Remotely Operated Vehicle (HROV) was designed for ship hull thickness measurement and crack detection, along with ultrasonic transducers.

Moreover, electromagnetic testing methods can be applied together with an ROV. Lynn and Bohlander (1999) performed the Dry Film Thickness (DFT) testing using an ROV on the US Navy ships. By means of the magnetic induction operation, the DFT probe was used to measure the thickness of the non-magnetic coatings on the ferrous substrate.

4.3.2. Autonomous Underwater Vehicles (AUVs)

As a free-swimming autonomous system, the CetusII AUV (Trimble and Belcher, 2002) (Trimble, 2003) was designed for ship hull damage or contraband survey using a sonar. To ensure that the ship was fully covered and the globally-referenced survey information was recorded, the AquaMap Long Baseline (LBL) navigation system was utilized. A transponder network, which was deployed near the ship, was utilized by this system.

The imaging sonar is one of the most commonly used sensors employed on AUVs. Since they are able to detect at high accuracy over both short and long distances, they can be used for the inspection of hulls and even port environments. In (Damus et al., 2004), (Vaganay, Elkins, Willcox, Hover, Damus, Desset, Morash and Polidoro, 2005), (Vaganay et al., 2006), (Hover, Vaganay, Elkins, Willcox, Polidoro, Morash, Damus and Desset, 2007), (Kokko, 2007) and (Vaganay, Gurfinkel, Elkins, Jankins and Shurn, 2009), researchers from MIT and Bluefin Robotics developed a Hovering Autonomous Underwater Vehicle (HAUV). This vehicle has been widely utilized for hull inspection. DVL and acoustic beams were applied to the hull-relative navigation and the simultaneous range-based navigation, respectively. For the sake of conducting high-resolution image-based hull inspection, the DIDSON was used. A great progress made by this study was the inspection of the hull without contacting the vessel. Specifically, the HAUV conducted a free-fly movement normal to the vessel at the same time the plate and profiles were inspected using the DIDSON, in the case that the HAUV remained over one meter away from the hull.

Packard et al. (2010) developed an AUV for a high-resolution autonomous survey of ship hulls, confined harbors and precise target reacquisitions, referred to as Remote Environmental Monitoring UnitS or REMUS-100. Using a high-resolution imaging sonar system, the multi-perspective view of a single target was derived at a moment. In (Bin MS et al., 2016), an AUV system was built for hull inspection. The wide view of the ship hull was derived using two onboard cameras. Additionally, an imaging sonar was used for viewing the hull in the turbid water.

Considering that binocular vision approaches are able to not only provide autonomous navigation information but also obtain a 3D visual model of the hull for visual inspection, they have been becoming a hot topic in AUV-based hull inspection studies. In (Hong et al., 2019) and (Hong and Kim, 2020), an autonomous in-water visual inspection system, namely, the KAIST Mango-2 AUV, was developed. While the stereo camera performed real-time SLAM, images of the side hull surface were stitched. To obtain the 3D reconstruction of the surveyed hull surface, Tani et al. (2022) built a Zeno AUV system on top of a stereo vision device.

4.4. Comparison of the Underwater NDT Techniques for Different Hull Defects

The underwater hull inspection is conducted when a ship is docked in the water and allows for early detection of hull damages in order that repairs can be carried out promptly.

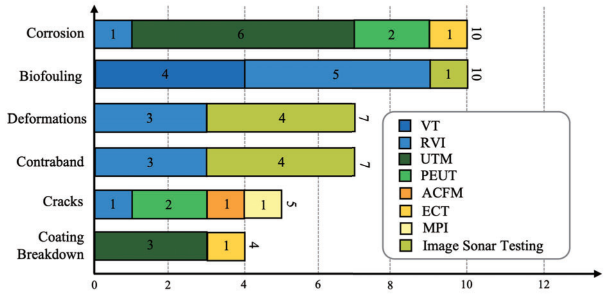


Figure 8: The histogram of six types of hull defects with regard to the frequency of the utilization of each underwater hull inspection technique.

The histogram shown in Figure 8 provides a statistic of the utilization times of eight hull inspection techniques on each of six types of defects, based on the publications reviewed in Section 4. It is shown that surface defects are normally focused by underwater inspections. Visual inspection and high-resolution image sonar testing techniques were normally used for inspecting these defects. To determine the condition of the corrosion and coating, UTM inspection was used because it was able to measure the thickness of hulls. Electromagnetic methods, such as MPI, ECT and ACFM, were also used for underwater inspection.

5. Health Monitoring Based Ship Hull Inspection

Structural Health Monitoring (SHM) systems have become a recent development in the damage detection of ship hulls. To archive the structural response when a ship is normally operated, these systems utilize different sorts of accelerometers, sensors and strain gauges (Frangopol and Soliman, 2013) (Beko, Ivošević and Dlabač, 2021).

Different tasks can be fulfilled using the SHM systems, including damage detection, damage diagnosis, damage prognosis, monitoring the structural response in normal operations, validation of design assumptions and useful life estimation (Lauzon, Benhamou and Andoniu, 2021). Modern SHM systems can also be used for early detection and location of ship hull cracks (Banovs, Unbedahts and Rijkuris, 2013). In (Salvino and Brady, 2008), an SHM system that used a series of techniques, for example, statistical feature extraction, time-frequency signal analysis and real-time diagnostic, was proposed for the detection of cracks and structural damages of high-speed vessels at the earliest possible stage. In addition, extracting valuable information from long and consistent structure monitoring data to reduce measurement uncertainty is also worth investigating (Hageman, Meulen, Rouhan and Kaminski, 2022) (Hageman, Aalberts, Shaik and van den Boom, 2015).

In general, the SHM operation is performed using two types of approaches: the active SHM and the passive SHM approaches (Abbas and Shafiee, 2018). The active SHM approaches normally use a series of sensors or actuators to directly detect and estimate structural defects. In contrast, an external excitation generator is used by the passive SHM approaches to generate elastic waves within the structure. For the purpose of health assessment, a set of functioning parameters, for example, stress and vibration levels, are utilized. In this section, we will focus on four typical classes of SHM approaches, i.e., passive sensor-based monitoring approaches, vibration-based monitoring approaches, acoustic emission monitoring approaches and strain-based monitoring approaches.

5.1. Passive Sensor-Based Monitoring

A passive sensor is normally a micro-mechanical sensor which operates without using the electronics or energy supply. Instead, this sensor acquires the mechanical sensing energy from the deformations of the structures that it monitors. These compact "plug-and-forget" sensors do not demand external wiring, which simplifies the deployment of them. An example of such a sensor was introduced by (Bense, Florent, Frutos and Hebrard, 2014), which was a fully autonomous passive sensor developed by SilMech. This kind of sensor is capable of detecting and recording impacts, mechanical vibrations and both mechanical and thermal deflections in structures.

Kawasaki Heavy Industries Ltd. and Kawasaki Shipbuilding Corporation developed the fatigue damage sensor for FPSO vessels (Takaoka, Nihei, Vargas, Aalberts and Kaminski, 2010). The calibrated fatigue damage sensor was installed on the FPSO structure, which enabled the intuitive assessment of the fatigue level of the structure by measuring the crack length. However, the data of passive sensors has to be read by humans.

5.2. Vibration-Based Monitoring

To detect the occurrence and position of damages, vibration-based monitoring approaches employ variations of the dynamic characteristics of structures, including the damping ratio, mode shape, natural frequency and structural response. The equipment that is utilized for receiving the vibration response does not have to be located in the vicinity of the damage. Both manual excitation and environmental excitation can be used for vibration-based ship hull inspection. In the case that the structure is still in the operating state, damage inspection normally uses environmental excitation.

In (Zubaydi, Haddara and Swamidas, 2000) and (Zubaydi and Haddara, 2002), autocorrelation functions were used to assess the response of stiffened plates under the exciter and accelerometers. To detect the position and extent of different crack damages, neural networks and finite elements were utilized. For the purpose of inspecting the cross-stiffened plates of oil tankers, both the experimental and analytical methods were developed in (Budipriyanto, Swamidas and Haddara, 2005) and (Budipriyanto, Haddara and Swamidas, 2006). Using the finite element model, the optimal arrangement of strain gauges and accelerometers was determined, which was used to evaluate vibration responses. The damage identification and localization method was presented on top of the root mean square of the dynamic response magnitude.

Zhang, Guo, Hao, Yang and Li (2020) proposed a theoretical method for locating ship damages and measuring the degree of damages. Under high-precision modeling, dynamic characteristic parameters, such as natural frequency and model shape, were used to train the back-propagation neural network for damage identification. In (Ma and Wang, 2021a) and (Ma and Wang, 2021b), a steel ship plate crack location and level method was proposed using acceleration signals. With the nonlinear finite element model, a CNN-based model was also introduced for crack detection. On top of two different vibrodiagnostic signal analysis methods: spectrum analysis and time waveform analysis, Muc et al. (2018) introduced two crack detection approaches for ship hulls.

It is noteworthy that the vibration-based monitoring research remains in the theoretical simulation stage as of now. None of the practical applications to operational hulls have been found in the literature that we reviewed in this study. This lack of application should be attributed to the limitations of the sensors and data processing techniques involved. Leveraging deep learning methods for processing vibration signals offers possibilities in overcoming these limitations and potentially advancing a practical implementation.

5.3. Acoustic Emission Monitoring

The Acoustic Emission (AE) monitoring operates by mounting AE sensors onto the ship structure under inspection. When the structure receives an external stimulus, such as high pressures, loads and temperatures, elastic waves (such as Lamb waves) are released, which are captured by the AE sensors. The elastic waves can be utilized for the detection of structural damages, for instance, corrosion, crack initiation and growth, fracture, elastic corrosion cracking and plastic deformation (Anastasopoulos, Kourousis, Botten and Wang, 2009). To monitor these damages, emissions are constantly detected and logged when a ship is under normal operation.

In (Baran, Nowak, Jagenbrein and Bulglacki, 2012), corrosion and fatigue damages were detected using the AE equipment. With regard to these damages, the signals were isolated using pattern analysis from the background noise. A discontinuous and permanently installed AE testing system was developed for real-time detection of corrosion attacks on ship oil tanks (Tscheliesnig, 2004) and (Tscheliesnig, 2007). The system was able to distinguish the meaningful corrosion noise, which originated from the background noise, from the environment and structures. Wang, Lee, Serratella, Botten, Ternowchek, Ozevin, Thibault and Scott (2010) demonstrated that the AE monitoring was effective in roughly locating the structural degradation and increasing inspection efficiency.

Arifianto (2018) proposed an acoustic data emission method for crack detection in the ship propeller shaft. For the purpose of improving measurement accuracy and microphone sensitivity, a co-linear array of microphones were employed in the engine room of a ship, which was very noisy. A ship structure crack detection method was introduced by Kappatos, Georgoulas, Stylios and Dermatas (2009) based on the AE technique. On top of a set of basic features extracted in a lower dimensional space, new features were computed using an evolutionary method based on a linear transformation. To perform the crack classification task, these features were sent to a probabilistic neural network. In (Karvelis, Georgoulas, Kappatos and Stylios, 2021), ship hull crack inspection and SHM were considered as a classification task. Both discrete cosine transform and dimensionality reduction were used to process AE signals. Within the classification unit of the AE signals, a deep neural network was utilized for locating cracks.

In (Fromme, 2009) and (Fromme and Rouge, 2011), the utilization of distributed sensor arrays, which released low-frequency guided ultrasonic waves, in the permanent SHM of the large plate-like structures of ship hulls, was investigated. A hybrid model was developed for the display of the approximate locations and orientations of defects. For the sake of monitoring the thickness reduction of the wall of ship hulls caused by corrosion, guided ultrasonic waves in high frequency were further employed (Fromme, 2014).

5.4. Strain-Based Monitoring

Strain-based monitoring first measures the strain of the structure under service loads at the beginning of the service life of a hull as the baseline. Then it continuously monitors the strain. Significant changes in magnitude or shape in the strain distribution indicate possible structural damages. The baseline strain can also be obtained from instantaneous measurements of undamaged structures. In practice, electrical strain gauges and fiber optics have been widely used for strain-based SHM method (Silva-Campillo, Pérez-Arribas and Suárez-Bermejo, 2023).

To investigate the impact of sea ices on hull loads, Pran, Le Breton, Sagvolden, Espeland and Mejlaender-Larsen (2009) used Bragg grating strain gauges to monitor the stress data on an icebreaker during its operation in the ice-covered areas. Silva-Muñoz and Lopez-Anido (2009) proposed a strain-based SHM system for composite hull joints based on distributed embedded fiber Bragg grating sensors, in which FE models were used to determine the sensitivity of crack growth to strain changes. Silionis and Anyfantis (2022) designed a new strain-based damage monitoring strategy of the hull girder on top of a statistical pattern recognition method. Furthermore, they (Silionis and Anyfantis, 2023) developed a ship hull corrosion-induced thickness loss monitoring method through remote strain sensing. Specifically, the operational variability was introduced based on cargo filling rates and the synthetic strain response data was generated using FE. In (Sireta and Storhaug, 2022) and (Sireta, Van der Cammen and Storhaug, 2022), the strain gauge data was used together with 3D FE analysis to predict fatigue damages and extreme stresses of the hull structure. In real-world scenarios, the majority of predictions can be implemented using no more than 8 strain gauges. The approach has been effectively applied and validated along with Det Norske Veritas.

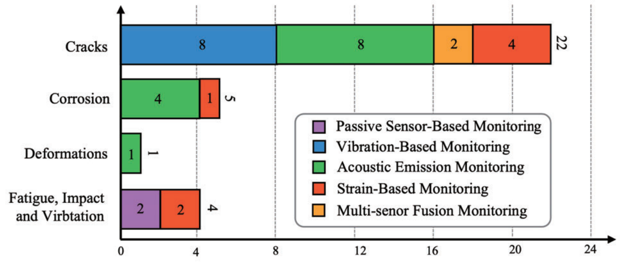


Figure 9: The histogram of three types of hull defects with regard to the frequency of the utilization of each health monitoring-based inspection method.

The monitored stress data can also be used to analyze the fatigue of the hull. Andoniu, de Lauzon, Hageman, Aalberts, L'Hostis and Ledoux (2021) employed stress monitoring as a reference, to build a mathematical model for the spectral fatigue analysis of FPSOs. This model was used to assess the impact of the description of the wave energy on the evaluation of fatigues in FPSOs. In (Hageman and Thompson, 2022), the fatigue damage values derived from strain measurements were compared with the fatigue damage data estimated using the wave hindcast data of a frigate-type hull.

5.5. Comparison of the SHM Systems for Different Hull Defects

With the help of SHM systems, the condition of hulls can be monitored and hull damages can be determined during the voyage of a ship. Figure 9 shows a histogram in which a statistic of the utilization times of three hull health monitoring techniques is demonstrated corresponding to each of the three types of defects, based on the publications reviewed in Section 5. As can be observed, vibration-based SHM techniques were normally used for detecting hull cracks. This observation should be due to the fact that cracks usually alter the vibration behavior of the ship hull. In contrast, acoustics-based SHM methods, which are more versatile, were used to identify cracks, corrosion and deformation on the hull. Besides, the integration of multiple sensors in the SHM system has emerged. In the literature, this sort of technique has shown the ability to perform more comprehensive and effective hull inspections.

6. Discussion

Ship hull inspection is necessary for safe navigation because it enables the proper functioning of a vessel. Therefore, the inspection operation needs to be carried out on a regular basis. Traditionally, hull inspection is manually conducted in-dock using visual testing, ultrasonic thickness measurement, ultrasonic testing, electromagnetic testing, etc. However, in-dock inspection is time-consuming and economically unproductive, because the vessel has to be out of service, arrive at the designated port, empty its cargo, wait for available docks and undergo a series of pre-inspection preparations. Regarding the manual inspection, false alarms or missed defects may also threaten the operational safety of the vessel.

Reducing the time out of service and increasing the accuracy of hull inspection are two priorities in the future development of hull inspection techniques. Despite numerous studies that have been completed in recent years, there are still many challenges that need to be addressed in future development. We will discuss seven challenges in this section.

6.1. Challenges of Reducing Time Cost

Shipowners may suffer a huge loss if the unavailability of the ship is taken into account during the inspection operation. In this situation, the challenges will be due to improving the efficiency in order to reduce the time cost of the operation. Three challenges can be identified as follows.

6.1.1. Reduction of Preventive Operations

In-dock hull inspection generally requires an inspector to perform the close-up inspection operation of each part of the hull. This operation may encounter dangers, such as fall accidents, oxygen shortage, rafting accidents and overheating (Ahmed et al., 2015). Therefore, hull inspection involves a set of preventive operations, including cleaning, lighting, ventilating and temporary set-up of cherry pickers or ladders (Poggi et al., 2020). These operations significantly increase the time cost of in-dock inspection tasks.

In contrast, the robot-based inspection avoids the above-mentioned risks as the inspector can operate the robot at a safe place rather than accessing different operation locations. In this case, the preventive operations can be omitted. As a result, the time cost is greatly reduced. Given that rational path planning algorithms (Muthugala, Samarakoon and Elara, 2022) or multi-robot collaboration techniques (Grippa et al., 2022) (Ruediger, Paine and Banerjee, 2022) are applied, the efficiency of the robot-based inspection will be further improved.

6.1.2. Inspection with Ship Afloat

To reduce the time cost of regular inspections, classification societies have approved a range of in-water inspections and underwater surveys instead of the in-dock survey, which allow the vessel to be inspected while it stays in the water without leaving service. Since underwater inspection disturbs the shipping schedule less and takes a shorter period out of service, it is more economical than in-dock inspection. If defects can be repaired afloat, repair operations will be conducted during underwater inspection.

Underwater inspection is typically conducted in the case that the ship is berthed in the water with debilitated currents and tidal streams. For purposes of deciding the status of the appendages, plating and welding, both the visibility and cleanliness of the hull below the waterline have to be adequately high. Therefore, future development should be focused on performing underwater inspections in various sea conditions, water temperature and visibility conditions.

Commercial underwater vehicles further improved the efficiency of hull inspection with a user-friendly interface and quick deployment. However, the challenge of underwater vehicles is due to the fact that they are usually remotely controlled, which requires an additional vehicle operator besides the inspector. With the development of onboard graphical processing units and vision-based perception sensors, the automation level of underwater vehicles can be further enhanced. As a result, the dependency on the operator will be alleviated.

6.1.3. *Inspection without Ceasing the Service*

Hull inspection without ceasing the service will be given emphasis during future development. This goal can be achieved using an SHM system. This system monitors the condition of a ship and performs the early detection of hull defects in real-time by deploying a series of sensors on the ship. These sensors are able to receive signals during the operation of the ship. The design of highly accurate sensors and their deployment rules play important roles in the development of SHM systems.

To expedite the detection of concealed failures and anomalous ballast conditions during ship navigation, the integration of wireless sensor networks and the Internet of Things (IoT) may be useful for improving the SHM system (Yang, Shi, Chen, Dong and Hu, 2017). This approach enables concurrently collecting the data of stress variations, hull deformation and twisting, vibration impact on hull structure and acceleration information. These data are then transmitted back to the remote monitoring system via the maritime satellite network or GPRS wireless network. The remote monitoring system is capable of analyzing those data, monitoring the status of ships and facilitating prompt maintenance and rescue planning.

To expedite the detection of concealed failures and anomalous ballast conditions during ship navigation, the integration of wireless sensor networks and the Internet of Things (IoT) could help improve SHM (Yang et al., 2017). This approach allows for the concurrent collection of data on stress variations, hull deformation and twisting, vibration impact on hull structure, and acceleration information. These data are then transmitted back to the remote monitoring system via a maritime satellite network. The remote monitoring system is capable of analyzing this data, monitoring the ship's status, and facilitating prompt maintenance and rescue planning as necessary.

The most advanced technology currently introduces structural digital twins into the field of SHM, using hull data collected by sensors to provide a digital copy of the physical structure to describe its characteristics and properties. This technology can improve the efficiency and reliability of structural health monitoring and prediction (Bhat, Nadathur, Knezevic, Aalberts, Kolsters, Amuda, Atebe, Pasala, Hoang, Luong, Huynh, Righetti, Hageman and Yu, 2021). Digital twins-based lifecycle management can also provide operational data feeds, detailed structural analysis based on as-is asset conditions, and automated structural integrity reporting. External environmental data, such as wave data, can be used by the structural digital twin method for fatigue analysis (Eric, Zhenghua and Sankaran, 2022).

6.2. Challenges of Increasing Inspection Accuracy

Traditionally, skilled inspectors, who grasp the wide knowledge of the hull structure, have to be employed for conducting manual hull inspection operations. However, both the expertise and experience of the inspectors may affect the accuracy of hull inspection. Three challenges that current hull inspection methods encounter can be identified which influence the inspection accuracy.

6.2.1. *Challenge of Sparse Sampling of Locations*

The traditional acoustic-based manual inspection methods, such as UTM, require that the probes stay very close to the surface to be inspected. In this context, the inspector has to find a clean region or clean off the fouling before performing the inspection task. Therefore, this operation usually results in the reasonably sparse sampling of sensor measurements. As a result, critical sections may be missed as there are often not enough resources for cleaning the entire hull. In contrast, visual inspection methods can be used to find the approximate location of surface defects, while they cannot detect internal defects. This results in a fairly sparse sampling of the hull structure and may be not representative of the true condition of the entire structure.

To address the above-mentioned issues, future sensor technology development needs to achieve the scanning and visualization of the wider area or enable the detection of internal structures without removing the coating or biofouling. Multiple sensors can also be brought together in order to build a practical system. In (Sheppard et al., 2009), for instance, defects on the composite hull skin were visually found along with the laser shearography or the traditional tapping. A UT method was further used to assess the full extent of these defects. Wilken et al. (2015) incorporated the stereo cameras and inertial sensors mounted on the helmet of the inspector into the ship structure inspection system. In this situation, image capturing, automatic spatial referencing and 3D modeling were integrated in the same system. The use of these sensors alleviated the reliance on the skills of the inspector.

6.2.2. *Challenge of Uncertainties of Manual Inspection*

In practice, the majority of hull inspection operations still require that human inspectors access every position of the hull structure and identify all possible defects with hand-held devices. They have to concentrate on observing a large amount of data, which often contains only a few data of actual defects (Xie et al., 2021). Since this kind of operation is tedious, the inspectors may ignore some defects. Both the experience and expertise of them may also have an impact on the detection and assessment of defects, in particular, when the defects that occur in the early stages are encountered because these defects are not easily identified.

Consequently, a prevailing focus of development is put on the preprocessing of the hull data, which is subsequently presented to inspectors for assessing the condition of the hull, using computer algorithms. Among these algorithms, deep learning techniques which are able to acquire general defect representations from a large quantity of hull data, produced the more precise and robust defect detection results (Waszak et al., 2022). The advantages of deep learning methods in hull inspection are as follows: Firstly, deep learning algorithms exhibit rapid data processing capabilities for acquired hull data, with certain implementations achieving real-time processing (Zhou et al., 2022). Secondly, they could excel in the identification of early defects or defects with incomplete observations by effectively capturing deep features associated with these anomalies. Furthermore, they can also determine the size, severity, and presence or absence of defects, collectively contributing to enhanced defect detection accuracy (Kai et al., 2021).

6.2.3. Challenge of Large Volumes of Labeled Data

The application of automatic data processing methods has been explored for the purpose of increasing inspection efficiency and reducing the demand on the inspector. Traditional automated visual inspection approaches were typically developed based on a collection of hand-crafted features, which described different image characteristics, such as color, edge, shape and texture. Nevertheless, these hand-crafted features are usually struggling with generalizing to a different domain. In other words, features tailored for an inspection scenario are difficult to apply to a different scenario.

Recently, deep learning techniques have experienced significant growth in the context of hull inspection. These techniques are able to learn features from a large set of labeled training samples. In contrast to the hand-crafted features, these features are more generic. Nevertheless, the main drawback of those techniques is that a large labeled data set is required, which may be not practical in some cases, particularly for underwater hull inspection. To address this issue, Waszak et al. (2022) acquired a large-scale image segmentation data set for underwater ship lifecycle inspection, analysis and condition information (LIACI). Four types of hull defects, including corrosion, paint peel, marine growth and defects were considered. In (Momber, Langenkämper, Möller and Nattkemper, 2023), a visual data annotation method was developed for the protective coating system on the stationary marine steel structure. This method can be potentially applied to the field of ship hull inspection.

6.2.4. Challenge of Inaccurate Defect Localization

In practice, inspectors have to manually record the location of defects, or mark them using photographs or videos. Since the localization process usually relies on the markings labeled on the hull or outdated hull design drawings, it is labor-intensive and error-prone. In the scenario of underwater hull inspection, divers normally use hull markers for locating defects. Due to the complex underwater environment, the inaccurate localization problem is even worse.

Compared with the manual methods, the use of robots enables the effective localization of observations by automatically locating defects while positioning themselves. With the development of on-board computers, these robots can make use of vision systems for state estimation based on different Kalman filter and SLAM methods. The research and development of onboard sensors, including LiDAR sensors, monocular cameras, optical flow sensors, RGB-D cameras and stereo-vision cameras, will further boost the performance of defect localization.

7. Conclusion

In this paper, we reviewed a large number of publications related to ship hull inspection. Particularly, we focused on the different NDT techniques involved in many inspection tasks. In terms of these techniques, we investigated a series of manual inspection approaches and the automatic data processing methods and automated platforms used for automated inspection.

To be specific, we first reviewed the background knowledge of hull inspection, including different types of hull defects, various types of NDT techniques applied to hull inspection and different automated platforms used for data collection. This knowledge is able to provide readers with extensive basic knowledge in order that they can understand the following survey easily. Then, existing ship hull inspection approaches were divided into three groups, i.e., the in-dock, underwater and health monitoring-based approaches. The survey was performed in terms of these groups. Regarding the in-dock and underwater hull inspections, particularly, the associated approaches were categorized into three sets, including manual inspection approaches and the automatic data processing methods and automated platforms employed for automated hull inspection. Within each of the first two sets, the approaches were investigated with regard to the type of NDT techniques. For the health monitoring-based hull inspection, both the vibration-based and acoustic emission monitoring methods were reviewed. In addition, we briefly surveyed a set of other related methods to hull inspection. Finally, discussions were further made regarding the publications surveyed in this study.

CRediT authorship contribution statement

Bosen Lin: Writing original draft preparation, literature collection and analysis. **Xinghui Dong:** Conceptualization of this study, literature collection and analysis, revision of article presentation.

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